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Evaluating the performance and effectiveness of ladder stability devices

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Evaluating the performance and effectiveness of ladder stability devices

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This report serves to summarise the project work undertaken during a study to evaluate the performance and effectiveness of ladder stability devices, particularly where intended for, or used in, the UK market. It describes the test methodologies used to undertake the collection of dynamic data using an innovative stability platform. Later sections interrogate this data in order to examine the manner in which instability occurs in the ladder and stability device systems, relating it to both the ladder's structure and the user's behaviour. The manner of operation of stability devices is then scrutinised and mathematical modelling of the stability criteria controlling their effectiveness undertaken. A predictive model is developed that will establish the stability performance of any conventional stability device on the basis of readily available mechanical data. A simple workshop test which will determine acceptable levels of stability performance is also described which would be appropriate for inclusion in technical standards. Additional consideration is given to manual footing of ladders and the effectiveness of this technique is also quantified. A final section deals with possible avenues for the dissemination of this vital information.

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Executive Summary

This report details the background, methodology and findings of an extensive investigation into the issue of the performance of leaning ladder stability devices and manual ladder footing. This work has been funded by the Health and Safety Executive to provide a factual basis on which to make recommendations regarding safety practice within the community.

An initial literature review examines the current state of knowledge and this information is presented in a summarised form. A further examination of the standards and legislation relevant to ladders is also undertaken and a summary presented.

A market survey was undertaken to determine the range and nature of ladder stability devices that are available to the UK market and these are categorised into clear groups on the basis of functionality, comprising top mounted, base mounted, platform, tripod, foot enhancement, tie-off and unorthodox sections. Sample products were obtained of the generic types for illustrative purposes, however no specific proprietary products were appraised.

In order to identify the demands placed upon ladders and hence the stability demands which need to be met by auxiliary devices, extensive user trials were conducted. Seven challenging tasks were performed by 52 individuals, each one self-determining the level of risk they took. Each task was replicated for consistency. An additional trial identified what each participant understood by 'footing' and recorded their personal footing preference in photographic and data recorded performance. In total 780 trials were undertaken.

This data set was critically analysed and manipulated to produce a set of parametrics which accurately represent most onerous conditions of reasonable use. These parametrics then provide the basis for the development of two main outputs.

A set of predictive modelling tools were developed which permit the appraisal of the stability performance of any conventional ladder stability device over four potential failure modes (base slip, top slip, flip and top contact). Given a limited number of dimensional values any such device can be evaluated and its performance determined. The simple meeting of critical values will identify whether it offers adequate safety, whilst safety enhancement is quantified by the amount over this threshold.

A simple workshop test is devised which will permit the rapid appraisal of real products. The application of pairs of loads will identify a pass/fail level of acceptability in all four failure modes. This is eminently suitable as a base line test in a technical standard to ensure minimum product performance.

Ladder slip resistance is also appraised. It is apparent that current ladder feet offer adequate slip resistance and enhancement is not necessary. Maintenance, however, is essential to ensure that the capacity of the feet to offer sufficient grip is retained.

Ladder devices intended to correct for ground slope are scrutinised and the performance of ladders in this environment considered. Ladders can work safely at lateral slopes of up to 22° although 16° should be considered a safe limit. Similar values for back slope are 12° and 6°. Additional devices are unnecessary and will not enable safe use at greater angles.

Ladder footing was modelled and the effectiveness of different footing techniques appraised. Footing is ineffectual against the failure modes affecting the top of ladders and, although offering benefit, unnecessary to improve base friction. It can be of benefit in preventing flip but this is highly dependent upon the technique employed. Some techniques can reduce the stability in all modes. Individuals footing ladders should apply weight downwards on the ladder (standing on a rung) or push against the ladder stiles, although this is five times less effective. It is imperative that the weight is evenly distributed across the ladder and this can best be achieved by the provision of a platform or stool to do this artificially. Alternatively, the loading of the ladder with customised weights would be as effective.

Finally, the key recommendations are that:

- There is a need for a technical standard to ensure quality and performance
- Devices could be certified for use, the criteria being demonstrable compliance with adequate performance in all four failure modes
- Footing technique should be prescriptive and its limitations recognised
- An extensive degree of market and user education is required

As part of the validation of this work this report has been reviewed by Dr Brian Ellis, BRE and Dr Gerhard E Völkel, independent engineering consultant. Their comments have been addressed in completing this work and their recommendations for further work are currently being considered by HSE.

1.0 BACKGROUND AND SCOPE OF THE STUDY

Ladders continue to be a safety concern for both consumers and professional users, with significant numbers of deaths, hospitalisations and serious injuries attributable to their use. In accident statistics, ladders are commonly one of the most injurious products within both the domestic and industrial environments and this leads to considerable human suffering and financial cost. This is more surprising given the other objects accounting for injuries, such as grinders, power saws, etc. and activities undertaken, such as vehicle maintenance. The fact that such patently dangerous tools and activities are responsible for lower accident rates than ladder use suggests that there is a fundamental problem associated with both the design and application of ladders to tasks.

In order to address at least some of these problems a range of devices and methodologies have been introduced to apparently increase the margin of safety provided by the ladder system. Manual ladder footing has traditionally been a means of temporarily raising the level of stability provided and this is specifically recommended in Health and Safety literature. Mechanical devices intended to offer a similar or greater level of stability enhancement are also cited and this has spawned a wide diversity of such items in the market place.

Such is the reliance on these interventions that it is essential that a full understanding is maintained of the value of them so that they can properly form part of an on-going development of safety practice and legislation.

1.1 THE PROBLEM

As previously identified, manual footing and mechanical stability devices are cited as being required to improve the stability of ladders prior to tying-off or during short duration tasks. However, what is meant (or understood) by the term footing is undefined and its effectiveness unquantified. Accordingly, mechanical devices intended to offer the requisite equal or better performance also remain unquantified, and relative benefits are therefore undetermined.

There is a pressing need to understand the requirements of ladder users in terms of the envelope of performance that ladders must provide. As part of this, the interpretation of manual footing and the stability benefits that such interpretations bring must also be quantified to ensure that the current requirements offer the best level of safety to ladder users.

Once this benchmark information is acquired the performance of mechanical devices must be scrutinised to ensure that they do, indeed, offer a benefit over a naked ladder and, should manual footing offer a performance increase, that they also match or exceed this.

It remains untenable to disseminate safety practice instruction based on apocryphal or unsubstantiated interventions. Accordingly, in order to justify the current recommendations and plan improvements in the future the empirical performance of ladder stability enhancement techniques must be determined.

1.2 AIMS OF THE PROJECT

The stated aims and objectives of the project are:

- **Aim 1:** Establish the types of ladder stability devices that are available
- **Aim 2:** Undertake a test programme to determine the performance of the product range when challenged with realistic dynamic loads representing true consumer behaviour.
- **Aim 3:** Quantify the stability of a ladder with no footing support.
- **Aim 4:** Determine what individuals understand by the term ‘footing’ a ladder and quantify the stability of a ladder with an individual adopting various footing strategies.
- **Aim 5:** Develop a tool to quantify the stability performance of the currently available stability devices.
- **Aim 6:** Propose draft requirements for a performance-based test to quantify, and improve, the stability of ladder safety devices.
- **Aim 7:** Determine a program of dissemination of the information.

During the project evolution, Aim 2 was revised in conjunction in agreement with the Health and Safety Executive. In order to avoid problems related to specific product endorsement or criticism, and through the development of a highly accurate predictive model, rather than test all proprietary products a model was generated which can be used to demonstrate the safety of any given ladder stability device.

1.3 THE BENEFITS OF THE PROJECT:

The benefits of the project can be summarised as

- **Benefit 1:** The true effect of footing can be determined.
- **Benefit 2:** The effect of different footing strategies can be understood such that best practice can be identified and hence become integrated into policy.
- **Benefit 3:** The performance of mechanical devices can be objectively compared to each other and manual footing.

- **Benefit 4:** A better technical standard will help eliminate inferior products appearing on the market place.
- **Benefit 5:** The number of accidents involving ladders will be reduced.

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2.0 LITERATURE REVIEW

2.1 ACCIDENTS IN THE WORKPLACE

2.1.1 MARCODE¹

The Health and Safety Laboratory (HSL, 2000) carried out an investigation into accidents involving all types of ladders. They analysed MARCODE accident data, with particular emphasis on causation. The data was analysed for the years 1990 to 1995, inclusive. The data showed a steady increase in numbers until 1993, after which time the numbers of accidents declined. The severity of the accidents has remained constant. The majority of accidents (56%) resulted in major injuries, although this figure is partially explained by the nature of the sample; HSE-investigated accidents tend to be more serious. The study found the peak age profile of people injured in ladder accidents to be between 36 and 55. However, in their study, the age of 14% of the individuals was unknown. The victims of the accidents were either employed or self-employed. There were very few trainees involved. The industries that showed the highest incidence of ladder accidents were construction, manufacturing, agriculture and the service industries.

2.1.2 Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995 (RIDDOR) data

Employers, those in control of work premises and self-employed people are required under RIDDOR to report some work-related accidents, diseases and dangerous occurrences. This is a legal requirement and enables the Health and Safety Executive and local authorities to identify where and how risks arise, and to investigate serious accidents. Incidences of the following must be reported:

- A death or major injury.
- An over-three-day injury (an employee or self-employed person is unable to work for over three days after suffering accident at work, but does not have a major injury).
- A work-related disease.
- Dangerous occurrence (something happens that does not result in a reportable injury, but which easily could have).

¹ MARCODE is the Database of Investigated Accidents (originally Marches Code)

RIDDOR data on incidence and occupational groups associated with falls from a height involving ladders (all types of ladder) was obtained for the five main industrial sectors, known to have the highest incidence of ladder accidents:

- Agriculture.
- Construction.
- Manufacturing.
- Service industries.
- Energy.

The data refers to injuries reported to the following bodies:

- Food Operations Directive (FOD).
- Chemical and Hazardous Installations Directive (CHID).
- Nuclear Safety Directive (NSD).
- Local Authorities (LA).

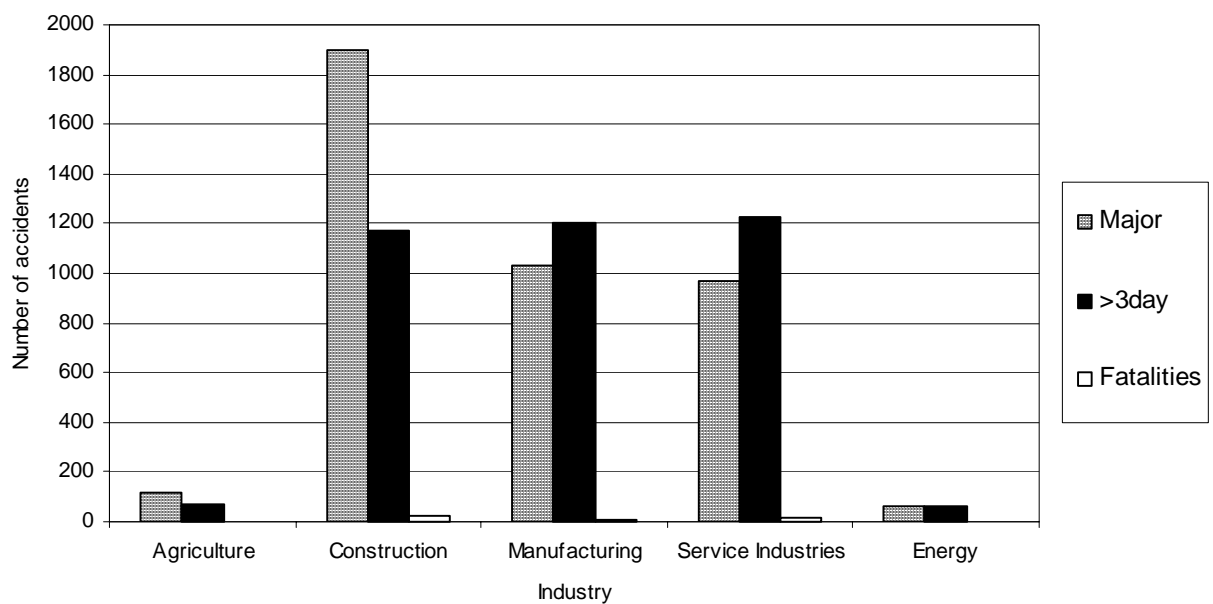


Figure 1

A comparison of the numbers of injuries resulting from ladder-related falls in the major industrial sectors

Figure 1 shows the large differences in the numbers of accidents occurring between the industrial sectors.

As can be seen, injuries resulting from falls related to ladder use are most common in the construction industry, which has a much higher number of major injuries and fatalities than the other industries. The numbers include all registered injuries, whether they are inflicted upon employed, self-employed, trainees, or members of the public. A major injury is regarded as a serious injury, and an 'over three day injury' refers to a slight injury, but nevertheless one that has lasted for more than three days. If this lasts over three days, the employee is required to provide a self-certificate in order that they may be registered as 'sick'.

Table 1 shows the numbers of non-employees (self-employed, members of public, trainees, work experience) involved in falls associated with ladders in the industrial sectors. Construction still shows the highest numbers of injuries sustained, with the percentage of non-employed injured being 12%. Of these, 10% were trainees or individuals on work experience, which could suggest that a lack of knowledge or experience is a contributory factor to ladder falls injuries. Similarly, agriculture shows a figure of 11% injured from ladder falls.

Table 1

Numbers of major and >3 day ladder accidents sustained by non-employees of the main industrial sectors

| Industry | Serious Accidents | Total number of accidents |
|---------------------------|--------------------------|----------------------------------|
| Agriculture | 21 (11%) | 191 |
| Construction | 358(12%) | 3094 |
| Manufacturing | 66 (3%) | 2243 |
| Service industries | 106 (5%) | 2210 |
| Energy | 4 (3%) | 130 |

Both agriculture and construction industries tend to employ fairly large numbers of semi-skilled, transient workers, which leads to a large proportion of the workforce being self-employed. This employment status may mean that their level of training is less tightly monitored, which may account for the high numbers of accidents.

2.1.3 Ladder Accidents Across the Industrial Sectors

Figures 2 to 5 show a comparative analysis of the types of ladder accidents, which occurred across the five selected industrial sectors between 1997 and 2000.

Figure 2 (Agriculture) demonstrates a reduction in numbers of serious or ‘major injuries’ over the three years, whereas the number of slight or ‘over three day injuries’ remains constant. However, ‘major injuries’ predominate. This trend can also be seen in the construction industry in figure 3.

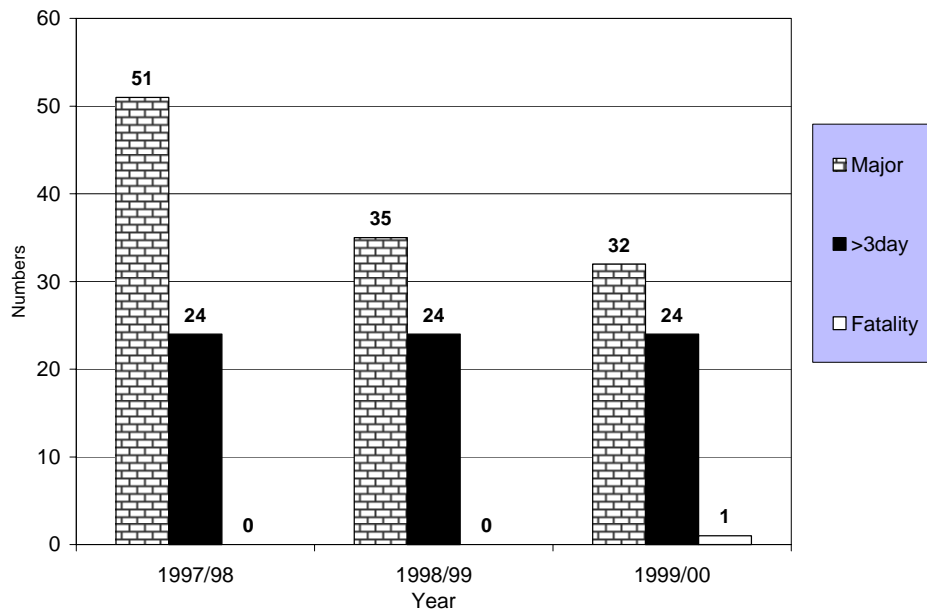


Figure 2

Reported ladder accidents in the agricultural industry

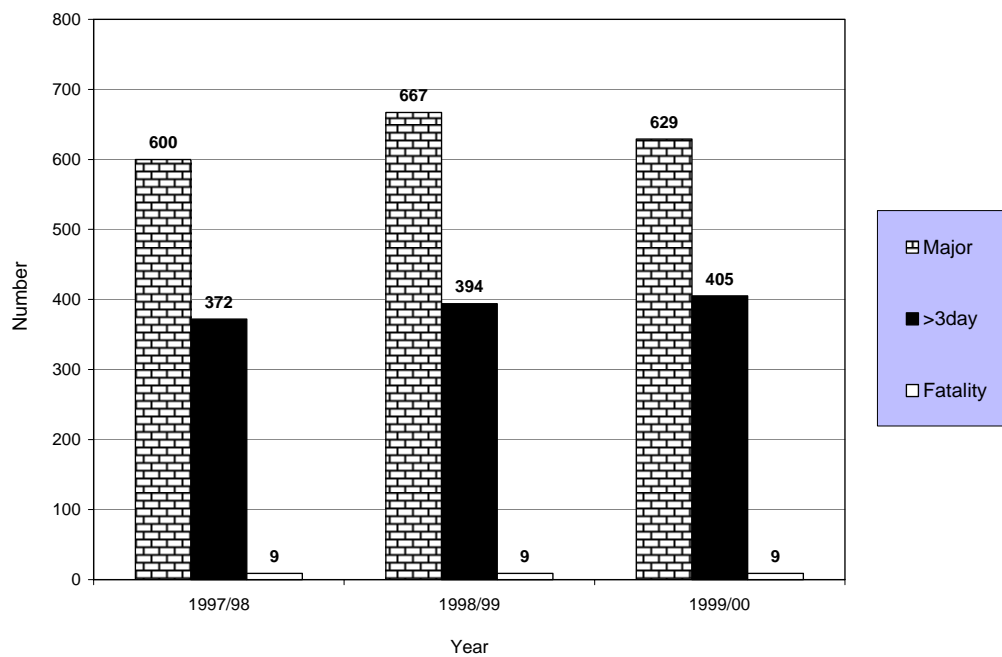


Figure 3

Reported ladder accidents in the construction industry

As can be seen from these figures, the numbers of accidents in the construction sector are far greater than those in other industrial sectors. However, further research into the events surrounding these injuries is necessary to determine the reasons for this association.

Figure 4 shows a decline in the numbers of injuries associated with the energy industry. From 1998 to 1999, there was a decline in serious or 'major injuries' in favour of slight or 'over three day injuries'; a trend also reflected in the manufacturing industry (Figure 4).

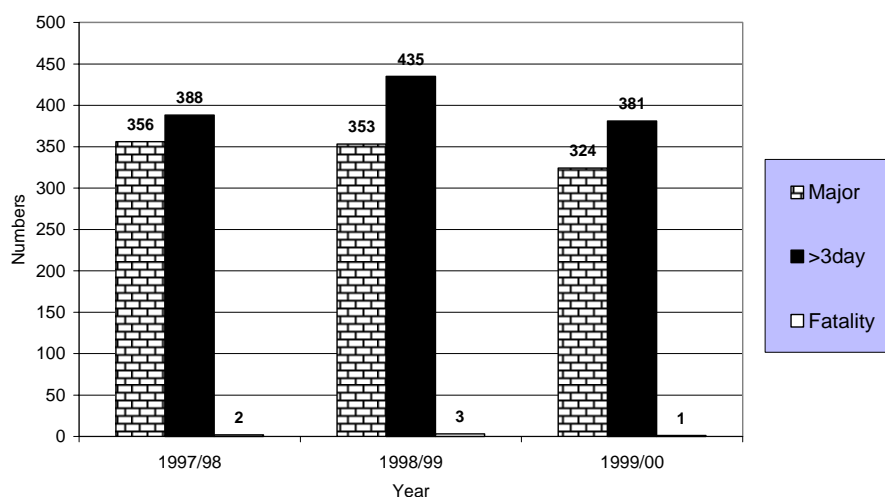


Figure 4
Reported ladder accidents in the manufacturing industry

It would be useful to know whether this decline is a true reflection of events or whether it is a result of other factors, such as a change in the reporting of injuries, a change in the nature of health care provision, changes in the size of the workforce or other such variables. If such variables could be excluded, with the same end result, then this might be an area for further research, in order to determine the reason for the reduction in major injuries.

2.1.4 Injury Profile

Table 2 describes two types of falls, namely low and high falls. A low fall is defined as a fall below two metres, whereas a high fall is a fall from a height above two metres (Health and Safety Commission, 2000). Interestingly, it appears that there are more low falls causing serious injuries than there are high falls. This is true for the construction and agricultural sectors. This situation is confirmed in other research in which it is reported that falls from relatively low heights are frequently serious, and it is not unusual for falls from 1.2 m (4 ') to be fatal.

In an analysis of fall accidents, Snyder (1977) showed that people who fell less than 6 m (20') landed on their heads 76% of the time. However, people who fell more than 6 m landed on their feet 63% of the time. In relatively short falls, the head is more likely to be injured than in the higher falls.

Table 2

The relationship between injury profile and distance fallen. These figures only includes accidents where the type of fall has been specified

| Industry | High Falls | | Low Falls | |
|---------------------------|------------|-----------|------------|------------|
| | Serious | Slight | Serious | Slight |
| Agriculture | 52 (66%) | 27 (34%) | 57 (59%) | 40 (41%) |
| Construction | 891 (69%) | 405 (31%) | 891 (57%) | 670 (43%) |
| Manufacturing | 447 (63%) | 262 (37%) | 514 (39%) | 819 (61%) |
| Service Industries | 383 (57%) | 289 (43%) | 492 (39%) | 769 (61%) |
| Energy | 23 (68%) | 11 (32%) | 37 (44%) | 47 (66%) |
| Total | 1796 (64%) | 994 (36%) | 1991 (49%) | 2345 (51%) |

However, once the total number of falls is considered, it can be seen that there are approximately 1500 more low falls than high falls. Furthermore, after adjustment for exposure, it may be anticipated that high falls will lead to a higher percentage of more serious injuries than low fall accidents. This is confirmed by Figure 5, which shows that high fall accidents account for the majority of major injuries, and low fall accidents result in more slight injuries.

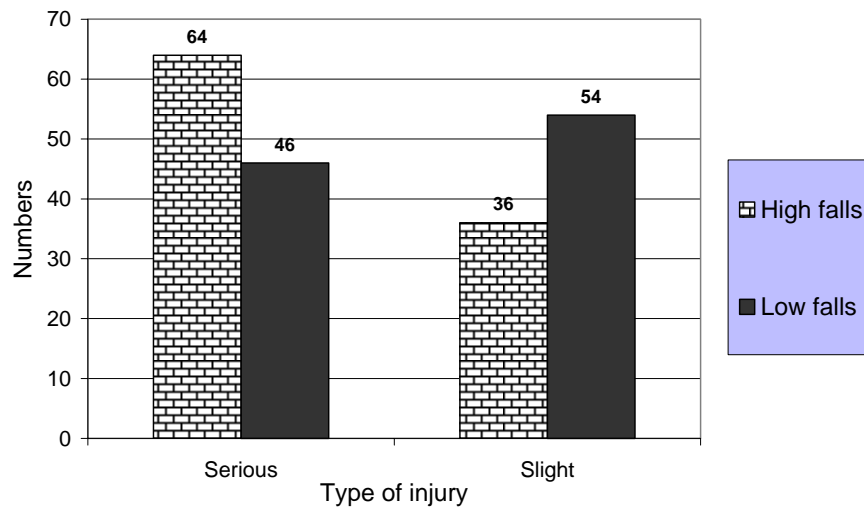


Figure 5

Percentage of total number of accidents by severity and height

2.1.5 Falls in the Construction Industry

Data from the HSE (HSE Presentation, 2001) on the fatalities in the construction sector between 1997 and 2000/01 showed that the most common cause of fatal accidents within this sector occurred as a result of a fall (52%). Of this, 23% were falls from ladders, although the type of ladder is not specified. The occupational groups most affected are shown in Figure 6 with painters and decorators being the most common victims of fatal falls from a ladder.

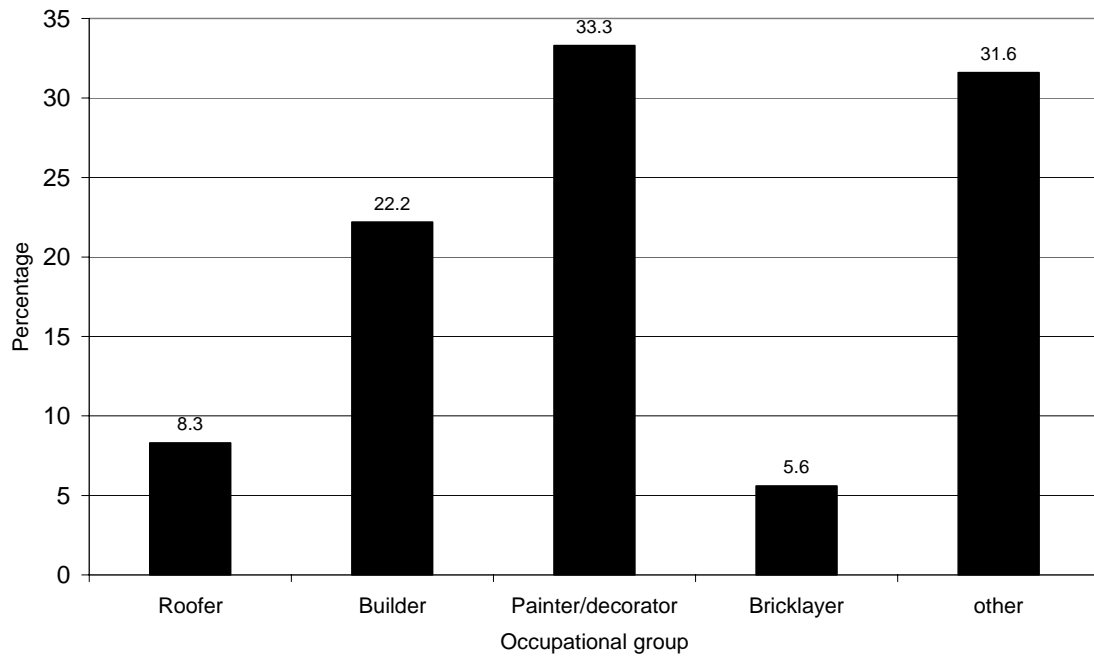


Figure 6
Falls from ladders by occupation

The causes associated with the falls given in Figure 6 are as follows:

- Untied or unsecured ladder (33.3%).
- No known cause (20.5%).
- Over-reaching (12.8%).
- Slipped/lost footing (7.7%).
- Defective ladder (5.5%).
- Knocked off (5.1%), over-balanced (5.1%), scaffold overturning (5.1%).
- Dismantling (2.6%).
- Age of victim (2.6%).

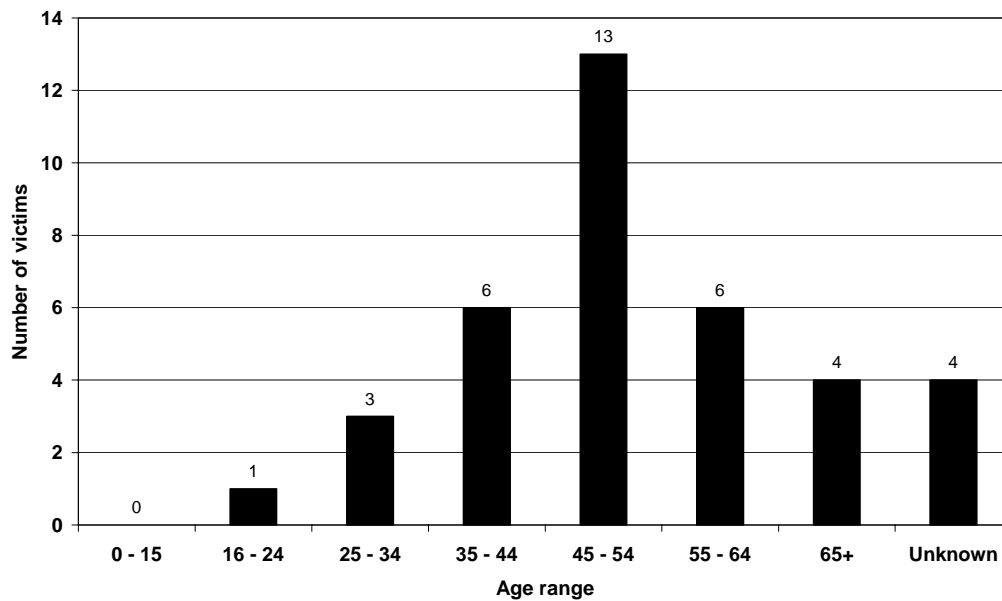


Figure 7
Ages of victims of fatal ladder fall accidents

Figure 7 shows the age range of those victims falling from ladders. This data shows a narrower age range than presented in the MARCODE data.

2.2 OTHER DATA ON LADDER ACCIDENTS

2.2.1 European Data

Axelsson and Carter (1995) reported that approximately 10% of ladder falls occurred during descent, while the victim was taking the final step. Despite the low fall distances involved, the result was often a serious injury. The authors speculated that the final step is particularly hazardous since the individual cannot easily visually perceive the transition from ladder to surface. Furthermore, the distance from the surface to the bottom rung was consistently less than the standardised distance between the remaining rungs. The point was made that despite building codes, which require stair risers to be equidistant throughout, there are no comparable requirements for ladders. The quality of ladders in use within the Swedish construction industry appears to be high, as mechanical failure was rarely reported as a contributing factor to the occupational accidents studied and almost all ladders reportedly met Swedish ladder Standards.

2.2.2 Australian and American Data

A paper by The Victorian Workcover Authority (2000), surveyed existing international research into the causal factors implicated in ladder accidents, in order to inform the development of regulations to control the hazards. The literature investigated was mainly from the USA and Sweden.

Cohen and Lin (1991) undertook an eighteen-month epidemiological study of workplace accidents involving portable stepladders. The subjects were drawn from a database of workers returning to a hospital Casualty Department. A random control group of workers, who had not experienced a stepladder accident, was also selected from the same companies. Using univariate analysis, a number of risk factors for a stepladder accident were identified. These were then analysed in order to determine their impact as predictors of stepladder accidents. Workers on the evening or night shift were six or seven times more likely to be involved in an accident; they tended to work longer hours and were less able to control their flow of work; their work often necessitated great strength but was often considered as 'boring'. This suggests that fatigue and greater exposure to the hazard may play an important role in accidents.

Stepladder accidents were also nearly five times more likely to occur on a slippery surface, of which the worst performer was concrete. There were also non-significant indicators. For instance, those involved in accidents were more likely to be stressed about home and financial matters, and also likely to engage in risk-taking behaviour.

2.2.3 Conclusion

The workers most commonly involved in accidents are painters and decorators within the construction industry, between 36 and 55 years of age. However, other industries and activities also appear to contain a high level of risk. Because of this it may be useful to investigate the nature of mechanisms and events surrounding 'major' and 'over three-day injuries', in order to determine the causal factors for the relationship between industry and injury profile, as well as the reasons for any changing injury profile. This may involve the collection of more detailed data than is presently required under RIDDOR. Finally, work-related accidents seem to be more frequent at the beginning of the working week and fatigue and organisational factors have also been implicated with the causation of ladder accidents.

2.3 UK HASS AND LASS DATA

Data was obtained from the Home Accident Surveillance System including Leisure activities (HASS & LASS data 1998). Table 3 presents a summary of the numbers and types of ladder involved in accidents, where the ladder type is specified. It can be seen that leaning ladders are involved in the second highest numbers of accidents of all ladder types.

Table 3
Numbers and types of ladders involved in accidents

| Ladder type | HASS count | LASS count | Total count | Total National Estimate |
|---------------------------|-----------------------|-----------------------|------------------------|------------------------------------|
| Leaning | 264 | 12 | 276 | 5 390 |
| Stepladders/ Steps | 677 | 21 | 698 | 13 632 |
| Loft ladder | 131 | 2 | 133 | 2 597 |
| A-frame ladder | 144 | 4 | 148 | 2 890 |
| Other ladder | 112 | 22 | 134 | 2 617 |
| Unspecified ladder | 780 | 95 | 875 | 17 088 |
| Scaffolding/tower | 75 | 68 | 143 | - |

2.3.1 Ladder and Stepladder Survey 1988

Hitchcock and Stroud (1988) carried out a survey on behalf of the CSU, into ladder and stepladder use in the home environment. The aims were to find out what ladder types were being used, how they were used, and for which tasks. This survey included details of ownership and storage, in addition to any accidents suffered during ladder use. The authors carried out a nation-wide telephone survey of 255 ladder users, and 15 visits were undertaken to observe people first hand, using their ladders at home. An additional 419 reported accidents were selected from the Home Accident Surveillance System (HASS) database for further analysis.

It was found that 73% of those people suffering an accident were male, aged between 20 and 50 years old. Surprisingly, victims aged 61 and over had the next highest incidence of ladder accidents (25%). These accidents occurred mainly during house repairs or renovation-related (DIY) or maintenance activities and took place more often outside the house (55%). Cleaning windows accounted for 10% of accidents.

2.3.2 Review of Ladder Accident Data 1988/89

The Research Institute for Consumer Ergonomics (RICE) carried out a review of DTI Home Accident Surveillance System data (HASS) on ladder accidents for the years 1988 and 1989 (DTI, 1997). This was done in order to understand the trends and user groups involved, and to provide a basis for the design of user trials into the stability of ladders. In total, 2,797 incidents were studied over the two-year period.

Accidents were found to affect a larger age group than previously thought; being evenly spread between the ages 20 to 69 years. Males were still the largest group affected (75%), with the majority of accidents taking place outside. The main activities for all accidents were household maintenance, cleaning and gardening.

Following this, HASS data was compared with PORS data (Dutch home accidents). The main findings were similar, except that there were a greater number of females in the PORS analysis (40%).

2.4 EUROPEAN DATA

2.4.1 Ladder Accidents In Sweden

Björnstig and Johnsson (1992) analysed data on ladder accidents in Sweden. Here, there were between 5,000 and 6,000 leisure-use ladder accidents per year, and 2000 work-related use accidents. These figures only relate to accidents requiring hospital care. The authors reviewed the hospital records of 114 ladder accidents, occurring between January 1985 and March 1986. The figures showed a higher proportion of males (81%) than females injured, than had been previously found in the UK. The average age of victims was 42 years old, which does correspond with previous research

2.4.2 The International Consumer Research And Testing Ltd (ICRT)

The ICRT (2000) carried out a large-scale, in-depth study funded by the Directorate General XXIV of the European Commission to undertake research into the safety of ladders. ICRT is an association of 26 consumer organisations from 22 countries, mostly in Europe. Their remit is to provide impartial and objective consumer information.

The aim of the study was to address the safety hazards associated with the construction and use of portable ladders and make recommendations for improvements in the safe use of ladders and stepladders.

The project was carried out in collaboration with 14 independent consumer organisations from the Member States of the European Union. Accident data were obtained from 9 countries. Details of 12,327 portable ladder accidents occurring in the domestic environment over the period 1987 to 1997 were collated. It was found that only limited information on ladder type was provided by some countries: The ladder type was not known in 71% of Finland's accidents and 61% of Sweden's. The data from the Netherlands showed that the accidents were split between leaning ladders (48%) and standing stepladders (52%).

Details of the severity of injury were obtained for 7,080 cases, which showed that 64% of accidents were severe requiring immediate professional medical attention and follow up treatment or in-patient care. A further 28% were moderate, requiring professional medical attention after the accident occurred, 7% were slight and 12 accidents were fatal. This seems like a low figure, more so as it is measured over twelve years, considering there are 50 fatalities per year, in the UK.

The authors were able to obtain details of 37 individual accidents from Finland. These revealed, males, aged between 30 and 70 years old to be the main victims involved in 57% of all accidents. Whereas, children aged between 3 and 9 years are involved in 19% of accidents. Of the accidents involving females, 56% occurred whilst they were using step stools.

Four countries provided information on activity when the accident occurred; Finland, Netherlands, Portugal and Sweden. However, although Finland provided information, in over 50% of the cases the activity was not known. The categories that were indicated by ICRT, other than "not known" and "other", were:

- Outdoor painting
- Indoor decorating
- Outdoor maintenance
- Carrying a ladder
- Moving a ladder

The latter two categories do not appear to be related to the task being performed whilst on the ladder. Of the cases allocated to one of the categories: outdoor painting, indoor decorating and outdoor maintenance, painting outdoors appears to be the most common activity. This concurs with the data on occupational sector involvement.

2.4.3 Conclusions

Ladder accidents are responsible for large numbers of injuries across Europe. Males aged between 20 and 60 are most likely to be affected. However, the incidence is highest between the ages of 40 to 60. Leaning ladders are the second most injurious type of ladder in UK home and leisure accidents.

2.5 CAUSES OF LADDER ACCIDENTS

2.5.1 Failures Due To Defects

There are two types of possible causes for defects (Goldsmith, 1985), which may result in a ladder failing: manufacturing defects and design defects. Manufacturing defects occur when the materials or workmanship of a ladder are faulty, and may be prevented by adequate quality control. Design defects occur when safety features or specifications for the materials or manufacturing process are insufficient to prevent a ladder failure. The critical point is made that a design is particularly defective when a failure occurs during types of use which are either promoted or intended by the manufacturer, or which could have been readily anticipated by him.

Goldsmith studied accident data (50 cases), and found the majority of failures were with aluminium stepladders and more often with extension ladders than stepladders. Of the 19 stepladder failures, the modes were:

- rail (or stile) failure with aluminium ladders (42%)
- bracing (support between rung and stile) failure with aluminium ladders (21%)
- unstable condition with aluminium ladders (16%)
- unstable condition with wood ladders (5%)
- cuts from sharp edges with aluminium (5%)

It is possible that age and ‘wear and tear’ of the ladder may contribute to these ladder failures. Previous research has only been carried out on ladders purchased specifically for testing and has not considered real life ageing and storage. However, the data shows that many ladders are over 16 years old (Hitchcock and Stroud, 1988).

2.5.2 Ladder Slippage

Hitchcock and Stroud (1988) reported that 5% of accidents studied are known to have resulted from a stepladder slipping. Similarly, Björnstig and Johnsson (1992) found that 41% of leaning ladders slid to the ground, whereas 48% fell sideways. In most cases, this was attributed to reaching out too far sideways or an unintentional movement of the ladder.

Axelsson and Carter (1995) questioned 85 ladder accident victims in Sweden to obtain detailed information about factors contributing to the accidents. Accidents were divided between straight ladders (n=39) and stepladders (n=33). Their findings agreed with previous research in that tipping sideways was the most common preceding event with users of stepladders, and misstepping the final step while descending accounted for 10% of all accidents. Furthermore, for straight ladders, slipping of the base was the most common event preceding the injury. Low angle of inclination was a common contributing factor.

2.5.3 Conclusions

User-related factors are by far the largest cause of accidents. These have been listed as misstepping, slipping and over-reaching, and may also result in the ladder slipping or tipping over. Additionally, there are a variety of factors implicated in accidents, such as manufacturing or design defects. Slipping of the base of leaning ladders is considered a major cause of accidents in user-reported surveys.

2.6 RESEARCH INTO STABILITY DEVICES

2.6.1 Consumers' Association study

A comprehensive review of ladder stability devices was undertaken by the Consumers' Association Research and Testing Centre (CARTC) on behalf of the DTI (1999). This provided a market survey and subsequent product appraisals of typical ladder stability devices. Whilst not highly technically based, it concluded that many of the devices were 'adequate' from an engineering perspective and that the majority, on the bases of expert opinion but not testing, offered low risk levels. However, the report goes on to recommend the need for a technical standard for stability devices as well as the need for more detailed research into their performance. Suggestions for the content of such a standard included dynamic testing, evaluating the effect of fitting the device on the ladder itself, user instructions, the development of a slippage test and durability.

2.6.2 Footing research

Hepburn (1958 on) presented a series of papers outlining the mechanics behind fundamental aspects of ladder use, including the quarter-length rule (75° angle), the dynamics of ladder loading and the theory and practice of ladder footing. Despite the age of these reports, the principles are still true and are applicable to any ladder structure in current use. This work underlined the fact that ladders obey the laws of physics and so can be accurately modelled and the loading calculated.

Hepburn concluded that the quarter-length rule was reasonable, but that if it could not be complied with tying the ladder, footing it or staking it would be required if, indeed, a ladder was the appropriate apparatus. In his discussion on loading he describes the necessity of footing and the perils of overloading as well as recommending the need for regular inspection and maintenance.

The work on footing concludes that unless the ladder is properly lashed and secured, the safety of the user depends on the correct application of the footing procedure. He clarifies this procedure as being the need for an individual, of equal or greater weight than the ladder user, applying that weight through the lowest rung of the ladder. He also suggests that weights may be used as an alternative.

2.6.3 Conclusion

The principles on which ladders operate have been understood for considerable time, and suggestions for improving the stability based on this knowledge and through the application of footing have also been made based on this understanding. However, these recommendations do not seem to have found their way into formal guidelines.

More recent reviews of ladder stability devices, whilst not technical in their nature, have been unsure of the benefits that many devices may bring and have recommended the need for a technical standard to ensure that performance of the ladder is truly enhanced.

2.7 STABILITY TESTING

2.7.1 UK Studies

The CSU published research (DTI, 1997) carried out by RICE in 1993 to investigate issues relating to the use, performance, and testing of domestic ladders (Class 3), which included leaning ladders, combination ladders and stepladders. They found conflicting advice on the ladders regarding whether one or two hands should be used to hold on to the ladder when climbing. With respect to reaching, recommendations varied from 'do not lean out at all', to 'do not overstretch or lean out too far/excessively'.

The authors concluded that several of the recommendations made for safe use were vague and open to wide interpretation by users. A fundamental criticism was that recommendations often represented the ideal, and failed to give safe alternatives when ideal use was not possible.

Current safety advice and static tests for ladders did not appear to be preventing ladder accidents, as ladders built to comply with the Standards appeared to be failing under normal conditions of use.

The study aimed to establish the dynamic circumstances surrounding the use of domestic ladders, with particular reference to accidents, and normal use and misuse of ladders, in order to determine whether the current static ladder tests adequately predict the performance of ladders in real life. Whilst the study focussed on leaning ladders, some findings emerged relevant to all ladders.

- Any movement of the ladder (e.g. flexion of the structure) threatened the confidence of the user, the security of footings and the mechanical integrity of the ladder.
- Users generated forces in excess of their own body weight, through accelerative forces whilst climbing ladders. These were as high as 150% of the user's weight in the axial plane of the ladder; namely, down the ladder stiles.

Issues relevant to angle of leaning ladders were as follows:

- Reducing the angle of use reduced the frictional security of the ladder.
- Reducing the angle of use placed significantly higher loading levels on the ladder in the normal plane (at the preferred angle users were less careful on the ladder).
- There were no significant differences between side loading levels at 66° and 75°.
- Sway of the ladder platform in the normal plane is worse at 66° than at 75°.
- Sway of the ladder platform in the lateral plane was independent of angle but modified by task type. The sway was worse for reach tasks and relatively unchanged for lifting tasks. The user responding to the feel of the ladder accounted for these changes.
- Stress upon the ladder in the normal plane was higher (40%) at 66° than at 75°. Approximately 15% of this can be accounted for by changes in geometry, the rest by user behaviour.
- Stresses in the lateral plane were unaffected by changes in angle.

The recommendation was made for a slip resistance test when the ladder is set at 66°, in order to challenge the ladder design with 'real life' situations. It was further recommended that dynamic testing should be incorporated to type-approve ladder models for acceptable levels of stress and movement, as well as to test for endurance against a cyclical force.

DTI post research comments (DTI, 1997) stated that the 'Slip Factor' and 'Dynamic' test requirements would be addressed in the forthcoming revision of the European Standard (EN 131 parts 1 & 2). The DTI argued, that dynamic testing of production samples of ladders for endurance was not considered necessary, provided the Classification for Use, used in the old British Standards, was included in the European Standard. The reason for this was that the maximum static vertical loads, quoted in the Standard by the Classification categories i.e. Class 1, 2 and 3, were arrived at by taking into account not only the loads expected, but also the variations of endurance expected in the three classes.

However, the origin of the values for the Classification categories is not patent and the work demonstrated that loads greater than the user's own weight could readily be generated in use. It was also suggested in this report that the nature of use for Class 3 (domestic) and Class 2 (light trades, now EN131) is unlikely to be substantially different.

2.7.2 European Studies

The most recent research into the stability of ladders was carried out by the ICRT (2000). The test programme was based on EN 131, with the addition of a number of consumer requirements not included in EN 131, for example the presence of user instructions, stability testing of portable ladders and requirements for accessories. They tested a total of 243 ladders. Each brand was tested using three samples. In their conclusions they made the recommendations that further work should include:

- The assessment of subjective safety and acceptability levels.
- The development of a dynamic test to investigate levels of force and movement generated by users.
- Ongoing, random, quality control endurance testing for all ladders.

2.7.3 Design Recommendations

Axelsson and Carter (1995) proposed two design modifications that would improve ladder safety. These were stabilisers on the base of ladders, and equidistant spacing between all rungs, including from the ground surface to the first rung. They argued that there is a need for improved user education. None of the occupational users interviewed in the study recalled receiving any information about safe ladder use and few were familiar with the risks associated with low angles of inclination when using leaning ladders. In addition, few were aware of the potential safety benefits provided by simple mechanical supports.

Ladder manufacturers were criticised by Goldsmith (1985) for continuing to produce ladders with minimal safety features, despite the fact that 65,000 people each year in the USA were estimated to suffer injury associated with the use of a ladder. He stated that until manufacturers are forced to meet higher levels of safety in the ladders which they market, inferior and hazardous ladders will be produced, purchased and used by the consuming public. He subsequently suggested improvements to ladder design, to increase safety and reliability.

The display of warnings was given as a simple design feature to prevent accidents. However, it is pointed out that these must be placed where the user can easily see them and take the appropriate precautions. He recommends the use of adequate quality control to prevent mechanical failures and improvements to the design in order to make the parts stronger.

2.7.4 Conclusions

Despite the high numbers of victims suffering the consequences of a fall from a ladder, there has been little research into the area of stability of stability devices which may assist ladders. Yet the ladder accident statistics suggest that there is a need for research into this area, in order to understand the performance of ladders when challenged with real-life use.

Ladder manufacture is largely controlled through the application of voluntary British and European Standards. The UK differs somewhat from other European countries in offering a Standard specific to ladders intended for domestic use (BS 2037 : 1994). However, the European Standard (BS EN131 : 1993) does not discriminate between 'domestic' and 'light trades' use. This discrepancy is the subject of considerable debate.

2.8 OVERALL CONCLUSIONS

Despite the studies conducted, and the knowledge gained, ladder accidents are still responsible for large numbers of occupational and domestic injuries across Europe. This demonstrates that the existing safety Standards could be improved to address the real users and uses of ladders. The highest incidence of accidents is seen amongst males between of 40 and 60 years of age, who are the main users of this equipment with common activities being DIY and maintenance. Workplace statistics show that the construction and agricultural industries have the highest incidence of ladder accidents, with painting and decorating as the occupation most commonly suffering fatalities.

There is clearly a range of activities which the ladder user may undertake which, whilst undesirable, fall within the diversity of normal use. These present a challenge for the manufacturer, since they do not want the user to undertake these activities, but must accept that they will. This is normally termed 'reasonably foreseeable misuse'. There is some skill necessary in defining the borders between foreseeable misuse and abuse, and manufacturers may require outside expertise in order to achieve the necessary balance. This distinction has important implications for a manufacturer. Current legislation requires that their products must be safe in conditions of normal use or reasonably foreseeable misuse.

This means that the manufacturer must appraise the range of tasks that will be undertaken with their product, and design it such that it presents the minimum of risks in these situations. This precludes product manufacturers from applying numerous warnings to their products advising users not to undertake activities which they quite patently will do. Failure to enact these responsibilities can culminate in the manufacturer facing criminal prosecution in addition to civil liability claims.

There is a very small amount of research relating ladder stability devices, and even less to ladder footing. This is curious given the apparent capacity for benefit these interventions may have on ladder use and accidents. It is also the case that the citing of these techniques in relevant legislation and guidance would normally be evidence based. This does not appear to apply in this instance.

2.9 OWNERSHIP

Hitchcock, D. and Stroud, P. (1988) in a telephone survey of 255 people, showed that most respondents (52%) use two ladders, 29% use only one ladder and 19% use at least 3 ladders. Most households owned these ladders (93%), with only a minimum being borrowed (7%). No ladders were hired. Of stepladders used, over 50% were made of wood, whereas over 50% of extendible ladders were made of aluminium.

The majority of ladders were less than 10 feet high when fully extended. Most of all the ladders purchased (60%) were bought from DIY outlets. Small, DIY shops were the preferred purchase venue, rather than large retail outlets, such as a superstore. However, the preferred purchase venue is likely to have changed since this research was carried out, due to the rise in numbers and popularity of the superstores.

Ladders were generally kept for long periods of time. Over 50% of the ladders were aged between 1 and 10 years, but 28% were more than 16 years old, which supports the need to test 'used' or second hand ladders during research.

There were relatively few defects reported. The most common defect (18%) was mould or corrosion. This may be due to the choice taken for their storage location. Only 13% of ladders were stored in the recommended way (supported along the bottom stiles or by separate supports), whereas over 50% were stored by leaving them against a wall or similar. Very few ladder accessories were being used. These were mainly with leaning ladders.

2.10 EFFECTS OF LADDER RUNG SHAPE, SPACING AND ANGLE

In a study by Juptner (1976) preferred rung shape for improved ladder safety was investigated. The study involved altering rung shape to see how it affected user behaviour.

The variable measured was the distance reached by the participant when putting bolts into prepared holes. The researchers found that the reach envelope was significantly reduced (11 cm) by a rung with curved sides.

McIntyre (1979) carried out a study examining the mechanics of ladder climbing with special emphasis on the effects of rung spacing and user characteristics on the ability of the user to ascend a ladder. The report argued that accidents where the user fails to negotiate the ladder safely (e.g. failure to locate one or more body parts on the ladder, or difficulty in co-ordinating movement patterns) may be due to factors beyond the control of the user. These factors might include the dimensions of the ladder or encountering unexpected distractions. The adoption of an inappropriate gait may be another factor.

In order to further analyse this, two experiments were carried out. The first was designed to ascertain the temporal characteristics and gait patterns used by participants when ascending a ladder, having received no instructions regarding climbing technique. However, the results of the initial study revealed little evidence to suggest a preferred climbing gait. The purpose of the second experiment was to examine the effects of rung spacing and specific anthropometric characteristics of the participant, on their ability to ascend the ladder using an experimenter-defined gait.

Twenty male participants were assigned to one of two ten-member groups according to their height. The mean standing height for the tall and short participant groups was 1.92 m and 1.71 m respectively. Each participant performed at least 3 trials; each trial corresponded to one of the following rung spacings:

- 0.305m (normal based on ANSI, 1972)
- 0.203m (narrow)
- 0.406m (wide)

The results showed that participants in the taller group spent less time in contact with the ladder rung, and more time in the airborne phase, compared to those in the shorter group. Furthermore, there were indications that users have a preferred rate of ascent which is maintained despite changes in the climbing apparatus.

Instances of overshooting of the target rung were found when rung spacing was 0.203m (narrow). This overshooting occurred only at the participants' feet. It was suggested that visual monitoring was a likely explanation for the hands being accurately placed.

The primary role of the hands is the maintenance of stability. This was shown by force data, which also demonstrated that for the short participant group, increases in rung spacing were accompanied by increases in forces applied. Additionally, there was also an increase in the parallel (side to side, known as 'sway') to perpendicular (up and down, known as 'bounce') force ratio for narrow and wide rung spacing.

Thus, those ladders which have either narrow or wide rung spacing increase the forces required to safely ascend or descend thereby increasing the likelihood of a ladder-user being unable to exert the required hand-stabilising forces. However, the decreased effort required to ascend ladders with the narrower rung spacing would lessen the possibility of an accident occurring for this type of ladder.

2.11 LADDER USAGE

2.11.1 Angle of Leaning Ladder Use and Stature of the User

An investigation by Dewar (1977) analysed accident consideration particularly accidents attributed to misplacing of feet or 'stumbling' when climbing. On the basis of accident reports, Dewar noted that 66% of ladder accidents resulted from the ladder slipping, whilst the remaining 34% were attributed to the user misplacing his feet.

The focus was on two factors which might affect the chances of an error of feet misplacement occurring; angle of ladder and stature of the user.

The study included analysis of displacement and rotation of pelvic girdle and trunk, as well as rotation of knee and hip joints. There were 35 male participants who were filmed climbing a ladder set at 70.4° and 75.2° to the horizontal. The body movements demonstrated whilst climbing were compared with the participant's normal walking gait.

Dewar found that when instructed to use one of two angled ladders people most commonly chose a 3:1 (vertical distance: horizontal distance) angle ratio. It was noted that, at a steeper angle, the user often experienced feelings of heightened insecurity due to a fear of falling backwards. This is combined with an increased awkwardness in climbing the ladder. This issue was further explored by Dufresne (1992) who found users consistently tended to use the ladder at lower than the recommended angles of usage. RICE (1997) also confirmed this during later research for the DTI. The results indicated that when a ladder is set at a steeper angle the user's hands play a greater role in maintaining balance. With a steeper angled ladder Dewar found greater posterior displacement i.e. leaning further back from ladder. He concluded that the user's hands were contributing to stability of the body. If the hands were to slip there was less chance of the user regaining his balance. The study also found greater differences in body movements in tall and short participants. This may be due to the dimensions of ladders being best suited to the 'average' user. Therefore, users falling within the extremes of the size range have to modify their movements, which in turn leads to an increased risk of accidents. This agrees with research carried out by McIntyre (1979).

2.12 RISK COMPENSATION

A popular theory known as 'risk compensation' is widely promulgated in the automotive safety arena by John Adams (1995), and suggests that individuals will compensate for safer equipment and environments by undertaking riskier activities. In reality, this manifests itself as the using up of safety margins as performance benefits. A simple example would be that when consumers were provided with better braking in vehicles, they brake later and harder, rather utilising the benefit as an increased safety provision.

This theory goes on further to suggest that different individuals are predisposed to different levels of risk, and even that it might be possible to categorise groups of individuals on their risk taking attitude.

This disposition can lead some individuals to behave in ways involving very high risk because they perceive that they are safe – for instance, if a leaning ladder is ‘footed’ the ladder user may be inclined to lean out much further. However, in controlled studies there has been little, if any, evidence of risk compensation occurring. (Thompson et al 2001)

In a large study by Hitchcock and Stroud (1988) on user behaviour with ladders, a telephone survey was carried out. This found that 60% of respondents claimed they carried out safety checks prior to using a ladder (e.g. ensuring the ladder was level, the fixings were secure, the ladder angled correctly). Yet, there were no significant differences between the number of accidents reported where safety checks had been made, and the number of accidents reported where safety checks had not been made. This suggests that fewer safety checks are made than claimed by the respondents, or that when safety checks are made they are not identifying the potential causes of accidents. In addition, 15 people aged between 16 and 85 were observed at home either performing or simulating a task that they normally performed whilst using their ladder. The authors admitted the potential problem of the ‘Hawthorn Effect’; the positive consequences of benign supervision (Roethlisberger & William, 1939). Despite this, several observations of problems or unsafe use were made, for example:

- A ladder was used in front of a doorway (leaning ladder).
- People missed their step when climbing up and/or down (leaning and freestanding ladders).
- Children were playing in the vicinity of the ladder in several cases, which could have resulted in a collision.
- Users ‘over-reached’ rather than move the ladders.
- Several people carried loose items up the ladder, sometimes with both hands.
- Several users compromised when faced with a choice of either insufficient space to lean the top of the ladder properly and fully against a surface or to ensure the ladder was on even ground.
- A ladder was used at a steeper angle, due to uneven ground.
- A participant descended the ladder facing outwards.
- A participant used an extension ladder with a broken rope mechanism.
- Very few safety checks were made on ladders, with the exception of ensuring correct location of the platform at the top of the stepladders.
- Users stood on parts not designed for this, in order to facilitate a higher reach.
- No ladder accessories were used.

Generally the stepladders and short-length ladders were treated with far less respect than the longer, leaning ladders. Participants often attempted to use their ladders for tasks not suited to their ladder height or position.

Similarly, a study by Dufresne (1992) was designed to investigate the risk perceived by ladder users, in order to facilitate a better understanding of user's behaviour. This study was necessary because despite the manufacturers being aware of, and producing, ladders according to current standards, consumers frequently purchase a ladder that represents a safety hazard. This occurs because the specifications mainly address the requirements and test methods for ladder structure and do not consider the user's task requirements or their feelings of safety on the ladders. However, it has been shown that the perception of risk and the consequences of exposure affect human risk-taking behaviour. The results indicated that ladder users compromised between hazards perceived at different ladder inclinations, in order to select a preferred inclination. The recommended ladder inclination is 75°, whereas the mean preferred inclination was 65.2°; which is considerably lower than the recommendations. The author proposed design modifications which would reduce the risk of ladder slippage and increase sideways stability, thereby accommodating the user's preferred inclination, whilst presenting a safer ladder to use.

2.12.1 Conclusions

Research shows that leaning ladder angle plays a part in influencing the user's feelings of security and therefore affects behaviour. At steeper angles, the secure and correct placement of the hands becomes vitally important, as they enable the user to maintain stability throughout the task.

Furthermore, those ladder users of a larger or smaller than average size are more likely to have an accident, which might indicate a need for customisation of equipment for such individuals. This would impact most upon employers, as they are required to provide 'suitable and safe' equipment.

It has been shown that users tend to use ladders for whatever purposes they deem necessary, whether their ladder is the correct equipment for the task or not. Thus, the current display of warnings may be futile as it may be expected that users will not comply with the recommendations. An improved design accommodating known usage is suggested as an effective alternative to increased warnings. However, improvements to warnings may still be made.

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3.0 INSTRUCTIONS AND WARNINGS

3.1 GUIDELINES AND STANDARDS ON WARNINGS AND THE SAFE USE OF PRODUCTS

The content and appearance of warnings has been given much attention. Research has shown that warnings and instructions may serve two purposes (Page, 2000). For a new user, these provide new information and for a more experienced user, they can serve to attract attention to a hazard.

In 1988, the DTI published instructions and safety information to help manufacturers with all aspects of writing instructions (Cooper and Page, 1988). In addition, they also published a document on safety instructions (CSU, 1998), which is intended to give manufacturers a better awareness and understanding of the consumer's needs of safety information.

Similarly, American (ANSI, 1990) guidelines state that manufacturers have a duty to warn ultimate users of dangers inherent in the product in terms of its:

- intended use; and
- reasonably foreseeable misuse.

The American Standards, ANSI Z535.1, 2, 3, 4 and 5 (1991) are useful on the development of warnings. The most relevant ones give useful advice on signs and labelling.

There are various other standards providing advice on instructions to be included on labels, as well as separate instruction leaflets guides (BS 4884: 1992; BS 4899: 1991; ISO Guide 37 1990).

The most useful of the current Standards available to manufacturers is ANSI Z535.4 1991 Product safety signs and labels. This Standard contains details of product safety signs and labels. The areas covered are outlined in Table 4 and serve as an indication of the issues that need to be addressed in the production of effective warnings and labelling.

Table 4
Product safety sign and labels in ANSI Z535.4 1991

| Sign classification | Letter style and size |
|--------------------------------|--------------------------------------|
| Hazard classification | Letter style |
| Signal word selection | Letter size |
| Multiple hazard identification | |
| Sign or label format | Sign and label placement |
| Panels | Location |
| Panel arrangement | Protection |
| Safety alert symbol | |
| Border | |
| Word message | |
| Pictorial | |
| Safety sign and label | Expected life and maintenance |
| Colours | Expected life |
| Standard colours | Maintenance |
| Signal word panels | Product user |
| Message panels | instructions |
| Pictorial panels | Replacement |
| Border | Installation procedures |
| Colour options | |
| Pictorials | |
| Recognition | |
| Testing for understand ability | |

3.2 WHY WARNINGS FAIL

3.2.1 Risk and Hazard Perception

Young et al (1990) reported that many research papers have noted that terms such as: hazard, risk and danger are all interchangeable to the layperson. However, there is also disagreement amongst experts as to what is meant by risk, although at the root of most definitions is the possibility of loss. This has three essential elements:

1. the loss itself;
2. the significance of these losses;
3. the uncertainty associated with the losses.

These factors are entirely subjective. Thus uncertainty has been suggested as a contributor to the overall risk of any situation (Yates 1992). When analysing risk, experts consider the likelihood of loss to be the most important measure. However, lay people are far more likely to consider the severity of loss or injury.

Karnes et al (1986) suggested that this was because the likelihood of injury or loss in most domestic settings is too low for most people to contemplate and so potential severity is far easier and more relevant. For the layperson estimation of high severity, low risk events is very poor.

Page (2000) suggests that the presumption that most people will avoid risk seems to be a reasonable one. However, this is not universally true and some people are indifferent to risk, whilst others will seek out risk. The author describes such people as 'thrill-seeking'. Thus, the personality and the situation influence the individual behaviour and risk-taking. Different levels of risk perception are described for different circumstances. People who are high-sensation seekers have also been found to tend towards dependencies on addictive substances, such as alcohol and drugs. Research by the British Medical Association (1987) showed that some consumers persisted in potentially harmful activities even when they were well aware of the consequences.

Page (2000) reports that people are more willing to accept voluntary risks than involuntary ones, it being common for people to dismiss risks on the basis of 'it won't happen to me'. This situation is especially likely if the risks are familiar and under their personal control.

Yates (1992) found that judgements on the levels of risk associated with a situation or actions were made on the basis of the relative frequency of the loss and subjective reasoning on cause and effect.

Many experiments have also shown (Karnes et al, 1986) that benign experience with a product or situation may produce some lessening of the perception of risk. This leads to a situation where those people with experience of a product or situation may judge the risks to be lower than those with less experience of a product do.

The perception of risk therefore varies both with the individual, and with their level of expertise in the area of risk assessment. Furthermore, some individuals actively seek out risk, rather than avoiding it. It has also been found that where a product or situation is familiar, the perception of risk is likely to be lessened.

3.2.2 Compliance With Warnings

Lehto and Miller (1986) described warnings as stimuli that alert people to hazardous conditions. However, little research has been addressed directly to the effects of warnings on decision-making (Stewart and Martin, 1994). Page (2000) reports that people are habituated not to respond to unimportant stimuli, and many warnings are neglected not because of a conscious decision but due to habit.

It has also been shown that people are more likely to comply with a warning message in conditions of low cost and when they see another person complying (Wogalter et al 1989). In addition, warnings or instructions that reinforce beliefs about the consumer's ability to control accidents may be useful. The context in which the warnings are encountered, and the nature of the message itself, affect the quality and credibility of the message. (Handmer and Penning-Rowse, 1990).

Other research by Robinson (1986) and Strawbridge (1986) on the design of instruction manuals and warnings indicated that there is a steady decline in the number of subjects who first noticed, then read and finally followed a warning.

When critical information was embedded within the rest of the instructions, compliance with the warning was significantly reduced. Although highlighting of warnings increased the numbers who read them, some people were able to fully recall warnings yet failed to carry them out. The placing of warnings within a specifically dedicated section dramatically increased the numbers who read, recalled, and complied with warnings.

In work on the general public's compliance with warnings and instructions, Leonard et al (1986) advocated the use of 'signal' words in an attempt to improve the levels of compliance. These are as follows:

- DANGER - an imminently hazardous situation which, if not avoided will result in death or serious injury;
- WARNING - a potentially hazardous situation which if not avoided could result in death or serious injury;
- CAUTION - a potentially hazardous situation which if not avoided may result in minor or moderate injury.

Frantz (1999) indicated in a recent paper, that excessively comprehensive lists of warnings were not to be recommended. Pictograms are often suggested as being a good resolution to the issues of warnings but research by Page (2000) found that they are poorly understood, and that there development and testing is frequently not undertaken due to expense. Therefore, providing warnings about all risks associated with a particular product is an incorrect approach.

The provision of warnings requires consideration of the potential impact, both positive and negative, of adding a particular warning to a product or manual. Furthermore, this consideration should not be limited to the potential warning at issue, but should also extend to the likely impact that such a proposed warning might have on the perception of, and response to, other warnings on the product and to warnings in general.

3.3 DEVELOPMENT OF EFFECTIVE WARNINGS

McGuire (1988) made the following recommendations to manufacturers, in order to establish the level of care exercised in preparing its product-use instructions. These were as follows:

- ensure that the instructional material is reviewed by several knowledgeable and responsible people and the final version is not signed off by the technical writer alone;
- carry out crucial testing of the material with consumers before wide scale market introduction of the product;
- document how the instructions were tested, what the tests showed and how they acted on the findings of such tests;
- ensure that warnings about misuse, abuse and inherent dangers are spelled out and their consequences described.

The ANSI test ANSI Z535.4 : 1991 for symbols requires the following:

- an appropriate test group of at least 50 people who are representative of the final users of the product
- score results based on:
 - correct responses
 - wrong responses
 - critical confusions (opposite to the correct response)
 - no response
- an acceptance level of:
 - more than 85% correct responses
 - less than 5% critical confusions
 - modification and re-testing of unsatisfactory symbols until a satisfactory one is found

However, this would be expensive to test, but possibly warranted due to the high numbers of ladder fall accidents.

There is also an ISO Standard, ISO 9186: 1989 for the development of public information symbols but this only requires a 66% rate of certain or likely understanding of the symbol with no requirement for assessing critical confusions. This would also be expensive to test. Testing may be expensive but considering the requirement on manufacturers to take reasonably practicable steps to make their products safe, as well as the potentially serious consequences of ladder fall accidents, it may be recommended.

3.4 LABELLING ON LADDERS

Lawrence et al. (1996) concluded that despite obvious safety labelling and warnings, these often remained unread. There was a definite need to raise awareness of these safety messages. They expressed concern that EN 131 does not have any requirement for safety labelling. It was suggested that this is reviewed and ladders conforming to the Standard should be labelled. It was also suggested that a review of the Standards is carried out, to justify current test loads and methods used and the inclusion of performance and fatigue-testing methods.

4.0 COMPARISON OF EUROPEAN, NATIONAL AND INTERNATIONAL STANDARDS

A search was carried out of existing relevant standards relating to ladders. The standards were taken from the UK, Europe, America, Canada and Australia, as these countries all have populations with comparable characteristics. Initially EN 131 : 1993 and BS 2037 : 1994 are reviewed here and a comparison made. EN 131 is currently under review by Committee B/512.

Subsequently, these are compared with other international Standards. The aim was to discover which contained requirements, or test methods, more stringent than BS EN 131. All standards reviewed are listed in Table 5. Those national standards identical to BS EN 131 were not reviewed. These relate to countries which have adopted EN 131. A list of these can be found in Table 6

BS 1129: 1990 : Portable timber ladders, steps trestles and lightweight stagings is also not reviewed, as the scope is similar to BS 2037 except for the materials used. It also differs from BS 2037 only in the dimensions of the platform and the depth of step, and in that compliance only depends upon the quality and type of woods used. There are no design verification tests.

Table 5
This contains a list of all the standards reviewed

| Standard | Title | Country |
|-----------------------------|--|---------------------------|
| EN 131 Part 1 1993 - | Terms | European |
| EN 131 Part 2 1993 - | Specification | European |
| BS1129 : 1990 | Portable timber ladders, steps trestles and lightweight stagings | UK |
| BS2037 : 1994 | Portable aluminium ladders, steps trestles and light weight stagings | UK |
| EATS13/1 : 1987 | Portable glass fibre ladders and steps, Technical specification | UK |
| AS 1657 : 1992 | Platforms, walkways and ladders for personnel | Australian |
| UL 112 : 1998 | Portable wood ladders (Underwriters independent Standard) | US |
| UL 184 : 1997 | Portable metal ladders (Underwriters independent Standard) | US |
| ANSI A14.1/2000 | Ladders- Wood safety requirements | US |
| ANSI A14.2/2000 | Portable metal ladders | US |
| AS/NZS 1892.1: 1996 | Portable ladders (metal) | Australia and New Zealand |
| AS/1892.2-92 | Portable ladders (timber) | Australia |
| ANSI A14.5 : 2000 | Ladders - portable reinforced plastic - safety requirements | US |
| CSA Z11 M81 | Portable ladders (rp: 03/83, 12/87) | Canada |

Table 6
European member state implementations of BS EN 131 Part 1 and BS EN 131 Part 2

| Standard | Title | Country |
|---------------------------------|--|----------------|
| UNI EN 131 Part 1: 1994 | Ladders - specification for terms, types, functional sizes | Italy |
| UNI EN 131 Part 2 : 1994 | Ladders - specification for requirements, testing, marking | Italy |
| DIN EN 131 Part 1 1993 | Ladders, terms, types, functional sizes | Germany |
| DIN EN 131 Part 2: 1993 | Ladders; requirements, testing, marking | Germany |
| NBN EN 131-1: 1993 | Echelles - terminologie, types, dimensions fonctionnelles | Belgium |
| NBN EN 131-2: 1993 | Echelles - exigences, essais, marquage | Belgium |
| NF EN 131-1: 1993 | Echelles - terminologie, types, dimensions fonctionnelles | France |
| NF EN 131-2: 1993 | Echelles - exigences, essais, marquage | France |

4.1 A REVIEW OF BS EN 131 : LADDERS

BS EN 131 : 1993 : Parts 1 and 2 were prepared under the direction of the Technical Sector Board for Building and Civil Engineering, and were published by the European Committee for Standardisation (CEN). The committee comprises the national standards organisations of the following countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom. The CEN members are bound to comply with internal Regulations, which stipulate that the European Standard must be given the status of a national standard, without any alteration. The Standard comprises two elemental parts:

Part 1: Specification for terms, types and functional sizes

Part 2: Specification for requirements, testing and marking

BS EN 131 supersedes Class 2 of BS 1129: 1990 and Class 2 of BS 2037: 1990. It covers types of portable ladders covered by BS 1129 and BS 2037.

In addition, it is also concerned with sectional, mobile and combination ladders, not previously covered in British Standards. It does not cover ladders for special professional use.

BS EN 131: Part 1 gives definitions and general terms, dimensions and general design characteristics, as well as technical requirements of safety for the materials used. Unlike BS 2037, there is only one duty rating of 110kg, with a maximum loading of 150kg for ladders to conform to this Standard. However, there is work currently in progress to separate this standard into two, performance-based, classes.

There are several types of ladder covered by BS EN 131, including:

- Mobile ladders.
- Rung ladders.
- Push-up extending ladders.
- Sectional ladders.
- Combination ladders.
- Leaning stepladders.

4.2 A REVIEW OF BS 2037 : 1994

This Standard supersedes BS 2037: 1990, Portable aluminium ladders, steps trestles and light weight stagings. It covers three classifications of ladder:

- **Class 1 – Industrial** – heavy duty, high frequency use and onerous conditions of use, carriage and storage. Suitable for industrial purposes. The maximum expected combined weight of user and tools is 130 kg.
- **Class 2 – Light trades** – low frequency use and less onerous conditions of use, carriage and storage. However, this class has been withdrawn and is now covered by BS EN 131.
- **Class 3 – Domestic** – light use only, maximum duty rating load is 95 kg.

There are several types of ladder covered by BS 2037: 1994, including:

- Single section ladders, including shelf ladders.
- Extending ladders.
- Standing stepladders, swing back steps, folding steps and ladder backed steps.
- Folding trestles.
- Lightweight stagings.
- Combination ladders.

This Standard also contains guidance on the following areas:

- Care and use of ladders; handling, storage and transport.
- Maintenance.
- Inspection.
- Painting.
- Cleanliness.
- Electrical hazards.
- Fixing of the ladder.

There is also a section on general use of ladders. Within this, users are advised that the ladder is not designed for 'side loading' and that 'such abuse should be avoided'. Furthermore, ladders should be kept close to the work and 'overreaching' should be avoided. It is also advised not to stand on the top tread and that the user 'should face the ladder' when ascending and descending.

4.3 CONCLUSION

Despite a requirement for EU Member States to adopt EN 131, only five countries have adopted it as their national standard. From the comparison with other national standards in the USA, Australia, and New Zealand, there are both similarities as well as major differences. EN 131 is the only national standard which lacks stability or performance-related tests. Furthermore, the test loads are much higher in other comparable standards. This implies that the test loads and the criteria applied for their selection may need to be re-evaluated. In addition, all other national standards have some requirement for safety labelling, with the exception of EN 131. However, as has been indicated, there are plans to include these elements into a revised standard.

4.4 REGULATIONS APPLICABLE TO LADDERS

A review of Health and Safety Regulations was carried out to discover which were applicable to the use of ladders. The following includes the relevant clauses from the cited Regulations.

4.5 PROVISION AND USE OF WORK EQUIPMENT REGULATIONS 1998 (PUWER 98)

The Health and Safety Executive (HSE) produced this document after consultation with industry. These Regulations apply to all workplaces and work situations where the Health and Safety at Work etc Act 1974 (HSW Act) applies and are intended to ensure that work equipment does not result in an accident, regardless of its age, condition, or origins. Ladders are covered under this guidance and are defined as work equipment.

4.5.1 Suitability (Regulation 4)

This regulation places a duty on employers to ensure that work equipment is suitable for the person and the task for which it is intended. This means the employer should ensure the equipment is used according to the manufacturer's instructions. Furthermore, employers should take into account the working conditions and the risks to the health and safety of the individual using the equipment.

4.5.2 Ergonomics (Regulation 4)

PUWER 98 recommends that employers should take into account the ergonomic risks. The equipment should take into account the size and shape of the individual and operators should not be expected to exert undue force or reach beyond their normal limitations.

4.5.3 Maintenance (Regulation 5)

An employer should make sure the work equipment provided is maintained to good working order and is in good repair. The frequency of maintenance should take into account the intensity and frequency of use, operating environment and potential risks to health and safety of equipment failure.

4.5.4 Risk Assessment and Inspection (Regulation 6)

Where a risk assessment has identified a significant risk to the individual from the work equipment, a suitable inspection must be made. Falls from ladders result in approximately 50 fatalities per year. Thus, ladders could be viewed as posing a significant risk.

4.5.5 Specific Risks (Regulation 7)

Where the use of the equipment involves a specific risk, every employer should ensure that use of the equipment is restricted to those individuals whose task it is to use it and that repairs are carried out by a specifically designated and trained person.

4.5.6 Information and Instruction (Regulation 8)

Employers shall ensure that all persons who use work equipment have health and safety information available and written instructions for the safe use of the equipment.

4.5.7 Training (Regulation 9)

Each employer must ensure that all persons using work equipment have received training on the health and safety issues and precautions to be taken.

4.5.8 Stability (Regulation 20)

Employers shall ensure that work equipment is stabilised. In the case of ladders, 'where the stability of the work equipment is not inherent in its design', or where it is mounted in a position where stability could be compromised, additional measures should be taken to ensure its stability. Ladders should also be at the correct angle and tied or footed.

4.6 THE MANAGEMENT OF HEALTH AND SAFETY AT WORK REGULATION 1999

This is the revised version of the 'Management of Health and Safety at Work Regulations 1992'. These Regulations require every employer and self employed person to make a suitable and sufficient assessment of the risks to workers or anyone else affected by their work. The hazards should be identified and preventive and protective measures undertaken to control the risks identified. Finally, periodic reviews should be carried out to ensure that the system remains effective.

4.7 THE WORKPLACE (HEALTH, SAFETY AND WELFARE) REGULATIONS (WHSW) 1992

These were drawn up after consultation with representatives from the Trades Union Congress, the Confederation of British Industry, local authorities and the HSE. These Regulations apply to a wide range of workplaces.

4.7.1 Falls (Regulation 13)

This covers falls or falling objects and states that practicable, suitable and effective measures should be taken to prevent any person falling a distance or being struck by a falling object likely to cause personal injury.

4.7.2 Ability to Clean Windows etc Safely (Regulation 16)

Windows and skylights in a workplace should be designed so that they may be cleaned safely. This may include windows, which pivot so that the outer surface is turned inwards or the provision of suitable conditions for the future cleaning of windows. This provision refers to access for ladders and requires a firm, level surface on which to place the ladders, and suitable points for fixing the ladder if they are over six metres in length. Furthermore, there should be suitable and suitably placed points for anchoring of a safety harness.

4.8 A GUIDE TO THE CONSTRUCTION (HEALTH, SAFETY AND WELFARE) REGULATIONS (CHSW) 1996

These are simplified construction Regulations, which also include new provisions arising from the implementation of an EC Directive on construction (92/57/EEC).

The CHSW Regulations explain the detailed ways of working in construction activities, and are aimed at protecting the health, safety and welfare of persons carrying out construction work, as well as giving protection to others who may be affected by the work. These Regulations apply to employers, employees and anyone doing construction work.

4.8.1 Safe Place of Work (Regulation 5)

Persons involved in construction have a general duty to ensure a safe place of work. This also applies to work at height and requires that ‘reasonably practicable steps’ be taken to provide for safety and the minimisation of risks to health. More than 50% of the fatal accidents in construction are the result of a fall. The Regulations aim to prevent falls from any height, but have specified certain steps to be taken for work over two metres high. Where the work cannot be carried out at ground level it is necessary to provide physical safeguards in order to prevent falls from occurring.

4.8.2 Precaution Against Falls (Regulations 6 and 7)

If this is not reasonably practicable, due to short task duration or task difficulty, it is advised to use personal suspension equipment such as rope access or boatswain’s chairs. If these are impractical for the reasons given above, equipment which will arrest falls must be considered such as a safety harness. Any specific equipment must be erected or installed under the supervision of a competent person.

4.8.3 Training and Inspection (Regulation 28, 29 and 30)

Construction activities must only be carried out by persons with relevant training or experience, or supervised by those with the appropriate levels of training or experience. Before any work at height is carried out, the place of work must be inspected by a competent person, who must be satisfied that the work can be completed safely.

4.9 ANNEX: AMENDING PROPOSAL OF DIRECTIVE 89/655/EEC CONCERNING THE MINIMUM SAFETY AND HEALTH REQUIREMENTS FOR THE USE OF WORK EQUIPMENT BY WORKERS AT WORK (SECOND INDIVIDUAL DIRECTIVE WITHIN THE MEANING OF ARTICLE 16 OF DIRECTIVE 89/391/EEC) VERSION 4.4

This Directive is intended to regulate safety on temporary work at height. The aim is to reduce the incidence and severity of injuries caused by falls from a height. It provides a hierarchy for the selection and minimum requirements for the use of access equipment for temporary work at height, as well as specific requirements for common forms of temporary access, such as ladders and scaffolding.

4.9.1 Regulation 4

Employers are required to select the most suitable and safest access equipment, based on their risk assessment. This selection must also take into account the frequency, the height and the duration of the task. Furthermore, they are required to put into place measures that will prevent or arrest falls from a height. Collective equipment (netting) should take precedence over personal protective equipment (lanyards). The presumption is made that ladders and rope access will only be used as workstations when the use of other, safer equipment (scaffolding) is not justified due to the low level of risk, the duration of the task, or other features of the site that the employer cannot alter.

4.9.2 Specific Provisions Regarding the Use of Ladders (Regulation 4.2)

Ladders must be positioned and secured to ensure stability during use. They must rest on a stable, immobile footing, such that the rungs are horizontal. The stiles must be secured by an anti-slip device. Ladders must be used in such a way that workers can access a secure handhold or support at all times. Any load to be carried must not prevent the maintenance of a secure handhold.

4.10 NATIONAL AND INTERNATIONAL REGULATIONS APPLICABLE TO LADDERS AND STEPLADDERS

In October 2000, the Victorian Workcover Authority produced the following review of national and international regulations applicable to ladders and stepladders, as a part of larger survey on the causal factors implicated in accidents involving ladders.

4.10.1 United States

The *OSHA Regulations Part 1926 Safety and Health Regulations for Construction (Duty to have fall protection – 1926.501)* provide that employees working at 6 feet (1.8 m) or more above lower levels shall be protected by guardrail systems, safety net system, or personal fall arrest systems – except when the employer can demonstrate that it is infeasible or creates a greater hazard to use these systems, the employer shall develop and implement a fall protection plan which meets the requirements of the Regulations.

Ladders – 1926.1053(b) provides in great, prescriptive detail for the use of fixed and portable ladders. The Regulations does not establish a hierarchy of control; employers are permitted to select fall protection measures compatible with the type of work being undertaken. The sections dealing with ladders (1053 (a) and (b)) do not indicate that ladders are to be avoided if safer alternatives are practicable.

4.10.2 Canada

Part II of the Canadian Labour Code provides overarching legislation. Standards are framed within the terms of this legislation. The available information on use of ladders recommends that a safety harnesses is used in conjunction with ladders when working 3 m or more off the ground or when working with both hands.

The Ontario *Occupational Health and Safety Act, Construction Projects O. Reg. 213/91*, regulate ladders under Part II General Construction. These provisions prescribe requirements for the design, manufacture and maintenance of ladders. In respect to use, a ladder is required to be placed:

“so that its base is not less than one quarter, and not more than one third, of the length of the ladder from a point directly below the top of the ladder and at the same level as the base of the ladder if the base is not securely fastened”.

Ladders that are used as a regular means of access between levels of a structure.

- “(a) shall extend at the upper level at least 900 mm above the landing or floor;*
- (b) shall have a clear space of 150 mm behind every rung;*
- (c) shall be located so that an adequate landing surface free of obstacles is available at the top and bottom of ladder;*
- (d) shall be secured at the top and bottom to prevent movement”.*

In British Columbia, s.13.8 of the *Occupational Health and Safety Regulation* places a number of “use restrictions” on ladders:

“(1) A worker must not work from the top two rungs of a portable single or extension ladder or the top two steps of a step ladder unless permitted by the manufacturer.

(2) A ladder must not be used as a scaffold component, nor as a horizontal walkway, ramp or work platform support unless it is part of a pre-manufactured or engineered system.

(3) A worker may work from a portable ladder without fall protection provided that

- (a) the work is a light duty task of short duration at each location,
- (b) the worker’s centre of gravity is maintained between the ladder’s side rails,
- (c) the worker will generally have one hand available to hold onto the ladder or other support, and
- (d) the ladder is not positioned near an edge or floor opening that would significantly increase the potential fall distance”.

4.10.3 New Zealand

The Occupational Safety and Health Service of the Department of Labour, New Zealand has developed *Guidelines for the Prevention of Falls* (January 2000) to assist duty-holders in meeting the requirements of the *Health and Safety in Employment Act 1992* and *Regulations 1995*.

The guidelines are “primarily aimed at the construction industry, in relation to the design, building, maintenance and demolition of structures”, but they also have application “to a wide range of work situations where workers are placed in a position from which falls are possible”.

They apply to work carried out from 3 m or more in height. However, “where there is a possibility of serious harm from a fall of less than 3 m, fall protection is still needed”.

A generic hierarchy of control is adopted: elimination, isolation or minimisation (the least preferred option). Control measures to prevent falls are not set out under this hierarchy, so it is not possible to discern whether ladders are included in, or excluded from, the hierarchy. Guidelines for ladders are fall under the heading “Temporary Non-Fixed Access and Platforms”, which also covers perimeter protection and cantilevered temporary work platforms. Ladders are required to comply with the relevant New Zealand Standards. The permissible heights for single, extension and stepladders are the same as those adopted in Australia.

4.10.4 Sweden

Section II (27) of Part B “Specific minimum requirements for on-site workstations” of the *Ordinance of the Swedish National Board of Occupational Safety and Health containing Provisions on Building and Civil Engineering Work* (AFS 1994: 52) states:

“27.1 Falls from a height shall be physically prevented in particular by means of solid cradles which are sufficiently high and have at least a toe-guard, a main handrail and an intermediate handrail or equivalent alternative.

“27.2 In principle, work at a height shall be carried out only with appropriate equipment or using collective protection devices such as cradles, platforms and safety nets”.

It further states:

“If the use of such equipment is not possible because of the nature of the work, suitable means of access shall be provided and safety harnesses or other anchoring safety methods shall be used”

These requirements have been harmonised with the European Union’s Council Directive 92/57/EEC on the implementation of minimum safety and health requirements at temporary or mobile construction sites. The Swedish ordinance and the EU directive establish a simple dual hierarchy here.

In the first instance, collective, passive protection devices must be used to prevent falls. If this is not practicable, individual, active devices must be adopted. Ladders do not appear to belong in this hierarchy.

A number of Swedish National Board of Occupational Safety and Health ordinances preceded AFS 1994: 52:

- Protection Against Injuries Due to Falls (AFS 1981: 14)
- Work on Roofs (ASF 1983: 12)
- Provisions on Ladders and Trestles (AFS 1985: 15).

Unfortunately, these were not readily available.

4.10.5 European Union

In addition to provisions reproduced above in Swedish ordinance AFS 1994:52, the European Directive 92/57/EEC Part B *Specific Minimum requirements for on-site workstations*, clause 6.4 requires that:

“Ladders must be sufficiently strong and correctly maintained. They must be correctly used, in appropriate places and in accordance with their intended purpose”.

Ladders do not appear to be included in the hierarchy.

Thus, it can be seen that there is little unity across national borders, with respect to specific regulations concerning the use of ladders.

4.11 OTHER INFORMATION

In order to ascertain the type of advice that would be provided to ladder users on request for information an enquiry was made of the HSE as to the relevant guidance they provide on ladder use. The following is extracted from the response:

Ladders are best used as a means of getting to a workplace. They should only be used as a workplace for short-term work. They are only suitable for light work. If ladders are to be used, make sure:

- *the work can be reached without stretching;*
- *the ladder can be fixed to prevent slipping; and*
- *a good handhold is available.*

However, this kind of work can still be dangerous - many ladder accidents happen during work lasting less than 30 minutes. The longer the ladder, the more problems there are in using it safely.

It gets harder to handle, is more difficult to foot effectively and it flexes more in use. Make certain there is no other better means of access before using a ladder. Many accidents result from using ladders for a job when a tower scaffold or mobile access platform would have been safer and more efficient. Make sure light tools are carried in a shoulder bag or holster attached to a belt so that both hands are free for climbing. Heavy or bulky loads should not be carried up or down ladders - a gin wheel or other lifting equipment should be used instead. For safe working the ladder needs to be strong enough for the job and in good condition:

- check the stiles are not damaged, buckled or warped, no rungs are cracked or missing and any safety feet are not missing;*
- do not use makeshift or home-made ladders or carry out makeshift repairs to a damaged ladder;*
- do not use painted ladders, as the paint may hide faults;*
- ladders made for DIY use may not be strong enough for site work and are best avoided.*

Check the ladder is secure. More than half of the accidents involving ladders happen because the ladder was not prevented from falling or slipping. Ladders are only safe when they rest on a firm, level surface. Do not place them on loose bricks or packing. They should also be secured by rope or other suitable stabilisation devices. Such devices must ensure that the ladder does not:

- 1. run sideways; or*
- 2. slide away from the wall.*

Also, make sure:

- the ladder is angled to minimise the risk of slipping outwards; as a rule of thumb the ladder needs to be 'one out for every four up';*
- the top of the ladder rests against a solid surface; ladders should not rest on fragile or other insecure materials such as cement sheet, or plastic guttering;*
- both feet of the ladder are on a firm footing and cannot slip;*

- *if the ladder is more than 3 m long, or used as a way to and from a workplace, it is secured from falling. This will usually be by fixing at the top, or sometimes the base;*
- *if the ladder cannot be fixed, a second person foots the ladder while it is being used (this also applies while the ladder is being fixed);*
- *the ladder extends a sufficient height (about 1 m) above any landing place where people will get on and off it unless some other adequate handhold is available; and*
- *where ladders are used in a run measuring a vertical distance of more than 9 m, suitable landing areas or platforms are provided. The only exception to this relates to some steeplejacks' ladders which may not have landing places this often. Nevertheless, provide as many landing places as possible.*

The HSE also produce a free leaflet containing relevant information: CIS49, General Access Scaffolds And Ladders, free for a single copy

Relevant legislation would include:

- *The Health and Safety at Work etc Act 1974*
- *Management of Health and Safety at Work Regulations 1999 Provision and Use of Work Equipment Regulations 1998 Workplace (Health, Safety and Welfare) Regulations 1992 The Construction (Health, Safety and Welfare) Regulations 1996*

Many of the free publications can also be downloaded from the HSE

Website: www.hse.gov.uk

It can be seen therefore that both footing and stabilisation devices are being currently promulgated as safety strategies, despite the apparent absence of evidential support to endorse these practices. Furthermore, the recognition of the importance of choosing the right access equipment raises further questions over the appropriateness of footing and stability devices when other structures may be safer.

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5.0 OVERVIEW OF RESEARCH

This research project can be summarised into six main components, each of which are reported in this document. The components and task within them are:

5.1 UNDERTAKE LITERATURE REVIEW

1. Scope the prevailing literature to understand the current state of knowledge
2. Review the current ladder legislation and standards

5.2 UNDERTAKE PRODUCT REVIEW

1. Evaluate the range of products available
2. Identify typical product groups
3. Identify and obtain examples of typical products

5.3 PILOT STABILITY TRIALS.

1. Establish test methodology
2. Finalise the trials methodology.
3. Undertake limited pilot trials to test methodology.

5.4 MAIN STABILITY TRIALS

1. Recruit subjects and commission trials.
2. Execute trials.
3. Validate trials.
4. Collect and process trials data.

5.5 DATA ANALYSIS

1. Analyse the trials data to produce usable output.
2. Process the data to generate user force parametrics.
3. Develop and test stability models
4. Produce stability predictor model
5. Combine the data sets to produce a performance test specification.

5.6 REPORT AND RECOMMENDATIONS

1. Prepare and deliver the final report of the work, including recommendations to the HSE.
2. Undertake a review of the project and hold a debriefing meeting.

5.7 KNOWLEDGE DISSEMINATION

1. Identify appropriate recipients.
2. Determine dissemination strategy.
3. Disseminate information.

6.0 LADDER STABILITY DEVICE REVIEW

A review was undertaken of the ladder stability devices available in the UK market. It emerged that the products could be classified into seven main categories based on their functionality and the mechanical principles on which they are meant to operate. These are summarised in the following Sections.

It also became apparent that there is considerable branding within the market place with the same product apparently appearing under several trade names and via several retail routes. The other issue which emerged early in the review was that there was a lack of evidential support for the performance claims of many devices. Their promotion was often supported by photographs of extreme tasks being undertaken with the benefit of the device, but the nature of the safety gain provided was not stated.

Much of the promotion of the devices takes the form of appealing to what appears intuitively right. Accordingly, because bracing struts or large friction surfaces look as though they should provide a benefit it is assumed that they do so. Unfortunately virtually none of the advertised products were promoted with accompanying engineering data to support the claimed benefits.

An additional problem was also identified in that the tasks that were promoted in some of the promotional material appeared to be in conflict with good ladder practice. To the prospective purchaser it appeared that some devices would permit ladders to be used in highly dangerous scenarios. This would appear to be in contradiction to the majority of published advice which recommends that the first decision taken is whether a ladder is the most appropriate device. Examples of this are shown in Figure 9.



Figure 9
Conflicts with good ladder practice

Some typical example products were purchased for examination. The quality of the supporting literature was highly variable, with some products having virtually no instructions or warnings whilst others went into great detail. Of note was the general lack of information regarding maintenance of either the ladder or the device although this may have increased significance given the changed loading patterns the device may place on the ladder in use.

6.1 LADDER TIE-OFF DEVICES

These devices are intended to be incorporated into the built environment to permit a ladder to be secured for routine maintenance and repair. An example of such a device is shown in Figure 10.



Figure 10
Ladder tie-off device

Whilst these devices are intended to provide additional stability to the ladder they do not fulfil the same function as the other categories here. Once the ladder is successfully tied off, it ceases to be a free-standing structure and becomes, to all intents and purposes, a weak staircase. Clearly the quality of the tie-off and the geometry of its installation will affect performance, but generally this type of device will convert the ladder into a stable structure. It is true that if the tie-off mountings are above normal reach from the ground a ladder will have to be used to access them. In this case a more conventional stability device may be sought.

Since the tied off ladder is a stable and semi constrained structure, these devices were not considered as part of this evaluation.

6.2 TOP MOUNT DEVICES

Top mounted devices are intended to be permanently, or semi permanently attached to the top of the ladder structure. They generally perform one or more of the following functions:

- Stand-off
- Storage
- Wheeled access

The stand-off function permits the ladder to be more rigidly engaged with the vertical surface rather than resting on protruding objects such as guttering. Some stand-off devices are shaped to also fit around stand pipes and other vertical structures.

Many products utilise the area between the ladder and the stand-off feet to provide a storage facility in the form of a moulded tray. Others provide hooks or other attachment points for hanging items when working at height.

A further feature of many of the top mount devices is that they are equipped with wheels rather than point contact feet. This facilitates the raising of the ladder up the vertical surface. In some instances these wheels are made from high friction rubber and are claimed to be safety devices in their own right.

Examples of typical top mount devices are shown in Figure 11.



Figure 11
Ladder top mount devices

6.3 BASE MOUNT DEVICES

Base mount devices locate permanently or transitorily to the region around the feet of the ladder. They may be clamped, bolted or otherwise affixed, or they may have a less substantial mounting where the ladder just rests in contact with it.

Many devices are intended to provide continuous benefit, such as those aiming to increase the grip of the ladder on the ground. Other, of a more structural nature, are intended to come into operation should the ladder start to move in some fashion, and are thereby offering a different type of functionality. Some devices attempt to achieve both through increasing the base area of the ladder and changing the frictional properties.

Examples of these types of product are shown in Figure 12



Wheels on photo are for demonstration purposes only

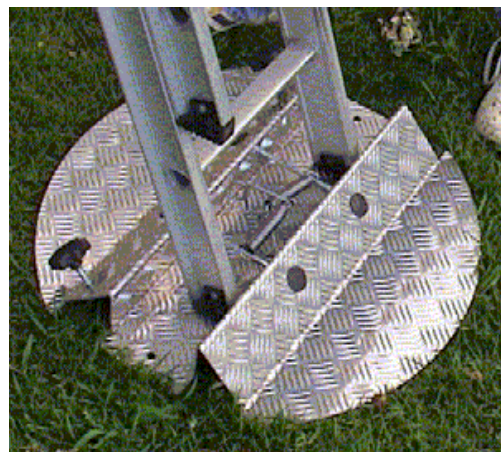


Figure 12
Ladder base mount devices

6.4 REPLACEMENT FEET

Replacement feet are arguably the simplest stability devices. They take one of several forms:

- Spikes
- Wheels
- Suction cups
- Deformable mouldings
- Articulated feet
- Replacement end caps

With the exception of wheels, they all work on the premise of improving the grip between the ladder and the ground although some may intend to increase the range of applications for a ladder as well. Of the different styles, the spiked feet will have the largest impact since they will rigidly couple the ladder to the ground. However, their range of applications is limited and, through promotion of ladder use on soft surfaces, they may introduce other hazards.

The functionality of the remaining types of foot will principally depend on the grip provided by the material use in its construction. Examples of typical product are given in Figure 13.



Figure 13
Replacement feet devices

6.5 LARGE TRIPODS

Tripods are a unique category of ladder stability device. They convert the ladder from a device which is dependent on a rigid vertical structure for its stability into one that is ground standing. This is generally achieved through the addition of a sub-frame to the front of the ladder which extends and props the ladder in its elevated position. The user is then at liberty to climb the ladder.

This device brings its own attendant problems. Firstly, the user must ensure that the substrate is appropriate to support the free-standing structure. Then the user must remember not to exceed a given point on the ladder at which the stability may no longer be sufficient. Lastly, there may be a restriction to the range of activities that may be undertaken with the ladder in this configuration.

This type of device liberates the user from the normal confines of ladder use and turns the leaning ladder effectively into a large stepladder with unorthodox geometry. This transformation appears to require some modification to the ladder structure, in the form of drilling holes, which may bring its own attendant problems.

This type of device may also be used when the ladder is leaning against a solid surface, as a secondary safety device. In this mode it emulates a very large version of the base mount structural devices, in that it provides alternative footing points should the ladder begin to move.

An example of a large tripod is given in Figure 14.



Figure 14
Large tripod device

6.6 STEPS AND PLATFORMS

Steps and platforms are usually devices which are temporarily fitted to the ladder to increase the comfort and usability. However, some are more permanently attached. The majority of these devices fold to permit access above them on the ladder so that the user may climb the ladder before extending the step and treading down onto it.

The step may extend out from the ladder in the forward or rearward direction and are generally narrower than the ladder's width. However, some devices are available which are significantly larger, though these appear to require the use of additional stability precautions such as tie-offs.

Examples of two types of step are given in Figure 15, and illustrate a forward and rearward extension.



Figure 15
Ladder step devices

6.7 SLOPE COMPENSATION DEVICES

Slope compensation devices intend to even out vertical differences between the placement of each of the feet. They generally consist of one non-adjustable foot and one that can be raised or lowered by means of some adjustment device such as a ratchet or peg. The ladder is placed on the sloping surface and then made vertical by lowering or raising the adjustable foot. This would appear to then restore the ladder to its conventional working position. An example of such a device is given in Figure 16



Figure 16
Slope compensation device

6.8 UNORTHODOX DEVICES

There are a number of other devices that, whilst working on similar principles to those in the main categories do so in a novel or unorthodox fashion. These devices are often complex and involve different functional components, such as a platform and a user safety harness. It appears they also aim to enable a ladder to be used in a range of circumstance for which it would not normally be appropriate.

Despite their apparent lack of conformity they normally address common problems of use and do so in a conventional manner in respect of mechanics. For this reason it is possible to include such devices in the modelling and prediction algorithms that appear later in this report.

An example of one such unorthodox device is shown in Figure 17



Figure 17
Unorthodox ladder device

6.9 CONCLUSION

Whilst, at first glance, there is a large diversity of individual products in the UK market place, closer scrutiny reveals that many of them are ‘badge engineered’ versions of the same products. Furthermore, these remaining products are largely generic and can be grouped on the basis of the functional design. All the products address basic principles of stability such as geometry or friction by fairly crude methods. This mechanical simplicity provides the means by which their performance can be quantified and modelled.

7.0 SUBJECT PROFILE

Ladder users are drawn from both domestic and professional groups within society and this is recognised within the current standards structure through the provision of standards for domestic and industrial ladder products. However, ladder stability devices are more prevalent within the professional group who may be obliged by health and safety requirements to use such items. Accordingly, in recruiting participants to undertake the user trials emphasis was placed on identifying those individuals who used ladders as part of their profession. However, some non-professional users were also participants to ensure that all types of user were fairly represented. The profile of the participants recruited is summarised in the following sections, however the selection criteria are given here as an overview of the sample population.

Age

Ladder users are primarily adults, and so a typical 18 plus aged population was used to represent them. It was particularly important to include older users, since they appear more likely to be involved in accidents and more seriously injured when they are. A further justification for this banding is that it also represents the age of the typical working population, so direct comparison between the groups could be made on this basis.

Gender

More men use ladders than women, though this relationship is affected by the use environment. However, from accident statistics it was determined that 70% of injured users were male and 30% female. Accordingly the subject panel attempted to follow this, although recruitment difficulties meant that the final ratio was 86 % male to 14 % female.

Experience

Experience is more difficult to control for, since it covers exposure to ladder products as well as duration of direct use. However, all subjects were required to have first hand experience of ladder use to qualify for participation.

All other key parameters, such as body dimensions, dynamic capabilities, etc. were considered to be adequately represented by effective sampling from the general population.

The subjects were selected for the trials were either drawn from an extensive panel of individuals maintained by RICE to support trials of this size, or from local organisations, representing employees of larger institutions, such as a university, as well as small one-person organisations, such as painters and decorators. These two trades in particular were of interest since they had been revealed to be over-represented in ladder accidents. Smaller organisations (SME, etc.) were eliminated on the basis that they may face the same problems as small organisations without the training infrastructure of larger concerns. Hence the behaviour of their employees would be represented by either untrained domestic subjects or fully trained professional ones.

Two sets of profiling were undertaken, examining anthropometric considerations as well as attitudinal ones.

Anthropometric evaluation

This involved measuring various body dimensions to ensure that our test population were representative of the population in general. Dimensions which act upon the ladder and its effective usability (and hence safety) were measured, including height, weight, leg length, knee height, shoulder height and grip reach.

Psychometric evaluation of attitudinal and behavioural responses

A range of generalised psychometric tests were used to generate a portfolio of the individuals risk taking and hazard perception characteristics. These were collected as a guide only and to provide the capacity for future evaluation if appropriate

Together, these tasks addressed issues of:

1. Perceived risk
2. Measures of 'Sensation Seeking'
3. Hazard perception rating scales

7.1 PARTICIPANT SUMMARY

In total, 52 participants were selected at random from the subject database, the only selection criteria being age, sex, ladder experience and availability during the trials period. The age range selected was 18 to 71 years to mirror the working population and the older user group (Table 7).

Table 7
Participant summary - age

| Youngest | Mean | Oldest |
|-----------------|-------------|---------------|
| 18 | 41 | 71 |

The distribution of females to males was 1:6, somewhat short of the 1:3 (Table 8) which would reflect the proportion of males and females observed in the accident records relating to ladders, but adequately representing the ladder users in the workplace. Subjects were advised that the trials would involve some physical activity and reaching, and that individuals with certain medical conditions were not suitable. In practice, no individuals retired from the trials.

Table 8
Participant summary - gender

| Males | Females |
|--------------|----------------|
| 45 | 7 |

Because the trials related to the loading of ladders, and ladders are defined by weight duty ratings, a breakdown of the weight distribution of the participants was undertaken. The weight bands correspond to the duty ratings in BS 2037 (Table 9).

Table 9
Participant summary - weight

| Weight band | n (%) |
|-----------------------|--------------|
| 95 kg or over | 13 (25%) |
| 110 kg or over | 2 (3.8 %) |
| 130 kg or over | 0 |
| Average weight 84.1kg | |

As previously mentioned, painters and decorators formed part of the subject group since these trades are over represented in accident statistics. Other professional users included maintenance engineers, site workers and emergency services personnel.

Each subject was allocated 60 minutes per complete trial, covering anthropometric survey, paper-based tasks and dynamic trials. However, it was vital that participants did not influence each other's perceptions or behaviour during the trial. Accordingly, each participant's arrival time was staggered so as to provide an overlap. This permitted participants to carry out all elements of the trial, with only minimal contact with each other.

Lastly, the subject's dominant hand was recorded so that, if necessary, correlation could be made to the effectiveness of task performance. This data is given in Table 10.

Table 10
Participant summary - dominant hand

| Right handed | Left handed |
|---------------------|--------------------|
| 45 (86 %) | 7 (14 %) |

7.2 ANTHROPOMETRIC DATA RESULTS

The data collected illustrate that participants used were representative of the general population at large. Comparison is made with data representing the 1st to the 99th percentile UK adult (i.e. excluding 2% of the population).

This was used in preference to the more normal 5th to 95th percentile range (i.e. excluding 10% of the population) on the basis of current design guidelines from the DTI (as featured in their publications 'Childata' and 'Adultdata' (DTI 1998 ADULTDATA. The Handbook of Adult Anthropometric and Strength Measurements & 1995 CHILDATA. The Handbook of Child Measurements and Capabilities) recommending an increased safety margin be used for safety critical products. Details of the dimensions measured, and how they compare with the 1st – 99th percentile data for the two populations are given in Table 11.

Table 11
Participant anthropometric profile – summary

| Dimension | Subject mean | 1st – 99th percentile |
|---|---------------------|--|
| Weight | 84.1 kg | 53 – 110 kg |
| Stature | 1755 mm | 1594 – 1918 mm |
| Leg length (greater trochanter to sole of foot) | 950 mm | 795 – 1038 mm |
| Knee height | 500 mm | 443 – 571 mm |
| Shoulder height | 1437 mm | 1301 – 1601 mm |
| Grip reach from shoulder | 651 mm | 641 – 832 mm |

In order to further understand the composition of the subject population, the parameters were broken down into bands and individual counts made. These are summarised below.

Table 12 give the data for the age bands. It can be seen that the majority of participants (30%) were in the 20 – 30 year age band, with the remainder spread fairly evenly across the range 20 to 70 years. Two individuals exceeded 70 and four were below 20 years of age. The data are presented graphically in Figure 18.

Table 12
Participant anthropometric profile – age

| Age Band | Count (n) |
|-----------------|------------------|
| <20 | 4 |
| 21-30 | 16 |
| 31-40 | 6 |
| 41-50 | 9 |
| 51-60 | 7 |
| 61-70 | 8 |
| 71-80 | 2 |

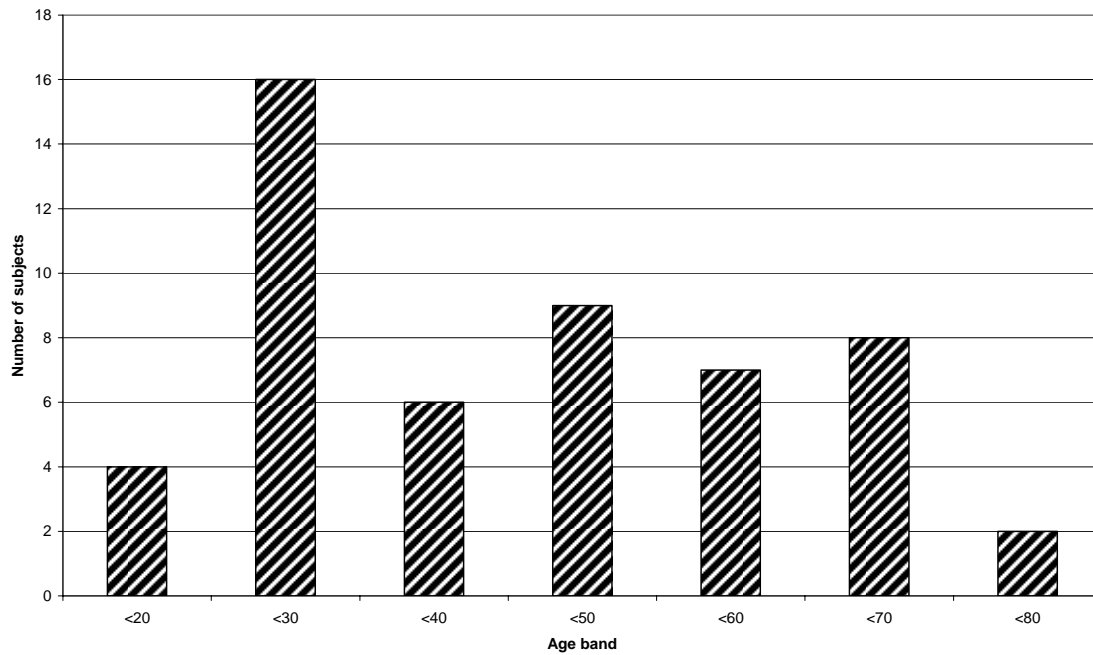


Figure 18
Participant age banding

The weight banding represented the normal population. The 70 – 80 kg band contained the highest number of individuals (30 %) although the mean was 84 kg. This data is presented in Table 13 and Figure 19.

Table 13
Participant anthropometric profile – weight

| Weight Band | Count (n) |
|-------------|-----------|
| <60 | 1 |
| 61-70 | 6 |
| 71-80 | 16 |
| 81-90 | 10 |
| 91-100 | 11 |
| 101-110 | 6 |
| >110 | 2 |

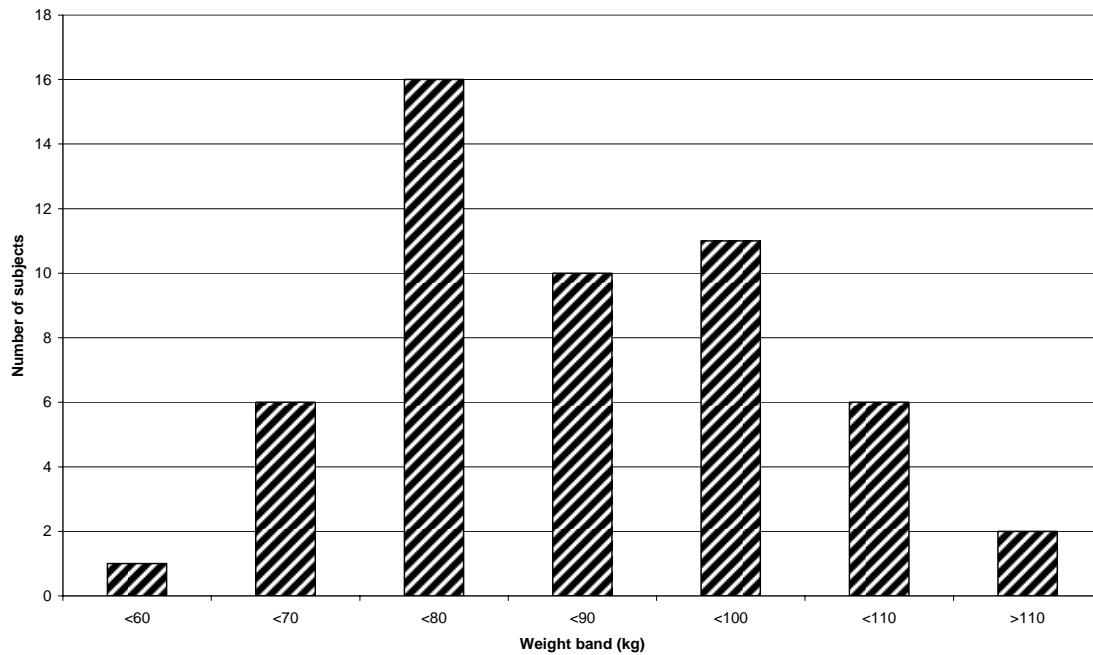


Figure 19
Participant weight banding

Participant stature distribution also fairly represented the normal population, with 38 % falling in the 170 – 180 cm band. The mean stature was 175.5 cm, which equates to 74th percentile of the British adult population. This is primarily because of the bias in the sample population towards younger males, who tend to be taller than their female or older counterparts. This data is presented in Table 14 and graphically in Figure 20.

Table 14
Participant anthropometric profile – stature

| Stature Band | Count (n) |
|--------------|-----------|
| <160 | 2 |
| 161 - 170 | 12 |
| 171 - 180 | 20 |
| 181 - 190 | 14 |
| 191 - 200 | 4 |

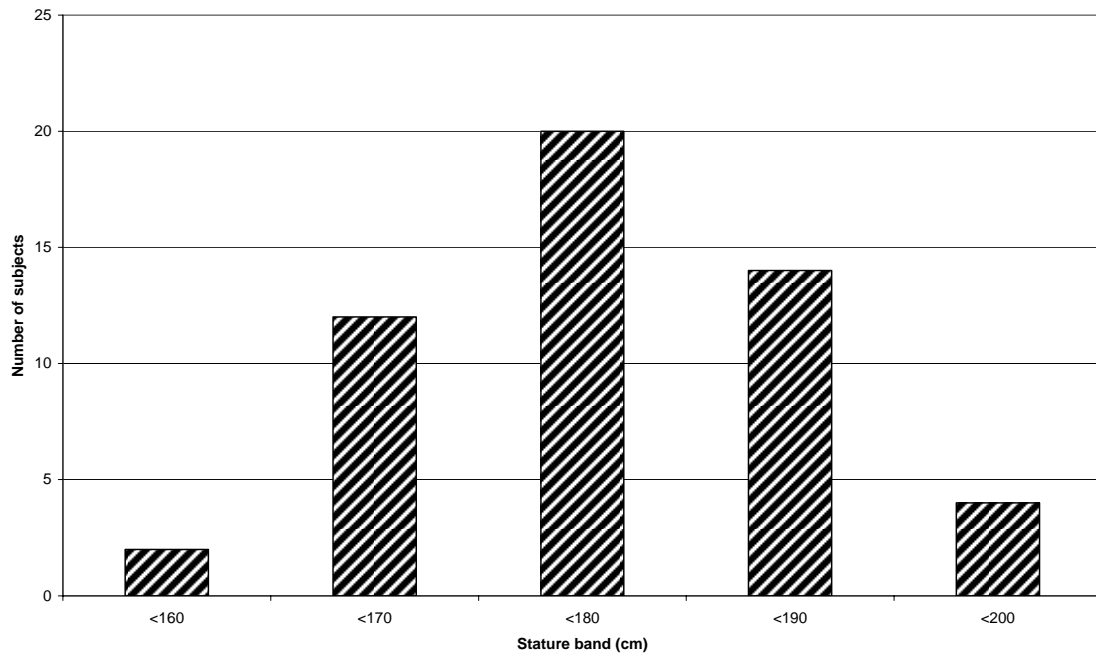


Figure 20
Participant height banding

The grip reach of the participants reflects their capacity to reach forward whilst in a normal standing posture, and so affects their footing technique as well as their initial mount and final dismount from the ladder system. The largest number of individuals (40%) fell in the 60 to 65 cm band, with a mean reach of 651 mm. This equates to a national population percentile of 63.1. This data is tabulated and in Table 15 and presented pictorially in Figure 21

Table 15
Participant anthropometric profile – grip reach

| Grip reach Band | Count (n) |
|-----------------|-----------|
| <60 | 4 |
| 61 - 65 | 21 |
| 66 - 70 | 20 |
| 71 - 75 | 5 |
| 75 - 80 | 2 |

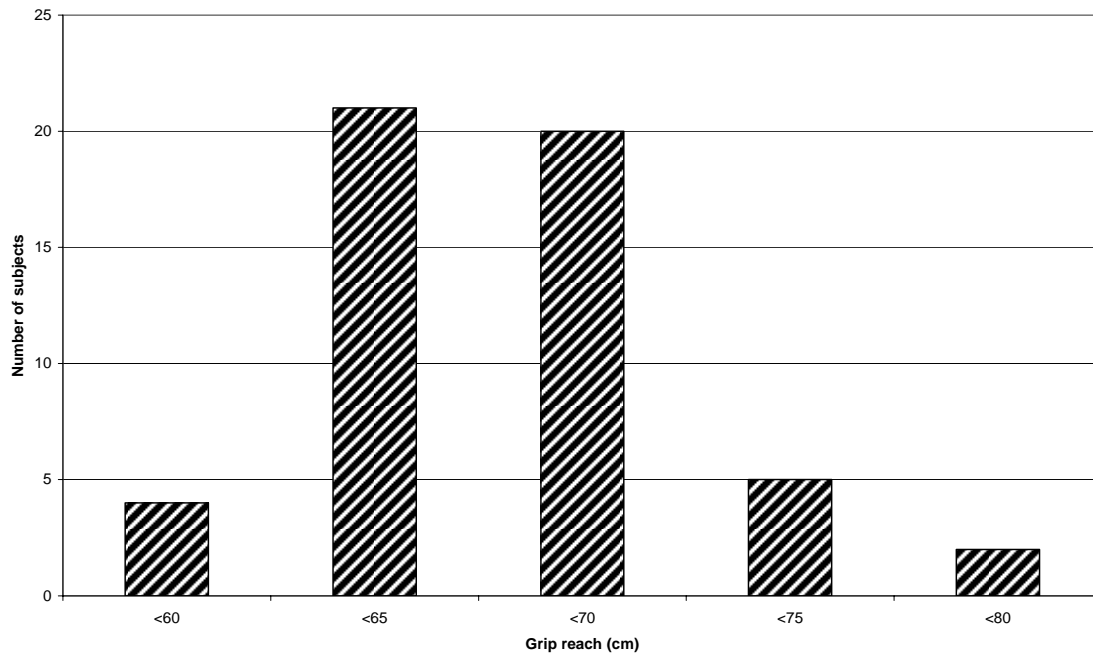


Figure 21
Participant grip reach banding

The leg length is influential on the location of the Centre of Gravity as well as the step height. Accordingly it was banded to evaluate the population make up. The band 90 to 95 cm contained the most individuals (29 %) although the mean leg length was 95cm. This equates to 87th percentile of the UK adult population. The bandings are shown in Table 16 and Figure 22

Table 16
Participant anthropometric profile – leg length

| Leg length Band | Count (n) |
|-----------------|-----------|
| <85 | 5 |
| 86 - 90 | 6 |
| 91 - 95 | 15 |
| 96 - 100 | 12 |
| 101 - 105 | 10 |
| 106 - 110 | 3 |
| 111 - 115 | 1 |

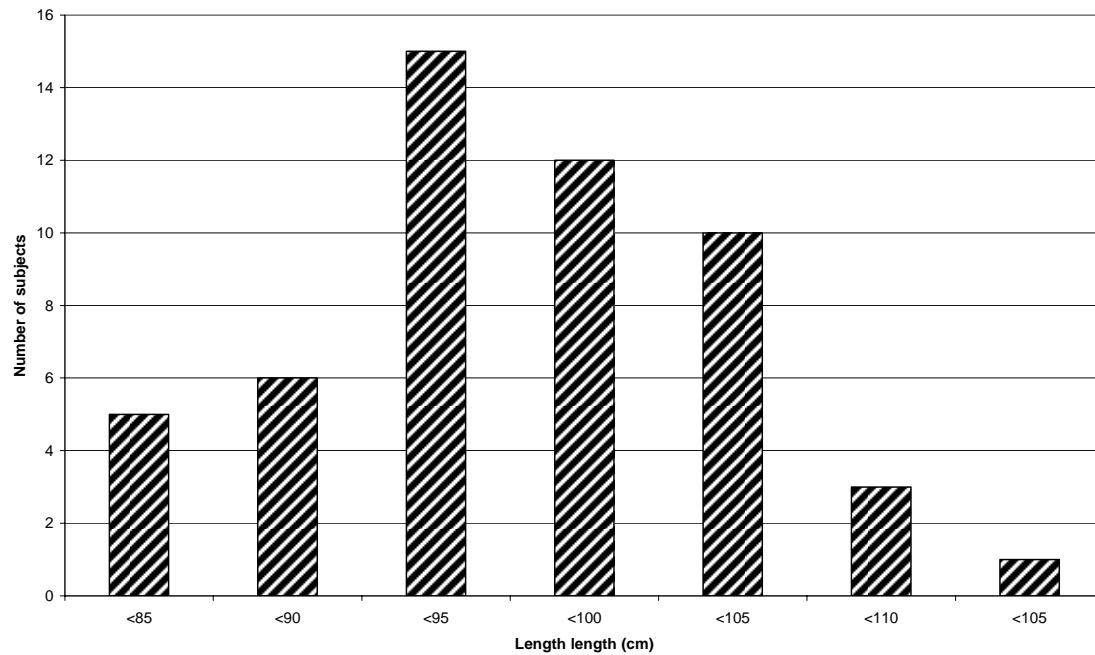


Figure 22
Participant leg length banding

The knee height of the individual has a significant effect on the step height. The knee height of the sample population was banded to establish the relationship between the lower limb components in case they may influence the Centre of Gravity location. The average knee height was 50 cm, with 50 % of all participants falling into the 50 – 55 cm band. The UK adult population equivalent of 50 cm is 65th percentile. This data appears in Table 17 and Figure 23.

Table 17
Participant anthropometric profile – knee height

| Knee height Band | Count (n) |
|------------------|-----------|
| <35 | 1 |
| 36 - 40 | 1 |
| 41 - 45 | 4 |
| 46 - 50 | 13 |
| 51 - 55 | 26 |
| 56 - 60 | 5 |
| 61 - 65 | 1 |
| >66 | 1 |

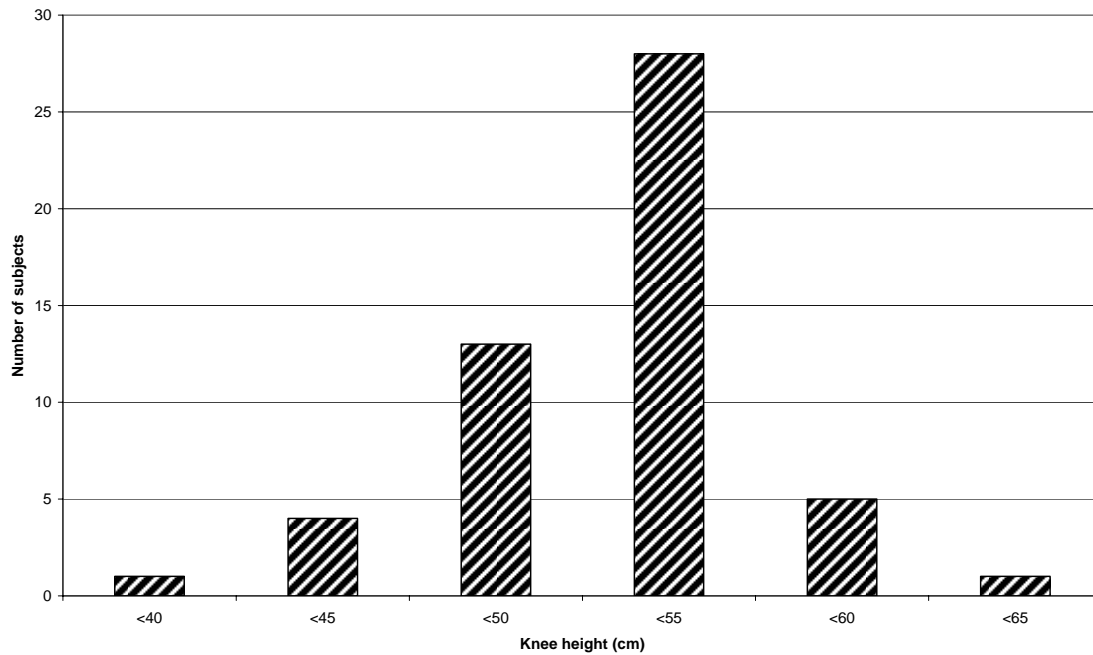


Figure 23
Participant knee height banding

The last dimension recorded was shoulder height. This represents a meaningful measurement for the height at which work is undertaken and so controls for the rung which may be chosen by an individual for a given task. The largest number of subjects appeared in the 140 – 145 cm band (35%) with a mean value of 143.7 cm. This equates to the 69th percentile of the UK adult population. The data is presented in Table 18 and also in Figure 24.

Table 18
Participant anthropometric profile – shoulder height

| Shoulder height Band | Count (n) |
|----------------------|-----------|
| <135 | 8 |
| 136 - 140 | 7 |
| 141 - 145 | 18 |
| 146 - 150 | 4 |
| 151 - 155 | 7 |
| 156 - 160 | 6 |
| 161 - 165 | 2 |

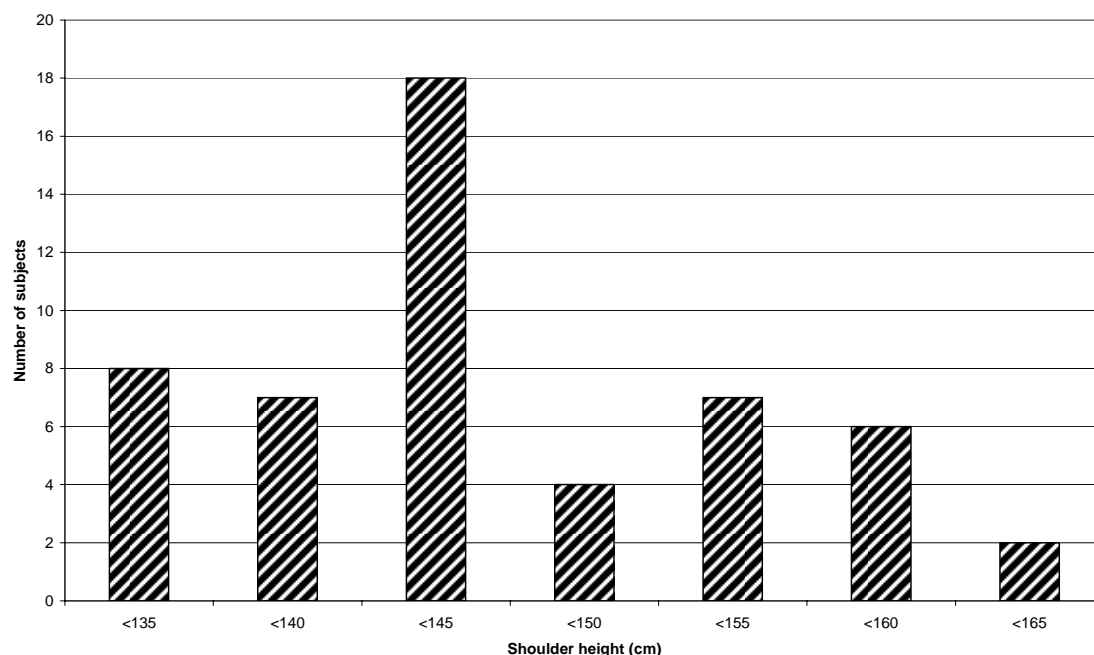


Figure 24

Participant shoulder height banding

7.2.1 Conclusions

It can be seen that virtually all measurements fall within the 1st and 99th percentiles, indicating our population was representative of the population in general. The data generated from the dynamic trials involving these individuals can therefore be considered as representative of that found in everyday use. Accordingly, any design criteria used in the construction and testing of ladder stability devices should be based on the dimensions readily available for this range of individuals in order to ensure that the maximum levels of safety are provided with the minimum of excluded individuals.

It should be noted that it is important to ensure that design of all products, but particularly safety critical ones, should be inclusive. That is to say that by designing for the least able, all other users generally find a usability benefit. This can be seen in features such as step height, where designing for those with limited mobility facilitates use by the more able. Therefore, where there is variability available within a design, emphasis should be placed on making it fit the extremes of the population, rather than focussing on the 'average'.

The results of the anthropometric and functional profiling can be found in Appendix 1 at the end of this report.

7.3 PSYCHOMETRIC EVALUATION OF BEHAVIOURAL CHARACTERISTICS

A small range of paper based and practical tasks undertaken by subjects set out to address the risk taking disposition and risk perception capabilities of each individual. By utilising a limited number of established testing methodologies, it was possible to create user 'profiles' reflecting their natural disposition towards hazard evaluation and risk management. The underlying causes of these attitudes were not explored, but will undoubtedly be, in some part, due to educational and cultural factors as well as possible genetic or dispositional components. The tasks and the data generated by each group undertaking them are detailed below.

Accident history

An important influence on the behaviour of ladder users is their exposure to accidents or near-misses. The participants were asked if they had ever been involved in a ladder accident and, if so, how many. The responses are shown in Table 19.

Table 19
Participant ladder accident history

| Accident history | Count (%) |
|-------------------------------------|------------------|
| More than ten times | 0 |
| More than twice but under ten times | 2 (4 %) |
| More than twice | 3 (6 %) |
| Yes once or twice | 12 (23 %) |
| No, never & other | 31 (60 %) |

The majority of individuals had not been accident involved, although nearly a quarter had fallen 'once or twice'. Surprisingly, 10 % of the participants responded that they had fallen between two and ten times from a ladder. No further investigation was made into the nature of these incidents, although it is anticipated that these falls were relatively minor. However, they should still exert an influence on the participant in help as a stark reminder of the limitations of ladder use.

Additional information was also gathered regarding the history of the participants with regard to ladders. The most salient points were that the mean length of time that ladder had been used was 24.5 years, reflecting the age distribution of the sample population, whilst 15 individuals had received some training on the use of ladders, 14 of those on a formal basis.

The first paper based task was intended to establish the range of activities that each participant felt was acceptable for them to undertake on a ladder. This was addressed by asking them to indicate whether they would personally perform a range of tasks. These are detailed, along with the responses, in Table 20.

Table 20
Participant task acceptance

| Task | Ladder use | |
|--------------------------|-------------------|----------|
| | Yes | % |
| Painting a ceiling | 36 | 69 |
| Accessing a loft | 48 | 92 |
| Replacing a light bulb | 20 | 38 |
| Cleaning a window | 31 | 60 |
| Wallpapering a room | 28 | 54 |
| Hanging curtains | 21 | 40 |
| Fitting a curtain rail | 34 | 65 |
| Repairing guttering | 48 | 92 |
| Trimming tree branches | 41 | 79 |
| Cutting a hedge | 24 | 46 |
| Cleaning outside windows | 44 | 85 |
| Making repairs to a roof | 41 | 79 |

It can be seen that there was a wide acceptance of the tasks, with only hedge cutting, curtain hanging and the changing of light bulbs falling below 50%. It is probable that the latter two were either considered unnecessary given the height of the typical participant, or that another means of reaching would be employed. The hedge trimming task is more complex and may represent a more dangerous activity or one for which ladders are not considered suitable.

A further evaluation was made of the tasks that the participants would consider undertaking in the home. These made up the tasks that they would later be asked to do for the dynamic trials, so it was interesting to observe whether the activities were reasonable. The responses are given in Table 21.

Table 21
Participant 'tasks in the home' responses

| Task | Would you do it ? | |
|----------------------|-------------------|----|
| | Yes | % |
| Drilling holes | 48 | 92 |
| Sawing wood | 45 | 87 |
| Tightening wing-nuts | 40 | 77 |

It was encouraging to note that at least three quarters of all the participants would undertake all the tasks that had been determined as indicative of reasonable use. Anecdotally, sawing and drilling were stated to be highly typical of tasks undertaken in the home, whilst there were few applications in the domestic environment which required reaching wing nuts, thus resulting in a lower score despite this being an easier task.

7.3.1 Hazard Perception and Rating

Different people have very different perceptions of hazards which they associate with apparently ordinary items. In order to quantify this, accident data from the Home Accident Surveillance System (HASS, Department of Trade and Industry 2000 Home Accident Surveillance System including leisure activities: 22nd Annual Report 1998 data. *Consumer Safety Unit, DTI*. URN 00/32.) was presented, indicating the relative likelihood of receiving an injury requiring hospital attendance. Subjects were asked to rank the relative hazardous nature associated with the various objects, such as a splinter, a rug and a power drill. The true hospitalisation figures were chosen to give quite large 'step' changes, to identify if subjects could readily identify a truly hazardous item. Concealed within this data was the hospitalisation figure for ladders and stepladders. In this way, the comparative threat posed by ladders when considered with other objects could be appraised.

The items and their associated hospital attendee figures are presented in Table 22.

Table 22
Relative injury rates from everyday items

| Item | Injuries | Correct scores |
|--------------------|-----------------|-----------------------|
| Indoor stairs | 230,200 | 7 |
| Splinter/grit/rust | 27,557 | 6 |
| Knife | 22,108 | 8 |
| Banister | 15,233 | 6 |
| Stepladder/ladder | 13,222 | 4 |
| Rug/mat | 8,574 | 3 |
| Lawn mower | 6,347 | 8 |
| Hammer | 4,472 | 7 |
| Power drill | 2,578 | 5 |
| Vehicle jack | 937 | 3 |
| Pliers | 273 | 8 |

The subject scores were also plotted in a histogram, and this data is given in Figure 25

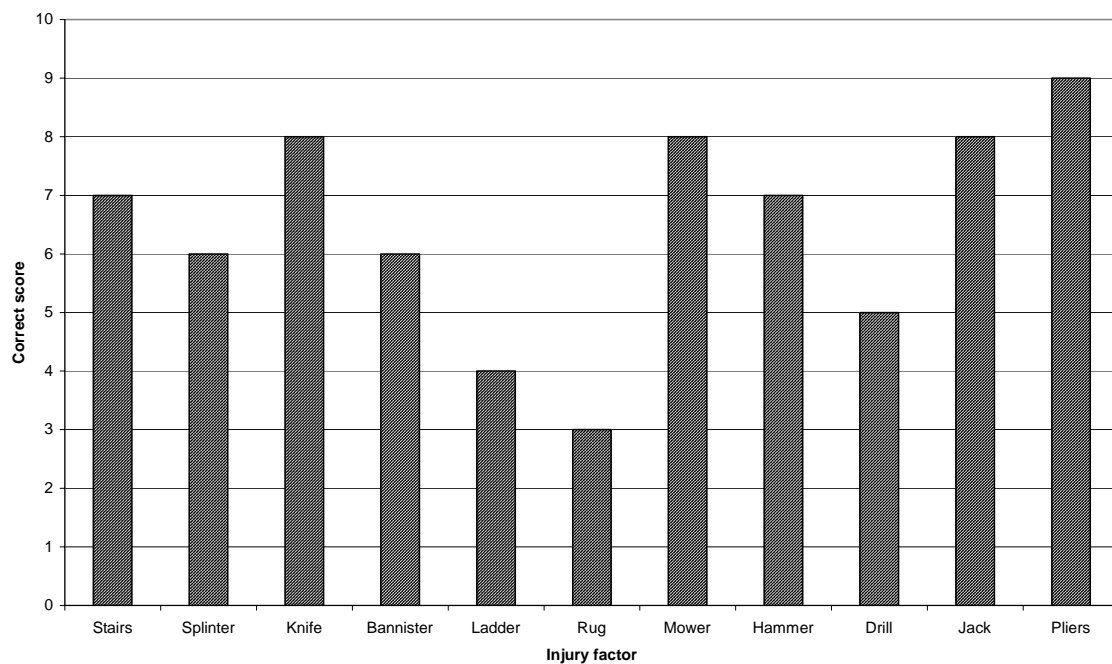


Figure 25
Participant relative injury rates scores

Generally the scores were poor, indicating that people had little knowledge regarding relative risk of injury. Only four individuals correctly placed ladders in their level of risk, indicating that for this product group there is a low level of perception of danger. However, it would be unfair to single out ladders given the relatively equal distribution of scores, which would indicate that they are little better than guessing on the part of the participants.

Conclusions

This result indicates individuals are poor at assessing relative levels of hazard for relatively familiar objects. This indicates that relying on a user's initiative to determine hazardous items, and hence appropriate safety intervention, is not a good practice. A typical example would be to leave a potential ladder user to determine whether a ladder offers sufficient levels of safety for a given task, or whether a stage or tower might be more appropriate. The user is unlikely to be able to accurately assess the relative hazard levels and make a valid judgement.

Risk Perception Rating Scales

Risk is the probability of a hazard being realised and, as such, represents the true threat to the individual. It is understood that individuals are extremely poor at determining likelihood of low risk events, and this causes them to place themselves in positions of peril. The scales used in this study were devised on the principle of a similar system used in the road safety arena, to analyse the subject's perception of the likelihood of dying due to a variety of causes. There are large steps between the numbers of victims in each scenario, making the ranking relatively straightforward. This technique also illustrates the level of risk associated with activities that can be avoided, such as rock climbing, as opposed to clinical disorders which cannot, such as cancer. The chance of winning the lottery was included as a rogue variable, the likelihood of which was believed to be fairly well known by the public.

Risk perception scores

Table 23 gives the range of events and their probability, as well as the magnitude of the steps between those probabilities. As can be seen, ladder accidents were again included, to see how well individuals could judge the true level of risk in comparison to other life threatening conditions. The probability data were all derived from data on the government website <http://www.Ukonline.gov.uk>.

Table 23
Risk perception rating

| Event | Probability | Rank | Magnitude |
|---------------|--------------------|-------------|------------------|
| Cancer | 360 | 1 | 1x |
| Road Acc | 15,700 | 2 | 50x |
| Rock climbing | 250,000 | 3 | 1000x |
| Ladder | 1,000,000 | 4 | 3000x |
| Canoeing | 2,000,000 | 5 | 6000x |
| Aircraft | 10,000,000 | 6 | 30000x |
| Lottery | 14,000,000 | 7 | 40000x |
| Lightning | 15,000,000 | 8 | 40000x |
| Fairground | 250,000,000 | 9 | 700000x |

The correct scores for the participants are given in Table 24, and presented in graphical form in Figure 26

Table 24
Risk perception rating

| Event | Probability | Correct scores |
|------------------------------------|--------------------|-----------------------|
| Dying of cancer | 1 in 360 | 18 |
| Dying in a road accident | 1 in 15,700 | 18 |
| Dying in a rock climbing accident | 1 in 250,000 | 5 |
| Dying due to ladder accident | 1 in 1,000,000 | 5 |
| Dying whilst white water canoeing | 1 in 2,000,000 | 14 |
| Dying on a passenger aircraft | 1 in 10,000,000 | 8 |
| Winning the jackpot in the lottery | 1 in 14,000,000 | 8 |
| Dying from a lightening strike | 1 in 15,000,000 | 15 |
| Dying on a fairground round | 1 in 250,000,000 | 3 |

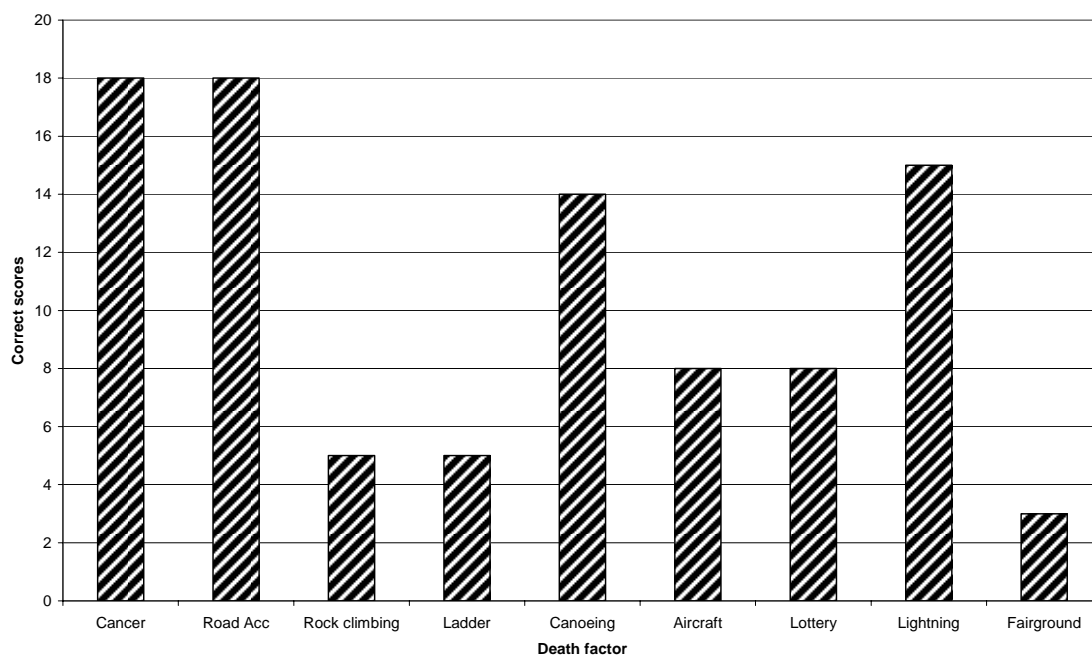


Figure 26
Participant risk perception scores

It can be seen that the participants split the events into two groups – high probability and low probability. The better recognised events such as death through cancer or road accident elicited high number of correct scores, however canoeing and lightning strike were also successfully located by many individuals.

The other events were much less well perceived and only small numbers of individuals correctly identified their correct position in the probability ranking. Ladders only received 5 correct scores.

Conclusions

This reinforces with understanding that individuals are poor at estimating relativity of low-level risk. However, some of the activities chosen are quite well publicised and this may give various benchmarks for risk assessment. The most interesting observation is that ladders were poorly placed in the rankings by the participants. It is normal that if a user is aware of the risk they better manage their safety strategy, so poor quantification of risk is a safety dis-benefit.

Ladder and task rating scales

This data shows the apparent level of risk perceived by the subject when undertaking each of the tasks in the trials. It is intended to illustrate if any of the tasks were felt to be more ‘risky’ than others. Perception of high risk is known to be associated with behaviour modification, so may prove a useful key to safety. The scale used to generate the scores is shown below.

Self-assessment form

How safe did you feel whilst carrying out this task?

Please circle a number between 1 and 11 after each task.

Very safe

1 2 3 4 5 6 7 8 9 10 11

Very unsafe

Very safe

Very unsafe

A horizontal number line with tick marks at every integer from 1 to 11. The numbers are labeled below the line.

Table 25 presents the data from the participants. The higher the score, the more hazardous the task was perceived.

Table 25
Task risk perception rating

| Task | Mean score |
|----------------------|------------|
| Task A - Drilling | 4.9 |
| Task B - Low nuts | 2.9 |
| Task C - Sawing | 5.1 |
| Task D - Hi Nuts | 3.4 |
| Task E - Bucket up | 6.6 |
| Task F - Bucket down | 6.5 |
| Task G - Pull Force | 4.8 |
| Task H - Footing | 2.1 |

These data are presented as a histogram in Figure 27.

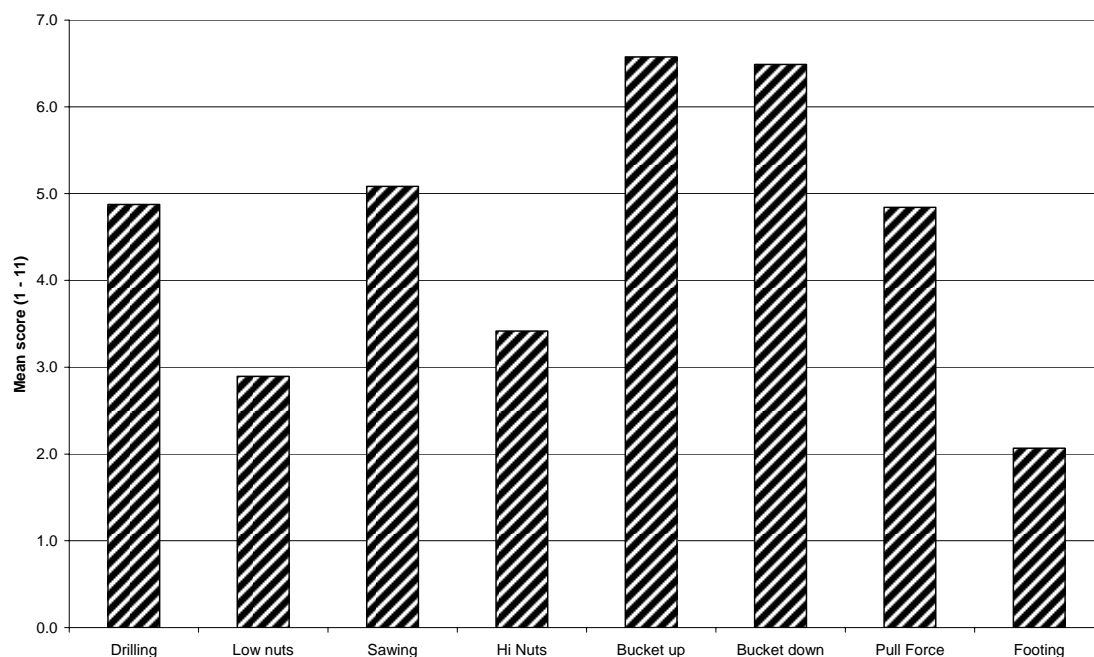


Figure 27

Averaged risk perception score for participants

All the tasks were considered to possess some level of risk, although the low wing nuts (reaching out) and the high wing nuts (reaching up) were perceived as less so than the dynamic tasks of sawing, drilling and pulling. Curiously, footing the ladder produced a mean score of 2.1 – some way from being considered ‘very safe’. All tasks are described in more detail in Section 8.

Measures Of Sensation Seeking

This is a recognised trait defined by Zuckerman (1994) as the seeking of varied, novel, complex and intense sensations and experiences, and the willingness to take risks to achieve such sensations. The measure of sensation seeking is an important behavioural variable to quantify, as it allows the performance of the participant to be understood in terms of norms of behaviour, which then places the individual in a rank of likelihood to take risks.

The Zuckerman scale is a relative scale, i.e. the empirical values on their own do not have merit. The great benefit lies in the comparative scores between individuals in a given population. Using this score it is possible to correlate personality traits with behavioural traits, such that the Zuckerman score could be used as a precursor to risk taking and hence accidents.

The complete set of Zuckerman questions used for this task are shown in the participant booklet in Appendix 5.

Summary

The average sensation seeking score for the participants was similar for males and females at 18.6 and 18.3 respectively, as shown in Table 26.

Table 26
Zuckerman mean scores

| | Male | Female |
|-------------------|-------------|---------------|
| Mean score | 18.6 | 18.3 |

A scatter diagram was plotted (Figure 28) of the sensation seeking score against the participant's age, and a weak negative correlation is observed - the older the participant, the more likely they are to have a lower sensation score. This agrees with previous research by Zuckerman (1994). This suggests that older users will behave in a less risky fashion, which accounts for their score in the previous risk perception task. When older people are involved in accidents, they are more likely to be injured than younger individuals and those injuries are likely to be more serious due to their more fragile physiology.

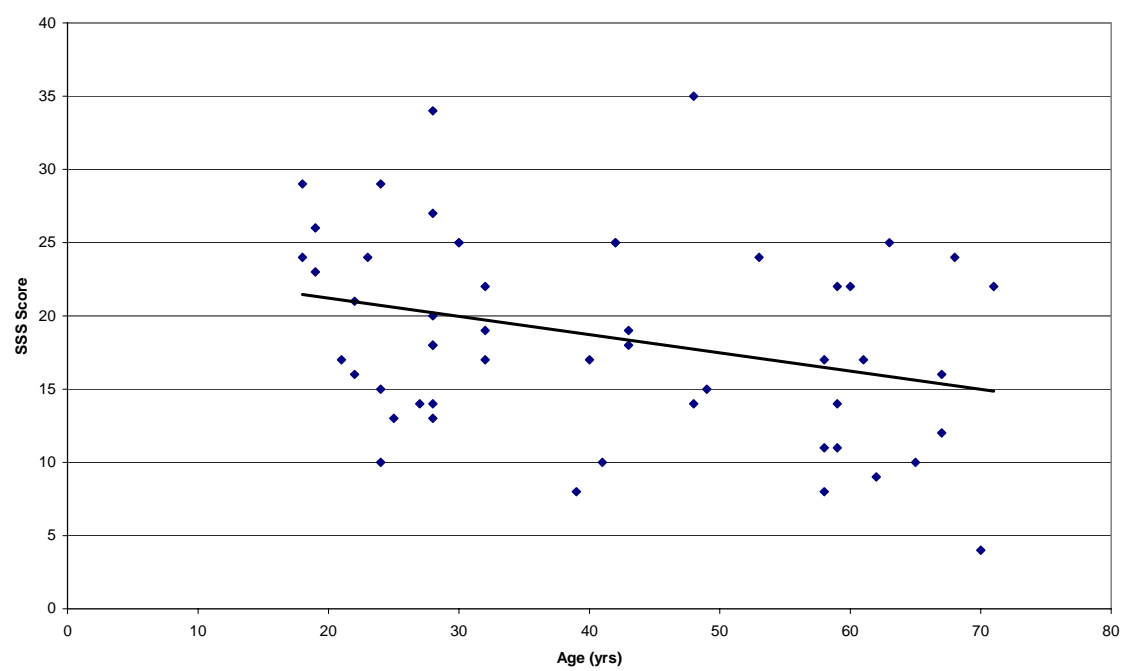


Figure 28

Scatter plot of participant's age and sensation seeking score

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8.0 STABILITY TRIALS

This section describes the participant trials undertaken as part of this project to determine the demands that ladder users place on ladder systems during the course of normal and reasonable use. A more detailed description of the equipment and data manipulation is contained in Section 13 along with further discussion of the engineering principles in the Technical Annex.

8.1 OVERVIEW

The mechanical test programme was based on established techniques pioneered and developed by RICE and previously used to evaluate the need for dynamic testing of leaning ladders and to investigate the stability of stepladders. The final data is statistically valid and will bear scrutiny by other agencies.

Comparison of static and dynamic force profiles

Much of the safety provision associated with ladders is controlled by static test requirements, although there is no requirement to extend this to ladder stability devices or combinations of these product groups. Static loading has been shown to have limited value in reflecting the demands placed on ladders in real use scenarios. For instance, a static load on a tread may be specified to support the weight of a 95th percentile male, which would seem appropriate. However, from previous RICE work (Research Programme into the Need for Dynamic Testing of Domestic Ladders. Research Institute for Consumer Ergonomics (*RICE*) report for the Consumer Safety Unit, DTI. 1997) it is known that such users may typically load the system with up to 1½ times their mass, or even greater in certain circumstances. Accordingly, once a safety margin is included, the requirement may be far higher than originally imagined.

The test program was therefore necessary since the static loading requirements currently incorporated in the relevant Standards was not believed to fairly represent normal use and was therefore not suitable for providing the demand forces for stability devices. In order to acquire the appropriate information it was necessary to devise simple trial tasks which would place maximum reasonable demands on the ladder and so provide a benchmark against which stability device performance could be measured.

Once the test program was finalised, it was challenged by undertaking limited pilot trials which did not form part of the main data gathering exercise and consequently are not separately reported. These pilot trials illuminated several areas which were not adequately considered, and allowed some degree of iteration in the development of the test.

As part of the research, and in addition to evaluating the performance of current stability devices, it was hoped that it would be possible to identify an algorithm or model which would adequately relate stability performance, such that predictions could be made of as yet un-marketed ladder stability device designs.

Pilot trials

The pilot trials were conducted using RICE staff to test the equipment, the suitability of the tasks devised and the validation of the test rig and metrics. In addition, the test rig itself required some considerable development to ensure sufficient stiffness and reliability.

Main stability trials

Following the pilot study, the finalised trials were staged and the data collected. A single extending ladder was erected on the rig and challenged with the tasks intended to illicit drive towards each of four identified failure modes.

Subjects drawn from RICE's database were recruited for the main trials. Ethical approval was not necessary for these trials provided participants were supplied with appropriate safety equipment, were adequately briefed about the tasks involved and felt free to control their actions, or even leave the trials.

From the data generated by these trials, it was possible to show the true forces and drives placed upon a ladder system under conditions of 'reasonable use'. This could then be carried forward to the data analysis where the various demands placed on the ladder could be rationalised into a representative set of applied loads and hence facilitate the development of a model which would allow the assessment of various stability device designs.

Predictive modelling

The primary output from the trials and the subsequent data analysis was a number of engineering models which would allow the prediction of the level of stability enhancement offered by any given stability device. This utilises a number of key parameters associated with the ladder and device as a system but which could be readily quantified by measurement. These are combined with the force data acquired in the trials to determine intrinsic stability factors. These then relate to nominal values which demonstrate adequate stability in each of four modes.

This model obviated the need to test real world product, since any product in conjunction with any ladder can be evaluated and the acceptability of the stability provision ascertained. In this way direct comparison can be made between products, naked ladders and manual footing to establish their relative performances. In addition, minimum performance specifications can be established which will provide a benchmark for acceptance of a device providing adequate stability for use in industry.

Test Specification

On completion of the analysis it was also possible to determine the parameters that must be considered for a performance test intended to ensure adequate safety for ladder stability devices. These key variables were identified from the data processing, and appropriate values were derived. The end product is a workshop test that can be easily, cheaply and routinely undertaken with manufactured devices and ladders and which will simply demonstrate adequacy of performance through clear pass/fail criteria. This could be directly incorporated into a technical standard, utilised by independent assessors or applied by manufacturers in order to endorse current products.

8.2 INTRODUCTION

The mechanical test programme was devised in order to quantify the true forces and drives placed upon a ladder system under conditions of 'reasonable use'. The data generated by these trials was then intended to enable the development of a predictive modelling tool to determine stability performance and the identification of a simple, geometry based, test procedure such that predictions can be made of as yet untested ladder stability device designs, as well as offering a means of quantifying the performance of these devices more easily. In addition to considering mechanical devices, manual footing was also considered as a means of stability enhancement.

It was considered imperative that the performance of the ladder used in the testing program was challenged by users behaving as they chose to do. By recruiting a sufficiently large subject panel it would be possible for all types of behaviour to be adequately represented whilst still obtaining a credible set of amalgamated values. For these reasons tasks were selected that permitted individuals to be as demanding of the ladder system as they felt comfortable. In this manner, the participants could be said to be behaving as they would normally, and this would prove a true representation of reasonable ladder use.

8.3 METHODOLOGY

The main focus of the test methodology was to accurately record the precise location of the centre of gravity of the ladder and user, as a system, whilst the user undertook 'reasonable tasks'. By identifying the position of the centre of gravity, and comparing it to the forces occurring at the top and base of the ladder, in conjunction to the frictional demand at these locations it would be possible to determine when the ladder was stable, when it was at the point of instability and when it was unstable (effectively, when it had fallen over).

When modelling the processes that ladders are involved in, and the forces that they need to resist, it became apparent that there are four distinct failure modes. These would provide the key to the tasks to be used in the trials as well as the data collection techniques.

Failure mode identification

The four modes were identified as follows, acknowledging the nature and vectors of the forces involved. In order to maintain clarity on the terminology, Cartesian references are used throughout. The x-axis represents a horizontal plane parallel to the treads of the ladder. The y-axis is a horizontal plane perpendicular to the treads of the ladder. The z-axis is in the vertical plane.

- **Base slip failure mode**

This is the mode most commonly anticipated in ladder failure. It involves a situation where the ladder feet demand more friction from the ground than is available. Consequently the feet slip. Given that the ladder is resting against an immovable object in the form of a wall or other vertical surface, the feet must slip rearwards in the y-axis in an accelerating process which causes the ladder system to collapse and the user to fall.

- **Top slip failure mode**

This mode occurs when the top of the ladder stiles demand more friction than the vertical surface can supply and consequently the ladder moves sideways in the x-axis. Ultimately this reaches a point of criticality which, if exceeded, will cause the ladder to fall sideways.

- **Flip failure mode**

This is a less recognised failure mode where a rotational force about the ladder feet becomes sufficiently strong that it over comes the stabilising torsion available on the structure and causes the ladder to rotate around one stile. The ladder then consequently flips over with a high probability that this will precipitate the fall of the ladder and user.

- **Top contact failure mode**

This mode is less catastrophic and represents an extension of normal use. As load is placed upon the ladder, particularly during tasks, the action forces drive the top of the ladder away from the vertical surface. Ultimately, the contact with the surface is lost and it becomes necessary for the user to actively intervene to prevent the ladder falling backwards in the y-axis. Failure to act quickly enough or in the correct fashion will result in the ladder becoming irretrievably unstable as it rotates rearward about its feet.

The tasks necessary to generate drives towards failure in each of these modes could be engineered by mounting them on the perpendicular surface against which the ladder was leaning. The geometry of this is illustrated in Figure 29

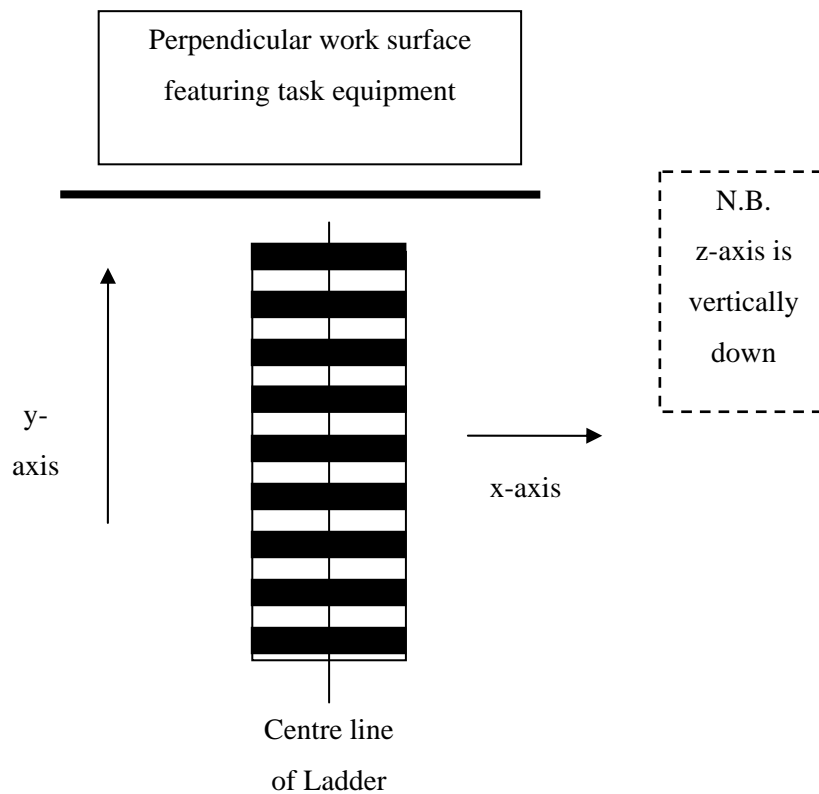


Figure 29
Schematic of the trial area and planes of ladder forces

Once these failure modes had been identified, representative tasks were designed within which it would be possible to observe reasonable use as defined by the participants behaving in a natural manner. They would be free to determine the forces they applied, within the constraint of their own limits of security. It was also hoped that there would be the opportunity to observe 'reasonably foreseeable misuse', where participants behaved in a manner unintended by the ladder manufacturer but which can be readily anticipated.

The method of data capture is detailed in Section 8 onwards but can be summarised as comprising a data logger which recorded at 50 Hz the output of four multi-directional force transducers located at the four potential contact points of the ladder. The data was recorded during the ascent by the user, the task duration and the final descent of the ladder.

A unique element of the methodology employed is that it was continuous. The ladder was lightly restrained on the upper surface of the rig, using nylon ties. These still permitted the correct level of stability feedback to be given to the user, but would stop the ladder falling over. In this manner it was possible to evaluate the behaviour of the users as they approached, or even exceeded the critical point of stability, without the need to abandon the trial each time. This resulted in vastly greater amounts of data than could be collected by previous techniques. Figure 30 shows the test rig in use, with the trial task board located at the top and Figure 31 a subject about to undertake a task.



Figure 30

A participant undertaking a lifting task on the test rig



Figure 31
Participant at the start of a task

The practical application of the data resulting from the trials would allow consideration of two major considerations:

- **Instability**

A performance envelope could be determined for the ladder in conjunction with the various users. This information then enables a specification to be determined which will not just be optimised for a single user or task profile but will accommodate normal user behaviour and expectation.

- **Safety margins**

Where the demands of the user were met and exceeded by the ladder, the additional capacity of the ladder can be referred to as the safety margin. This allows for other, unforeseen, factors which in use may serve to compromise the safety of the user. This margin would have to be small or non-existent to warrant the need for additional stability devices,

The tasks to be undertaken were devised to:

- accurately represent normal activities for which ladders may be utilised
- permit participants to commit themselves to a self-determined level of security
- challenge the ladder in the four failure modes identified
- be controlled
- be reproducible
- be quantifiable.

Details of the tasks are contained in the following sections. Each participant repeated each of the dynamic tasks, so as to increase the validity of the generated data. The footing task was, however, only undertaken once.

No ladder stability devices were attached to the ladders used in the participant trials. Whilst this may seem intuitively wrong, these trials were intended to establish the true forces that could be generated by users undertaking reasonably foreseeable activities. Once these forces were determined ladder structures, including all conventional stability devices, could be accurately modelled since they are geometric structures. Accordingly, device fitment was not required since a higher degree of stability estimation could be calculated than could be obtained through testing.

In order to make the data generated more meaningful, a number of transformations were undertaken. Initially, the raw data was manipulated to convert the electronic signals into calibrated force measurements. These could then be processed such that a derived value would indicate the level of stability in the various failure modes.

These variables are used as the metrics to quantify the ladder stability in the trial results below. It should be noted that these data represent aggregated values from all the trials. Overall, 2 trials were conducted for each of 7 tasks were conducted with the 52 users plus each user undertook a footing technique task once, making a total of 780 individual trials. As previously stated, these trials could continue even if a participant exceeded the point of instability, providing vastly improved quality and quantities of data over previous test programs which would be curtailed by any overbalancing.

8.4 THE LADDER USED IN THE TRIALS

The ladder used in the trials was a popular model of extending ladder. It is designed to comply with BS2037 Class 1, giving it 'Industrial' status with a duty rating of 130 kg. The ladder is manufactured from aluminium extrusion and is fitted with rubber covers at the feet and horns. It is supplied with an additional extruded aluminium bar which is intended to be bolted across the ladder feet, presumably to improve the stability. This device was not used in the trials.

8.5 DATA PRESENTATION AND INTERPRETATION

The data transformations are a transient process, with the sub-output being discarded after main output has been collated into a generalised data set. However, a graphical depiction of the stability and performance of the pladder is temporarily provided and some of these have been retained for illustrative purposes. These include for each trial, a presentation of the data cloud of points representing the centre of gravity, the ground reaction forces and the frictional demand. These are illustrated in the following sections.

8.5.1 Centre Of Gravity

The centre of gravity data takes the form of a series of virtual points, superimposed on a representation of the outline of the ladder. Each data point represents a calculated value derived during the trial data collection period. The resulting graphic indicates the focus of the centre of gravity along with any excursions, in the form of a 'data cloud'. This is very useful in gaining a rapid indication of the degree to which the ladder is being challenged by the user. Figure 32 shows four trial outputs illustrating the difference between trial tasks and subjects.

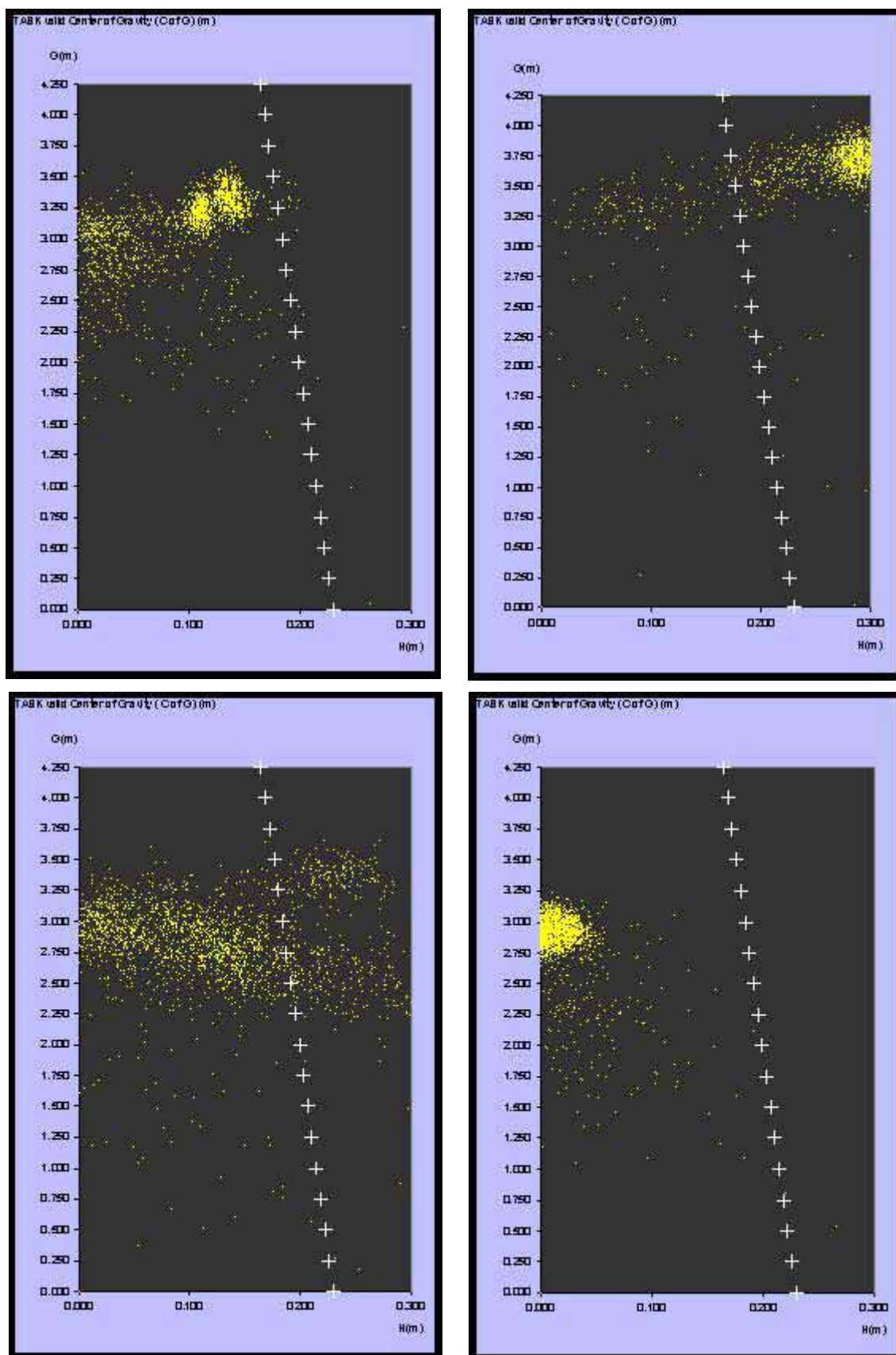


Figure 32

Examples of Centre of Gravity output

8.5.2 Location of the applied load

The reaction forces at the top and base were separated out such that a time-related trace was recorded for the duration of the trial. This was manipulated such that the applied load could be mapped onto the geometrical location for each data collection point. This further enables the location in vertical height and horizontal offset to be determined. These data are then plotted and the output can be seen in the examples in Figure 33.

In these four images the pair on the left represent the load point in the base vertical plane whilst the pair on the right the load in the upper horizontal plane. Both of these are time based series, with time on the x-axis and dimension (height or offset) on the y-axis.

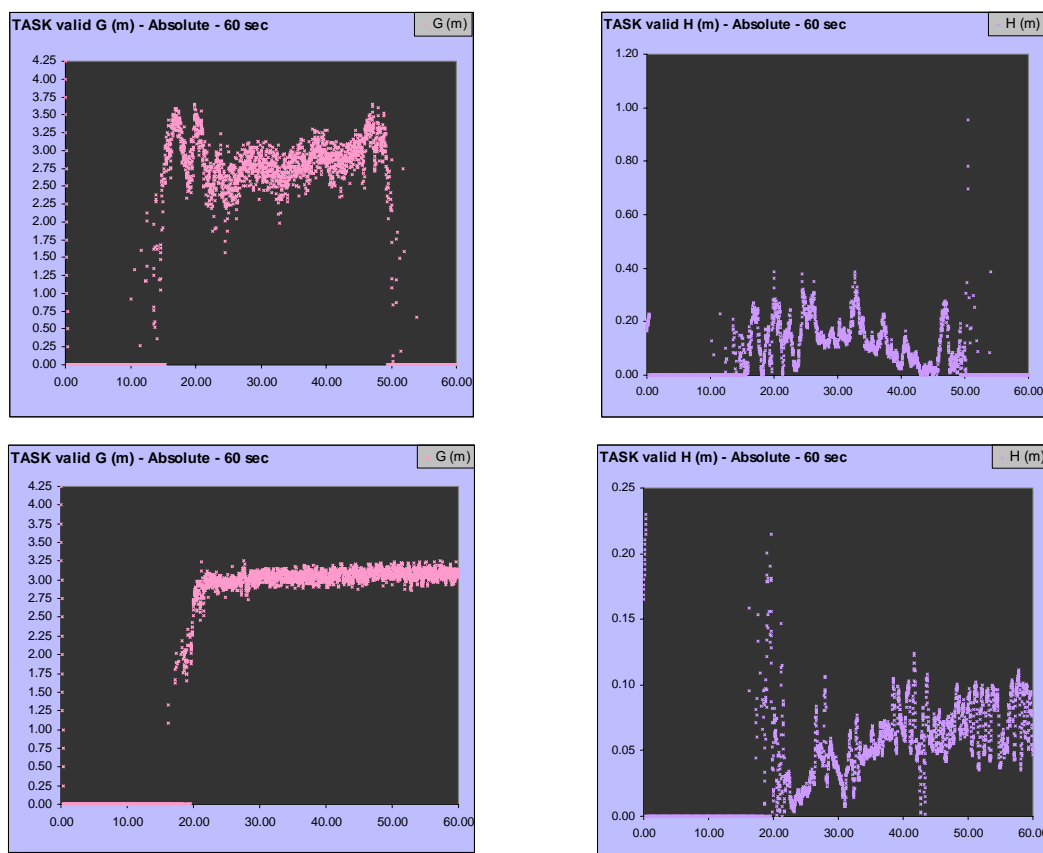


Figure 33
Examples of applied load.

8.5.3 Force reactions

The reaction output represents the force needed to counter the force generated by the ladder and user system. This is measured in pairs in the x-, y- or z- dimensions at the top and base of the ladder. The pairs of dimensional values are plotted against a time series to show the force demand placed upon the base during normal use. In the three examples shown in Figure 34, the first depicts the ladder base reaction during the mount and the dismount phase of the trial and in the z- and the y-axis. The second shows a similar data trace but for the task itself, whilst the third illustrates the ladder top reaction during the trial phase, in the y- and the x-axis.

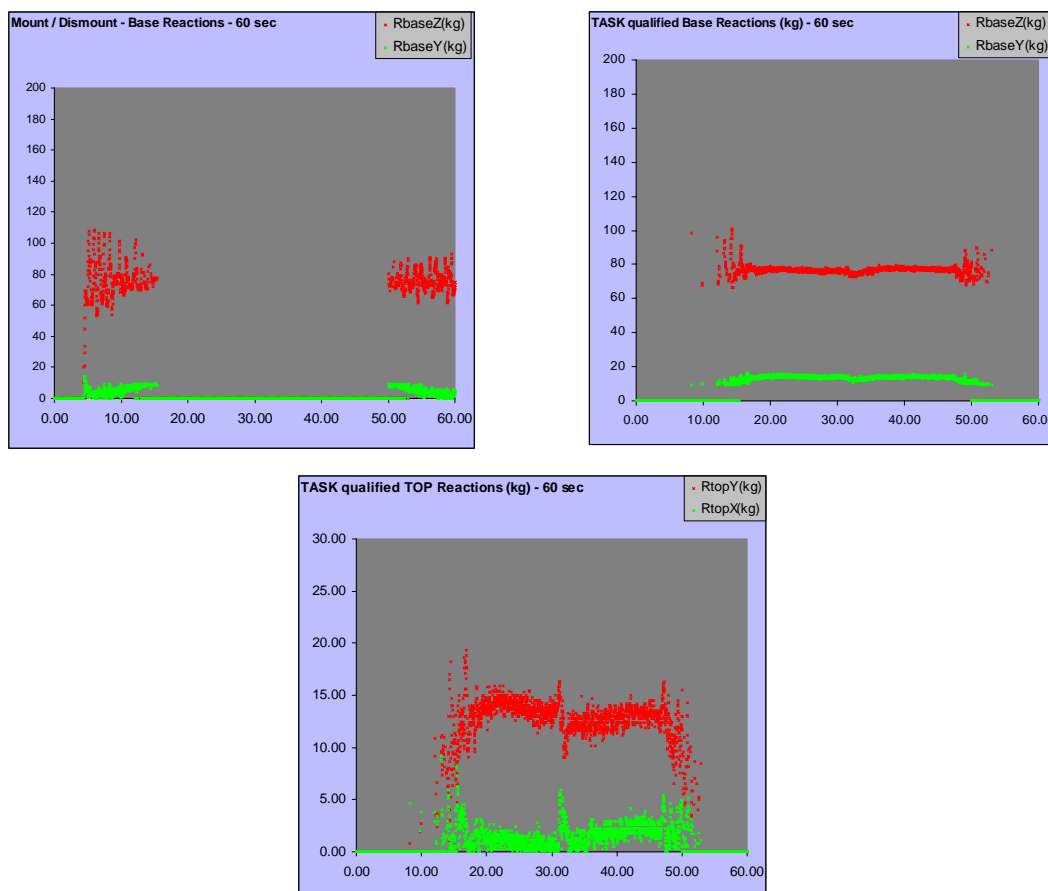


Figure 34

Examples of the ladder top and base reaction output

8.5.4 Frictional Demand

The final graphic depiction is of the frictional demand placed upon the ladder feet and the stile tops during the trial. This is expressed in the normal manner being the ratiometric between normal and planar action. Figure 35 gives two examples of this output, again time-related. The graph on the left depicts the base frictional demand, whilst that on the right shows the ladder top frictional demand.

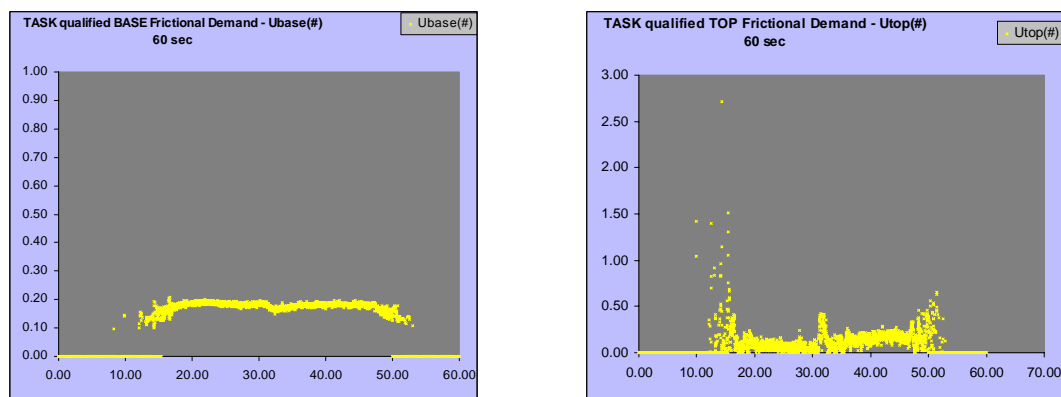


Figure 35
Examples of the frictional demand output

8.6 TASK A – EXTENDED FIXED PRESSURE DRILLING

Task A represented drilling into a resistive substrate such that a constant force would be applied which the ladder would have to oppose. Participants extended to the right of the ladder as far as they felt comfortable in order to apply a cordless drill to the task of drilling a hole in a metal bar. The self-determination of the degree of extension ensured that different interpretations of reasonable use could be accurately represented.

8.6.1 User-defined Task Parameters

The metal bar used as the resistive substrate was located on the work surface perpendicular to the ladder. The centre of the bar was located at a point 635 mm from the right hand stile of the ladder, representing the 50th percentile adult arm length. Users could then choose at which point around this central location they wished to drill.

8.6.2 Discussion

This task involved the application of force through a disadvantageous body posture. Accordingly, the forces that could be generated were quite low compared to other tasks. However, it is known that this type of task involves a complex relationship between the user and the ladder system, whereby the user will apply sufficient pressure through the tool to complete the task whilst monitoring the stability of the ladder through normal feedback. The force applied can be sufficiently high that the drill becomes the top point of contact for the ladder system and the tops of the stiles are no longer in contact with the surface. At this point, the ladder is technically unstable and it is only the intervention of the user as they iterate about the point of contact criticality that prevents the system from failing.

This type of tasks can generate large periods of instability. In practice this instability may not be realised, since the user is providing additional support through the work piece. It is also the case that the level of control that this offers ensures that the failure mode is progressive, rather than catastrophic and permits the user to recover from positions of increasing instability.

Other failure modes are also driven by this task, particularly the flip failure mode due to the asymmetric force application and the friction failure modes due to the demands placed upon the ladder to ground interface.

8.7 TASK B - LATERAL REACH EXTENSION

The participant was required to extend as far as they felt comfortable in order to tighten wing nut fastenings on a mounted bar. Encouragement was given to reach as far as the participant felt they could in an effort to accurately represent a demanding reaching task in real life, where the user may be reluctant to relocate the ladder.

8.7.1 User-defined Task Parameters

The bolts to be tightened were mounted horizontally, centred about a point 635 mm from the right stile of the ladder. This represented the 50th percentile arm reach for an adult.

8.7.2 Discussion

The leaning task is probably the most common application of ladders – for cleaning, maintenance and ‘Do-It-Yourself’ (DIY) tasks. In these scenarios the user is inclined to reach as far as possible in order to minimise the number of times that the ladder must be relocated, although the task itself is not that demanding. The user is heavily dependent on the feedback from the ladder system to determine the proximity to the stability limits.

8.8 TASK C – LATERAL REACH EXTENDED SAWING

The participant was instructed to attempt to saw through a 100 mm square block located on the work board, using a short hand saw.

8.8.1 User-defined Task Parameters

The block was centred around a point 635 mm from the right stile of the ladder, representing the 50th percentile adult arm length.

8.8.2 Discussion

This task was considered demanding by most participants due to the disadvantageous position dictated by the location of the work piece and the high level of physical activity demanded. The cyclical nature of the sawing activity was also difficult to maintain due to the saw sticking, which would generate relatively high transient forces. These would require the user to compensate with their mass, which often occurred after a time lag leading to a perceived lack of security.

The constant motion also ensured that the participant was unable to maintain a steady reference point, such that gradual shifts in Centre of Gravity or reach would accumulate to a point where the stability of the system was challenged.

8.9 TASK D - EXTENDED HIGH REACH.

The participant was instructed to tighten wing nuts along a vertical bar, stretching up as high as they felt comfortable.

8.9.1 User-defined Task Parameters

The task was located offset 500 mm to the right of the participant.

8.9.2 Discussion

This task was not considered overly demanding since the participants were relatively static on the ladder and were in control of the degree of reach. However, the displacement of their Centre of Gravity from the ladder both upwards and to the right ensured that this task was demanding for the ladder system. Additionally, the progressive plateaus of force representing the extension to each new work piece provided good quality data concerning the overall stability.

8.10 TASK E – HIGH LATERAL LOAD PLACEMENT

The participant carried a bucket of mass 11.5 kg (representing a 2.5 UK gallon bucket full of water or cement) up the ladder, and placed it onto a hook on the work board. This was an asymmetric carrying task, involving an unstable load, where the user may only hold on to the ladder with one hand. It required a degree of strength and necessitated leaning out from the ladder.

8.10.1 User-defined Task Parameters

The hook was located at a point 635 mm from the right stile of the ladder representing 50th percentile adult arm length.

8.10.2 Discussion

This task involved carrying a heavy, unstable load and placing it in a fixed position, located to the right of the ladder. This was a demanding task that was effective in representing real life use well. A variety of lifting techniques were employed, with more experienced users carrying the bucket underneath the ladder. However, the final lift required a high degree of co-ordination in that the subject had to use their mass to compensate for the offset of the bucket from the ladder.

8.11 TASK F – HIGH LATERAL LOAD RETRIEVAL.

The participant ascended the ladder, retrieved the 11.5 kg bucket from the hook on the board and descended the ladder with the bucket. This task involved the retrieval and carrying of a heavy and relatively stable load backwards down a ladder, whilst only having one hand available for stability. Some users also chose to move the bucket from one hand to the other.

8.11.1 User-defined Task Parameters

The user was free to choose the most appropriate method for accomplishing this task.

8.11.2 Discussion

This task involved leaning to the right to remove the load from the work surface before descending the ladder with the load. It challenged the system in a similar fashion to Task E, but ensured that the participant had to lift the bucket without the benefit of acclimating to the mass whilst carrying it up the ladder. The descent also proved challenging, since foot placement was obscured and hence progress less precise.

8.12 TASK G – LATERAL EXTENDED PULLING

The participant ascended the ladder and located a force gauge onto an eyelet on the board to the right of the ladder. They then were required to pull on the gauge as hard as they felt possible, given the stability offered by the ladder.

8.12.1 User-defined Task Parameters

The eyelet was located at a point 635 mm from the right stile of the ladder, representing 50th percentile adult arm length.

8.12.2 Discussion

This was considered a challenging task, and one that participants felt most destabilised the ladder system. Even though they had control over how hard they pulled, they reported that they felt this directly threatened their security. This task was intended to directly challenge the ladder primarily in the flip mode, which had previously not been explored.

8.13 TASK H - LADDER FOOTING.

Participants were requested to foot the ladder on the trials rig.

8.13.1 User-defined Task Parameters

The user was free to choose the most appropriate method for accomplishing this task.

8.13.2 Discussion

The subject was asked to adopt their normal footing position. If they were unfamiliar with the term, a scenario was described where their colleague was working on an unsecured ladder and they were asked to provide additional stability at the base. In this case what would their adopted strategy be?

A photographic record was made of each participant along with a normal trial data logging to establish the level of benefit provided by each posture. This is discussed in more detail in Section 9.

8.14 STABILITY FAILURE MODES

Section 12.1 of this report details the possible failure modes that ladders may experience. It should be noted that with the exception of Task H (footing) y of the tasks undertaken could result in any type of failure depending on the manner in which the participant undertook the activity. This was an inherent component in generating truly representative data without artificial restrictions.

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9.0 LADDER FOOTING TECHNIQUES

Manual footing of a ladder has traditionally been the means by which stability is enhanced whilst the ladder is tied off prior to use, or during short duration tasks. However, it is not a productive intervention requiring the dedication of an individual for the duration. It also suffers from the possibility of lack of vigilance, since the footing task may involve long periods of boredom when the temptation must be to occupy the time with a secondary activity. The apocryphal image of the tradesman's assistant standing at the base of the ladder smoking a cigarette and watching the world go by may not be very far from the truth.

A more significant problem may be identified through the lack of prescriptive methods for effective footing. This means that individuals required to undertake this task may have to rely on their own initiative or exposure to others to learn a technique. The imprecision will inevitably result in variations of the safety benefits provided.

There appears to be no readily available guidance to individuals, professional or consumer, on the appropriate way to foot a ladder or, if it is correctly done, what margin of safety benefit is to be expected. Accordingly, it is possible that primary ladder users may be confidently undertaking tasks in the belief that additional stability is being provided by manual footing, when in fact no benefit is available. This clearly has safety implications.

As part of the participant trials used to generate data within this research, an additional task was introduced to explore what the participants understood by the word 'footing'. This was undertaken in the most practical fashion by asking participants to foot an erected ladder, whereupon a photographic record was made. Whilst this was done data was collected through the ladder structure that would enable later interrogation of the additional stability contributed to the system. In this way it was possible to correlate the ladder stability performance with the precise footing style. This relationship is discussed more fully in Section 19.

Four generic types of footing were observed in the trials, and these are summarised in Table 27.

Table 27
Observed footing techniques

| Method | Count (%) |
|-------------------------|------------------|
| Two feet plus both arms | 7 (13) |
| One foot plus both arms | 30 (58) |
| Arms only | 11 (21) |
| Other | 4 (8) |

One interesting observation regards the question as to what footing is attempting to protect against. Without this point being clarified it makes the task of selecting an appropriate stance more difficult. Accordingly, individuals were working under the dual limitations of being unclear what they were trying to prevent as well as unclear as to the best method to achieve this. In the same way there was confusion over whether footing was an active process, requiring energy input to prevent an instability event, or a passive process whereby the footer was placed such that they would limit the consequences if such an event occurred.

The various strategies adopted by the individuals are illustrated in the following sections.

9.1 BOTH FEET AND BOTH ARMS TECHNIQUE

This technique was seen in only 7 of the participants (13%). The subjects invariably adopted an upright posture whilst standing on one of the lower rungs. The hands generally gripped the ladder's stiles at around shoulder height. Figure 36 gives illustrations of examples of this type of footing.



Figure 36

Both feet and both arms footing

Curiously, whilst this means of footing appeared popular with those who had undertaken training in ladder use it also generated a paradox.

In supposedly providing additional stability to the ladder it required two people to be standing on the ladder at one time, a practice which is warned against in the instructions for use supplied with ladders and specifically identified in a pictogram used by the manufacturers.

9.2 ONE FOOT AND BOTH ARMS TECHNIQUE

It can be seen that the majority of individuals (58 %) adopted a stance with one foot on the ground and the other on one of the lower rungs, whilst their arms were braced against the ladder stiles. Within this general style there was considerable variation, largely dependent on the gross body posture, with some individuals bent over whilst others were quite upright. Variations of this style are shown in Figure 37.



Figure 37
One foot and both arms footing

This technique seems to best encapsulate the confusion surrounding footing. The uncertainty of precisely what action was required was exhibited in the variety of postures adopted.

Some of these are partly a function of the gross morphology of the individuals, but despite this there were still numerous alternative techniques.

It was noted that this technique appeared to require active participation of the individuals, with many adopting a 'braced' stance requiring constant energy input. This clearly has the potential to lead to fatigue and so represents a strategy which is unlikely to be maintained for protracted periods.

9.3 ARMS ONLY TECHNIQUE

Some participants braced themselves against the ladder using their arms only. Again there was variation with some individuals applying their body weight through their arms whilst others were more passive. Examples of this technique are shown in Figure 38.



Figure 38
Arms only footing

It is conceivable that, in the real world, some individuals will iterate between this position and one with a single foot on the ladder. This is particularly so if the task duration is long, since a rigid static posture is likely to rapidly lead to muscle pain.

9.4 UNORTHODOX TECHNIQUES

In addition to the more conventional techniques, several unorthodox postures were also observed.

Some of these were variations of the normal methods, such as wedging the feet against the base of the ladder stiles, whilst others were highly unusual. These included one individual who moved underneath the ladder and proceeded to pull down on the rungs.

Some of these techniques are illustrated in Figure 39.

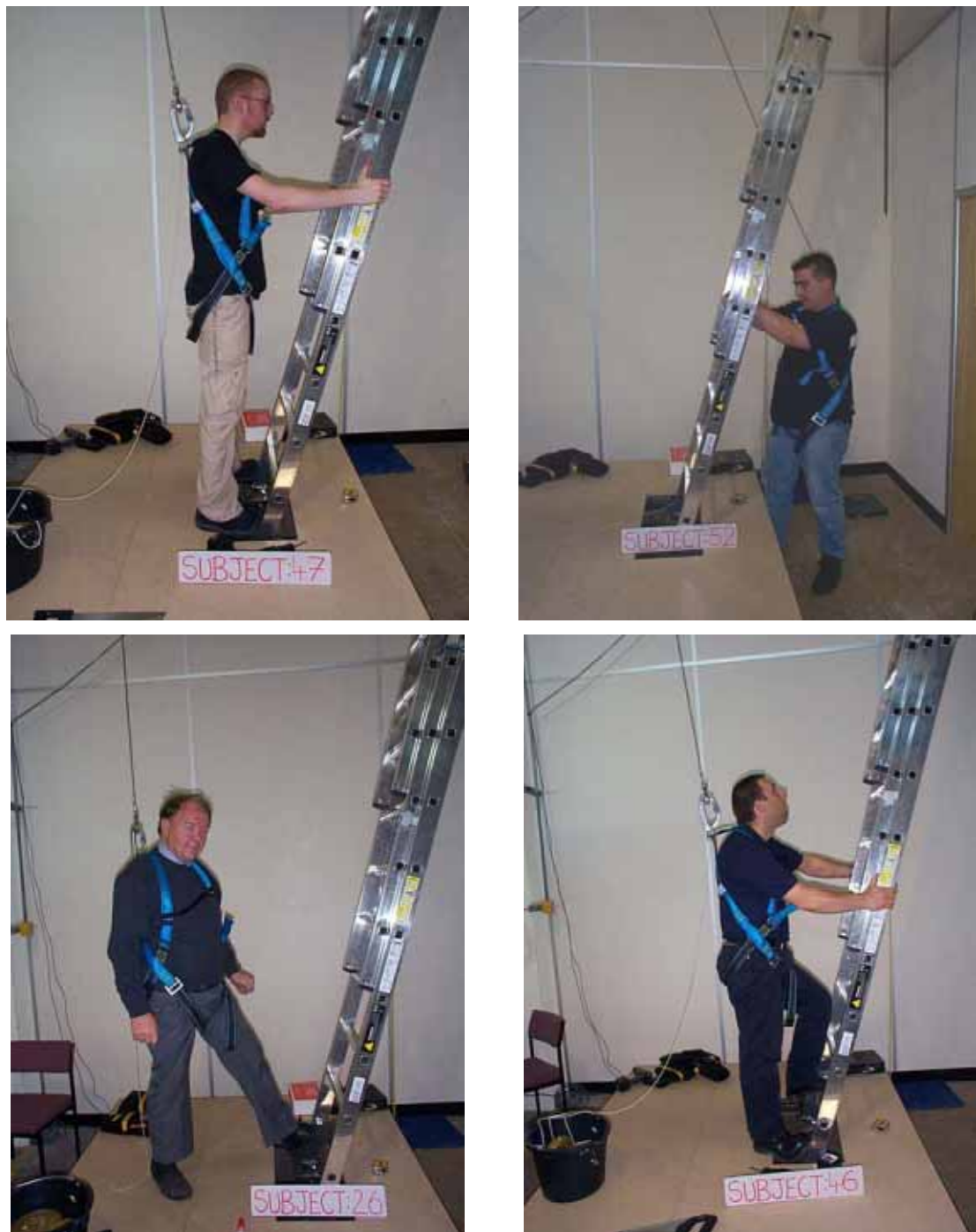


Figure 39
Unorthodox footing techniques

Whilst these alternative methods may not all be as practical as the conventional ones, it is interesting to observe people's inventiveness. It also provides valuable data on the relative effectiveness of different mass placements and bracing strategies.

A fully detailed description of the data analysis and the quantification of the benefits to be gained from footing are provided in Sections 19 of this report.

10.0 REASONABLY FORESEEABLE MISUSE

One of the important considerations in this research is that of reasonable use. It is only through an understanding of what users expect from their products that the definition of acceptable safety can be made. Unfortunately, 'reasonable' is a highly subjective term and it is often the case that what the manufacturer considers reasonable does not match that which the user does.

However, when a product group has been in use for some time and people are familiar with it, it may be argued that reasonable use is the range of activities which the general population will undertake. Whether these comply with the original intentions of the manufacturer or not is largely irrelevant, since such widespread practice cannot, generally, be altered. Because of this it is possible to quantify 'reasonable' through the undertaking of trials providing they are suitably rigorous in their definition.

This area of product safety is specifically addressed by UK consumer protection law and, whilst this does not currently extend to professional use, the principles are transferable. In particular, it should be remembered that professional users tend to represent better informed consumers in a different environment. For this reason, therefore, the concepts of normal use and reasonably foreseeable misuse can be applied equally to both groups.

Products clearly have a specific intended purpose, and their design is largely tailored to this purpose. A simple example would be a flat-bladed screwdriver. Its intended purpose is to drive home and remove slot-headed screws. Accordingly, these tasks can be considered 'normal' use. However, there is also a range of tasks which are undertaken with this implement that can be readily envisaged and are so widespread as to be considered as secondary uses. These may be associated with the primary purpose, or may be a totally different task. Again, in the case of the screwdriver, a secondary task may be to remove cross-headed screws or, more commonly, to open tins of paint. These applications are so common as to be considered reasonably foreseeable and so would be termed 'reasonably foreseeable misuse'. Clearly, using a product for a task completely alien to its intended function or design can be considered abuse. Using a screwdriver as a hammer or to stab an individual would fall into this category.

In the UK there are consumer protection laws applicable to specific product groups. All other products, including ladders and stability devices, are covered by more generic safety legislation, typically The General Product Safety Regulations 1994 (GPSR). The GPSR require that only safe products are made available, either new or second-hand and contain reference to the terms ‘normal use’ and ‘reasonably foreseeable’. The Regulations offer clear guidance as to the meaning of ‘safe product’ and the elements to be considered when assessing the safety of the product, as follows:

“safe product” means any product which, under normal or reasonably foreseeable conditions of use, including duration, does not present any risk or only the minimum risks compatible with the product’s use, considered as acceptable and consistent with a high level of protection for the safety and health of persons, taking into account in particular -

- a) the characteristics of the product, including its composition, packaging, instructions for assembly and maintenance;
- b) the effect on other products, where it is reasonably foreseeable that it will be used with other products;
- c) the presentation of the product, the labelling, any instructions for its use and disposal and any other indication or information provided by the producer; and,
- d) the categories of consumers at serious risk when using the product, in particular children”

As stated in the Regulations, the composition of the product and its instructions and warnings must all offer an acceptable level of safety. This places onerous requirements on the manufacturer to ensure that a product is suitable for the range of applications to which it is likely to be applied, and that the instructions are adequate to allow consumers to assemble and use the product safely. Clearly this means that, for ladders and stability devices, they must be safe when used in a manner which users feel reasonable.

It is inescapable that working at height is an inherently risky activity. However, that risk can be managed effectively by designing products that offer acceptable levels of stability and strength and then by arming the users with appropriate information on how to control the residual risks. It is unacceptable for the manufacturer to merely tell users not to undertake activities that may lead to instability if those activities are considered reasonable by the user.

This has been the subject of much argument within the safety community as it appears that ladder manufacturers consider a wide range of tasks undertaken at height to be unreasonable, whilst consumers clearly buy ladders specifically to undertake those tasks. Because of the complex nature of ladder accidents, few cases have been before the courts to resolve this, but precedent indicates that manufacturers have been enjoying a period of grace, and that in future they will need to produce ladder products which can better accommodate the user's expected behaviour.

With specific regard to ladder stability devices, there is a considerable responsibility with respect to the requirement to ensure the product is safe when used in conjunction with other products. Clearly a ladder stability device is intended for use with ladders and it is the device manufacturer's responsibility to ensure that adequate safety is maintained in all reasonable circumstances. This may require extensive testing with different ladder combinations, or the stating of specific ladders with which the device may, or may not, be used. Whilst this requirement is expressly stated, and a further requirement is to record all such technical information it is highly likely that such records are not maintained. This makes it difficult for both manufacturers and users to establish levels of safety.

Ladder devices also suffer from a paradox of use. It can be argued that the first decision to be made when working at height is the most appropriate means of access. Indeed, this is a requirement as part of the risk assessment for professional users. Accordingly, given the limited range of applications which meet the requirements of a ladder to be used safely (firm surfaces, level ground, no particulates or lubricants, good access etc), plus the requirement to tie the ladder off, it seems that ladders are only going to be applicable to a restricted number of tasks.

However, a stability device appears to extend that range of tasks. By claiming to overcome some of the safety limitations (grip, slope etc), their presence advocates the use of ladders in applications which clearly contradict established good practice guidelines. The issue remains that they are encouraging users to do things on ladders that they should not.

Against this must be weighed the true safety benefit that the device supplies. In other product areas it would be normal to anticipate that such information is readily available, since the product is advocating taking of additional risk which it is purporting to manage. Unfortunately, the majority of stability devices do not appear to be accompanied by such data.

Once such data is provided, instructions and warnings can be devised such that prohibited activities are depicted in an unambiguous fashion, and that users are aware of the consequences of ignoring this advice. Importantly, the safety message must not be diluted by using the instructions to warn users against activities they will clearly undertake, merely as a means of shifting the burden of liability from the manufacturer.

10.1 REASONABLE USE IN TRIALS

During the trials, participants were free to choose the extent to which they pushed the ladder system. The majority of participants remained within the typical behaviour patterns recommended by the ladder manufacturers in their instructions and warnings although interpreting the limits (such as 'do not over-reach') themselves. The range of use was relatively varied from the sedate to the highly challenging, however all were displayed in the form of conventional practices. This was unlike previous work involving stepladders where unorthodox postures and actions were observed. This is most probably explained by the more restricted stability provided by the leaning ladder in conjunction with the increased flexibility and raised task height which combine to control the user's behaviour.

11.0 FUNCTIONAL TYPES OF LADDER STABILITY DEVICE

From evaluation of current products available and from the potential intervention strategies, it is possible to distinguish between two types of ladder stability device by means of their function. This differentiation is essential to the understanding of their performance and subsequent modelling and predictions. The two functional types are discussed in the following sections in sufficient detail for third parties to independently identify specific products as being one type or the other.

11.1 DEVICE AUGMENTED LADDER

The most common type of stability device is referred to as the 'Device Augmented Ladder' or DAL. A DAL can be defined as:

'a plain or nominal ladder fitted with any generalised structure or interposing material, which modifies the effective footing at the top or base, either as geometrical adjustment of active point loading position, ground reaction vector magnitude adjustment, or modification of frictional coefficient at the grounding interface.'

In practice, this means that the DAL is a combination of ladder and device which changes the interaction with the substrate at the top or base by means of a geometry change, a direction or strength of force change or a frictional change. It can be seen, therefore, that this is the most common type of system in use. A DAL is considered, for modelling purposes, as a combination of two separate theoretical ladders, the accessible ladder and the active ladder.

The accessible ladder

The accessible ladder is the original or nominal ladder (the 'real' ladder), located in a fixed point in space and available to a user. It is reasonable to consider that any given user will behave upon the ladder in a normal manner irrespective of the exact nature of the underlying support configuration and the particular physics which are in operation to keep it there. It is therefore possible to take the accessible ladder to be a reference upon which a standard load vector (SLV) can be applied at an appropriate applied load point (ALP). This forms the basis of the later modelling and testing regimes.

The active ladder

The active ladder is a virtual geometric plane which contains the four potential point contacts to ground, and by some arbitrary structural means holds the accessible ladder in spatial registration. Note that by ground we mean generally both the horizontal and vertical support surfaces without distinction. Conceptually, this is more readily portrayed as a virtual ladder, generated as a result of the application of the device to the real ladder. This virtual ladder will act as a normal ladder but is not directly accessible to the user. An example would be a device which alters the location that the ladder rests against a wall. The real ladder remains unchanged and the user will demand the same performance of it whilst the active ladder changes from its original state, superimposed over the real ladder, to a new state in a plane removed from the physical structure.

The complex relationship between the accessible and the active ladders means that the interplay between the SLV acting at the ALP on the accessible ladder, and the consequential dynamics effect upon the underlying active ladder, defines the stability of the entire system, and this, by inference, reflects back on the accessible ladder also. The stability modelling algorithm discussed in Section 16 of this report is configured on this basis.

11.2 TRIPODS

Tripods are a unique type of stability device which enable the ladder to act as a free standing structure. For the purposes of this study a Tripod is defined as:

‘a plain or nominal ladder fitted with any kind of structure or interposing material which provides total support at the horizontal ground plane only. This structure is free standing, and employs four potential point contacts. The rear pair are the original ladder feet, while the forward pair are arbitrarily placed by the particular geometry of the device.’

Tripods can permit the user to access the ladder in this free-standing mode up until a given point in the ladder's height (dictated by the precise geometry of the device and ladder combination). After this point the tripod would become unstable. However, if a ladder equipped with a Tripod is also located against a wall, the device will switch from being a Tripod to being a DAL at the point where the loading shifts to the top of the ladder stiles and away from the Tripod base. In this manner, this type of device may actually perform two distinct roles which require two modelling systems.

General discussion

Both types of stability device are economically but sufficiently defined structurally and kinematically to allow predictions of stability and action duress at critical locations within the frame. Using these predictions it has been possible to evolve stability models.

These require a small number of key geometrical and other basic system parameters which are easily measured, and use this data with a prescribed SLV and ALP to produce performance indicators. These take the form of normalised stability indices, each set being intrinsic to the particular configuration of ladder and stability device under consideration.

It is important to realise that the exact nature of the underlying ladder structure, connecting a nominal ladder to the ground, is generally irrelevant to issues of stability. It is the active endpoints of these structures, specifically the active ground point contact positions, the modification of ground contact frictional coefficient, and the gross final attitude of the accessible ladder which are the determining variables. The weight and mass distribution of additional components, such as stability devices, is relevant however, and arises through a displacement of, and magnitude increase in, the total system Centre of Gravity.

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12.0 THEORETICAL CONSIDERATIONS OF DAL STABILITY

A DAL will remain stable in use provided the total drive magnitude and effective action point is such as to be below a level necessary to cause structural motion of the ladder system. This motion can be translational and amounts to slippage, or rotational and amounts to loss of critical ground contact with a possible gross shift in the attitude of the system. Slippage arises when a level of frictional demand exceeds a natural upper limit, specific to the nature of the two materials in actual contact. Rotation will occur when the system exceeds a critical torsional balance about any specific axis. Provided the geometry of the system and the mass distribution is known, then the various drives can be calculated with certainty, for any given single point loading vector. In this study four possible stability failure modes are identified which can arise with a DAL, and normalised stability indices are determined accordingly. These parameters are essentially indicating a level of dynamic balance within the overall structure. The modes of failure are respectively base-slip, top-slip, rotational flip and loss of top-contact.

This research employs the concept of a standard load vector SLV acting at a standard applied load point ALP, and accepts that this parameter fairly represents a maximal duress on the structure equivalent to the demand placed by human user undertaking strenuous, but reasonable, tasks. Strictly these are parametrics, designed to quantify an equivalent metric understood to be potentially more complex and sensitive to functions of other unspecified variables. With this accepted, then standard mechanical dynamics will determine the duress on the system, and the proximity of the system to criticality and hence failure.

In strict terms, a four contact point rigid structure is indeterminate from a dynamics perspective. In practice any ladder or DAL will ordinarily take up a stable stance using only three true ground contact points (note that the general term grounding is used to signify ladder contact with either the ground proper, or the upper contact support surface, without distinction). These can be two at the base and one at the top, or one at the base and two at the top, but never all four. There are therefore four underlying strictly stable configurations, and the system will assume any one configuration, but can easily and quickly switch between these configurations with a high degree of unpredictability. Ordinarily this transient resettling will be undetectable by a user since the ladder footing will assume the appropriate pattern with minimal actual motion of the overall ladder structure.

It should be realised that this physical reality is unavoidable, and is nothing to do with ladder construction, placement, or ground surface flatness, but is in fact a fundamental aspect of the kinematic principals of rigid structures.

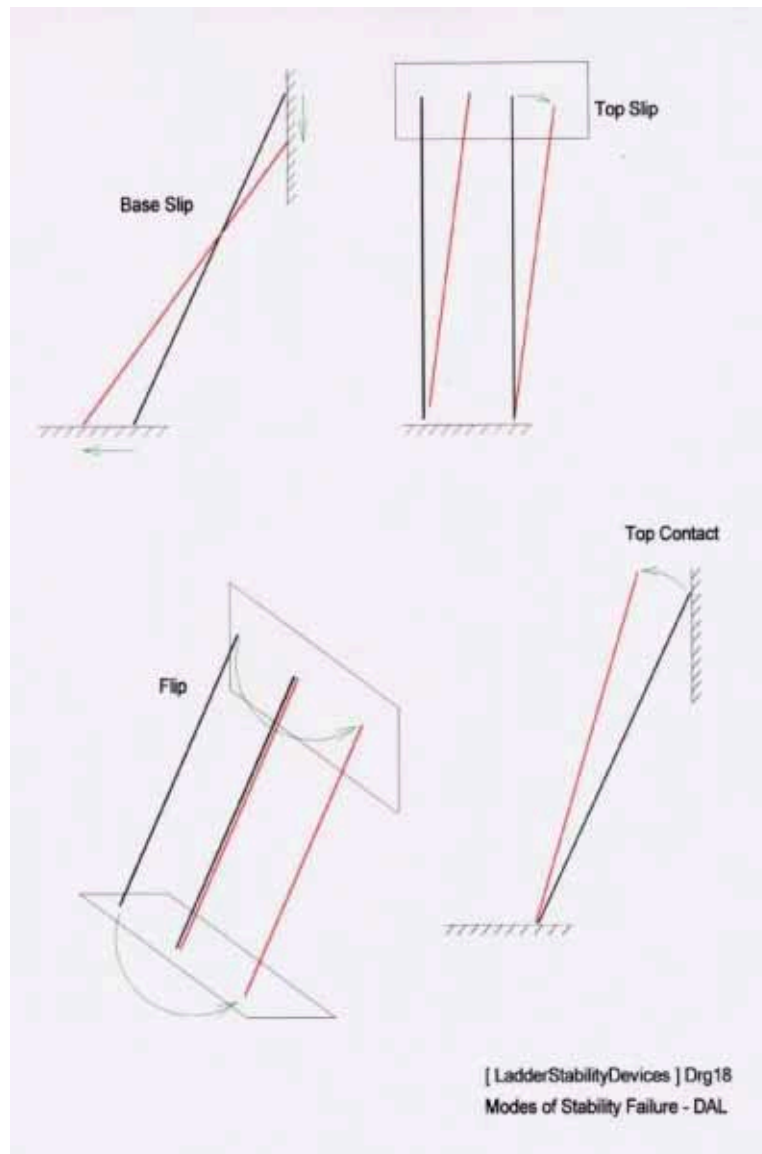
This phenomenon effectively amounts to micro stability modes, and is quite fundamental to the correct understanding of how ladder grounding operates, particularly how the true grounding points can settle or migrate according to the immediate dynamics demanded by the user. In the case of a particularly flexible ladder it may be the case that four points each take up a portion of the load, but even then one of the contact points will be a minor component. There is value in providing additional potential contact points beyond the minimalist three, in that it is an enlargement of the usable geometric or stability envelope, however this is constructed in a piecewise fashion. This means that the system will still rest on only three points but it has a larger range of options from which to select the three. Strictly, the concept of redundant footing implies that a design is not per-say limited to any total number of potential grounding points. The physical reality still prevails nevertheless, and forces the structure to assume only three active point contacts at any one time. The technical model described in this report is based on a pair of potential points in the horizontal ground plane, and similar pair in the vertical ground plane. Practically this corresponds to most conceivable and symmetric DAL configurations, however a designer can analyse a multipoint structure of any size, by progressively selecting pairs of positions, and working the analysis as normal for all possible point-pair combinations.

12.1 CLASSES OF INSTABILITY

There are four classes of instability identified which impact upon device augmented ladders. These can be specified as:

- Base-slip
- Top-slip
- Flip
- Loss of top-contact

Each of these is illustrated in diagrammatic form in Figure 40

**Figure 40****Modes of stability failure****Base slip**

This failure mode is the one that is most often imagined as the cause of a ladder system failure. A loss of grip occurs at the base points of the ladder and, because the ladder is at an angle to the vertical surface, the ladder base slides horizontally away from the vertical surface. In this fashion the ladder top slides down the vertical surface in an unrestricted fashion, taking the ladder user with it. This is normally associated with a low grip surface at the ladder base, which offers poor retention.

Top Slip

Top slip occurs when the top of the ladder moves sideways against the vertical surface to the point where the ladder system becomes unstable and there is a complete lateral failure. This type of failure is immediate and results in the user falling to the side of the ladder system.

Flip

Flip failure is a less obvious failure mode system. It involves all the forces of the ladder system being directed through a single stile, such that a rotation occurs. This causes the ladder to flip around such that the side which was facing the vertical surface now face away from it. This action destabilises the ladder system and would typically cause the ladder to fall to the side, although it may invoke either base slip or top slip as part of this process.

Loss of Top Contact Loss

Loss of Top Contact (referred to as 'Top Contact') failure involves the top of the ladder moving away from the vertical surface, primarily in the plane of the ladder. Whilst not immediately unstable when this initiates, the whole system is then entirely dependent upon the user to restore stability or topple. Unfortunately, the user may not always be in a position to take appropriate action and so failure may be unavoidable.

12.2 DISCUSSION

The issues controlling general stability are briefly presented below.

12.2.1 Causes of failure in different modes

At any particular time a DAL will show tendencies towards instability simultaneously in all four modes. The criteria of safety is that all such tendencies as consistently within the limits of physical capability of the combined structure under a defined load.

- Base-slip and top-slip are due to frictional failure where a frictional demand exceeds the natural upper friction limit of the ground contact interface, leading immediately to motion.
- Flip mode failure arises from the geometrical condition of the ladder system, and occurs when a critical torsion balance is reached, and again leads to motion.
- Top normal contact can be lost in certain circumstances, leading immediately to a highly unstable condition where the ladder is entirely unconstrained at the top location points. Any sudden movement by a user at this time can rapidly destabilise the system.

12.2.2 Frictional capability

The frictional capability of any surface-to-surface interface is known to be reliably a function of the material types and surface finishes of the two contacting substances. It is not, however a function of total contact area or the shape of that area, and not a function of the load magnitude itself but rather the ratio between normal and planar force vectors. These are important physical realities and should be properly understood in order to comprehend the stability of the ladder system. It is important to note that issues relating to the durability of the substances making up the contact points between the ladder and the ground are not addressed here, although, although these issues are certainly determined by the following, and numerous other, factors.

12.2.3 Contaminants

Pair sets of materials will therefore offer a frictional duress limit which is completely defined by the nature of the substances themselves, and the surface condition or finish. It is also important to appreciate that the expected frictional performance of objects in contact is invalid if there is any intervening material (grit, dust, fluids etc). This then means that contact is not directly between the two substrates but rather between each substrate and the intervening material and thus will be a 'pair of pairs' acting in series. Either one of the pairs failing in strength will release the entire contact system to motion. This is also true of any material acting as a lubricant which may affect the frictional integrity at a contact interface. This could be liquid or solid particulate, such as water, or sand. Only small amounts of such material are required to replace the frictional capabilities of the design material with that of the lubricant and hence drastically reduce the level of resistance offered.

12.2.4 Determination of frictional characteristics

The predictive stability models detailed in this report require prior knowledge of the minimum reliable limiting friction capability of the ladder system and is numerically expressed in $U_{base\lim(\#)}$ for the system base contact and $U_{top\lim(\#)}$ for the top contact points. These parameters must be determined by particular auxiliary tests or otherwise obtained before being supplied to the model. The workshop stability tests defined by this work will, however, place the ladder system at high real duress, and will directly test its frictional capability and so demonstrate empirically the adequacy of these parameters. It should be noted that for all ladders used in this testing, the standard stile feet and caps were retained.

12.2.5 Impairment of ladder feet

Ladders are generally supplied with caps to the top and base of the styles made of material which is durable and yet offers a high degree of friction. These can only be effective if this material remains the one in contact with the ground or vertical surface. The practical implication for ladder usage is that end contact pieces should be maintained free of contaminants such as oil and similar, and free of any compacted particulate material such as cement dust or sand. In normal use, the low total area contacts will have to endure arbitrarily high local pressures and this can easily drive loose debris into the top surface of the manufactured contact material. This will readily alter the designed frictional interface, without the user necessarily being aware.

12.2.6 Maintenance of ladder feet

Loss of material from the ladder feet through abrasion is not detrimental in itself, and could very arguably be desirable in that new facing material is constantly being regenerated. For ordinary plasticised type feet, occasional clearing with a medium flat file would be worthwhile. Simple measures to clear dust pools or other granular material at the ladder base area, and arguably at the top face if this is a loose surface, are also advisable. Accordingly, the maintenance of the ladder system is integral to the level of safety it provides and, given the emphasis that users place on liability to slippage, should be an obligatory part of safe ladder use.

12.2.7 Friction limits

From earlier work by the authors and others concerning direct measurement of frictional limits of a nominally loaded typical ladder on cement, it was found that actual traction failure limits produced consistently reliable minimum $U_{\text{base lim}}(\#)$ values of 0.5, with very high probability of reaching 0.6. In all practical testing and, for the purposes of normal use, water does not modify this condition. Examples of typical frictional values are given in Table 28.

Table 28
Friction coefficients (μ) from German Standard DIN 4421 and prEN12812

| Material combination | Friction coefficient (μ) | |
|-------------------------------|--------------------------------|---------|
| | Maximum | Minimum |
| Wood/wood (with grain) | 1.0 | 0.4 |
| Wood/wood (against grain) | 1.0 | 0.6 |
| Wood/steel | 1.2 | 0.5 |
| Wood/concrete (or mortar bed) | 1.0 | 0.8 |
| Steel/steel | 0.8 | 0.2 |
| Steel/concrete | 0.4 | 0.3 |
| Steel/mortar bed | 1.0 | 0.5 |
| Concrete/concrete | 1.0 | 0.5 |

12.3 HARD AND SOFT FAILURE MODES

Stability failure can either be soft or hard. Base slip, once begun will continue relentlessly. The forces towards motion are amplified ever more during the event and the process is fast and positively driven away from stability. This is therefore a type of hard failure with no warning or recourse open to the user.

Top slip, however, is somewhat benign in that loss of traction does not ordinarily go on to magnify the effect. In this fashion it is seen as a soft failure. Small initial motions can be easily detected by a user, and the impetus to motion can be removed at will. The ladder will then stabilise, albeit at a slight side tilt, and this is ordinarily a recoverable situation. Real trial data shows that users are, in fact, continuously and routinely operating at and beyond the technical limit, with the ladder hunting for contact laterally at the top. Strictly this motion was not observable due to the ladder tethering regime used in the trials during this research, however upper values of $U_{top}(\#)$ were easily reaching a value of 5, being ten times the nominal technical limit of, say, 0.5. It appears that many users will naturally operate at the prevailing limit, and adjust and compensate accordingly. An important implication here is that the formal stability index $S_{intTop}(\#)$, when subjected to the maximal duress to be anticipated by users in the form of the standard load, may well technically fail the numerical criteria of stability, as could the prescribed workshop tests. However, that does not invalidate the criteria, merely point to the fact that it is dependant upon the user to prevent failure at this point.

Whilst this may be an effective strategy, it is not one of good safety policy since the user may not always be able to adequately intervene. Accordingly, best practice dictates that the criteria remain at the safety threshold.

Base frictional demand, $U_{\text{base}}(\#)$, observed in the research trials very rarely exceeded value 0.25. Furthermore this parameter was also largely free of strong transients above this value. Accepting a conservative value of base limit friction of $U_{\text{base,lim}} = 0.5$, then the stability index $S_{\text{intBase}}(\#)$ is ordinarily and reliably at value 2 – well inside the limit. In practice this means that a ladder will not slip under conditions of maximal reasonable use providing it is located on a suitable ground material and that the interface between the ladder and the ground is maintained free of lubricants.

Flip mode failure is of the hard type, and essentially determined by ladder geometry and weight. The impetus to instability arises either due to an extreme sideways (x – axis) offset displacement of the user's mass Centre of Gravity, or equivalent shift of the same due to a high force activity. This is basically a combination of gross position of the user on the ladder, and the vigour applied to the task. The associated stability index $S_{\text{intFlip}}(\#)$ will ordinarily approach quite closely the value 1.0 in a high duress condition, and is likely to routinely exist just within the limit for much of the task event.

Top-contact failure is of the hard type. This can arise with a light weight but strong subject, exerting a high planar (y-axis) drive, sufficient to cause full contact loss at the ladder top. In this condition the ladder can chaotically destabilise with any small x-axis or additional y-axis drive. The criteria for stability is evaluated by $S_{\text{intContact}}(\#)$. This measures the proximity of the top normal contact reaction $R_{\text{topY}}(\text{kg})$ to a prescribed minimum allowable value – $R_{\text{contact}}(\text{kg})$.

It is evident that the four modes of instability are of real qualitative, quantitative and consequential difference. None provide any precursor or warning which makes it difficult, if not impossible for the user to intervene. Bearing in mind the global stability criteria that all index parameters are greater than 1.0, but not necessarily much greater than this, then adaptations are conceivable within a ladder or DAL design which may better balance the indices at a value just at or above the criticality. This adaptation would therefore produce an arguably more efficient ladder in terms of overall safety.

It is normal practice to apply an additional amount of safety performance, the 'safety margin', to safety thresholds. However, in this circumstance this is not appropriate, since it would not provide any additional protection but would place greater demands on ladder manufacturers.

The safety margin in this model is intrinsically contained within the identification of 'reasonable use' derived from the dynamic trials. By allowing the participants to self regulate their behaviour, all reasonable levels of demand are anticipated. In addition, by using a suitably high value (95th percentile plus) for the various force vectors a further level of safety is provided since the probability for all the vectors simultaneously reaching this threshold is exceptionally remote.

In practice, users making the most onerous demands on the ladder in reasonable use will approach, but not exceed, the safety limit. Users behaving in a more conservative fashion will enjoy an increased margin of safety through their reduced demand. It is only those users who are abusing the ladder system who will exceed the ladder safety threshold and proceed into instability. Accordingly, an additional safety margin is unnecessary.

12.4 DEVICE TYPES – A CLASSIFICATION SYSTEM

As part of the evaluation of the methods of operation and the subsequent modelling and test methodologies, a classification system for the types of device that may be used in a DAL was required. A reasoned classification system is proposed therefore, which is intended to identify and clarify the functionality and operational requirements of an otherwise generalised set of potential inventions or adaptations. This classification system is discussed in this section.

Primary classification

A device can be defined as a component or system which affects a nominal ladder in any aspect which pertains to stability. A nominal ladder so configured becomes a DAL. It is not necessary to constrain a device to be any single identifiable object, rather a modifying regime which brings about a systemic structural change, and with it potential repercussions to the stability status of an adapted ladder.

For the most part, it is likely that any particular device will be clearly a footing or topping type, and in this case a distinction is reasonable into base contact or top contact modifier types. Where weight or mass is reconfigured, while otherwise leaving the ladder with its normal stance and grounding arrangement, then this device is nominated to be of the mass modifier type. However, a device can, in principal, affect the mechanical status in numerous ways simultaneously, and hence a universal modelling approach is required which can reasonably manage any conceivable configuration.

Accordingly, the Primary Classification can be shown to be whether a device is a:

- (I) Base contact modifier
- (II) Top contact modifier
- (III) Mass modifier

Primary types (I) & (II) affect stability either by readjustment of the accessible ladder (and hence the SLV and ALP), the ground contact point geometry, the prevailing limiting contact friction capability, or, indeed, all three. Type (III) leaves the ladder at nominal attitude and with nominal grounding geometry and frictional capability, but modifies the standing weight loading of the structure which will generally affect the overall stability.

Intended purpose

The intended purpose of a device can be to either provide some improved utility to a user, or to improve the stability status of the apparatus. These possibilities are summarised in the classification into either of the following groups:

- (I) Utility enhancer
- (II) Safety enhancer

The utility enhancer is a device which purports to give some additional functionality to a user, but does not claim to improve any safety margins. An example would be a tool tray or ladder platform. Such a device should be deemed acceptable provided the four intrinsic stability indices are not depressed below the critical value 1.0 when the device is in use. Caution should be exercised in that increased functionality may bring with it increased user demand which can, in itself, have safety implications.

The safety enhancer type should demonstrably improve at least one of the indices in order to legitimately claim to be effective. These are typically devices marketed as safety aids, such as stand-offs and additional base supporting structures. However, it could technically reduce another index in so doing and thus be considered as lowering the overall safety of the system. Whilst it is possible to argue that such a device might only be intended for use in a specific circumstance where the increased safety mode will be in evidence, it is unlikely that this could be controlled for in everyday use. **However, provided that all four stability indices remain above criticality, and at least one index is elevated above the value for a naked ladder, the stability device may be considered to be ‘effective’ (i.e. it is truly providing additional safety).**

Accordingly all the safety indices should be above criticality for the device to be considered safety compliant. This class distinction is irrelevant to the proposed technical model which simply numerates the stability status of any given system with given physics, and does not consider its intended purpose.

Coupling regime

A distinction must be made on the basis of the means by which the device mechanically connects to the ladder and hence the manner in which it reacts with the ground. There is special significance to this aspect of design which can profoundly affect both the actual stability of any DAL structure, as well as the possibility of meaningfully modelling stability.

Two categories of coupling regime are used:

- (I) Rigid coupled
- (II) Loose coupled

It is necessary to distinguish between a fully rigid coupling, such as additional supporting legs which are firmly bolted to the ladder, and a loose mechanical coupling to ground such as a pad or other device on which the ladder is placed. There are certain pressing restrictions placed upon the nature of the actual footprint of the DAL in final contact with the ground, and this is dependent upon the designed coupling regime. In addition, the nature of the coupling is intimately linked with the correct location of the active ground contact points when assigning geometric values for the predictive stability model.

Where a rigid coupling is utilised, the designer is obliged to terminate that component with a near perfect single point ground contact. If the designer attempts to utilise a distributed area contact the actual ground contact point location will be undefined and hence uncertain. The base area, being by definition rigidly held, cannot conform to a distributed support surface without generating an erratic and uncertain grounding contact. This will result in uncertain kinematics, and hence uncertain stability. For this type of device the position of the grounding points should be clear geometrically for modelling purposes.

Where loose coupling is utilised the designer is obliged to terminate that component with a distributed area ground contact, such as a mat or tray. Such an area can settle correctly and will stabilise on an arbitrary surface without any special problem.

For this type of coupling, any attempt to utilise a single point contact will not be effective, since the actual ground contact point location is unconstrained and will result in a mechanically untenable system. In this class case the effective ground contact point location for modelling purposes should be taken at the ground interface, but co-linear with the coupling connection centre, wherever that falls within the distributed footing contact.

Operational mode

Lastly, it is necessary to distinguish between a class of device which is permanently in operation, and a class which is designed to be called into action once motion, possibly due to a stability failure, has commenced.

Two operational mode categories are used:

- (I) Active – normally operative
- (II) Reactive – normally inoperative

The active class is simply designed in to work at all times. The reactive class is normally quiescent and non functional, but will come into effect provided some gross geometrical adjustment occurs in the ladder. Ordinarily this would be a secondary system, which is presumably intended to curtail an instability condition once initiated. The assumption could also be made that the resultant modified status of the ladder, once triggered, is only temporary and intended as a short term holding measure only whilst some intervention is made by the user.

This reactive class of device should, predictably, be modelled in the reactive or operative mode, and should also be workshop tested when in this mode.

As a general note for workshop stability verification tests, the detail and subtlety of the dynamics should be bypassed and the system fully tested empirically.

12.5 PERFORMANCE REQUIREMENTS OF DEVICES

The presence of any device will, in general, adjust the prevailing four stability indices away from the nominal ladder values (otherwise it would be having no effect). Some may rise while others fall giving weight to the suggestion that safety performance may be task related for some devices. The minimum technical performance of any device should be dictated by the criteria that all intrinsic stability indices remain above the critical value 1.0 with the DAL configured with the device, and correctly loaded with the specified SLV at the specified ALP.

It should be clear, therefore, that the functional quality of devices is defined in terms of the total DAL construction of which the device is a component, and not expressed as an attribute of the device in isolation. In this way, safety performance can be seen to be a property of the device and the ladder and, as such, that performance may well vary across different ladder products. This being the case, it is evident that stability verification should generally be obtained using a range of available nominal ladders to which the device is to be qualified for use.

12.6 DAL MODEL DIMENSIONING – ADVISORY METHODS

The full schedule of the DAL measurable parameters is given in Section 16 of this report and in the accompanying diagrams and Technical Annexe. These are in the dimensional classes of length, angle and weight, and should be obtainable with minimal technical difficulty.

A configured DAL will potentially modify the gross attitude of the accessible ladder, or the active footing patterning, or both. It is vital that the active ground contact points are identified correctly for meaningful modelling outcome. Where the design assures that these are clearly approximate point contacts, then the situation is obvious and point centres are taken. Where these contact points are in fact distributed areas. Such as for pads at the ladder base or devices on which the ladder rests, the criteria is that the geometric locations should be taken at the ground, and co-linear with the coupling connection axis, wherever that falls on the distributed footing contact. Note that in this case of contact construction, this must be a loose coupling to the DAL according to the kinematic requirements already defined.

Weight Centre of Gravity within the accessible ladder, as denoted by the M , should be determined with the fully assembled DAL by the workshop test described in Section 16.6.

The ALP location is broadly equivalent to the user's own centre of mass. When considering user working heights in other terms such as footing position or any other anthropomorphic point, then an offset allowance should be made, referenced to the ALP.

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13.0 TECHNICAL SECTION

This project aims to establish an understanding of leaning ladder stability when used in conjunction with additional devices fitted for the purpose of either extra usability or enhanced user safety, a system referred to as a Device Augmented Ladder (DAL). The process undertaken to achieve this is a natural extension to the author's earlier work reviewing the stability and performance of stepladders. This work is intended to collectively identify and define potential modes of performance failure of three major classes of ladder configuration – together being ladders, DALs, and large Tripods. In doing this it is necessary to consider the mechanical physics involved, and formally model each system as stability prediction algorithms.

This process is highly technical and requires an understanding of some basic principles of mechanics as well as the mathematics involved. It may have little direct value to individuals interested in the practical outcome of this research or the implications for ladder and ladder accessory design. For this reason the calculations and associated details of the data processing are presented in a separate Technical Annexe. This Annexe can be read as a stand-alone document although reference is made to this main report. There is some duplication of information such that this report is adequately detailed and the Annexe is presented in appropriate context. However, the presentation of the findings in these two forms ensures that the reader can access the most appropriate level of information or refer to the principles underlying the work at their discretion.

In this main report the Technical Section restricts itself to the basic concepts behind the modelling and the practical outcomes in terms of definitions and testing. It is not intended to be a robust substantiation on the processes involved, but will provide the reader with sufficient information to comprehend and apply the stability prediction and testing regimes.

Central to the stability concept is the employment of a Standard Load Vector (SLV) and an Applied Load Point (ALP). This is a load that represents the maximum demand placed upon the ladder by the user in normal use. A large section of this research work involves the practical determination of the correct SLV and ALP through extensive user trials involving reasonable but demanding tasks and this is detailed in Section 8.

Theoretical models of ladders systems are generated which are accurate predictive representations of real world ladder configurations associated with demanding users. The models are not prescriptive in that no constraint is placed on any particular constructional element, ensuring that it is not design restrictive. Effectively they define containment envelopes within which any ladder is qualified as adequate with regard to stability. They will allow designers or testers to conceptually manipulate a system and generate a range of optimisations, and to better understand the relationships practically governing ladder and device performance. These models are directly supported by practical workshop loading regimes, and associated straightforward pass-fail tests which enable rapid testing of current or prototype systems.

The effect of fitting any auxiliary device to an otherwise simple ladder, will be in general to shift the baseline stability index values to new levels. This will arise from either geometrical rearrangement of the locations of the points where the system reacts with the ground, modifications to the friction values at these locations, or assisting in adjusting the gross position of the user which will cause a subsequent shift in the ALP. Such devices could be intended to enhance usability during certain tasks, or to improve safety. The modelling used is unconcerned with the intended purpose of any device, and will simply indicate the level of stability safety impartially. On this basis it should be fully realised that a device may well improve stability in one mode, whilst at the same time eroding safety in another mode.

At the most basic level it is essential that the act of fitting or implementing some device shall not reduce one or other safety margins below or outside the critical safety envelope. Provided this is assured, then a device should be classified as effective. Where safety enhancement is claimed by a manufacturer, then the additional requirement of measurable increase in stability index should be demonstrable.

The general technical objectives are:

- To provide a sound analysis of ladder stability
- To identify and explain the crucial issues
- To generate adequate mathematical tools to predict, measure and optimise the prevailing safety envelopes of the ladder classes DAL and Tripod.

The core of this process is standard mechanical dynamics and the theories of structures, hence the process should be transparent and unequivocal. This is substantiated through the mathematical proofs given in the Technical Annexe. The subtlety however is in isolating the correct magnitude of the SLV and the associated applied Load Point, ALP.

These are proposed as universal parameters, since they are defined by the user, and have great bearing on the theoretical and practical performance of a ladder. If these are set high then designers are more constrained, or utility is wasted. If set low then clearly there is erosion of real safety levels. Care is therefore exercised to pitch these standard values correctly at statistically valid levels.

The main additional elements can be identified thus:

- The development of a proposed classification system for DAL devices, as detailed in Section 12. The discussion of the performance of various arrangements, highlighting the most pertinent kinematic and dynamic functionality.
- The reasoning and utility of the manual footing of leaning ladders are evaluated and the effect of this strategy is extensively measured, including the different footing techniques illustrated in Section 9.
- The effect of ground slope on the performance duress on the leaning ladder is examined and the benefit of devices intended to address this problem is evaluated.

A large database of useful data is generated, generally quantifying dynamic activity on the laboratory reference apparatus. A large pool of information pertaining to high shock loading during the mounting phase is developed but not used in the greater analysis, as this is not a stability issue. This will have significance, however, regarding strength and durability of components, and is therefore available for later contribution to such usage if appropriate.

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14.0 DYNAMOMETER RIG

Figure 41 shows the principal elements of the dynamometer rig, and Figure 42 the rig itself.

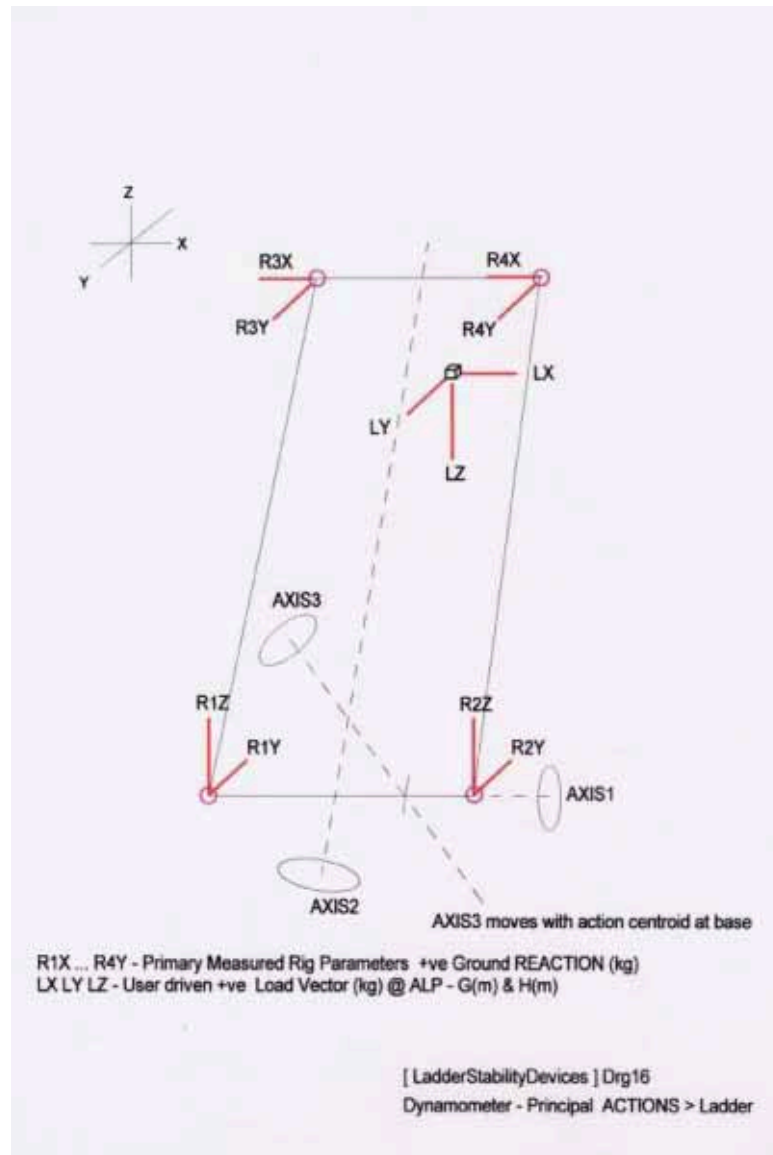


Figure 41

Dynamometer principal actions



Figure 42

Dynamometer upper and lower components

An essential component of this research was the collection of accurate data regarding the real world use of ladders. In order to acquire this information it was necessary to run extensive user trials utilising a bespoke data collection tool. This draws on the same technology as the device developed to appraise stepladder safety in the author's previous work, but the configuration is altered to the new task of appraising leaning ladders.

A full-size force dynamometer was developed which fully supported a trial reference ladder. The specification of the reference ladder itself is unimportant, but the model was an extending ladder comprising three sections and was drawn from the range of a well-known manufacturer.

The ladder was purchased new. A flat steel plate at each of the four ladder endpoints carried the structure, and supplied ground reaction as necessary. These reaction responses were continuously monitored by dual-axis steel cantilever transducers, producing eight dimensions of action measurement in total. Vertical forces at the ladder top and lateral forces at the base were ignored, since these are generally near to zero at all times. Whilst this is clearly obvious from the most basic mechanical considerations, previous work of this type has also generated these measures, and they have been seen to be miniscule. The array of measured actions is sufficient to fully define the total system dynamic as required in this work.

The electronic signals were recorded at 50 Hz on a PC based data logger as raw trial data files. These were later corrected for zero tare and scaled to engineering units in the appropriate spreadsheet analysers. This conditioned data thereafter represents additional ladder loading entirely due to a user activity, above any system pre-stress or standing load due to ladder weight. Appropriate mechanical modelling generates the final time variant data set of dynamics parameters, pertaining to user driven load magnitude and concentration point of application.

14.1 CONSTRAINT OF LADDERS

The trial regime operated such that extreme usage may well occur, and accordingly it was possible that the ladder may become destabilised on occasion. Whilst there was no interest in observing any actual structural failure in stability, it was essential to ascertain the natural operational limits achieved by users. By constraining the ladder it is therefore possible to allow users to seek and act at whatever limit they reach, irrespective of the fact that stability may from time to time be technically breached. This also affords some real enhancement in actual user safety and comfort in the trials, and ensures that the ladder geometry and rig attitude is held truly constant for the duration, which facilitates continuous high accuracy measurement.

The tethering took the form of nylon ratchet ties at the grounding points. Whilst they prevented catastrophic failure of the ladder system, they were sufficiently loose so as to provide normal feedback to the user of the ladder's condition. In this way it was possible to ensure that the behaviour of the users was not altered through the provision of a rigid or pinned structure.

14.2 PRIMARY RIG SENSORY PARAMETERS

The dynamometer generates a set of independent electronic channel signals corresponding to 8 point contact loading vectors, and arising from compound transducers at each of the 4 ground contact points.

These signals present as time variant analogue voltage levels which modulate linearly with the particular action magnitude. A tare correction for standing zero is made and engineering scaling adjusts to kg force units. Subsequent recorded data is directly due to user activity therefore, and is not responding to the standing weight of the trial ladder.

The structural dimensional constants are identified thus:

- **I (m)** Ladder length
- **A (m)** Ladder half-width - Top
- **B (m)** Ladder half-width - Base
- **J (deg)** Ladder altitude angle

Sensory parameters are generated and serve as raw data for all subsequent engineering measurements and extended analysis. These are instantaneous values updating at sampling frequency, and evaluated over the active period – specifically from first to last ladder contact by the user. The general analysis following and the parameters obtained are based on standard dynamics principals, assuming static balanced linear forces within the ladder structure, and balanced torsions in axis denoted 1 .. 3.

The composite ground reactions are identified thus:

- **R_{base}Z** Total Base Z Ground +ve REACTION > Ladder (kg)
- **R_{base}Y** Total Base Y Ground +ve REACTION > Ladder (kg)
- **R_{top}Y** Total Top Y Ground +ve REACTION > Ladder (kg)
- **R_{top}X** Total Top X Ground +ve REACTION > Ladder (kg)

The frictional demand is identified thus:

- **U_{base}** Base Frictional Demand (#)
- **U_{top}** Top Frictional Demand (#)

The user generated equivalent load vector is identified thus:

- $LZ = R_{base}Z$ User generated load at ALP - Z (kg)
- $LY = R_{base}Y - R_{top}Y$ User generated load at ALP - Y (kg)
- $LX = R_{top}X \times I/G$ User generated load at ALP - X (kg)

$$L = \sqrt{LZ^2 + LY^2 + LX^2} \quad \text{Total user generated load magnitude (kg)}$$

For the footing trials (Task H only) – The user drive vector is identified thus:

- $FZ = R_{base}Z$ +ve User ACTION > Ladder – Base Z – Footing activity (kg)
- $FY = -R_{base}Y$ +ve User ACTION > Ladder – Base Y – Footing activity (kg)

14.3 CALIBRATION METHODOLOGY

Four identical transducers, each capable of responding to two action vectors simultaneously, constitute the dynamometer. By design these transducers are reliably linear in response, and naturally free of cross-talk effects.

Point loading of individual transducers was initially undertaken with known loads at the time of their manufacture, and the amplifier channel gains were individually set to achieve a nominal 125 kg/V.

Upon completion of the rig proper, and with the trial ladder registered, a series of reference loads were applied to the ladder at strategic positions. Initial nominally correct computed values produced by the trial mechanical model were fine corrected in the spreadsheet analysers to closely tally with the known references in terms of force or displacement. The corrections required were of the order of low single figure kg and low single figure centimetres, and arose due to positioning tolerances during rig assembly and ladder mounting, and small settling asymmetries. Results in measurable dynamometer output are produced, accurate generally to about +/- 1 % of scale range.

Exact calibration records exist but are not provided with this report.

14.4 RIG SENSORY PARAMETER ASSUMPTIONS

It will be noted that the rig devised for this evaluation only collects data from eight channels, representing the x- and y-planes at the upper registration and the z- and y-planes at the base registration. It may appear that there is therefore 'missing' data representing the z-plane at the upper and x-plane at the lower registration. However, it can be justified that collection of this data is unnecessary.

Primarily it can be shown through first principles of structures that forces in these two dimensions will be negligible. This is a function of the ladder behaving as a rigid structure, even though there is an intrinsic degree of movement. Accordingly, rigid structure dynamics apply and these are specific and robust about the nature of force management, and can readily demonstrate that these dimensions cannot account for any significant forces in ladder use.

Additionally, previous trials conducted by RICE (DTI 1997) have recorded in these dimensions during ladder trials and demonstrated that they are, in practice, negligible despite this appearing somewhat counter intuitive. Finally, scale models of ladders have been constructed to demonstrate these principles, employing wheels free to rotate in the given dimensions. With these models it can be readily shown that there is no reaction in these dimensions to reasonably applied forces, indicating that no forces are acting in this way.

The absence of forces in these given planes are not readily accepted, even by experienced engineers, and it proved necessary to undertake a small number of additional trials at the end of the main project to demonstrate the validity of these assumptions. The data generated was used to respond to queries raised in the peer review process. A summary of these additional trials and the processed data they generated, along with a more complete discussion of these issues can be found in Appendix 6 at the end of this report.

15.0 ANALYTIC AND DATA PROCESS METHODS

Raw volt level signals were initially captured at the time of the trial with a PC based data logger, and were stored as bulk data files for post process. The files were named according to user ID number (00...99), Task type (A ... G or H) and repetition number (1 or 2) e.g. 07F2.

A pair of major Microsoft Excel analyser spreadsheets were constructed to process raw instrumented data sets into endpoint parameters as necessary. Spreadsheet 'Analyser 1' handled task types A through to G (the general task types), while spreadsheet 'Analyser 2' handled task type H (manual footing).

Initially, time-variant volt level raw data was baseline adjusted to zero then scaled to engineering units through prior set calibration factors, and produced eight elemental ground contact point reaction levels as previously described. These were processed through the particular modelling algorithm to generate time variant user load and action location parameters. Data was then segmented into sections equivalent to the mount / dismount phase and the actual task phase, allowing better resolution of the various endpoint measures needed. Each raw data block was embedded in turn in the analyser, and the full set of output generated are then copied and tabulated within a respective archive sheet. This is a transient process whereby the bulk analysis result is discarded prior to accepting the next cycle of data.

Master analysis sheets exist as 'Collation 1' for Task type A through to G (general tasks), and 'Collation 2' for task type H (manual footing). These contain the entire data sets of all trials, and are the basis of a graded statistical analysis leading to the various universal standard parameters as defined.

15.1 SINGLE-TRIAL ANALYSIS PARAMETERS

Raw instrument recorded data blocks were successively embedded into the analyser spreadsheet which initially produces usable primary rig parameters – calibrated and scaled to engineering units. These are time variant values updating at a sampling rate interval of 20 ms, and extending over the whole activity period.

The primary rig parameters are identified thus:

- **LZ (kg)** Instantaneous load in z-axis
- **LY (kg)** Instantaneous load in y-axis
- **LX (kg)** Instantaneous load in x-axis

- **L (kg)** Instantaneous total vector magnitude

- **G (m)** Instantaneous ALP co-ordinate
- **H (m)** Instantaneous ALP co-ordinate

- **R_{base}Z (kg)** Instantaneous Base Reaction Z
- **R_{base}Y (kg)** Instantaneous Base Reaction Y

- **R_{top}Y (kg)** Instantaneous Top Reaction Y
- **R_{top}X (kg)** Instantaneous Top Reaction X

- **U_{base} (#)** Instantaneous Base Frictional Demand
- **U_{top} (#)** Instantaneous Top Frictional Demand

This data is segmented into two major blocks corresponding to the ascent/decent phase and the task phase separately. Thereafter they are managed separately producing appropriate endpoint trial parameters for both phases. These are single value measurement results which collectively characterise and quantify a given trial.

Task parameters fairly numerate the pure activity phase of ladder use and are the basis of the greater determination of a standard load vector and standard applied loading point – SLV and ALP. Ascent/descent parameters characterise the typically high shock or transient loading at the base arising from a user mounting the ladder, more or less harshly. This is predominantly due to hard initial foot impact, and vertical user mass acceleration reactions. While this information is not relevant to stability in the forms expressed, it is highly relevant to structural durability issues.

The choice of measures used are designed to extract clear boundary limit information derived from typically erratic and volatile source data. This is because the users are highly active and in constant motion, and understandably produce similar patterning in the signal stream. However, the trials were established to determine the extremes of reasonable use, and particularly the fall-off of parameters near critical boundaries.

15.2 DATA FILE AND DIRECTORY STRUCTURE

The Technical Annexe contains information which identifies the data file and directory structure pertaining to the trials. This provides correct nomenclature if scrutinising the data archive.

15.3 TYPICAL EXAMPLE TRIAL ANALYSIS SPREADSHEETS

A number of the single trial analysis spreadsheets are preserved for full inspection if required. The bulk being generated on a transitory basis only to generate various trial characterisation parameters which are harvested and collated, and processed statistically later. Trial types A through to G are processed within Analyser 1 and represent practical user tasks. Trial type H is manual footing trial results and processed within Analyser 2. They contain the full data extraction algorithm and generate results in numerical and graphical formats, and are available as active spreadsheets. Examination of these files will give deeper insight into the true dynamic and qualitative nature of the mechanics, and the various performance parameters of central interest.

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16.0 THEORETICAL STABILITY MODEL – DAL

Part of the analysis required the development of a numerical modeller of a generalised DAL structure. The technical model assumes a pair of potential point contacts in the horizontal ground plane, and a similar pair in the vertical plane. Using key measurable structural dimensions, information defining structural mass Centre of Gravity and defined loading vectors, the dynamic status of the total frame can be determined, and ultimately expressed as normalised stability indices.

The user's activity was modelled as a point action vector, designated the standard load vector, or SLV. This is considered to act at a known position in space, designated the applied load point, or ALP. In reality the user is placing the ladder structure under duress in distributed fashion, they are applying forces at numerous locations and at variable magnitude. This drive arises due to the following variables:

- Their weight and gross attitude
- The additional weight of tools or other objects
- Contact reactions to ground – being solid surfaces about the ladder
- Inertial actions due to user motion or attitude change

Although the forces acting on the ladder are distributed as described, they can be resolved into a single directed vector at a single point. This vector and point of application is, in effect, an equivalent or parametric drive which places the ladder under duress, from a rigid systems point of view, without distinction. The extensive user trials provide the practical values of SLV and ALP for both modelling and workshop stability verification tests. Standard dynamics and rigid structure mechanics are used to develop the formal model.

A virtual construct termed the active ladder is extensively used. This is a simple flat ladder equivalent, which is, by definition, co-planar with the true DAL ground contact points and is weightless. This serves as a normalised action frame against which various action drives are applied. These drives arise from the SLV itself, the structural mass Centre of Gravity, and the responding ground reactions, and are technically mapped onto the active ladder. It is generally the case that both the location of the ALP and the mass Centre of Gravity will be displaced from the active ladder by a measurable degree.

A standardised algorithm can thereafter fully determine the system dynamics referenced to the active ladder, and will produce appropriate stability status indices.

The SLV and ALP are referenced to the accessible ladder at all times, and defined by the parameters $L_{std}Z$, $L_{std}Y$, $L_{std}X(kg)$, and $G_{set}(m)$ and $H_{set}(m)$. This action vector is mapped into the active ladder at a position denoted α , hence is a referred or normalised ALP. A limit position is calculated and denoted β , which indicates an extreme point where the referenced ALP must reach to achieve critical torsional balance, or instability. This permits a scaling calculation for flip mode failure.

Four concurrent modalities are identified, as discussed in Section 12.1, by which the DAL structure can destabilise or fail. Base and top slip modes arise as friction limit failures, where demanded drive exceeds the inherent capability of the particular materials at the contact interface. Flip and top contact failure are rotations, and occur when there is a critical loss of ground contact points, below the mandatory three. This occurs when a magnitude of destabilising torsion meets a stabilising torsion about a crucial axis, that is they are in critical balance.

Friction is considered as both a demand level and as a reliable limit failure. We define frictional demand in terms of the ratio between planar and normal load, in the conventional manner. Physics gives us that this parameter is insensitive to total area of contact, but is sensitive to the materials in contact, and the state of surface finish. Experimentally, upper frictional limits can be found with simple test rigs, progressively loaded until cohesion failure is observed. These values are typically erratic, however very reliable lower limits can be found which translate into reliable working limits in the model – these parameters being $U_{baselim}(\#)$ and $U_{toplim}(\#)$. These must be supplied to the model as input values, and are taken as ratiometrics when calculating $S_{int}Base(\#)$ and $S_{int}Top(\#)$.

Top contact failure is defined as a reduction of the top normal reaction – $R_{top}Y(kg)$ – below a critical value defined by $R_{contact}(kg)$. The value here is debatable, but could reasonably be set at about 3 kg based on previous measurements and allowing for transient loading. Hence the parameter $S_{int}Contact(\#)$ will descend to value 1 when $R_{top}Y$ reduces to 3 kg, in this case.

The model determines the mechanical duress which arises in the arbitrary DAL structure, and measures the drive towards instability expressed as proximity to prevailing critical limits.

The stability indices themselves are fully normalised and dimensionless parameters, and indicate stability integrity as a number which is value 1.0 (unity) precisely at a maximal limit or a critical balance. Collectively the four parameters $S_{\text{intBase}}(\#)$, $S_{\text{intTop}}(\#)$, $S_{\text{intFlip}}(\#)$ and $S_{\text{intContact}}(\#)$, demark an envelope of qualified safety. Provided none are less than value 1, then the structure is compliant to the minimal requirement for stability, under the specified standard loading condition. In practice the standard load is adjusted to maximally duress the DAL for each failure mode in turn. There are strong natural interlinks between drives to stability failure as a function of applied load magnitude and varying geometry, and some can increase while others decrease. There are therefore optimums to be found in terms of DAL design.

16.1 ACCESSIBLE AND ACTIVE LADDER – MODELLING DISTINCTION - DAL

The accessible ladder is the ordinary or nominal ladder as made available to the user. This ladder is therefore the physical structure upon which a user will work and apply load to the DAL as a whole. The SLV is reckoned to be applied on, and registered at, the ALP with respect to the accessible ladder.

Generally the basic ladder will be displaced in space through intervening devices, and will finally contact the ground through some arbitrary construction or arrangement, with modified ground contact geometry or modified frictional capability, or both. This final configuration of ground contacting is germane to the stability status of the total structure.

A notional or virtual ladder is created which underlies the real structure, and is termed the active ladder. This is a simple plane which contains the four potential grounding contact points. This construction behaves as a normalised action frame, functioning as a dynamic equivalent to an arbitrarily complex real system, and allows a tractable method of analysis based on a standardised dynamics sub-system. The process is a type of mapping, and is allowed according to the principals of dynamics and rigid structures.

From the viewpoint of the active ladder, the ALP lies at some displacement in space which is fully determined by the system geometry. Also the mass Centre of Gravity is likewise removed by some amount. By figuring the drives on the active ladder arising from the standard load, the effect of weight Centre of Gravity, and the true grounding geometry of the structure, the propensity to instability can be directly determined.

16.2 ANALYTIC MODEL PARAMETERS - DEFINITIONS - DAL

In this section there are listed the formal parameters utilised in the stability modelling algorithm. They consist of various classes of parameter type as described, and produce a normalised set of stability indices via the defined algorithm.

Measured Structural Parameters

The measured structural parameters can be identified thus:

- **I (m)** Total length of Accessible Ladder
- **A (m)** Active Ladder – Upper Semi-width
- **B (m)** Active Ladder – Lower Semi-width
- **C (m)** Ground contact planar displacement of Active Ladder
- **D (m)** Ground planar displacement of Accessible Ladder
- **F (m)** Access Limit dimension at G
- **W (kg)** Total Weight – combined Ladder + Devices
- **M (m)** Weight position of C of G referenced within Accessible Ladder
- **J (deg)** Base Elevation Angle – Accessible Ladder
- **K (deg)** Base Elevation Angle – Active Ladder

User Specified Parameters :

The user specified parameters can be identified thus:

- **U_{baselim} (#)** Maximum reliable frictional limit - Base
- **U_{toplim} (#)** Maximum reliable frictional limit - Top

Prescribed Standard Parameters :

The prescribed standard parameters can be identified thus

- **L_{stdX} (kg)** Standard applied load vector (SLV) – x-axis
- **L_{stdY} (kg)** Standard applied load vector (SLV) – y-axis
- **L_{stdZ} (kg)** Standard applied load vector (SLV) – z-axis

- **G_{set} (m)** Standard Offset dimension to determine ALP parameter G (m)
- **H_{set} (m)** Standard Offset dimension to determine ALP parameter H (m)
- **R_{contact} (kg)** Minimum permissible R_{top}Y(kg)

Modelled Performance Parameters :

The modelled performance parameters can be identified thus:

- **G (m)** Applied Load Point (ALP) – co-ordinate
- **H (m)** Applied Load Point (ALP) – co-ordinate
- **S_{int}Base (#)** Normalised Intrinsic Stability Index – Base slip mode
- **S_{int}Top (#)** Normalised Intrinsic Stability Index – Top slip mode
- **S_{int}Flip (#)** Normalised Intrinsic Stability Index – Flip mode
- **S_{int}Contact (#)** Normalised Intrinsic Stability Index – Top contact mode
- **U_{base} (#)** Friction Demand - Base
- **U_{top} (#)** Friction Demand – Top
- **R_{base}Y (kg)** Total Reaction – Base - Y axis
- **R_{base}Z (kg)** Total Reaction – Base - Z axis
- **R_{top}X (kg)** Total Reaction – Top - X axis
- **R_{top}Y (kg)** Total Reaction – Top - Y axis

Intermediate Modelling Parameters – Transient usage only :

The intermediate modelling parameters can be identified thus:

- **I, p, g, h, m, n, r, s, t (m)** Virtual dimensions defining Active Ladder
- **X1 .. X8(m)** Temporary construction dimensions
- **Q1 .. Q3(deg)** Temporary construction angles

16.3 STANDARD LOAD VECTOR SLV AND APPLIED LOAD POINT ALP - DAL

In order to develop a test methodology it is necessary to determine the SLV and ALP for the DAL structure. These parameters are obtained from key results within the 'Optimisation' spreadsheet and are set at the following qualified high levels:

- **L_{stdX}** - 95th Percentile of all LX95 = 22.6 kg (23 kg)
- **L_{stdY}** - 95th Percentile of all LY95 = 12.3 kg (13 kg)

This parameter set at qualified low level as defined :

- **L_{stdZ}** – 5th Percentile of all LZ5 = 60.0 kg (60 kg)

This parameter set at qualified high level as defined :

- **L_{stdZ}** – 95th Percentile of all LZ95 = 128.1 kg (128 kg)

These parameters set at qualified high levels as defined :

- **G_{set}** = I(1) - 95th Percentile of all G95
= 4.25 – 3.86
= 0.39 m (390 mm)
- **H_{set}** = 95th Percentile of all H95 – F(1)
= 0.28 – 0.145
= 0.135 m (135 mm)

Note – I(1) is measured total ladder length of trial ladder = 4.25 m

Note – F(1) is measured Access Limit Dimension for trial ladder at G_{set}=0.39 m

Each of the four defined stability failure modes is determined by the particular simultaneous combination of standard load vector components, since this is three-dimensional. Table 28 illustrates the maximal duress in each failure mode in terms of the relative SLV vector magnitudes.

Table 28
Loading to determine stability failure in different modes (values in parenthesis)

| Failure mode test | L_{std}Z | L_{std}Y | L_{std}X |
|---|-------------------------|-------------------------|-------------------------|
| Test1 – S_{int}Base (#) & S_{int}Contact (#) | LOW (60 kg) | HIGH (13 kg) | ZERO (0 kg) |
| Test2 – S_{int}Top (#) | LOW (60 kg) | ZERO (0 kg) | HIGH (23 kg) |
| Test3 – S_{int}Flip (#) | HIGH (128 kg) | ZERO (0 kg) | HIGH (23 kg) |

Evidently, to test all failure contingencies, two levels of L_{std}Z are required, with single high strength vectors in X and Y sufficient.

The correct set of SLV component values should be entered into the predictive model, and the relevant intrinsic stability parameter determined at this point. This will represent the worst case, producing in effect the lowest reliable stability index pertaining to that failure mode. The operation is three stage therefore, to deduce the full set of four stability indices.

In a similar fashion the workshop stability proving tests call for a specified set of load vectors per each of the three tests 1 to 3.

It is important to make it clear that the SLV value for both modelling purposes and workshop stability proving tests are identical.

16.4 INTRINSIC STABILITY INDICES – SINTBASE, SINTTOP, SINTFLIP & SINTCONTACT – DAL

The primary function of the stability modeller is to predict the global safety assurance of any given DAL by numerated values indicating proximity to stability failure. The stability indices are dimensionless quantities normalised to value 1.0 at criticality, and can be universally compared across arbitrary configurations. Stability pertaining to a given failure mode is assured if the relevant parameter attains a value equal to or greater than 1. Total system stability integrity occurs if all indices meet the criteria.

The stability modeller requires categories of information in the following classes :

1. Structural geometric – Directly measurable key dimensions
2. Weight – $W(\text{kg})$
3. Prescribed standard parameters – SLV , $G_{\text{set}}(\text{m})$ and $H_{\text{set}}(\text{m})$ and $R_{\text{contact}}(\text{kg})$
4. User supplied parameters – $U_{\text{baselim}}(\#)$ and $U_{\text{toplim}}(\#)$

This generates output parameters :

1. Intrinsic stability indices - $S_{\text{intBase}}(\#)$, $S_{\text{intTop}}(\#)$, $S_{\text{intFlip}}(\#)$ and $S_{\text{intContact}}(\#)$
2. Computed ALP – $G(\text{m})$ and $H(\text{m})$
3. Contact reactions – $R_{\text{baseZ}}(\text{kg})$, $R_{\text{baseY}}(\text{kg})$, $R_{\text{topY}}(\text{kg})$ and $R_{\text{topX}}(\text{kg})$,
4. Contact frictional demand – $U_{\text{base}}(\#)$ and $U_{\text{top}}(\#)$

There are three verification tests each requiring a specific set of SLV component magnitudes, which sequentially stress the system maximally. When employing the modelling algorithm, each test is done by assigning the prescribed values of SLV components given as elements in L_{stdX} , L_{stdY} and $L_{\text{stdZ}}(\text{kg})$, and specified in Table 28, and the particular valid stability indices noted.

Test 1 - Maximal duress to base slip and top contact failure – $S_{\text{intBase}}(\#)$ & $S_{\text{intContact}}(\#)$ valid

Test 2 - Maximal duress to top slip failure – $S_{\text{intTop}}(\#)$ valid

Test 3 - Maximal duress to Flip failure – $S_{\text{intFlip}}(\#)$ valid

These criteria are automatically and empirically tested during practical workshop performance checks, this also being a three stage process.

16.5 PRACTICAL WORKSHOP STABILITY VERIFICATION TESTS – DAL

Figure 43 illustrates the workshop test for DAL systems.

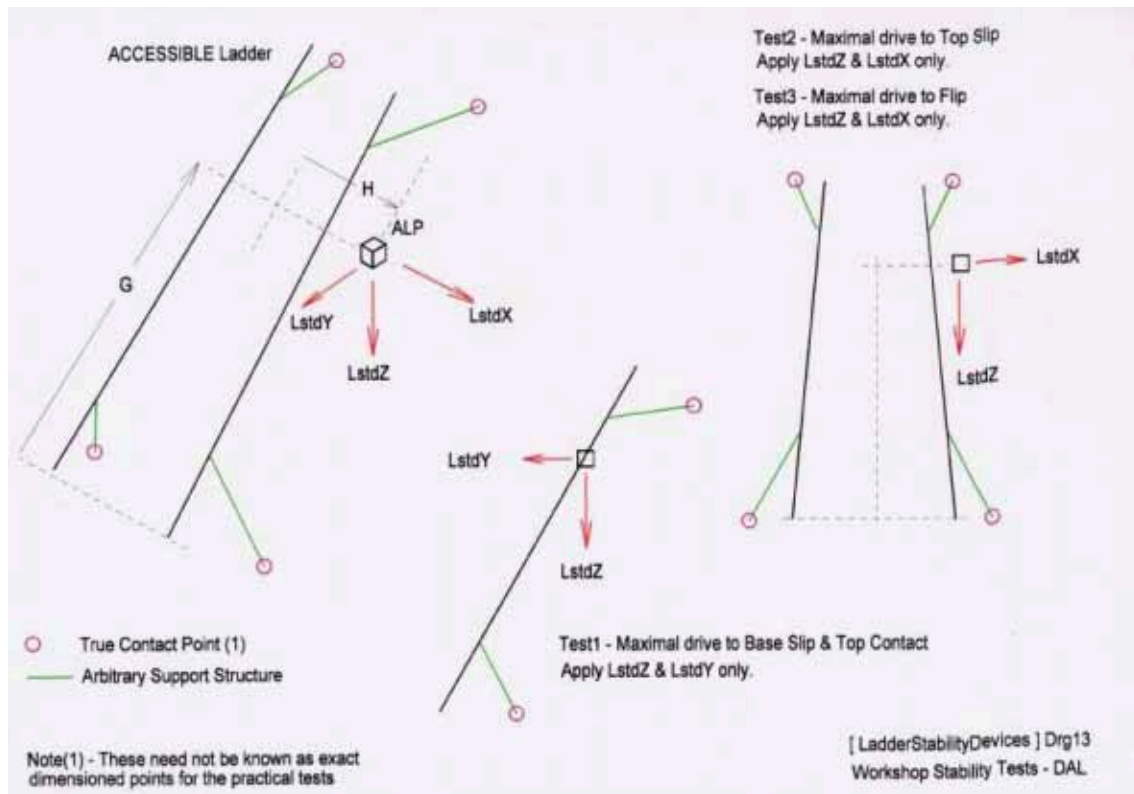


Figure 43

Workshop stability tests

The parameters $G_{\text{set}}(\text{m})$ and $H_{\text{set}}(\text{m})$ define the ALP for the DAL. These are referenced to the accessible ladder. Note that the access limit dimension $F(\text{m})$ is found directly at $G(\text{m})$, and $H(\text{m})$ is found by $H = F + H_{\text{set}}$.

The three tests (1 to 3) should be performed in sequence with the prescribed values of SLV. This varies for each test and specific sets of values of $L_{\text{std}}Z(\text{kg})$, $L_{\text{std}}Y(\text{kg})$ and $L_{\text{std}}X(\text{kg})$ are required and given in Table 28.

Provided the ladder remains upright for all three conditions, the ladder is qualified compliant.

The SLV is applied at the ALP, but the ALP lies outside the physical ladder. Any simple but strong temporary projecting structure will be required to perform this operation.

The DAL is defined and tested in a fully configured form, hence employs a given ladder with a given additional retrofit support system. It follows that a DAL strictly requires a specific ladder as part of the stability qualification regime. It will be generally the case however that DALs are created ad hoc, with arbitrary nominal ladders. It is a fact that the final stability status of any given configuration is sensitive to the nominal ladder in terms of geometry and mass distribution. This is recognised as beyond the control of a DAL stability device manufacturer. For this reason a designer should test with differing types of ladder covering available geometries and weight, and perhaps qualify on this basis. For instance the maximum relevant dimensions for which they have tested which maintain a cross modality index of 1.0 or greater.

17.0 THEORETICAL STABILITY MODEL – TRIPOD

The tripod is capable of flip failure about any one of three axis at the base. The mechanical condition where instability occurs is at a point of torsional balance. The combined action drive of the user expressed as a SLV acting at the ALP, the structural weight Centre of Gravity, and the base geometry fully determine the critical points of balance.

The predictive model expresses stability as three indices $S_{int1}(\#) \dots S_{int3}(\#)$, which are calculations based upon the relative surfeit of corrective torsional drive acting against a destabilising drive. A resultant index value of 1.0 indicates that the highest user duress is just able to reach the natural limit envelope of the system, hence is in a qualified safe status.

The model is crucially dependent upon the SLV magnitude, and this must be determined correctly. There is a strong geometric argument with this ladder configuration, in favour of a polar type of standard action vector, matching a more circular than rectangular symmetry. The authors have not directly measured tripod activity, but can reasonably infer from DAL information, the level of drives in operation.

From a functional point of view the tripod is equivalent to a regular leaning ladder, albeit that the support system is entirely different. However where the leaning ladder tends to offer restricted forward access, typically because of a large planar obstruction (typically a wall), the tripod is somewhat more accessible in this direction. In addition, the natural portability of the tripod configuration readily allows a user to place the structure in any attitude to the work intended, but particularly such that they can work in reverse stance, i.e. work towards the rear of the structure. The leaning ladder DAL data is strongly indicative that lateral (x-axis) user generated drive is much stronger potentially than is forwards (y-axis) drive. If it is considered that this is reasonably an ergonomics issue, in terms of ease of access or user comfort, then a pragmatic argument is to consider that a user on a tripod can, and will, operate at all horizontal planar angles non-preferentially. The use of polarised or axis specific forces for the tripod should therefore be rejected, and a single omni-directional force serving as single maximal SLV drive should be chosen. Hence the use of a standard load vector $L_{std}O(kg)$, which is a fixed value horizontal planar drive allowed to operate at any bearing.

The required high duress standards for the Tripod are taken directly from the DAL parameters :

- The maximal value $L_{std}X$ is taken from the DAL parameters and assigned to $L_{std}O$ also.
- The minimal value $L_{std}Z$ is taken from the DAL parameters and assigned to $L_{std}Z$ also.

The action placement of the user, represented by the ALP location, is equivalent to the DAL definition, and is partially specified through the $H_{set}(m)$ parameter.

The ALP height parameter $G(m)$ is allowed to be variable in the formal technical model, with stability indices $S_{int1}(\#) \dots S_{int3}(\#)$ responding accordingly. For a given structural format, the model will allow a maximal value of $G(m)$ to be found, occurring at the first failure of any one of the three axes. This essentially defines a maximal allowable operating height for the user, on any given fixed tripod structure. It should be realised that this limit height is not related directly to the total accessible ladder length, but is simply measured from the ground. In this manner it can be seen to be relational to the stability device and its precise manner of attachment to the ladder.

The spatial location of the ALP is practically close to the user's mass Centre of Gravity, and when determining the operational height limits by defining an equivalent footing height limit, the intervening distance must be allowed for.

17.1 ANALYTIC MODEL PARAMETERS – DEFINITIONS - TRIPOD

Measured Structural Parameters :

The measured structural parameters are identified thus:

- | | |
|------------------|--|
| • A (m) | Structural dimension |
| • B (m) | Structural dimension |
| • C (m) | Structural dimension |
| • J (deg) | Elevation angle – Accessible ladder |
| • K (deg) | Riser Closure angle - Accessible ladder |
| • W (kg) | Total Weight – combined structure |
| • M (m) | Weight C of G of combined structure within Accessible Ladder |

Design Variables :

The design variables are identified thus:

- **G (m)** Applied Load Point (ALP) – Model variable determines H (m)
(Set by designer)

Prescribed Standard Parameters :

The prescribed standard parameters are identified thus:

- **L_{std}O (kg)** Standard applied load vector (SLV) – Planar horizontal & Omni-directional
- **L_{std}Z (kg)** Standard applied load vector (SLV) – Z axis
- **H_{set} (m)** Standard set distance offset from Access Limit Dimension F(m) edge limit

Modelled Performance Parameters :

The modelled performance parameters are identified thus:

- **F (m)** Access Limit Dimension at G(m)
- **H (m)** Applied Load Point (ALP) as f(G)
- **S_{int1} (#)** Normalised Intrinsic Stability – Failure pivot axis 1
- **S_{int2} (#)** Normalised Intrinsic Stability – Failure pivot axis 2
- **S_{int3} (#)** Normalised Intrinsic Stability – Failure pivot axis 3

Intermediate Modelling Parameters – Transient usage only

The intermediate modelling parameters are identified thus:

- **p, q, m, n, r, s, t (m)** Virtual dimensions
- **Q (deg)** Construction angle

17.2 STANDARD LOAD VECTOR SLV AND APPLIED LOAD POINT ALP - TRIPOD

These parameters are set at qualified high duress levels as defined in Table 29:

Table 29
Standard Load Vectors and Applied Load Point value for tripods

| Parameter | Value |
|-----------------|---------|
| $L_{std}Z$ (kg) | 60 kg |
| $L_{std}O$ (kg) | 23 kg |
| H_{set} (m) | 0.135 m |

$G(m)$ is left as a design variable and is undefined within the provided stability performance model. However $G(m)$ achieves a natural upper limiting value by restraint in values of $S_{int1}(\#)$ to $S_{int3}(\#)$, each required to be equal to or greater than 1.0 for assured stability in the three tip failure modes.

The stability model as presented will identify for a designer the maximal conditionally safe ALP altitude at $G(m)$, for a given ladder in this configuration class. The corresponding distance $H(m)$ is then directly computed from appropriate measured or prescribed parameters and hence fully defines the ALP.

The ALP will generally lie outside the ladder structure within a line locus, parallel with the side riser and in the plane of the ladder. So with $G(m)$ allowed to be variable, $H(m)$ is forced a distance $H_{set}(m)$ beyond $F(m)$, the access limit dimension.

For practical workshop stability verification purposes $F(m)$ is best found by direct reference at the inner face of the side riser, existing at any given testing altitude $G(m)$. The ALP is then easily located a further distance $H_{set}(m)$ beyond $F(m)$.

The SLV is applied at the ALP as prescribed by both the model definition and workshop procedures, these being directly equivalent. The tripod requires a single set of SLV component magnitude values for all conditions, but the direction of $L_{std}O(kg)$ varies with the tripod geometry.

17.3 INTRINSIC STABILITY INDICES – SINT1, SINT2, SINT3 – TRIPOD

The primary function of the stability modeller is to predict the global safety assurance of any given Tripod through numerated quantities indicating proximity to stability failure. The stability indices are normalised to value 1.0 and can be universally compared across arbitrary configurations. Stability pertaining to a given failure mode is assured if the relevant parameter attains a value equal to or greater than 1. Total system stability integrity occurs if all indices meet the criteria.

The stability modeller requires categories of information in the following classes :

1. Structural geometric – Directly measurable key dimensions
2. Weight – $W(\text{kg})$
3. Prescribed standard parameters – SLV , $H_{\text{set}}(\text{m})$
4. ALP altitude parameter $G(\text{m})$ – Design variable

This generates output parameters :

1. Intrinsic stability indices $S_{\text{int}1}(\#)$, $S_{\text{int}2}(\#)$ and $S_{\text{int}3}(\#)$ as function of $G(\text{m})$
2. Computed ALP as function of $G(\text{m})$

There are three verification tests requiring a single universal SLV , which individually stress the system maximally towards the respective failure modes. When employing the modelling algorithm, the test is done once by assigning the prescribed values of SLV given as elements in $L_{\text{std}O}(\text{kg})$ and $L_{\text{std}Z}(\text{kg})$, and defined in Table 29, and the prevailing stability indices $S_{\text{int}1}$, $S_{\text{int}2}$ and $S_{\text{int}3}(\#)$ are simultaneously figured as a function of $G(\text{m})$. These indices are therefore qualified at a defined ALP altitude.

The model ignores results for $G(\text{m}) < 1\text{m}$, and stability indices should not be calculated or expected in this altitude range. There is no assigned upper limit to which $G(\text{m})$ can take as a numerical system variable, but the stability criteria itself dictates an upper working limit.

- **Test 1** - Maximal duress to axis 1 failure – $S_{\text{int}1}(\#)$ valid
- **Test 2** - Maximal duress to axis 2 failure – $S_{\text{int}2}(\#)$ valid
- **Test 3** - Maximal duress to axis 3 failure – $S_{\text{int}3}(\#)$ valid

These criteria are sequentially and empirically tested during practical workshop stability performance tests.

17.4 PRACTICAL WORKSHOP STABILITY VERIFICATION TESTS – TRIPOD

Figure 44 illustrates the workshop tests for tripod devices

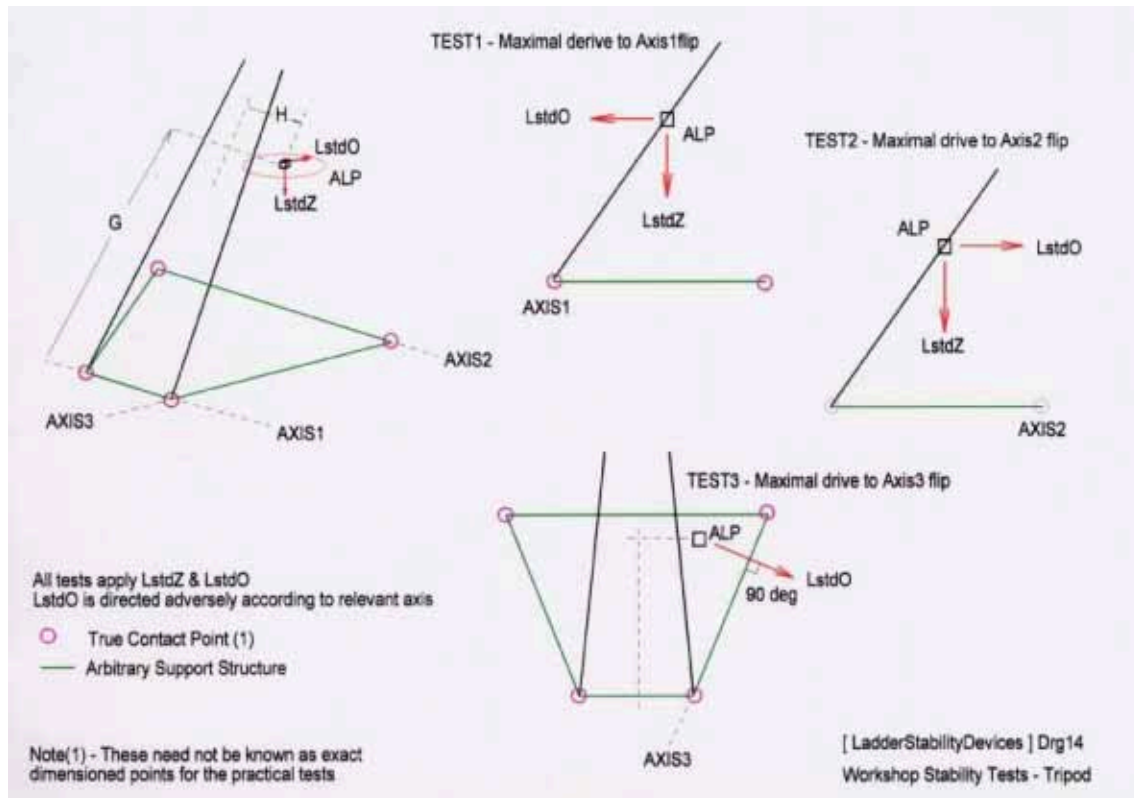


Figure 44

Workshop stability tests - tripod

There is no prescribed height for the ALP, which is equivalent to the maximal working altitude of the user. The parameter $G(m)$ can be chosen at any value and the workshop test performed. However $G(m)$ determines the position where the access limit dimension $F(m)$ should be determined empirically. The variable $H_{set}(m)$ with $F(m)$ now fixes $H(m)$, and hence the ALP is determined.

The three tests 1 to 3 should be performed in sequence with the prescribed values of $L_{stdZ}(kg)$ and $L_{stdO}(kg)$. Note that $L_{stdO}(kg)$ is of fixed magnitude but variable direction. This is always applied in the horizontal plane containing the ALP, but directed adversely to each failure axis in the base.

The implication is that some maximal $G(m)$ will be evident for any given structure, hence an arbitrary Tripod configuration will have associated a qualified working height.

Provided the ladder remains upright for all three conditions, the ladder is qualified compliant.

The SLV is applied at the ALP, but the ALP lies outside the physical ladder. Any simple but strong temporary projecting structure will be required to perform this operation.

The Tripod is defined and tested in a fully configured form, hence employs a given ladder with a given stability device system. It follows that a Tripod strictly requires a specific ladder as part of the stability qualification regime. It will be generally the case however that Tripods are created ad hoc, with arbitrary nominal ladders. It is a fact that the final stability status of any given configuration is sensitive to the nominal ladder in terms of geometry and weight Centre of Gravity, which is itself a function of the extended length of the ladder. This is recognised as beyond the control of a tripod stability device manufacturer. For this reason a designer should test with differing classes of ladder covering available geometries and weight, and perhaps qualify on this basis.

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18.0 MODELLING SPREADSHEETS – PREDICTIVE MODEL IMPLEMENTATIONS

The modelling algorithms for DAL and Tripod configurations are fully detailed in the Technical Annexe and can be implemented via any convenient method. The authors utilise two major active spreadsheets which fully implement the specified algorithms, and can be used to explore the stability and general performance of arbitrary ladder configurations in the relevant class.

- **Stability Predictor 1** - DAL Stability Modeller – Interactive spreadsheet

This software is illustrated in Figure 45.

Ladder Stability Devices Project - ESRI / WB - June 2002 ... Sep 2002

DAL Stability Performance Predictor

File [LadderStabilityDevices] StabilityPredictor1

Measured Structural Parameters

| | |
|---------|------|
| I (m) | 7.44 |
| A(m) | 0.20 |
| B (m) | 0.25 |
| C (m) | 1.80 |
| D (m) | 1.80 |
| F (m) | 0.18 |
| M (m) | 2.98 |
| J (deg) | 75 |
| K (deg) | 75 |
| W (kg) | 25 |

Prescribed Standard Parameters

| | | |
|------------|----|----|
| LstdX (kg) | 20 | 35 |
| LstdY(kg) | 18 | 22 |
| LstdZ (kg) | 72 | 72 |

| | |
|----------|-------|
| Gset (m) | 0.35 |
| Hset(m) | 0.155 |

| | |
|---------------|---|
| Rcontact (kg) | 3 |
|---------------|---|

User specified parameters

| | |
|--------------|-----|
| Ubaselim (#) | 0.6 |
| Utoplim (#) | 0.6 |

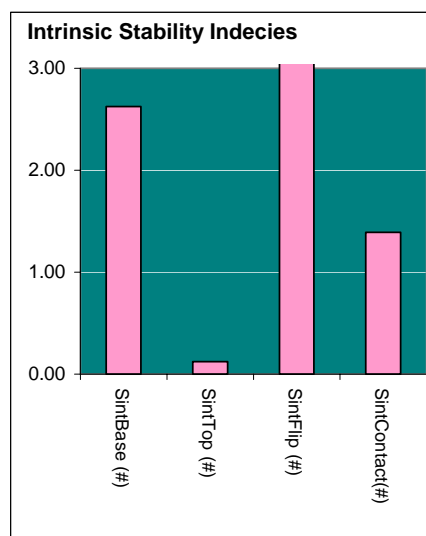


Figure 45 – Example of the Predictor 1 software output

Users should enter parameters in the data fields denoted :

- Measured Structural Parameters
- Prescribed Standard Parameters
- User Specified Parameters

Note that three defined sets of SLV parameters L_{stdZ} L_{stdY} & $L_{stdX}(kg)$ are required to sequentially check for stability compliance in four failure modes.

The sheet will process this data and generate all output parameters in accordance with the specification. This data is presented both numerically and graphically.

- **Stability Predictor 2** - Tripod Stability Modeller – Interactive spreadsheet

This software is illustrated in Figure 46.

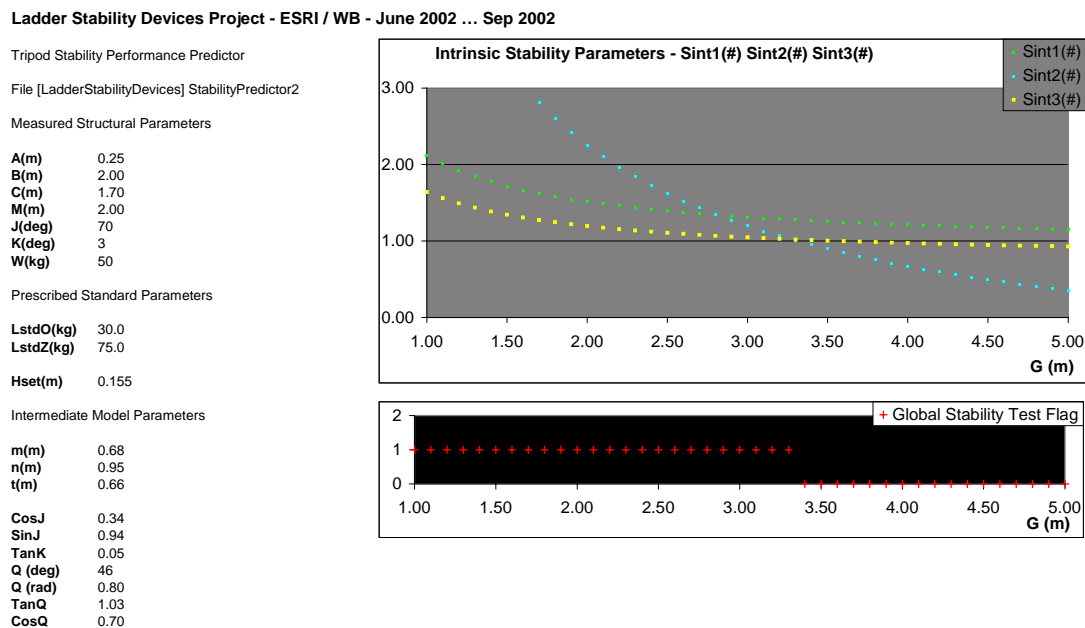


Figure 46 – Example of the Predictor 2 software output

Users should enter parameters in the data fields denoted :

- Measured Structural Parameters
- Prescribed Standard Parameters

The sheet will process this data and generate all output parameters in accordance with the specification. The height parameter $G(m)$ is incrementally considered over the range 1 to 5 m, with stability estimates made over the whole of this range. The parameters S_{int1} to S_{int3} are tested for compliance to be greater than 1.0.

Provided all are compliant then the global stability flag will indicate this. An upper limit of $G(m)$ for the given structure will be determined. This data is presented numerically and graphically.

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19.0 MANUAL FOOTING – THEORETICAL CONSIDERATIONS

For manual footing to be of benefit, then an improvement must be afforded in one or more stability indices. Furthermore, this improvement should be worthwhile. Lastly, it should be reliably maintained over the entire period of user activity. It is important to note that improvements in safety envelope margins may be redundant if the user/ladder system is already comfortably placed within the calculated safe zone, expressed numerically as $S_{intTop}(\#)$, $S_{intBase}(\#)$, $S_{intFlip}(\#)$ and $S_{intContact}(\#)$. Additionally, if ‘footer’ performance is variable or erratic during the event, then the actual additional safety utility afforded will vary from time to time, meaning that it could reduce to zero or even reverse, generally unpredictably. This is at best useless and worse dangerous. A small number of trial participants definitely exhibited such counterproductive actions upon the ladder, meaning that the issue of footing seems more profound than previously thought. An example is shown in Figure 47



Figure 47

Highly asymmetric footing technique

The 'footer' is generally imparting a directed action vector which offers zero torsional action benefiting top-slip failure or top-contact failure. Furthermore the leverage is adverse and imparts very little modified contact action at the top, hence has negligible effect upon $U_{top}(\#)$ or $R_{top}Y(kg)$, and does not improve $S_{intTop}(\#)$ or $S_{intContact}(\#)$. It can therefore be seen that even with good technique, footing will do nothing to improve ladder stability in:

- Top slip failure mode.
- Top contact failure mode.

The benefits in the remaining failure modes are discussed in sections 19.1 and 19.2 below.

19.1 FLIP MODE

When considering failure in flip mode, it is evident that any nominal footing action could aid this situation through counteractive torsions about the principal ladder axis. **However for this to be of benefit, the 'footer' is required to impart a particularly symmetric force, acting centrally and squarely within the ladder and balanced left to right, amounting to a structured and disciplined footing methodology.** For illustration, even a high force level directed and acting through a ladder side riser will have virtually zero effect on the torsional tension within the ladder, and hence similarly zero effect on $S_{intFlip}(\#)$. Due to observable variation in style and stance preference, the drive to the ladder is typically erratic in this particular respect of symmetry, but crucially the action Centre of Gravity is volatile and moving unpredictably between the ladder base contact points. The added torsional utility, acting to enhance flip safety, is instant to instant varying from some potentially useful upper value down to near zero, and could conceivably be negative in effect if the footing drive becomes overly asymmetric. In summary, flip stability can be enhanced in theory by prescribing a specified and disciplined footing technique, but is prone to be unreliable and unpredictable given an undefined or freestyle footing technique, and should currently be considered as non-existent.

No relative flip enhancement utility measure is attempted in this survey for these reasons. However, cursory examination of the two riser base forces and the degree of balance in particular, demonstrates the volatile nature of flip mode protection. A high efficiency manually delivered footing technique could nevertheless, realistically double the effective value of $S_{intFlip}(\#)$ at normal operational levels.

19.2 BASE SLIP MODE

Enhancement in base-slip safety margins is markedly less sensitive to footing technique asymmetries, and by contrast are more reliable and predictable. This failure mode is highly sensitive to footing actions, and can reasonably be measured. The mechanism is theoretically considered and numerically analysed, and is expressed as fractional changes in the frictional demand parameters.

The Frictional Demand for a non-footed ladder is $U_{base}(\#)$ for any given $R_{base}Y(kg)$ and $R_{base}Z(kg)$, and is generally given by :

$$U_{base} = \frac{R_{base}Y}{R_{base}Z}$$

The Frictional Demand for a footed ladder is $U_{foot}(\#)$ for any given $R_{base}Y(kg)$, $R_{base}Z(kg)$ & $FY(kg)$ & $FZ(kg)$, and is generally given by :

$$U_{foot} = \frac{R_{base}Y - FY}{R_{base}Z + FZ}$$

Ordinarily $U_{foot} < U_{base}$ and is consistent with an increase in $S_{int}Base(\#)$, but it is dependent upon the footing technique. In some trial case instances this was not true, with $U_{foot}(\#)$ exceeding $U_{base}(\#)$, and effectively reducing the safety status in base-slip mode failure.

19.3 MANUAL FOOTING – MEASURED UTILITY

Figure 48 provides background to the manual footing calculations

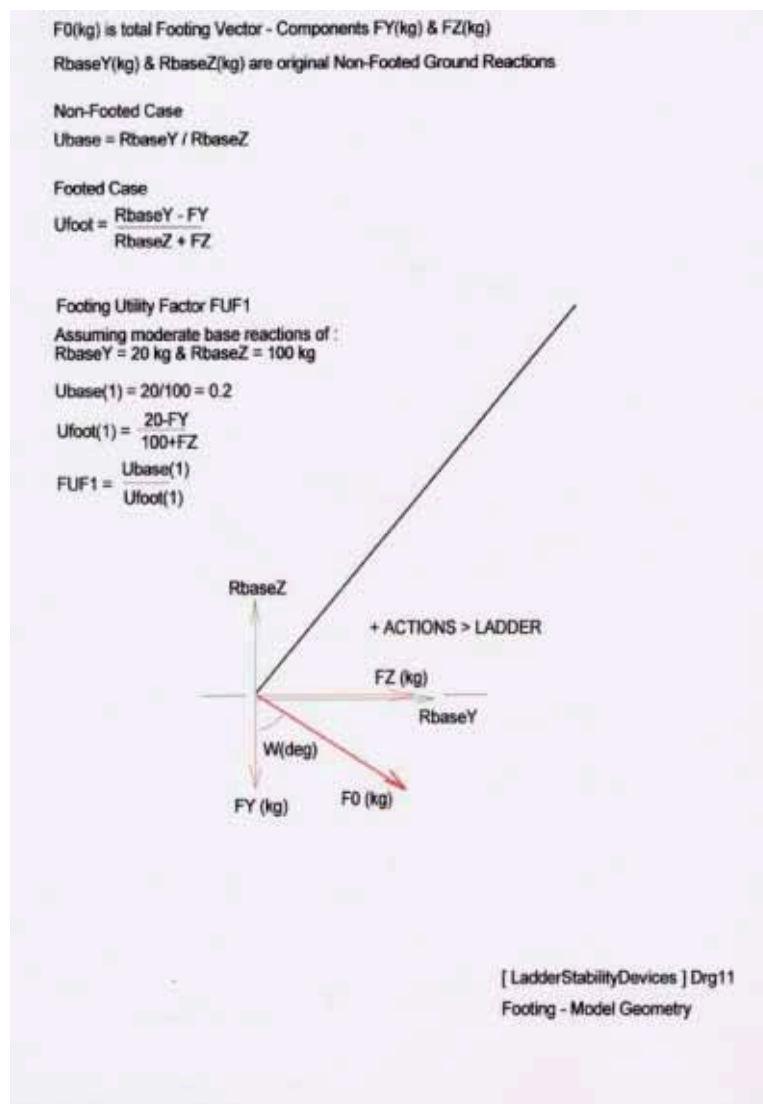


Figure 48

Footing model geometry

Footing trials produce time variant data sets measuring the mechanical drive developed at the ladder base, due to the action of the trial subject. This occurred with a zero loaded ladder, and are therefore direct measurements of the imparted drive only.

- $FZ = R_{base} Z$ +ve Footing ACTION > Ladder (kg)
- $FY = R_{base} Y$ +ve Footing ACTION > Ladder (kg)
- $FO = \sqrt{FY^2 + FZ^2}$ Total Footing Vector – Magnitude (kg)
- $W = ArcTan\left(\frac{FY}{FZ}\right)$ Footing vector argument (deg)

The held force levels are analysed into a single representative action vector in terms of magnitude and direction. These parameters are calculated from samples validated by conditional tests. This yields reliable footing strength measures, independent of user arbitrary settling and release activities.

Data acceptance test - $FZ > 0.5 \times 90^{\text{th}}$ Percentile of all FZ

- FZ_{med} (kg) Median of all valid FZ
- FY_{med} (kg) Median of all valid FY
- FO_{med} (kg) Median of all valid FO
- W_{med} (deg) Median of all valid W_{med}

The actual modification in U_{base} , and hence $S_{intBase}$, is a function both of the particular base load imparted by the ‘user’ on the ladder, and the force actions imparted by the ‘footer’. Both are therefore variables in any real situation.

Accordingly, a measure of footing utility has been developed.

Assuming a nominal standing base load of $R_{base} Y = 20\text{kg}$ & $R_{base} Z = 100\text{kg}$:

$$U_{base(1)} = \frac{20}{100} = 0.2$$

Revised base demand due to footing is calculated :

$$U_{foot(1)} = \frac{20 - FY_{med}}{100 + FZ_{med}}$$

We produce a normalised Footing Utility Factor FUF1 :

$$FUF1 = \frac{U_{base}(1)}{U_{foot}(1)}$$

| | |
|----------------------|---|
| FUF1 > 1.0 | Greater utility – Reduction in frictional demand – Increase in S _{int} Base(#) |
| FUF1 = 1.0 | No change |
| FUF1 < 1.0 | Reduced utility – Increase in frictional demand– Reduction in S _{int} Base(#) |

FUF1 is acceptable as a pragmatic measurement and would be broadly meaningful in all practical and real cases. It correctly ranks the added value of the footing activity with respect to base slip stability.

Arbitrarily high FUF1 values were observed in the trial analysis, with factors easily reaching 5. This corresponds to the frictional demand at the ladder base reducing to 20% of the nominal standing value without footing. A number of subjects yielded negative values for FUF1 indicating overcompensation and beyond, with full reversal of reaction vectors. The utility obtained from footing is evidently a highly erratic parameter within the conditions of this trial, and particularly with the freedoms allowed in style. A good number of trial subjects yielded FUF1 levels close to zero, indicating no measurable effect.

Definition of Footing Activity types :

- **Activity 1** 2 Feet + Arms
- **Activity 2** 1 Foot + Arms
- **Activity 3** Arms only
- **Activity 4** Other

A ladder will normally operate with a base frictional demand at a conservatively high value of 0.25, corresponding to high duress and the qualification tests in Section 8 of this report.

Also this parameter is not susceptible to high deviation in the form of transients. From previous work measuring friction limit performance levels of nominally loaded ladders on cement surfaces, the $U_{base\lim(\#)}$ parameter was very reliably observed at 0.5. With less certainty but high probability, values of up to 0.7 prevailed. If this is so, then the clear implication is that while ladder footing can easily improve $S_{intBase(\#)}$, it is arguably not required.

A number of trial results indicated very adverse footing actions. Some of these were completely mis-directed actions effectively reducing the prevailing safety envelope. Others pushed so hard that they overcompensated, through the zero condition, and actually reversed the normal ground reaction direction.

19.4 MANUAL FOOTING – OPTIMUM METHODS

Generally, an optimum footing action will deliver a single vector at the ladder, acting square-on and central, and at any convenient but low height. The applied action can be any combination of horizontal force towards the ladder, or down through the ladder. Directed forces outside of this quadrant are actively counterproductive. There is a marked disparity in direction sensitivity in relation to utility. As a rule of thumb, 1 kg horizontal in the y-axis is equivalent to 5 kg vertically down in the z-axis. A ‘footer’ can easily use their weight to generate z-action, however y-action will ordinarily require constant muscular activity.

A simple method, therefore, of achieving efficient and consistent footing is to stand centrally on the lowest rung with both feet, or via some simple seat, to sit at, or near, the ladder base. Both these approaches utilise only z-action arising through weight, and are therefore continuously sustainable by the person. More importantly, they tend to ensure the required action direction symmetry as previously explained.

It can be shown, therefore, that correctly applied footing can very usefully improve the flip mode stability of a ladder where users will frequently operate in close proximity to the safety envelope, but requires consistent and symmetric action delivery. Base slip safety margin can be technically improved, but is evidently not the most pressing requirement. Top-slip or top-contact mode is not easily modified due to the adverse leverage argument, and is practically independent of footing activity.

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20.0 GROUND SLOPE – EFFECT ON BASE FRICTIONAL DEMAND

Any ground inclination to the side (side slope mode) or the rear (back slope mode) will reduce slip stability margins. The slope alters the base reaction vectors adversely from a friction demand perspective. The additional slip potential in side-slope and back-slope mode was investigated from a theoretical approach, as detailed in the Technical Annexe, and useful measures which best quantify the effect are identified.

20.1 SIDE-SLOPE MODE

A side directed ground slope is problematic from a gross stability point of view because the ladder will rotate about a near vertical ladder axis between two distinct stable stances. This swing can be large for even small side slope gradients, and must be checked. A packing piece, or purpose designed extender device, can be arranged at the foot to take up the nominal slack. This will serve to eliminate the gross motion of the ladder, which will then perform equivalent to a ladder on flat ground. Note that it is not required, or possible, to wedge the shortfall since the ladder base will behave as a normal ladder, with load freely transferring between the feet, and hence likely to reach zero load on the packing device during real activity. However any interposed device or material must have reliable limit friction capability, at least equal to the designed foot.

The ordinary flat ground base frictional demand is defined as $U_0(\#)$. For a given ground incline of $T(\text{deg})$ the base friction demand rises to a new value $U_{T_{\text{side}}}(\#)$. Side-mode frictional demand rises relatively gently with increasing $T(\text{deg})$ initially, but more rapidly increases as $T(\text{deg})$ advances. For a given qualified maximal $U_0(\#) = 0.25$ as would reasonably prevail on flat ground, the formula gives us that $U_{T_{\text{side}}}(\#)$ will reach value 0.5 at about 22 deg – approaching a slip failure condition. However $U_{T_{\text{side}}}(\#)$ is below 0.4 up to about 16 deg, and which leaves a reasonable operational safety margin.

20.2 BACK-SLOPE MODE

The ordinary flat ground base frictional demand is defined as $U_0(\#)$. For a given ground incline of $T(\text{deg})$ the base friction demand rises to a new value $U_{T_{\text{back}}}(\#)$. Back-mode frictional demand rises aggressively fast with increasing $T(\text{deg})$ initially at approximately 0.02 per deg, and more rapidly still as $T(\text{deg})$ advances. For a given qualified maximal $U_0(\#) = 0.25$ as would reasonably prevail on flat ground, the formula gives us that $U_{T_{\text{back}}}(\#)$ will reach value 0.5 at about 12 deg – approaching a slip failure condition. However $U_{T_{\text{back}}}(\#)$ is below 0.4 up to about 6 deg, and which leaves a reasonable operational safety margin.

Clearly a rearward incline is the more critical condition with minimal tolerance to angle magnitude. As a rule of thumb for ground inclines, stability degradation in back-mode is broadly three times more sensitive to angle than is side-mode. Within the suggested angular limits given above, the ladders are nevertheless naturally liable to remain stable without additional devices or manual footing.

21.0 WORKSHOP TEST TRIALS

In order to demonstrate the practical application of both the predictive stability modelling and the associated workshop test regime, three trial evaluations were undertaken by the authors. First a naked ladder was measured then two stability devices were fitted to the ladder, one a DAL stand off device and one a DAL foot enhancement device. The dimensions needed to run the predictive software recorded. The software model was then run to predict the workshop test outcomes. The ladder systems were then subjected to selected test regimes to establish whether there was a correlation between the modelled and measured performance. For reasons of practicality these tests were restricted to Test 1 (for base slip and top contact failure), and Test 2 (for top slip failure). The data used for the modelling is given in Table 30 and the test results are presented in Sections 21.1 – 21.3.

Table 30
Dimensions recorded for modelling

| Variable | Naked ladder | Stand off DAL | Foot modifier DAL |
|------------------------------------|---------------------|----------------------|--------------------------|
| I Ladder length (Acc.) – meters | 4.5 | 4.5 | 4.5 |
| A Upper ½ width (Act.) – meters | 0.18 | 0.36 | 0.18 |
| B Lower ½ width (Act.) – meters | 0.24 | 0.24 | 0.24 |
| C Displacement (Act.) – metres | 1.96 | 1.91 | 1.5 |
| D Displacement (Acc) – meters | 1.96 | 1.81 | 1.96 |
| F Access limit at G – meters | 0.18 | 0.18 | 0.18 |
| W Weight - kg | 16.4 | 18.36 | 18.38 |
| M CofG location – meters | 2.38 | 2.49 | 2.26 |
| J° Elevation (Acc.) | 67 | 63 | 67 |
| K° Elevation (Act.) | 67 | 61 | 69 |

The test loads were used in pairs in accordance with the theory previously presented. The loads used are given in Table 31.

Table 31
Loading to determine stability failure in different modes

| Failure mode test | L_{stdZ} | L_{stdY} | L_{stdX} |
|---|------------|------------|------------|
| Test1 – $S_{intBase}$ (#) & $S_{intContact}$ (#) | 60 kg | 13 kg | 0 kg |
| Test2 – S_{intTop} (#) | 60 kg | 0 kg | 23 kg |
| Test3 – $S_{intFlip}$ (#) | 128 kg | 0 kg | 23 kg |

21.1 NAKED LADDER TEST

The output of the predictive modelling for the naked ladder are shown in Figures 49 to 51. Note that a stability indices below 1, as depicted by the pink bars, demonstrates instability in that mode in normal use.

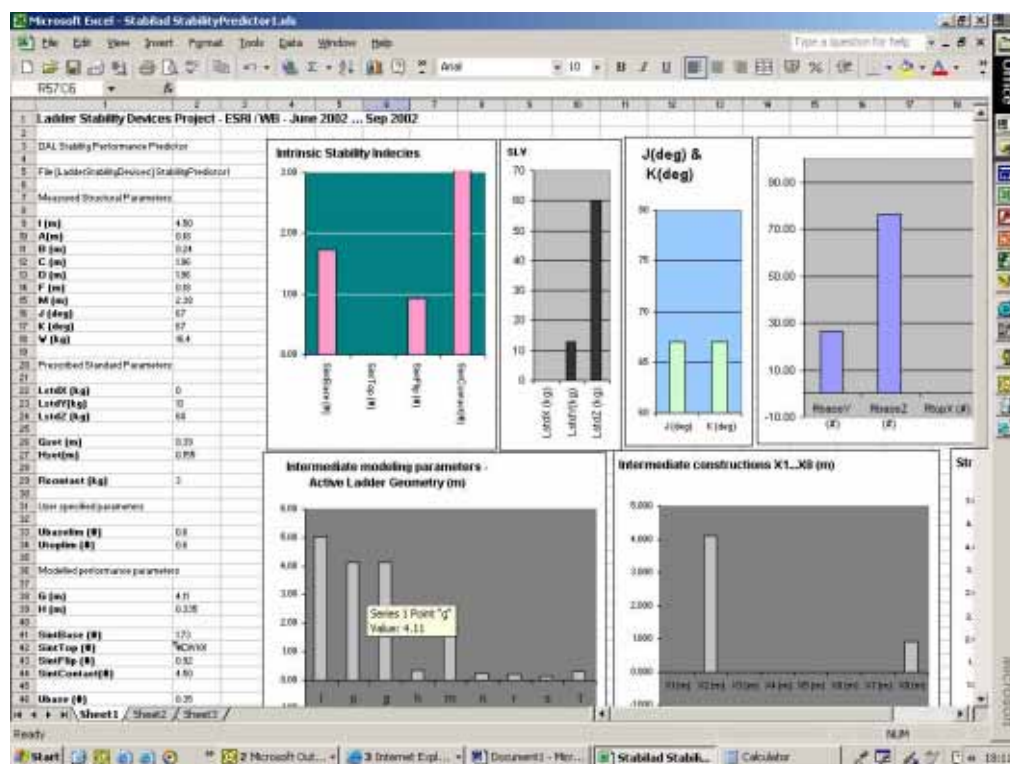


Figure 49

Naked ladder Test 1 output

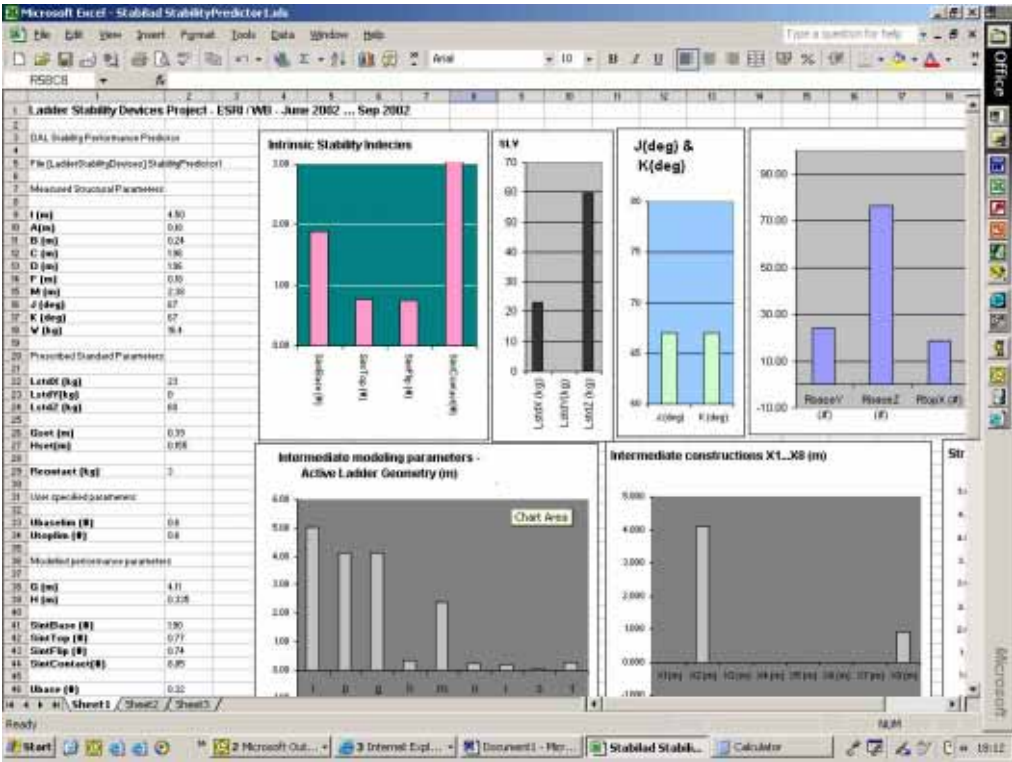


Figure 50

Naked ladder Test 2 output

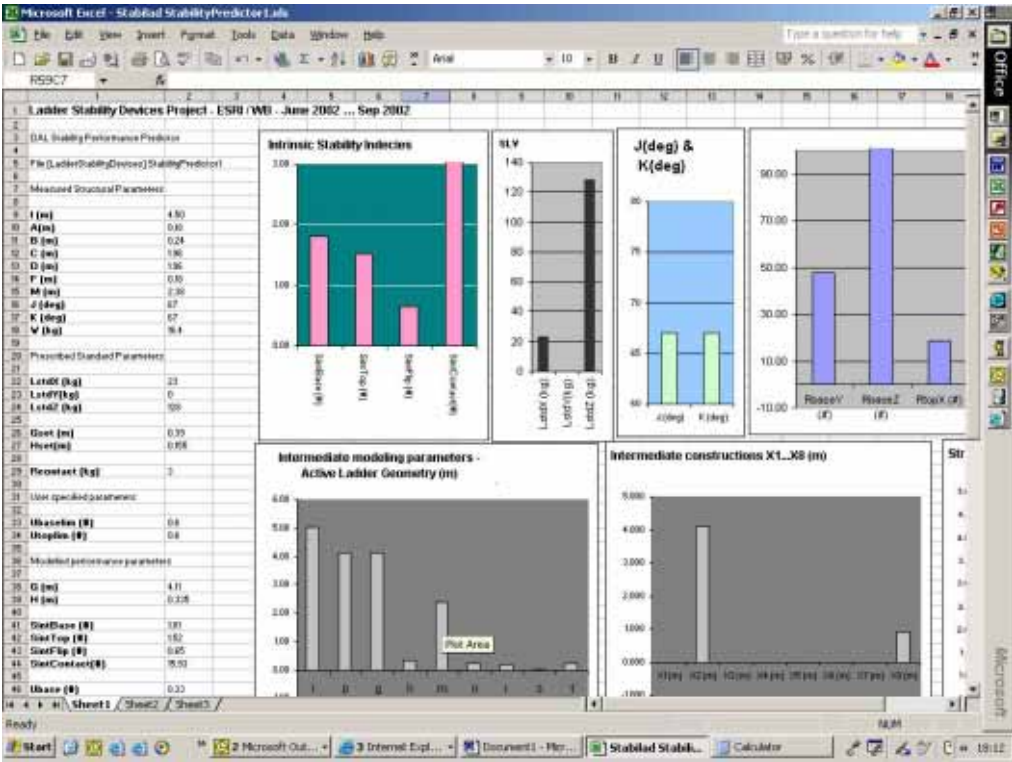


Figure 51

Naked ladder Test 3 output

These tests show that flip mode stability is insufficient in all test configurations. In addition, Top Slip failure can be anticipated in Test 1 and 2. However, more than adequate stability was offered in base slip and top contact modes, as predicted. In practice this means that a naked ladder is unable to offer adequate stability to users in most arduous conditions of use.

21.2 DAL SYSTEM TEST 1 – STAND OFF

The output from the predictive modelling of the stand off equipped ladder is shown in Figures 52 – 54. Again, note that any of the pink stability indices which drop below a value of 1 indicates instability in that mode.

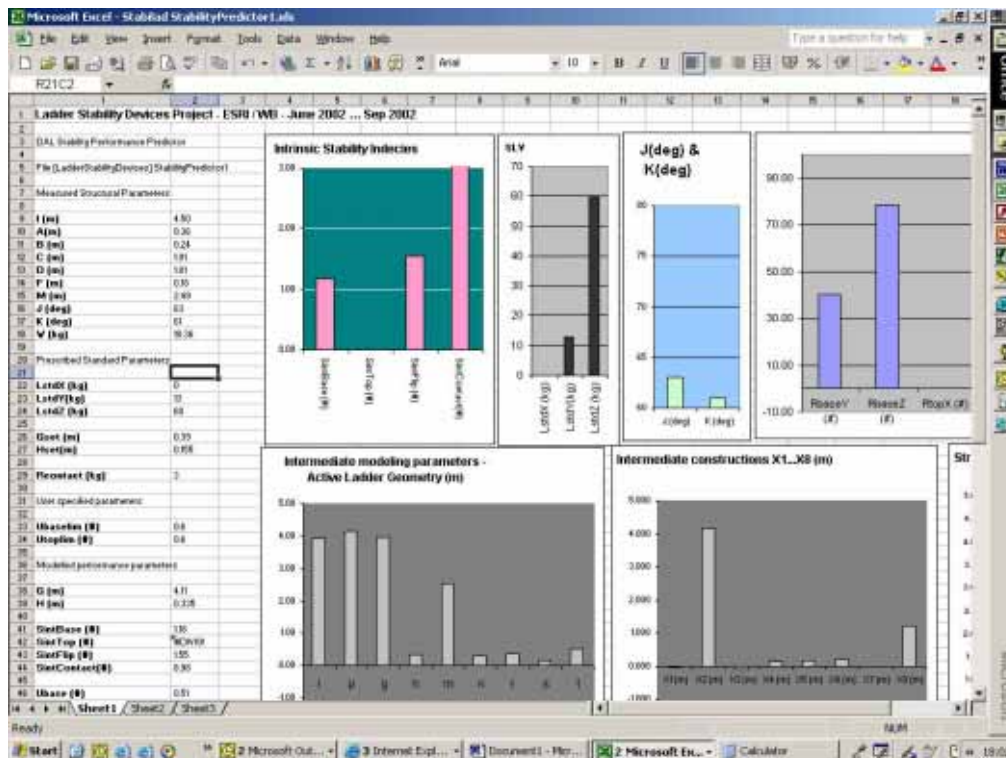


Figure 52

Stand off DAL Test 1 output

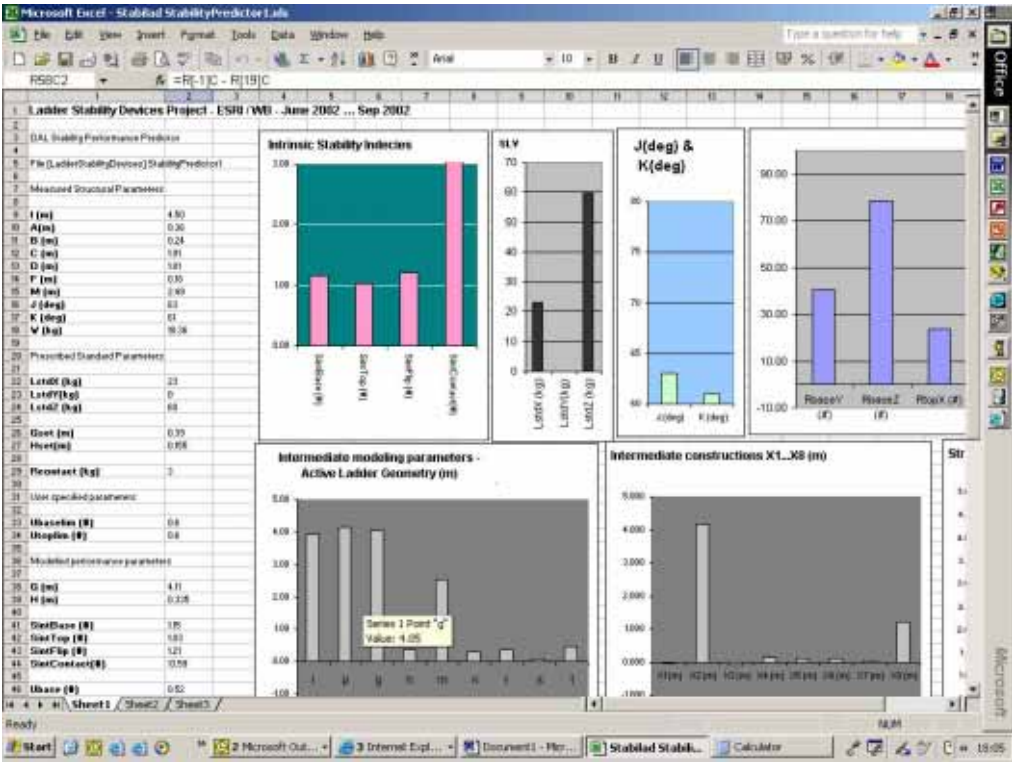


Figure 53

Stand off DAL Test 2 output

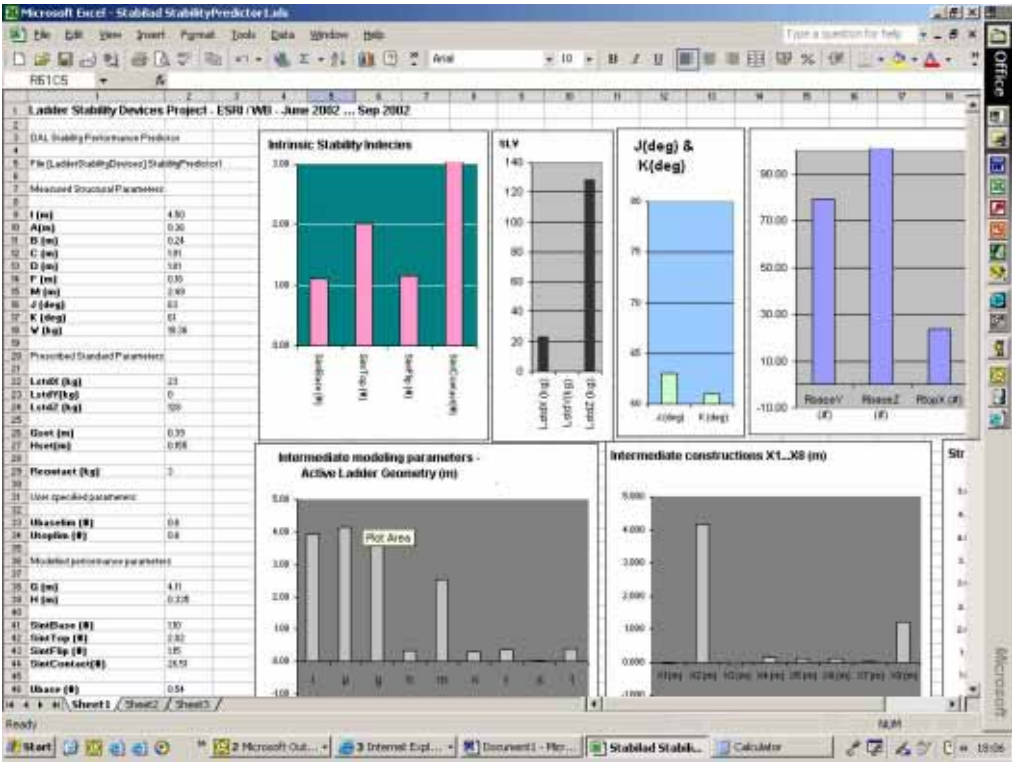


Figure 54

Stand off DAL Test 3 output

These models demonstrated only one potential failure mode – in Top Slip. All other modes offered increased safety over both the stability threshold and the naked ladder. Top slip was revealed in Test 1, designed to appraise the performance in base slip and top contact modes. This is probably as a result of the test compromising the grip of the upper caps on the wall, overcoming the static friction. In practice this may be overcome by the intervention of the user, although this is not a satisfactory safety strategy and better geometry would be more appropriate.

21.3 DAL SYSTEM TEST 2 – STABILISER FEET

The third set of predictive models were based on a ladder with stabiliser feet fitted. The output is shown in Figures 55 – 57. Again, the pink stability indices demonstrate insufficient stability if they fall below the critical stability threshold of 1.0

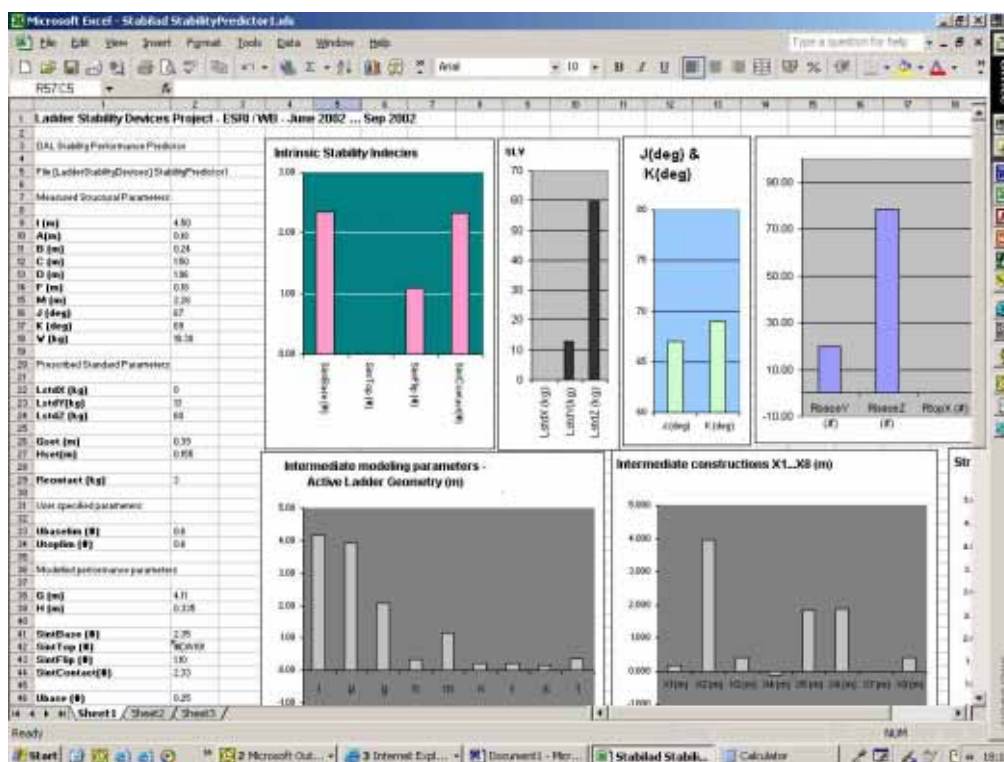


Figure 55

Stabiliser feet DAL Test 1 output

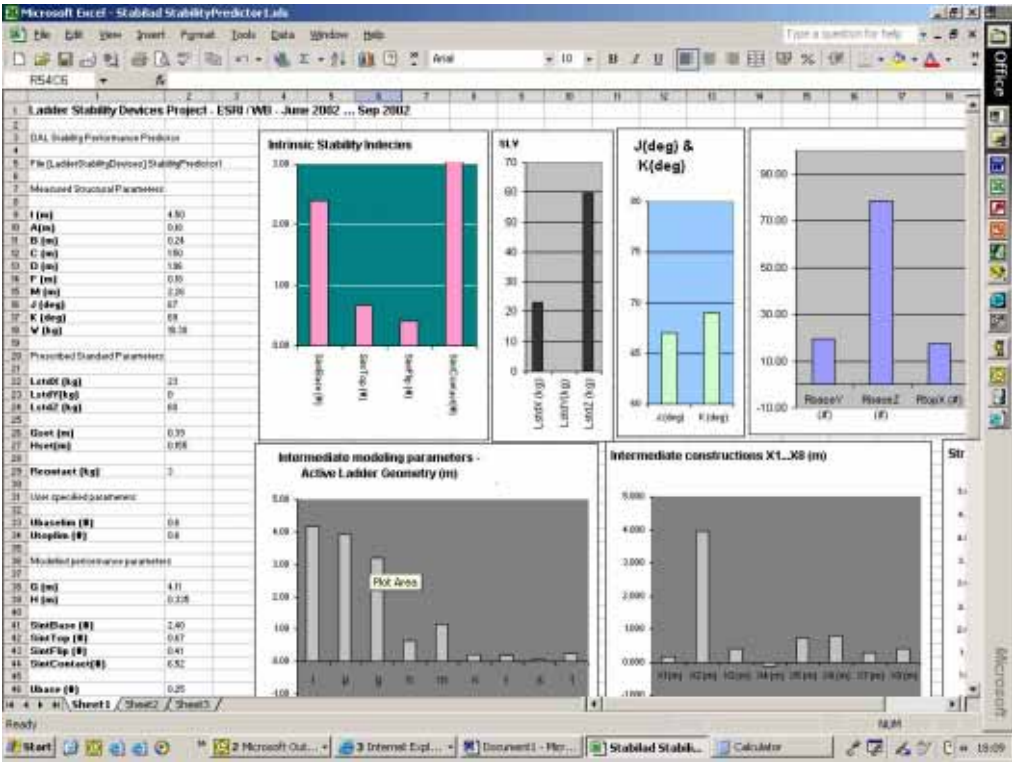


Figure 56

Stabiliser feet DAL Test 2 output

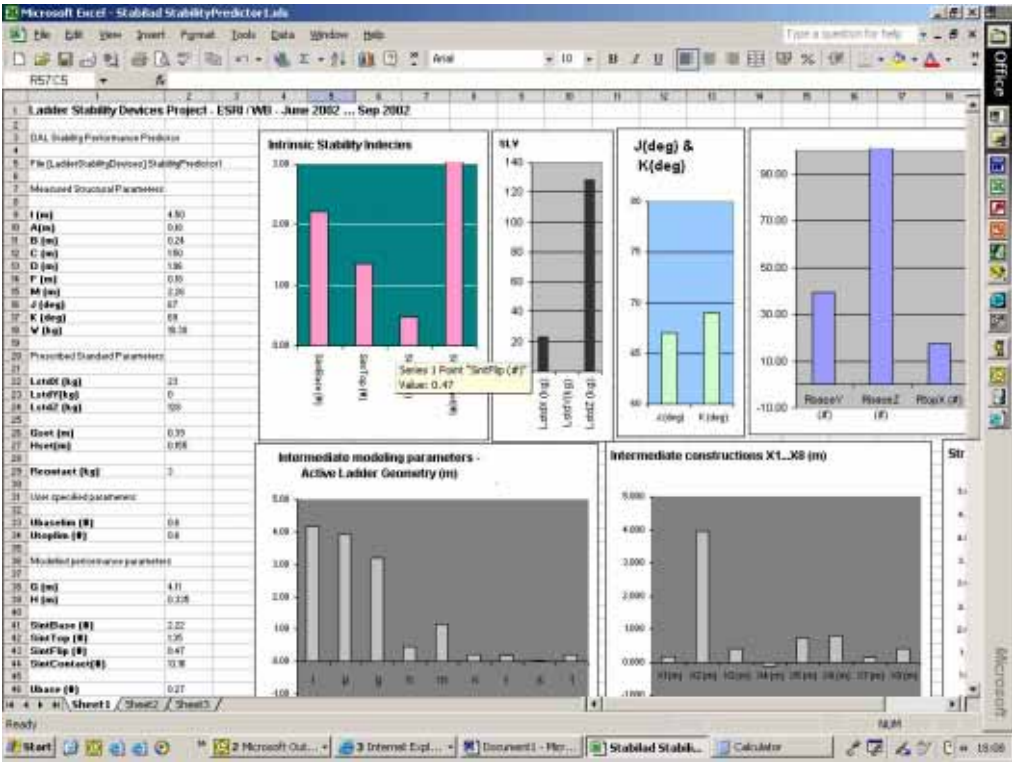


Figure 57

Stabiliser feet DAL Test 3 output

This DAL system demonstrated instability in the Flip mode in Tests 2 and 3 as well as Top slip instability in Tests 1 and 2. This would cause critical instability in both modes in conditions of reasonable use.

21.4 WORKSHOP TESTS

The practical tests undertaken only covered Tests 1 and 2. The results for these are shown in Table 32.

Table 32
Results of testing

| Test | Naked ladder | Stand off | Foot modifier |
|--|--------------|-----------|---------------|
| Test1 – S_{int}Base (#) | Fail | Fail | Fail |
| S_{int}Contact (#) | | | |
| Test2 – S_{int}Top (#) | Fail | Fail | Fail |

It can be seen therefore that the model predicted that there would be insufficient stability in the ladder in the configurations described and this was validated in the workshop test. The failure mode was almost universally due to the ladder flipping around a single stile. More accurate testing could be undertaken with measured friction characteristics at the top and base which may modify the predicted failure mode. In this instance default values were used which may have caused early failure in a mode that would normally be preceded by another controlled by frictional coefficients.

A sanitised image of a test result is shown in Figure 58.



Figure 57

Stabiliser feet DAL Test

21.5 SUMMARY OF TESTING

It can be seen from this illustrative testing that the predictive modelling is accurately shadowed by the workshop tests. This is logically robust since the test is derived from the modelled values. However, it demonstrates that either method can rapidly identify modes where stability may be lacking. It is likely that the model will be of most benefit to manufacturers and designers who need to rapidly appraise prototype designs, whilst the workshop test could be readily integrated into a Standard or Code of Practice such that independent verification could easily be undertaken.

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22.0 INFORMATION DISSEMINATION

It is recommended that a program of information dissemination is undertaken to promulgate this knowledge throughout the community. It is envisaged that this will ensure that the maximum benefit of this research is enjoyed by ladder and ladder stability device manufacturers and users as well as, employers, safety agencies, standards committees and safety practitioners. It is likely that the information may take different forms for each target group, and these forms will need to be agreed with the HSE on a case-by-case basis, and after the final findings and recommendations have been approved. At this time, the following information dissemination strategies are recommended :

- Circulate the findings amongst standards-making bodies and legislation authorities, in order to contribute to the pool of knowledge and to enable more effective and better targeted Standards and legislation.
- Publish the research findings in learned journals, to raise the academic awareness of the systems involved and to raise the general state of knowledge on the subject.
- Publish the research methodology and key findings in more popular publications, such as trade magazines, health and safety publications, consumer safety publications, general science periodicals, etc.
- Where possible, secure promotional opportunities through other media e.g. radio and TV.
- Promote the work through internet resources, such as the HSE web site, Loughborough University web site, ESRI web site, and other sites hosted for interested parties such as Trading Standards officers, safety practitioners, etc.
- Where possible, encourage international interest, particularly within the EC, where standards harmonisation is a key issue. This may be achieved through the numerous collaborative safety organisations distributed throughout the EC and in other countries.
- Develop guidance and instructional leaflets to educate manufacturers, employers and users of ladders and stability devices on identifying good design and best practice in use.
- Provide a central information resource where interested parties may obtain advice (this may be as part of the HSE's publication or advice service).
- Linking to the "Falls from Height" Key Priority Programme.

It is recognised that some of these dissemination strategies may require additional funding to be secured.

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23.0 CONCLUSIONS AND RECOMMENDATIONS

Following completion of this investigation, the following conclusions are drawn and recommendations made.

23.1 CONCLUSIONS

This study has evaluated the provision of safety, in the form of stability, made by naked ladder, manual ladder footing techniques and ladder stability devices. It has evaluated and quantified the demand made of the ladder by users when engaged in reasonable ladder-based activities. These activities have been performed up to the limits imposed by the users themselves, and thus accurately represent real life use. The innovative data recording method employed allowed the users to continue trials whilst the ladders were technically in a condition of instability, and hence the actual requirements, rather than those imposed by the ladder's capabilities have been critically scrutinised.

By considering ladder stability from the perspective of the needs and expectations of the user, it has been possible to produce a specification for typical use which realistically represents the normal and reasonably foreseeable demands that the ladder must withstand in order to provide an adequate degree of stability and safety.

This use pattern has been practically modelled into standard load vectors which, when applied to a ladder at an applied load point will act as a true parametric for conditions of most onerous reasonable use. From this point it is possible to generate models utilising the concepts of accessible and active ladders which will allow the prediction of the performance of stability devices on the basis of a small number of easily obtained dimensions. The parametrics can also be realistically used to determine the acceptability of real products through the development of a simple workshop test with clear pass/fail criteria. Accordingly, any stability product can be appraised and shown to be acceptable or otherwise.

When ladders fail as supporting structures (as opposed to mechanically), they can be seen to do so in one of four ways. Accordingly, there are four stability criteria which need to be met. A stability device should ensure that all the criteria remain above a level of criticality in order to be worthwhile. Provision of performance enhancement in one mode at the detriment of others would not be acceptable.

One group of stability devices (tripods) operates in an additional way in that they convert a leaning ladder into a free-standing structure. These need to be appraised in a different method, but still must meet the critical levels of stability. Their absolute levels of safety are likely to be user determined, since the user must not exceed a certain point if the ladder is not to be destabilised. Whether it is reasonable to anticipate that users will conform to this requirement remains unclear, but the presence of such devices opens up the opportunity for new types of accident scenario. It is analogous to having a stepladder with additional steps which must not be accessed.

There also remains the problem of whether stability devices endorse bad ladder practice. A strong argument exists that any scenario requiring a stability device should exclude a ladder from being the most appropriate form of access, and in this respect the products are mutually exclusive. However, if a device is so designed as to provide enhanced stability in all four modes and is only used in conditions where a ladder is appropriate, the benefit will be seen as an increase in safety for the user. Whether this safety benefit is later consumed as a performance benefit will depend on the user, but indications from other product areas do not suggest a favourable outcome.

Manual footing of ladder has traditionally been seen as a good practice for improving safety, particularly whilst a ladder is tied off or for short duration tasks. However, this research demonstrates that:

- **There is a great deal of imprecision in what is meant by footing**
- **Footing offers little or no benefit in preventing failures at the ladder top**
- **Footing offers an unnecessary increase in performance of ladder frictional demand**
- **Footing does have the potential to assist in preventing rotational or flip failures, but only if correctly undertaken by loading the sides of the ladder equally**
- **A structured and disciplined footing methodology is required whereby The ‘footer’ should be instructed to impart a particularly symmetric force, acting centrally and squarely within the ladder and balanced left to right.**

The variability in techniques and the possibility of a loss of vigilance leading to biased loading may readily lead to contributing to failure occurrence. The benefit of footing, therefore can best be realised by the provision of a stool or platform to distribute the load or by hanging static mass from the ladder rather than relying on a person.

Some stability devices are intended to deal with the problems of using ladders on slopes – primarily lateral slopes but conceivably surfaces sloping away from the vertical surface. The lateral slope devices take the form of adjustable leg extenders which return the ladder to its upright posture.

Given the frictional demand from the ladder and the conventional nature of the materials from which the ladder feet are made, these are simple to model and it can be concluded that side slip will occur at approximately 22° whilst 16° would enable safe operation with a margin for error. In rearward slope there is a higher degree of criticality, but it can be shown that instability will occur at 12° and that 6° should be a safe working maximum.

Despite intuitive reasoning to the opposite, there is no requirement for additional devices or footing to aid these scenarios. The limits are hard and the manner in which most devices are intended to operate will not affect the capacity of the ladder to remain stable outside of them.

A similar limitation is placed upon devices intended to offer enhancements to the base frictional demand. Simple physics will demonstrate that friction is a function of the properties of the two materials and is independent of area and loading. This, and previous work, has demonstrated that the material from which conventional ladder feet is made is adequate to resist slippage in normal use. The provision of larger area feet, or other such devices is either unnecessary or based on redundant levels of safety provision.

There is an issue relating to the proper maintenance of ladder feet, and failing to undertake this can lead to an accumulation of debris which can lower the frictional capacity below that required. However, this is equally true of any aftermarket device, which would require the same maintenance investment to retain performance. Accordingly, the most beneficial frictional intervention would be a procedure or device that ensures that the feet of the ladder are kept clean, since the feet themselves are adequate.

Whilst much of great practical value is derived from this work, one inescapable conclusion of this work is that many of the devices currently available are designed in accordance with intuition rather than mechanics or engineering. It is simply not the case that something that looks as though it should work will, indeed, work. This extends from mechanical devices through friction enhancement and into footing itself. Some devices have the capacity to enhance stability, but this may only be in one mode and they may actively reduce stability in others.

Some devices achieve nothing at all, despite appearing highly functional, and footing may be functional but only in restricted applications.

It remains the case that for an intervention or device to be considered as ‘effective’ it must ensure that the ladder achieves the minimum critical stability level in all four potential failure modes. In order for that intervention or device to be considered to ‘enhance’ safety it must increase the stability value in at least one of the modes whilst not causing the stability in the remaining modes to drop below the critical threshold.

However, a real danger remains that individuals using these techniques to apparently improve stability may behave in a manner that assumes such benefit has been gained without that benefit being present and so may place themselves in greater jeopardy. This extends from appropriate ladder placement through to the range of activities undertaken.

There remains a pressing obligation for manufacturers to quantify the performance of their products and to ensure that safety provision is raised across all possible failure modes. The models and test regimes developed in this research provide the tools to do this that were previously lacking.

23.2 RECOMMENDATIONS

The following recommendations are made:

- The test specification is validated against a range of proprietary devices. This should be undertaken independently of this research.
- A technical standard is developed for ladder stability devices based on the test methodology outlined in this report.
- Recommendations for ladder maintenance are improved to include regular inspection and cleaning of the feet, including surfacing with a file or other such device. Such maintenance should be included in instructions and warnings
- Stability devices could be certified prior to permitted use. Certification should rest upon demonstration of minimum acceptable levels of stability provision in all four failure modes
- The importance of footing is reappraised and its limitations recognised. Prescriptive footing practice should be stipulated to include equal weight distribution and recommendation for the use of a step or platform.
- Frictional requirements of ladder feet and aftermarket devices should be prescriptive with relevant technical standards

- The capabilities of the predictive stability software developed as part of this project and its capacity to offer rapid evaluation of ladder device systems and design should be fully explored.
- The possibility of releasing the predictive stability software as a stand-alone product, to be made available to interested parties should be evaluated.

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Appendix 1

Anthropometric and functional user profiling

Participant anthropometric and functional user profiling

| Subject | Sex | Age | Weight | Stature | Grip Reach | Leg length | Knee height | Shoulder height | Dominant hand |
|---------|-----|-------|--------|---------|---------------|---------------|----------------|--------------------|------------------|
| 1 | M | 32 | 111 | 180 | 67 | 95 | 52 | 146 | R |
| 2 | M | 58 | 90 | 179 | 69 | 95 | 51 | 151 | R |
| 3 | F | 28 | 79 | 160 | 56 | 86 | 44 | 130 | R |
| 4 | M | 32 | 79.5 | 179 | 68 | 98 | 52 | 144 | R |
| 5 | M | 48 | 76.5 | 182 | 66 | 101 | 51 | 150 | R |
| 6 | M | 60 | 98.5 | 174 | 68 | 101 | 51 | 156 | R |
| 7 | M | 67 | 100 | 178 | 68 | 91 | 32 | 143 | R |
| 8 | M | 28 | 72 | 180 | 65 | 95 | 52 | 158 | R |
| 9 | M | 62 | 74.5 | 168 | 61 | 92 | 50 | 137 | R |
| 10 | M | 63 | 95.5 | 177 | 63 | 99 | 50 | 143 | L |
| 11 | M | 49 | 91.5 | 180 | 65 | 100 | 54 | 150 | R |
| 12 | F | 18 | 61 | 165 | 60 | 89 | 51 | 135 | R |
| 13 | M | 21 | 101 | 183 | 67 | 90 | 53 | 150 | R |
| 14 | M | 43 | 102 | 175 | 63 | 95 | 48 | 140 | R |
| 15 | M | 48 | 93 | 183 | 62 | 100 | 53 | 153 | R |
| 16 | M | 59 | 99.5 | 187 | 67 | 104 | 56 | 155 | R |
| 17 | M | 58 | 81 | 180 | 70 | 102 | 52 | 153 | R |
| 18 | M | 27 | 73 | 171 | 61 | 94 | 50 | 141 | R |
| 19 | M | 19 | 75.5 | 180 | 62 | 93 | 50 | 142 | R |
| 20 | M | 39 | 74 | 177 | 66 | 92 | 49 | 140 | R |
| 21 | M | 19 | 77.5 | 190 | 76 | 109 | 57 | 160 | L |
| 22 | M | 43 | 91.5 | 192 | 70 | 110 | 61 | 157 | R |
| 23 | M | 67 | 70 | 167 | 64 | 84 | 51 | 138 | R |
| 24 | M | 61 | 89 | 180 | 72 | 106 | 48 | 150 | R |
| 25 | M | 68 | 76 | 171 | 65 | 101 | 53 | 142 | R |
| 26 | M | 59 | 93.5 | 170 | 61 | 92 | 50 | 142 | R |
| 27 | M | 41 | 126 | 183 | 66 | 103 | 51 | 147 | L |
| 28 | F | 28 | 82.5 | 165 | 57 | 91 | 46 | 136 | R |
| 29 | F | 59 | 66.5 | 168 | 63 | 86 | 43 | 133 | R |
| 30 | M | 53 | 85.5 | 171 | 65 | 93 | 49 | 141 | L |
| 31 | M | 71 | 101 | 174 | 64 | 96 | 42 | 142 | R |
| 32 | M | 30 | 66.5 | 172 | 61 | 96 | 46 | 139 | R |
| 33 | M | 28 | 82.5 | 166 | 57 | 86 | 43 | 134 | R |
| 34 | F | 25 | 65.5 | 159 | 62 | 84 | 47 | 131 | R |
| 35 | F | 28 | 65.5 | 169 | 62 | 90 | 45 | 137 | R |
| 36 | M | 23 | 70.5 | 184 | 63 | 89 | 50 | 148 | R |
| 37 | M | 24 | 74 | 176 | 64 | 99 | 49 | 141 | R |
| 38 | M | 24 | 85 | 195 | 74 | 104 | 59 | 160 | R |
| 39 | M | 40 | 86.5 | 188 | 70 | 107 | 55 | 156 | R |
| 40 | M | 24 | 95.6 | 191 | 75 | 99 | 55 | 155 | L |
| 41 | M | 28 | 83 | 173 | 69 | 99 | 53 | 142 | R |
| 42 | M | 30 | 75 | 178 | 66 | 96 | 51 | 141 | R |
| 43 | F | 70 | 53.5 | 159 | 59 | 94 | 46 | 131 | L |
| 44 | M | 22 | 94 | 176 | 69 | 93 | 49 | 142 | R |
| 45 | M | 18 | 60 | 175 | 66 | 83 | 52 | 141 | R |
| 46 | M | 28 | 71 | 167 | 62 | 92 | 54 | 134 | R |
| 47 | M | 22 | 78 | 182 | 66 | 92 | 52 | 147 | R |
| 48 | M | 58 | 87 | 164 | 64 | 85 | 47 | 130 | R |
| 49 | M | 42 | 80.5 | 175 | 67 | 101 | 50 | 142 | R |
| 50 | M | 42 | 109 | 177 | 64 | 94 | 52 | 143 | L |
| 51 | M | 65 | 105 | 166 | 62 | 89 | 45 | 139 | R |
| 52 | M | 32 | 99 | 167 | 64 | 85 | 50 | 133 | R |
| Mean | | 40.98 | 84.11 | 175.54 | 65.06 | 95.00 | 50.04 | 143.67 | |

Appendix 2

Perceived Hazard Scores

Participant perceived hazard scores

| Subject | Bannister | Rug | Drill | Splinter | Stairs | Ladder | Jack | Knife | Hammer | Mower | Pliers |
|---------|-----------|-----|-------|----------|--------|--------|------|-------|--------|-------|--------|
| 1 | 11 | 12 | 7 | 6 | 4 | 3 | 9 | 2 | 1 | 8 | 5 |
| 2 | 9 | 7 | 8 | 6 | 5 | 1 | 12 | 2 | 3 | 4 | 10 |
| 3 | 3 | 8 | 7 | 5 | 8 | 11 | 7 | 7 | 2 | 4 | 2 |
| 4 | 6 | 4 | 8 | 5 | 1 | 2 | 10 | 3 | 7 | 9 | 11 |
| 5 | 10 | 9 | 6 | 3 | 1 | 5 | 11 | 2 | 7 | 4 | 8 |
| 6 | 12 | 11 | 3 | 10 | 9 | 8 | 4 | 1 | 2 | 5 | 7 |
| 7 | 4 | 8 | 7 | 5 | 1 | 3 | 11 | 2 | 6 | 10 | 9 |
| 8 | 7 | 3 | 4 | 12 | 5 | 6 | 10 | 1 | 2 | 8 | 9 |
| 9 | 12 | 8 | 5 | 2 | 7 | 1 | 6 | 3 | 4 | 9 | 11 |
| 10 | 5 | 3 | 7 | 8 | 4 | 1 | 9 | 6 | 2 | 11 | 10 |
| 11 | 6 | 5 | 9 | 2 | 1 | 3 | 10 | 4 | 8 | 7 | 11 |
| 12 | 8 | 7 | 10 | 4 | 2 | 6 | 9 | 1 | 5 | 3 | 11 |
| 13 | 9 | 12 | 6 | 2 | 10 | 3 | 4 | 1 | 5 | 11 | 7 |
| 14 | 8 | 1 | 11 | 9 | 5 | 2 | 7 | 3 | 6 | 4 | 12 |
| 15 | 5 | 2 | 9 | 6 | 1 | 8 | 10 | 3 | 4 | 7 | 11 |
| 16 | 10 | 6 | 5 | 9 | 8 | 1 | 7 | 2 | 3 | 11 | 4 |
| 17 | 4 | 5 | 3 | 9 | 6 | 1 | 2 | 7 | 8 | 10 | 12 |
| 18 | 12 | 10 | 6 | 7 | 9 | 8 | 3 | 1 | 2 | 4 | 5 |
| 19 | 6 | 4 | 7 | 3 | 8 | 2 | 11 | 5 | 1 | 12 | 9 |
| 20 | 12 | 7 | 5 | 4 | 3 | 1 | 8 | 6 | 2 | 9 | 10 |
| 21 | 11 | 8 | 7 | 3 | 9 | 6 | 5 | 1 | 2 | 10 | 4 |
| 22 | 5 | 8 | 6 | 10 | 4 | 2 | 7 | 1 | 11 | 3 | 12 |
| 23 | 7 | 2 | 5 | 5 | 6 | 3 | 9 | 3 | 8 | 10 | 10 |
| 24 | 5 | 4 | 8 | 6 | 3 | 9 | 10 | 1 | 2 | 11 | 12 |
| 25 | 11 | 2 | 6 | 1 | 8 | 3 | 10 | 4 | 5 | 7 | 9 |
| 26 | 4 | 3 | 9 | 2 | 5 | 6 | 11 | 1 | 7 | 10 | 8 |
| 27 | 10 | 4 | 6 | 8 | 7 | 1 | 11 | 2 | 3 | 9 | 5 |
| 28 | 10 | 3 | 11 | 6 | 7 | 4 | 8 | 5 | 1 | 2 | 9 |
| 29 | 11 | 6 | 3 | 5 | 10 | 1 | 2 | 9 | 7 | 4 | 12 |
| 30 | 2 | 10 | 12 | 5 | 12 | 12 | 6 | 10 | 4 | 8 | 2 |
| 31 | 6 | 7 | 10 | 12 | 1 | 9 | 5 | 11 | 8 | 2 | 4 |
| 32 | 4 | 8 | 2 | 7 | 6 | 9 | 5 | 3 | 1 | 10 | 11 |
| 33 | 12 | 7 | 6 | 1 | 11 | 4 | 8 | 2 | 3 | 5 | 9 |
| 34 | 7 | 2 | 1 | 8 | 9 | 5 | 10 | 3 | 4 | 6 | 11 |
| 35 | 10 | 5 | 4 | 3 | 9 | 6 | 11 | 2 | 1 | 7 | 8 |
| 36 | 8 | 4 | 10 | 2 | 1 | 7 | 5 | 3 | 11 | 9 | 12 |
| 37 | 11 | 9 | 8 | 6 | 4 | 5 | 3 | 1 | 2 | 12 | 7 |
| 38 | 9 | 4 | 7 | 5 | 2 | 6 | 11 | 1 | 8 | 3 | 10 |
| 39 | 4 | 5 | 12 | 10 | 11 | 12 | 8 | 9 | 9 | 12 | 6 |
| 40 | 10 | 4 | 2 | 8 | 12 | 11 | 9 | 1 | 3 | 5 | 7 |
| 41 | 4 | 11 | 10 | 6 | 12 | 9 | 3 | 5 | 8 | 7 | 1 |
| 42 | 9 | 5 | 6 | 2 | 3 | 10 | 8 | 1 | 4 | 7 | 11 |
| 43 | 12 | 3 | 2 | 10 | 9 | 4 | 1 | 5 | 8 | 6 | 11 |
| 44 | 5 | 12 | 4 | 11 | 3 | 2 | 9 | 1 | 6 | 7 | 8 |
| 45 | 9 | 8 | 6 | 7 | 5 | 3 | 10 | 1 | 2 | 11 | 4 |
| 46 | 8 | 3 | 9 | 10 | 4 | 7 | 12 | 1 | 2 | 6 | 5 |
| 47 | 2 | 1 | 9 | 7 | 4 | 12 | 5 | 11 | 10 | 6 | 8 |
| 48 | 12 | 4 | 5 | 3 | 6 | 5 | 6 | 2 | 4 | 5 | 6 |
| 49 | 12 | 11 | 8 | 6 | 10 | 9 | 7 | 4 | 3 | 5 | 1 |
| 50 | 10 | 6 | 5 | 11 | 3 | 7 | 4 | 12 | 9 | 8 | 1 |
| 51 | 2 | 1 | 10 | 9 | 8 | 7 | 4 | 11 | 6 | 3 | 5 |
| 52 | 10 | 5 | 2 | 1 | 4 | 3 | 11 | 6 | 9 | 7 | 8 |
| Correct | 4 | 6 | 9 | 2 | 1 | 5 | 10 | 3 | 8 | 7 | 11 |

Appendix 3

Perceived risk scores

Participant perceived risk scores

| Subject | Fairground | Aircraft | Ladder | Cancer | Lottery | Road Acc | Lightning | Rock Canoeing climbing | |
|---------|------------|----------|--------|--------|---------|-------------|-----------|---------------------------|---|
| 1 | 6 | 7 | 5 | 1 | 9 | 2 | 8 | 3 | 4 |
| 2 | 5 | 6 | 1 | 2 | 4 | 3 | 9 | 8 | 7 |
| 3 | 6 | 4 | 1 | 2 | 9 | 3 | 8 | 5 | 7 |
| 4 | 5 | 4 | 3 | 1 | 7 | 2 | 9 | 6 | 8 |
| 5 | 7 | 3 | 6 | 1 | 9 | 2 | 5 | 8 | 4 |
| 6 | 8 | 5 | 3 | 4 | 9 | 1 | 6 | 7 | 2 |
| 7 | 7 | 8 | 4 | 1 | 9 | 2 | 6 | 5 | 3 |
| 8 | 6 | 7 | 2 | 1 | 8 | 3 | 9 | 5 | 4 |
| 9 | 6 | 7 | 3 | 1 | 9 | 2 | 8 | 4 | 5 |
| 10 | 6 | 9 | 1 | 3 | 7 | 5 | 8 | 4 | 2 |
| 11 | 7 | 6 | 3 | 2 | 5 | 1 | 8 | 4 | 9 |
| 12 | 6 | 7 | 4 | 1 | 9 | 2 | 8 | 3 | 5 |
| 13 | 3 | 4 | 8 | 1 | 9 | 2 | 6 | 7 | 5 |
| 14 | 6 | 8 | 5 | 1 | 9 | 2 | 7 | 4 | 3 |
| 15 | 4 | 8 | 3 | 2 | 9 | 1 | 7 | 6 | 5 |
| 16 | 7 | 8 | 2 | 1 | 9 | 6 | 5 | 3 | 4 |
| 17 | 4 | 3 | 2 | 6 | 7 | 1 | 5 | 9 | 8 |
| 18 | 9 | 8 | 2 | 3 | 5 | 1 | 7 | 6 | 4 |
| 19 | 6 | 8 | 1 | 2 | 9 | 4 | 7 | 5 | 3 |
| 20 | 6 | 7 | 2 | 3 | 9 | 1 | 8 | 5 | 4 |
| 21 | 1 | 7 | 4 | 3 | 9 | 2 | 8 | 6 | 5 |
| 22 | 4 | 5 | 6 | 7 | 8 | 2 | 9 | 3 | 1 |
| 23 | 9 | 8 | 4 | 7 | 9 | 8 | 8 | 8 | 7 |
| 24 | 5 | 4 | 7 | 8 | 9 | 1 | 6 | 3 | 2 |
| 25 | 8 | 4 | 5 | 1 | 3 | 2 | 6 | 7 | 9 |
| 26 | 4 | 6 | 2 | 7 | 9 | 1 | 3 | 8 | 5 |
| 27 | 7 | 8 | 3 | 1 | 9 | 2 | 6 | 5 | 4 |
| 28 | 6 | 9 | 5 | 1 | 8 | 2 | 7 | 3 | 4 |
| 29 | 7 | 8 | 1 | 2 | 9 | 3 | 6 | 5 | 4 |
| 30 | 1 | 8 | 6 | 4 | 9 | 7 | 3 | 2 | 4 |
| 31 | 7 | 6 | 5 | 2 | 9 | 1 | 8 | 3 | 4 |
| 32 | 6 | 9 | 5 | 1 | 7 | 2 | 3 | 4 | 8 |
| 33 | 4 | 3 | 8 | 1 | 9 | 2 | 7 | 5 | 6 |
| 34 | 5 | 4 | 6 | 1 | 9 | 2 | 3 | 7 | 8 |
| 35 | 4 | 7 | 3 | 2 | 8 | 1 | 9 | 5 | 6 |
| 36 | 8 | 6 | 5 | 1 | 7 | 2 | 9 | 4 | 3 |
| 37 | 3 | 4 | 7 | 2 | 9 | 1 | 8 | 6 | 5 |
| 38 | 7 | 6 | 3 | 2 | 9 | 1 | 8 | 5 | 4 |
| 39 | 8 | 9 | 6 | 3 | 9 | 4 | 9 | 7 | 8 |
| 40 | 4 | 6 | 7 | 2 | 9 | 1 | 8 | 5 | 3 |
| 41 | 5 | 8 | 1 | 6 | 9 | 4 | 7 | 3 | 2 |
| 42 | 4 | 2 | 8 | 3 | 7 | 1 | 9 | 5 | 6 |
| 43 | 5 | 8 | 3 | 1 | 9 | 2 | 7 | 6 | 4 |
| 44 | 4 | 8 | 2 | 3 | 7 | 1 | 9 | 5 | 6 |
| 45 | 5 | 8 | 2 | 6 | 9 | 1 | 7 | 3 | 4 |
| 46 | 8 | 9 | 5 | 2 | 7 | 3 | 6 | 4 | 1 |
| 47 | 5 | 6 | 2 | 8 | 9 | 1 | 7 | 3 | 4 |
| 48 | 7 | 8 | 4 | 3 | 9 | 1 | 5 | 2 | 6 |
| 49 | 1 | 5 | 8 | 6 | 8 | 3 | 7 | 4 | 2 |
| 50 | 1 | 3 | 5 | 2 | 9 | 6 | 8 | 4 | 7 |
| 51 | 9 | 8 | 7 | 2 | 1 | 3 | 6 | 5 | 4 |
| 52 | 2 | 9 | 3 | 4 | 5 | 1 | 8 | 7 | 6 |
| Correct | 9 | 6 | 4 | 1 | 7 | 2 | 8 | 5 | 3 |

Appendix 4

Participant ‘Sensation Seeking Scores’ (SSS)

Participant Sensation Seeking Scores

| Subject | Sensation Seeking Score |
|---------|-------------------------|
| 1 | 19 |
| 2 | 8 |
| 3 | 17 |
| 4 | 14 |
| 5 | 22 |
| 6 | 12 |
| 7 | 27 |
| 8 | 9 |
| 9 | 25 |
| 10 | 15 |
| 11 | 17 |
| 12 | 19 |
| 13 | 35 |
| 14 | 11 |
| 15 | 17 |
| 16 | 14 |
| 17 | 26 |
| 18 | 8 |
| 19 | 23 |
| 20 | 18 |
| 21 | 16 |
| 22 | 17 |
| 23 | 24 |
| 24 | 14 |
| 25 | 10 |
| 26 | 24 |
| 27 | 22 |
| 28 | 25 |
| 29 | 14 |
| 30 | 24 |
| 31 | 10 |
| 32 | 15 |
| 33 | 17 |
| 34 | 29 |
| 35 | 20 |
| 36 | 25 |
| 37 | 16 |
| 38 | 29 |
| 39 | 18 |
| 40 | 21 |
| 41 | 11 |
| 42 | 25 |
| 43 | 25 |
| 44 | 10 |
| 45 | 22 |
| 46 | 18 |
| 47 | 24 |
| 48 | 13 |
| 49 | 22 |
| 50 | 13 |
| 51 | 34 |
| 52 | 4 |

Appendix 5
Participant data recording booklet
(Including Zuckerman's Sensation Seeking Score Questions)

Consent form
ICE ERGONOMICS TRIALS

| | |
|---|------------------------|
| Subject Name | Subject No. |
| Address | |
| National Insurance number (if known) | Date of Birth |
| Date | Signature |

Thank you for agreeing to take part in these trials. Please be advised that they require a reasonable degree of mobility. Please inform a member of staff if you have any condition, mental or physical, which may affect your ability to undertake these tasks.

You have the right to withdraw from the trials at any time, either before or during the testing. If you wish to leave at any time simply inform the member of staff. You do not have to give an explanation.

If you have any questions, now or any time through the trials, please do not hesitate to ask us.

If you are content to proceed with the trials please sign the form below. Otherwise thank you for your time and effort.

I have read the information above and agree to take part in these trials:

Signed..... Date.....

Anthropometric data

Physical dimensions

| Body part | Measurements (kg/mm) | | | |
|---|----------------------|--|--------|--|
| Weight | | | | |
| Stature | | | | |
| Grip reach from shoulder | | | | |
| Leg length (greater trochanter to sole of foot) | | | | |
| Knee height | | | | |
| Shoulder height | | | | |
| Dominant hand | Right | | Left | |
| Gender | Male | | Female | |
| Age | | | | |

Task 1

Which of these tasks would you use a ladder for, regardless of what ceiling height or equipment you have at home?

Please circle either YES or NO

| Answer | Task | Ladder use | |
|--------|--------------------------|------------|----|
| 1 | Painting a ceiling | Yes | No |
| 2 | Accessing a loft | Yes | No |
| 3 | Replacing a light bulb | Yes | No |
| 4 | Cleaning a window | Yes | No |
| 5 | Wallpapering a room | Yes | No |
| 6 | Hanging curtains | Yes | No |
| 7 | Fitting a curtain rail | Yes | No |
| 8 | Repairing guttering | Yes | No |
| 9 | Trimming tree branches | Yes | No |
| 10 | Cutting a hedge | Yes | No |
| 11 | Cleaning outside windows | Yes | No |
| 12 | Making repairs to a roof | Yes | No |

Which of these tasks would you carry out at home?

Please circle either YES or NO

| Answer | Task | Would you do it ? | |
|--------|----------------------|-------------------|----|
| 13 | Drilling holes | Yes | No |
| 14 | Sawing wood | Yes | No |
| 15 | Tightening wing-nuts | Yes | No |

Task 2a

Which of the following 12 items do you think are involved in the most injuries?

Please write in a number from 1 to 12 beside each item.

1 = involved in the most injuries

12 = involved in the least injuries

- **Each item must have a different number allocated to it.**
- **Use each number only once.**

1 = most injuries 12 = least injuries

| Item | Injuries |
|--------------------|----------|
| Bannister | |
| Rug/mat | |
| Power drill | |
| Splinter/grit/rust | |
| Indoor stairs | |
| Ladder | |
| Vehicle jack | |
| Knife | |
| Hammer | |
| Lawn mower | |
| Pliers | |

Task 2b

A probability is the likelihood of something happening

Here is a list of probabilities:

1 in 360.....1 1 = the most likely
 1 in 15,700.....2
 1 in 250,000.....3
 1 in 1,000,000.....4
 1 in 2,000,000.....5
 1 in 10,000,000....6
 1 in 14,000,000....7
 1 in 15,000,000....8
 1 in 250,000,000...9 9 = the least likely

Each probability fits one of the events given in the table below.

Please choose which probability fits which event and write it in the appropriate column.

- **Each item must have a different number allocated to it.**
- **Use each number only once.**

Table of probability of events

| Event | Probability |
|---|--------------------|
| Dying on a fairground ride | |
| Dying on a passenger aircraft | |
| Dying due to ladder accident | |
| Dying of cancer | |
| Winning the jackpot in the lottery | |
| Dying in a road accident | |
| Dying from a lightning strike | |
| Dying whilst white water canoeing | |
| Dying in a rock climbing accident | |

Task 3

Instructions

In this questionnaire, each of the items below contains two statements, A and B. Please circle either A or B to indicate which of the choices *most closely* describes the way you feel. Where both items describe the way you feel, please choose the one that describes your feelings *better*. If you don't agree with either statement, choose the one which is *less offensive*, or which you dislike less.

In some cases you may find you do not like either choice. Please pick the one you dislike *least*.

It is important that you respond with only *one* choice, A or B.

We are only interested in *your real likes, dislikes and feelings*, not in how you are supposed to feel.

There are no right or wrong answers.

1. A. I like "wild" uninhibited parties.
B. I prefer quiet parties with good conversation.
2. A. There are some movies I enjoy seeing a second or even a third time.
B. I can't stand watching a movie that I've seen before.
3. A. I often wish I could be a mountain climber.
B. I can't understand people who risk their necks climbing mountains.
4. A. I dislike all body odours.
B. I like some of the earthy body smells.
5. A. I get bored seeing the same old faces.
B. I like the comfortable familiarity of everyday friends.
6. A. I like to explore a strange city or section of town by myself, even if it means getting lost.
B. I prefer a guide when I am in a place I don't know well.
7. A. I dislike people who do or say things just to shock or upset others.
B. When you can predict almost everything a person will do and say, he or she must be a bore.

8. A. I usually don't enjoy a movie or play where I can predict what will happen in advance.
B. I don't mind watching a movie or play where I can predict what will happen in advance.
9. A. I have tried marijuana or would like to.
B. I would never try marijuana.
10. A. I would not like to try any drug which might produce strange and dangerous effects on me.
B. I would like to try some of the drugs that produce hallucinations.
11. A. A sensible person avoids activities that are dangerous.
B. I sometimes like to do things that are a little frightening.
12. A. I dislike being with people who live life in the fast lane.
B. I enjoy the company of people who live life in the fast lane.
13. A. I find that stimulants make me uncomfortable.
B. I often like to get high (drinking alcohol or smoking marijuana).
14. A. I like to try new foods that I have never tasted before.
B. I order the dishes with which I am familiar, so as to avoid disappointment or unpleasantness.
15. A. I enjoy looking at other peoples' home videos or holiday snaps.
B. Looking at other peoples' home videos or holiday snaps bores me tremendously.
16. A. I would like to take up snow boarding or paragliding.
B. I would not like to take up snow boarding or paragliding.
17. A. I would like to try surf-boarding or water skiing.
B. I would not like to try surf-boarding or water skiing.
18. A. I would like to take off on a trip with no pre-planned or definite routes, or timetable.
B. When I go on a trip I like to plan my route and timetable fairly carefully.

19. A. I prefer “down-to-earth” kinds of people as friends.
B. I would like to have extrovert-type friends such as artists or writers.
20. A. I would not like to learn to fly an aeroplane.
B. I would like to learn to fly an aeroplane.
21. A. I prefer being above water rather than under it.
B. I would like to go scuba diving.
22. A. I would happily work with people who carry the HIV virus.
B. I stay away from anyone I suspect of carrying the HIV virus.
23. A. I would like to try parachute jumping.
B. I would never want to try jumping out of a plane.
24. A. I prefer friends who are excitingly unpredictable.
B. I prefer friends who are reliable and predictable.
25. A. I am not interested in experience for its own sake.
B. I like to have new and exciting experiences and sensations even if they
they are a little frightening, unconventional or illegal.
26. A. The essence of good art is in its clarity, symmetry of form and harmony
of colours.
B. I often find beauty in the “clashing” colours and irregular forms of modern
painting.
27. A. I enjoy spending time in the familiar surroundings of home.
B. I get very restless if I have to stay around home for any length of time.
28. A. I like to dive off the high board.
B. I don’t like the feeling I get standing on the high board (or I don’t go
near it at all).
29. A. I like to date members of the opposite sex who are physically exciting.
B. I prefer to date members of the opposite sex who share my values.

30. A. Heavy drinking usually ruins a party because some people get loud and boisterous.
B. Keeping the drinks full is the key to a good party.
31. A. The worst social sin is to be rude.
B. The worst social sin is to be a bore.
32. A. A person should have considerable sexual experience before marriage.
B. It would be better if two married persons began their sexual experiences with each other.
33. A. Even if I had the money, I would not like to associate with people who are part of the “jet set”.
B. I could conceive of myself seeking pleasure around the world with the “jet set”.
34. A. I like people who are sharp and witty even if they do sometimes insult others.
B. I dislike people who have their fun in the expense of hurting the feelings of others.
35. A. There is altogether too much portrayal of sex in movies.
B. I enjoy watching the sex scenes in movies.
36. A. I feel at my best after having a couple of drinks.
B. Something is wrong with people who need alcohol to feel good.
37. A. People should dress according to some standards of taste, neatness, and style.
B. People should dress in individual way even if the effects are sometimes strange.
38. A. Sailing long distances in small sailing crafts is reckless.
B. I would like to sail long distances in a small but seaworthy boat.
39. A. I have no patience with dull or boring people.
B. I find something interesting in almost every person I talk with.
40. A. Skiing fast down a high mountain slope is a good way to end up on crutches.
B. I think I would enjoy the sensations of skiing very fast down a high mountain slope.

Trial

Participant number.....

Self-assessment form

Please choose a number between 1 and 11 after each task.

1 = Very safe.....11 = Very unsafe

| | | | No. |
|--------------------------|---------|---------|-----|
| Task A – Drilling | | | |
| Task B – Low wingnuts | | | |
| Task C - Sawing | | | |
| Task D – High wingnuts | | | |
| Task E - Lifting bucket | | | |
| Task F - Lowering bucket | | | |
| Task G - Pulling | Force 1 | Force 2 | |
| Task H - Footing | | | |

*** N.B. REMEMBER PHOTO OF FOOTING WITH NUMBER PLATE !**

Feedback

Falls from a ladder

Have you ever fallen off a ladder? (Please choose from the options below)

1. More than ten times
2. Under ten times
3. More than twice
4. Yes once or twice
5. No, never Other

What is your job?.....

Which do you work with most of the time?

LEANING LADDERS / STEPLADDERS? (Please delete)

How long have you been working with ladders?.....

Have you ever had training on using ladders?.....

What training did you have?.....

When was this?.....

How did you feel while carrying out these tasks on the ladders?

.....

.....

.....

.....

.....

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Appendix 6

Report of additional validation trials

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Executive Summary

This report details the background, methodology and findings of an additional investigation into the issue of the performance of leaning ladder stability devices and manual ladder footing. This work has been funded by the Health and Safety Executive to provide a factual basis on which to make recommendations regarding safety practice within the community.

As a consequence of the counter intuitive nature of the mechanics involved, a need was identified to verify some of the principles on which the findings of the main study were based. In particular, it was felt that there was value in demonstrating that two data sets that were omitted from the original data collection on the basis of redundancy were indeed negligible. This study re-enacts a limited number of duplicate trials to the original research, with the purpose of collecting that data.

Forty six duplicate trials were conducted and the data collected and processed. It is shown that, after processing, these values are indeed negligible. Consequently the modelling and prediction made in the original report are valid and robust.

A further finding emerging from this additional work is that the provision of rubber feet to the top of the ladder contributes to a reduction in the security of the ladder base, and a recommendation is made that future ladder designs consider replacing these feet with wheels which permit movement in the vertical plane at the top of the ladder.

1 Background and scope of the study

During 2002 an extensive evaluation was undertaken of the nature and performance of ladder stability devices and of manual footing of ladders. This work was based on previous techniques developed to assess ladder stability, requiring time-based force data to be collected via a force platform whilst users undertook staged trials whilst mounted on the ladder.

The data collected in this manner was processed and formed the basis of a theoretical assessment of stability of ladder systems and led to the development of a proposed stability model. This model could be used to appraise of the levels of stability offered by any given leaning ladder system, either from the design specification or the actual product. The model further led to the development of a simple laboratory test which would allow a rapid assessment of whether a ladder did, or did not, offer adequate stability in use.

The modelling uses a set of derived parametric loads which represent the most arduous conditions found in normal foreseeable use. The parametric loads are calculated on the basis of certain fundamental principles of structures which is supported by experiential knowledge gained in previous ladder stability testing. In basing the models on these factors it was possible to use a refined rig which was selective in the data recorded, making the trials more efficient.

These further trials are undertaken in order to provide a reference source for individuals who may wish to employ the models developed, but who have not had the benefit of verifying the nature of the data generated in such testing. These individuals may wish to reassure themselves that the data not collected by the rig was genuinely redundant to the models.

Since a ladder contact the supporting surfaces through four point contacts, there is the possibility of twelve channels of force data to be collected (three dimensions at each point). In the main project trials only eight channels were recorded, since z-axis forces at the top of the ladder and x-axis forces at the base were known to be negligible. These additional trials mirror the original ones, but provide data for the additional four channels, in support of the assumptions made in the original work.

1.1 Aims of the project

The stated aims of the project are:

- **Aim 1:** Rerun a limited selection of trials in the same form as the original work.
- **Aim 2:** Collect the data from the four channels omitted in the original rig.
- **Aim 3:** Process the data in the manner described in the original research report.
- **Aim 4:** Present the findings.
- **Aim 5:** Demonstrate that those findings verify the original models.

2 Trials methodology

The trials were organised in a similar fashion to the trials in the main research project. A single work surface containing the tasks was presented at the head of the ladder, requiring the participant to reach upward or outward to undertake the specific task. A schematic of the trials layout is shown in Figure 1.

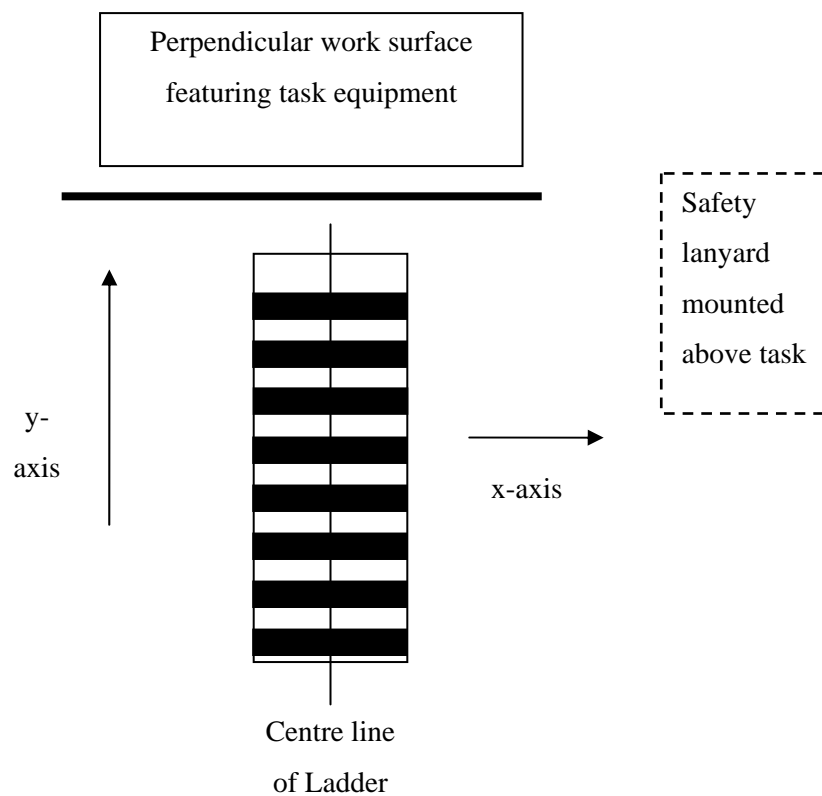


Figure 8
Schematic of task layout

A photograph taken during the trials is shown in Figure 2 to illustrate the physical environment.



Figure 2
The physical environment for the tasks

The tasks undertaken were the same as those in the main research work, and are summarised in the following sections.

2.1 Task a – Extended fixed pressure drilling

Task A represented drilling into a resistive substrate such that a constant force would be applied which the ladder would have to oppose. Participants extended to the right of the ladder as far as they felt comfortable in order to apply a cordless drill to the task of drilling a hole in a metal bar. The self-determination of the degree of extension ensured that different interpretations of reasonable use could be accurately represented. This task is shown in Figure 3.



Figure 3
Task A

2.2 Task b - Lateral reach extension

The participant was required to extend as far as they felt comfortable in order to tighten wing nut fastenings on a mounted bar. Encouragement was given to reach as far as the participant felt they could in an effort to accurately represent a demanding reaching task in real life, where the user may be reluctant to relocate the ladder. This task is shown in Figure 4.



Figure 4
Task B

2.3 Task c – lateral reach Extended sawing

The participant was instructed to attempt to saw through a 100 mm square block located on the work board, using a short hand saw. This task is shown in Figure 5.



Figure 5

Task C

2.4 Task d - Extended high reach.

The participant was instructed to tighten wing nuts along a vertical bar, stretching up as high as they felt comfortable. This task is shown in Figure 6.



Figure 6

Task D

2.5 Task e – high Lateral load placement

The participant carried a bucket of mass 11.5 kg (representing a 2.5 UK gallon bucket full of water or cement) up the ladder, and placed it onto a hook on the work board. This was an asymmetric carrying task, involving an unstable load, where the user may only hold on to the ladder with one hand. It required a degree of strength and necessitated leaning out from the ladder. This task is shown in Figure 7.



Figure 7
Task E

2.6 Task f – high lateral Load retrieval.

The participant ascended the ladder, retrieved the 11.5 kg bucket from the hook on the board and descended the ladder with the bucket. This task involved the retrieval and carrying of a heavy and relatively stable load backwards down a ladder, whilst only having one hand available for stability. Some users also chose to move the bucket from one hand to the other. This task is shown in Figure 8.



Figure 8
Task F

2.7 Participants

Four participants were used, drawn from a volunteer participant data base. They are summarised in Table 1

Table 4
Summary of participants

| Participant | Gender | Age | Weight |
|--------------------|---------------|------------|---------------|
| 1 | Female | 36 | 57 |
| 2 | Male | 33 | 81.5 |
| 3 | Male | 32 | 80 |
| 4 | Male | 25 | 78 |

Each participant undertook each trial twice in order to improve data consistence. Accordingly a total of 48 individual trials (4 participants x 6 trials x 2 repetitions) were undertaken.

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3 Technical objectives

In order to substantiate the findings of the main research project it is important that the physical stability modelling accords properly with reality. In the process of defining the model, various assumptions are made pertaining to the nature of the underlying mechanics, the magnitude of the ladder endpoint support vectors, and the consequent effect upon motional stability. In support of these, this work phase is primarily designed to obtain direct evidence of some predictions of real ladder performance, concerning the existence or significance of particular reaction vectors at the ladder contacting points. Specifically it evaluates in detail the top reaction vector in the z-axis, denoted $F_{top}Z(kg)$, and the base reaction vector in the x-axis, denoted $F_{base}X(kg)$.

The main research model proposes that the mechanical contributions due to the upper contact vector, $F_{top}Z(kg)$, and the lower contact vector, $F_{base}X(kg)$ can be neglected in a realistic modelling regime. This proposition is made through a series of arguments concerning the vectors existence, magnitude of contribution, or coupling effect upon the various stability modes. The objective of this additional research is to measure these actions directly and corroborate the modelling assertions.

The main research also made extensive comment on the nature of load distribution across four potential contacting points – the four ordinary ends of the ladder. In particular, a process has been identified, arising from the natural kinematic progress of the structure finding minimal and efficient registration, which preferentially causes a 3 point active mount. This essentially leaves one redundant ladder endpoint. The data streams presented as part of the findings of this additional research are able to illustrate the erratic and volatile nature of the various interchanges between footing distribution between the upper and lower contact pairs, and in particular the propensity to strong asymmetry collapsing to a genuine tripod mount.

The original main trial dynamometer configuration was not sensitised to register the forces $F_{top}Z(kg)$ and $F_{base}X(kg)$. For this additional work the rig is specifically reconfigured to respond to the forces under consideration and to record the output. Otherwise, all experimental conditions and methods are identical to the original situation, including use of the same ladder at same attitude, loose endpoint tethering and similar user task sets. Therefore, this data set can be confidently placed alongside the original main trial output for comparison or integration.

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4 Dynamometer rig configuration

4.1 Rig configuration

The configuration of the dynamometer rig is essentially same as used previously, although the specific ground reactions measured are modified. Figure 9 illustrates a schematic of the configuration employed.

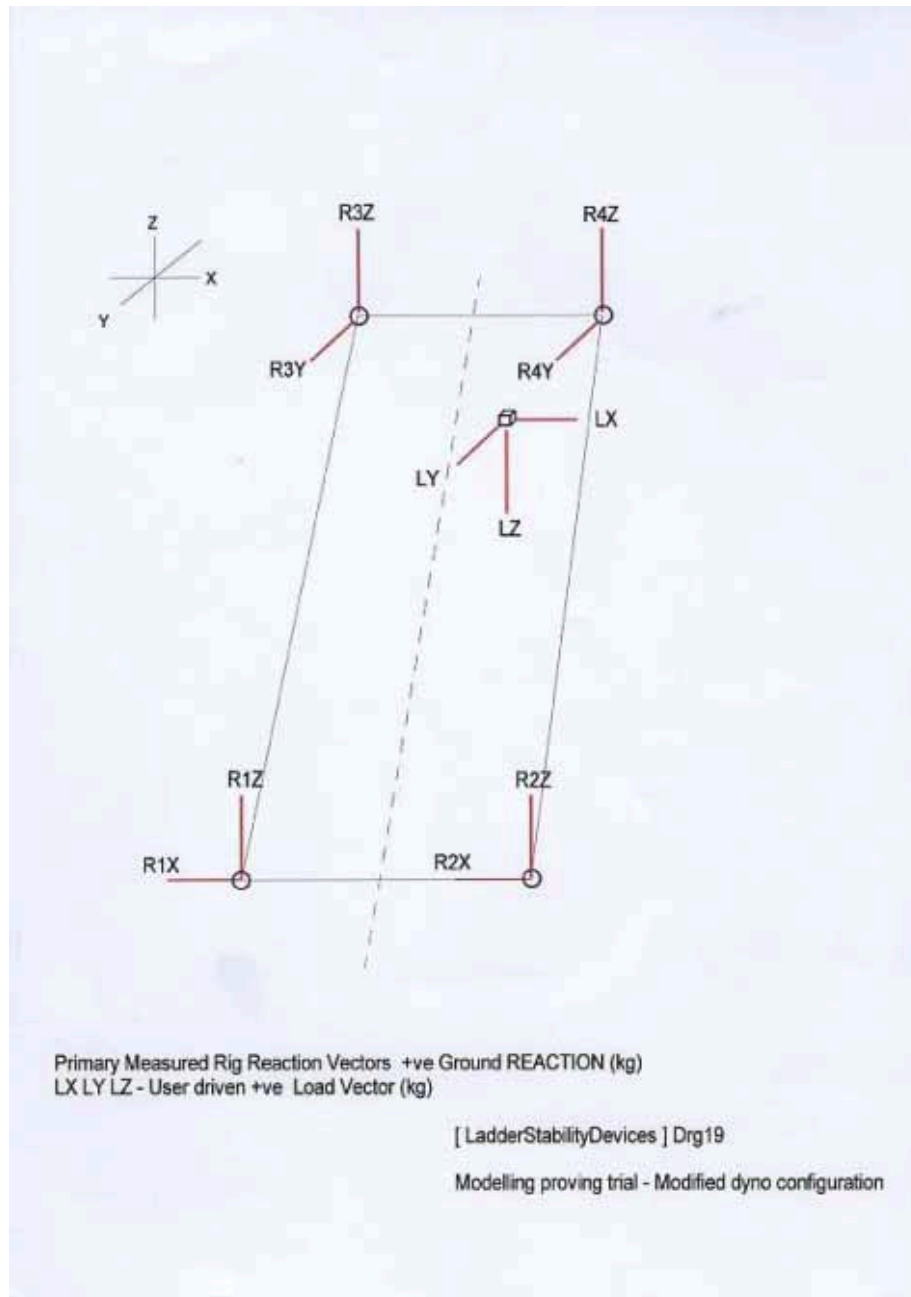


Figure 9
Schematic of the rig configuration

In this instance the dynamometer delivers 8 independently measured reactions nominated as R1X and R2X (base x- reactions), R3Y and R4Y (top y- reactions) and R1Z to R4Z (z- reactions at the top and base).

4.2 Ladder geometry

The ladder geometry and associated variables were recorded and are presented in Table 2

Table 2
Ladder geometry, placement and geometry

| Dimension | Reference | Value |
|-------------------------|------------------|--------------|
| Upper half width | A (metres) | 0.165 |
| Lower half width | B (metres) | 0.230 |
| Length | I (metres) | 4.250 |
| Elevation | J (degrees) | 76 |
| Weight | W (kg) | 17.4 |

5 Review of modelling arguments

The modelling scheme and essential mechanical arguments are extensively developed and described in the original Contract Research report. This report is intended solely to provide evidence substantiating the assumptions made in those models.

It is argued that the upper vector, $F_{top}Z(kg)$, is ordinarily of true zero magnitude, assuming a generally neutral condition throughout both the ascent/decent and the task phase. This occurs through degenerate mechanical slippage and relaxation within the ladder system. This is a demonstrable and logical consequence of the ladder, functioning as an untethered standing structure which conforms to a determinate 6 point suspension in spacial registration. The structure does not require the existence of such a force (i.e. $F_{top}Z(kg)$) and correspondingly does not generate the same.

Despite this, it is acknowledged and indeed expected that there will be the existence of short duration transient actions which arise from small ladder structural deformations under varying load. However, it is important to note that these will arise only about a perpetual and rapid decay towards zero of any standing or held load.

When properly examined in the context of standing stability, such residual perturbation forces as arise can be seen to be uncoupled to three of the four defined stability modes, specifically – Top-Slip, Top-Contact and Flip. This situation is readily predictable, and is a natural consequence of the kinematic standing structure constraint rules pertaining in this case.

There is a small detriment to the base slip failure mode, which is not accounted for in the current modelling scheme. However, in this case, the fractional increase in frictional demand at the ladder base, expressed in the stability index $S_{int}Base(\#)$, is ordinarily maximal at 0.3 % reduction, and hence negligible as originally stated.

As a consequence of this mechanical condition, it is reasonable to say that current ladder designs, employing a simple frictional block contact solution at the top, is technically a design flaw. Any method which deliberately enables rapid frictional de-stressing of a ladder, at the top and in a vertical direction, improves the total ladder performance.

Essentially this is because such de-stressing properly accords with the contacting reactions naturally developed in the first instance, and is not actually impeding this process. In practice, a top location device which did not offer such frictional resistance in this plane would be better than the current arrangement.

It is stated in the modelling calculations that the lower vector $F_{\text{base}}X(\text{kg})$ exists and is negligibly small, and can be ignored in a practical stability assurance regime. Again, detriment to base slip through omission is minuscule and reliably reduces $S_{\text{intBase}}(\#)$ no more than 0.3%. No mechanical coupling of this force modifies the other three stability modes.

Lastly, there may be some concern overall that there is insistence in the evaluation on a tripod modelling scheme. Specifically, there is no allowance for load sharing across 4 potential contact points. A close analysis of the formal modelling construction will reveal that the governing vector support scheme is composed of sums of parallel related sub-pairs, and that the actual fractional split is of no final consequence upon stability. In practice, under high load at high asymmetry, the literal tripod configuration is assured.

6 Processing and Presentation of data

The data is collected as streamed volt levels. This recorded volt level data is processed to produce calibrated and tare zeroed engineering values. Data sets consist of 8 action sensory channels recorded at 0.02 sec sampling interval for up to 100 sec.

Each of 46 obtained full trial histories (two missing trials from poor or incomplete data) are available in files as Excel spreadsheets of for individual or close examination.

Each data file is named in accordance with a coding protocol (Subject/Task/Repetition – e.g. 3B2), thus:

| | | |
|----------------------|------------|--------|
| 1st digit represents | Subject | 1 to 4 |
| 2nd digit represents | Task | A to F |
| 3rd digit represents | Repetition | 1 or 2 |

The tasks are coded as described in Section 2 of this report, and summarised in Table 3.

Table 3
Task coding convention

| Task | Activity |
|-------------|------------------|
| A | Drilling |
| B | Horizontal reach |
| C | Sawing |
| D | Vertical reach |
| E | Bucket lift |
| F | Bucket retrieve |

A small number of representative trial results are graphically presented in Section 7 of this report, and can be taken as fair illustration of typical types of performance.

Spreadsheet data output is presented entirely in graphical format, in the form of time variant action intensity of the various monitored vectors, and shown universally over 100 sec periods. Reaction forces are grouped in logical pairs, and 4 annotated graphs are produced. There are no special calculations as all information of special interest is obtainable by simple observation. The spreadsheet records can of course be reworked to more depth, should microscopic examination be required.

7 Full Trial data sets - Representative graphical series

The following figures depict representative full trial data sets, illustrating typical output from the trials themselves. Seven trials are presented, and in each case all eight action channels are displayed.

In each instance the associated figures, as given in Table 4, are shown.

Table 4
Figures associated with trial output

| Value title | Value | Figure location |
|--------------------|---|------------------------|
| Top Z | Forces in z-plane at the ladder top | Top left |
| Top Y | Forces in y-plane at the ladder top | Top right |
| Base X | Forces in x-plane at the ladder base | Bottom left |
| Base Z | Forces in z-plane at the ladder base | Bottom right |

For each image a pair of traces is shown, representing the paired reaction points at the upper or lower ladder ends.

Figure 1 – Output from Trial 1B1

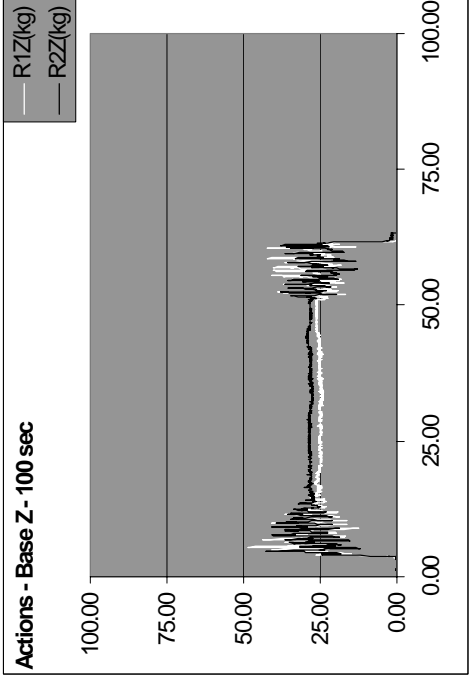
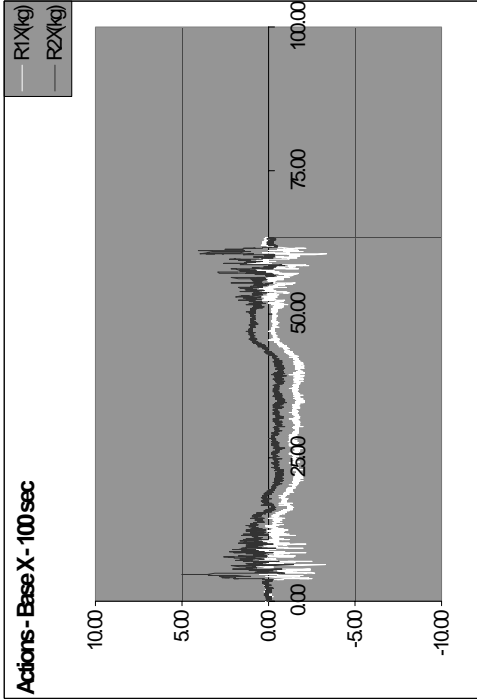
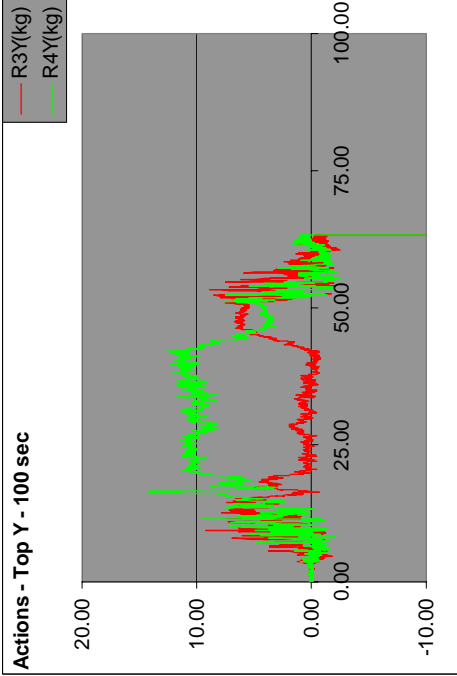
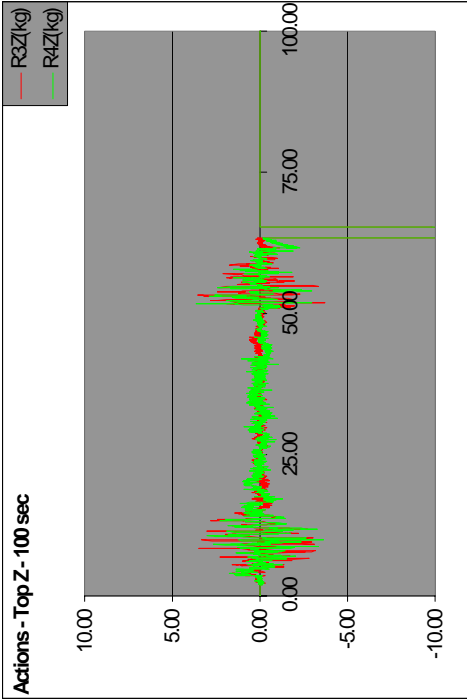


Figure 2 – Output from Trial 2C1

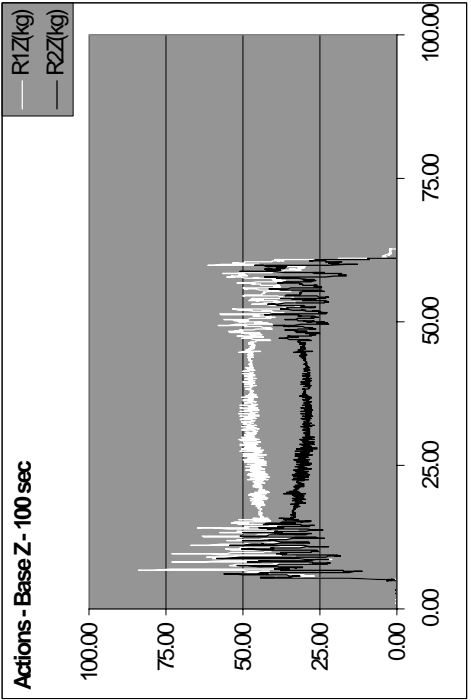
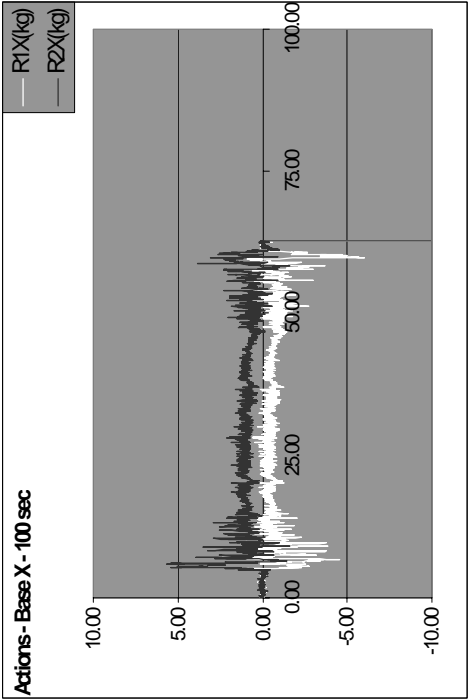
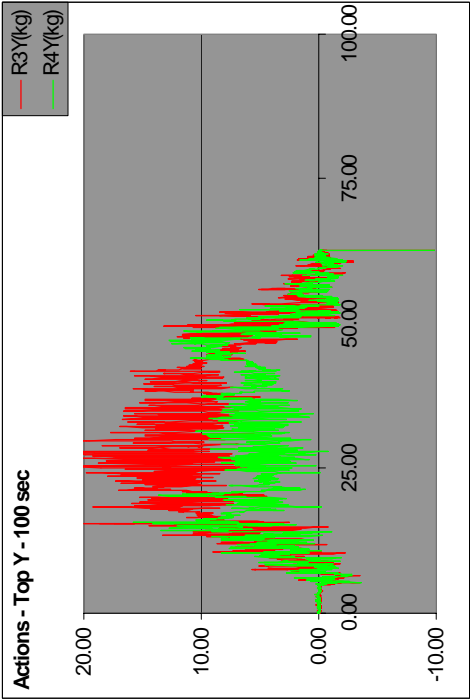
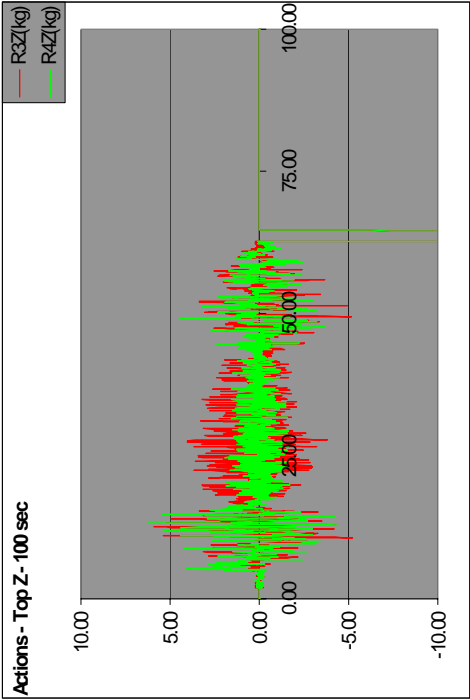


Figure 3 – Output from Trial 2D1

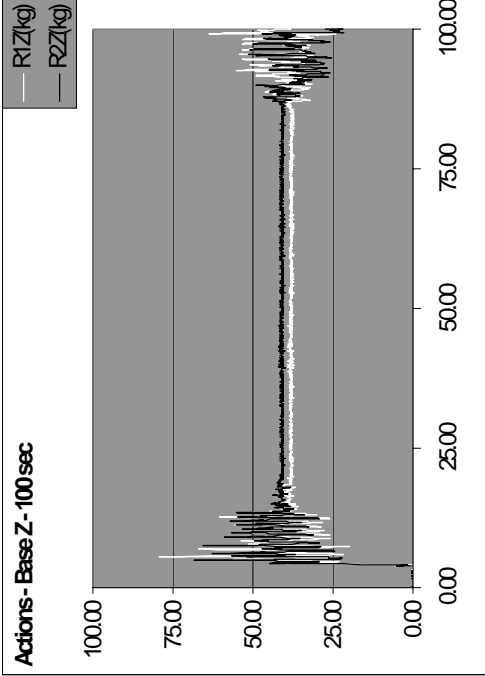
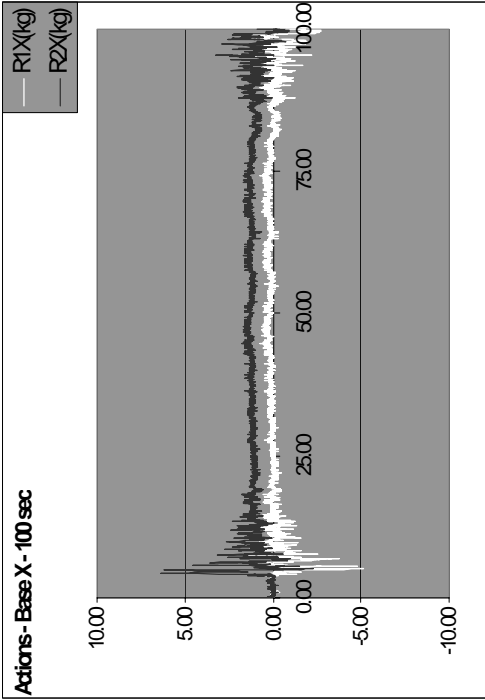
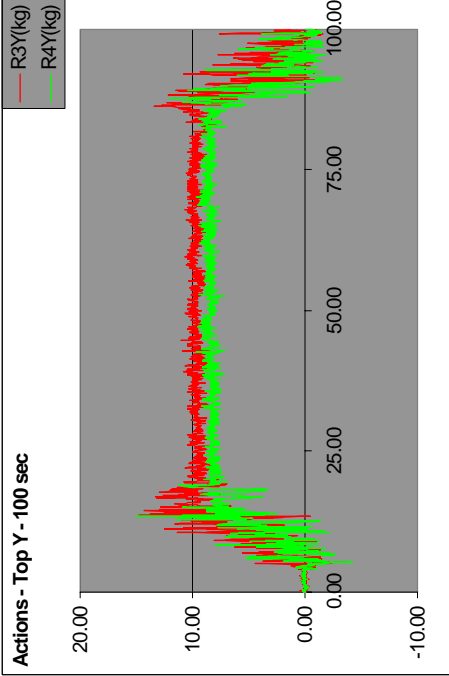
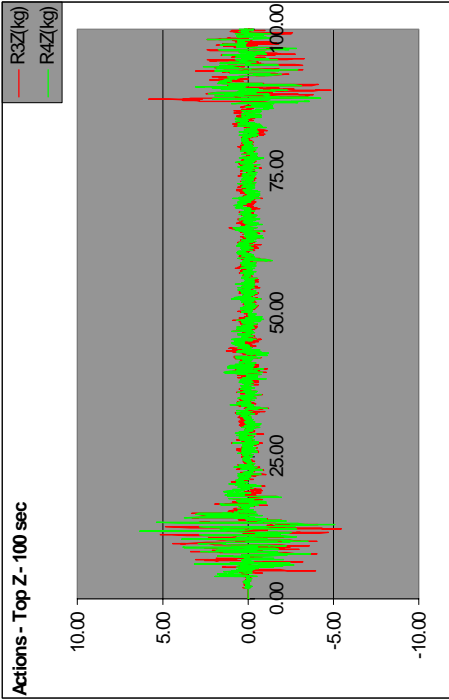


Figure 4 – Output from Trial 3E1

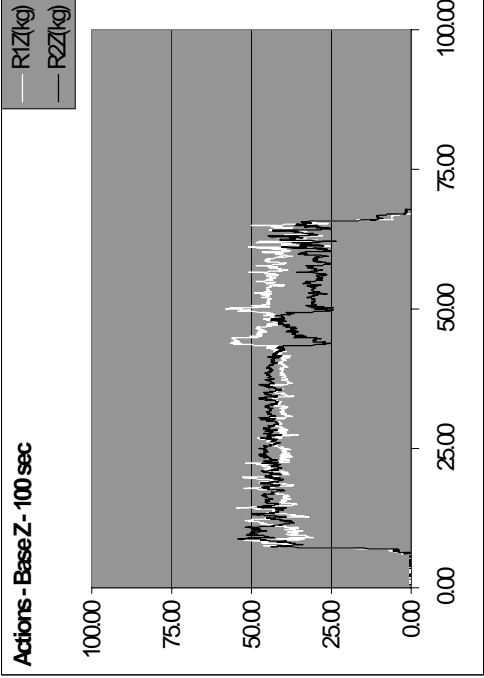
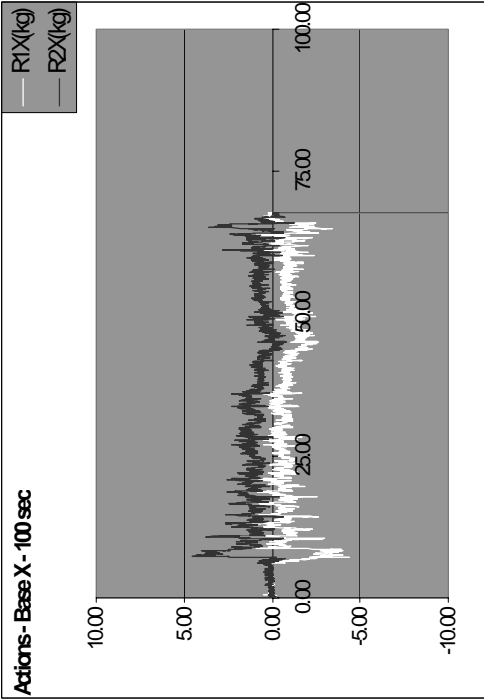
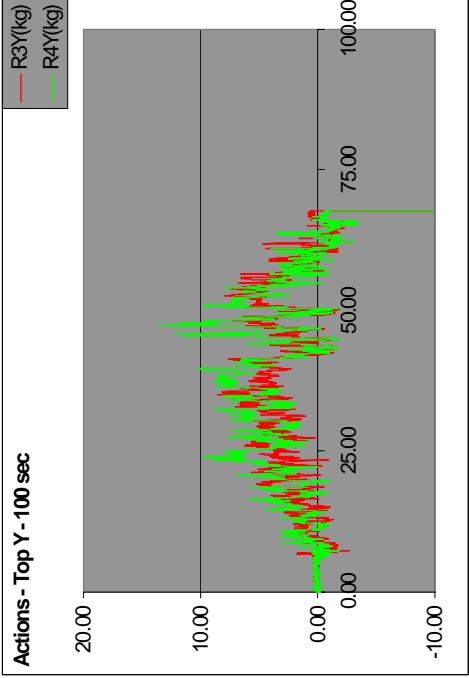
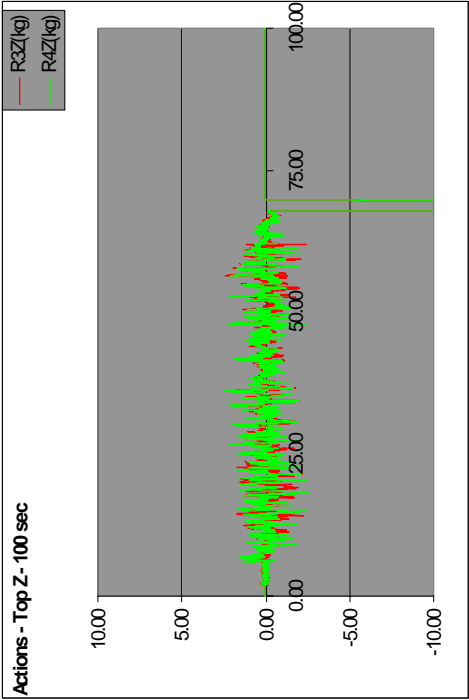


Figure 5 – Output from Trial 4A1

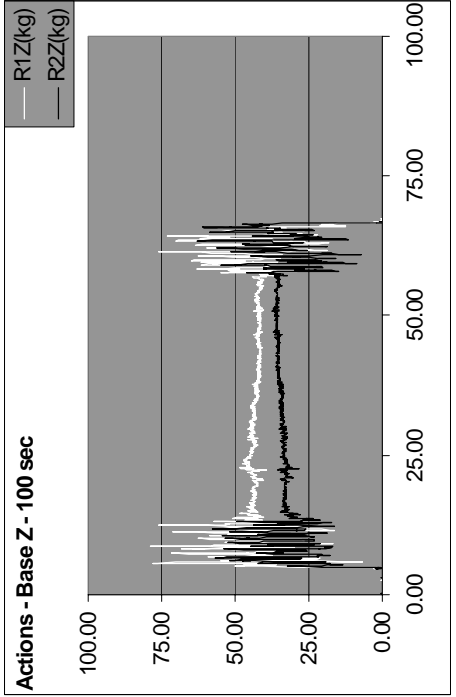
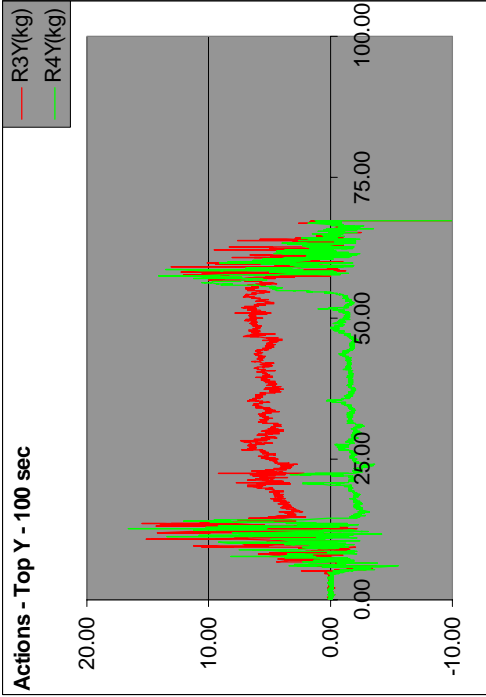
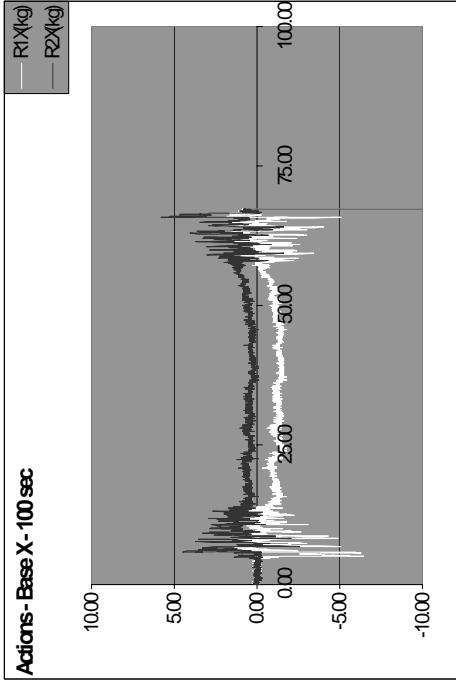
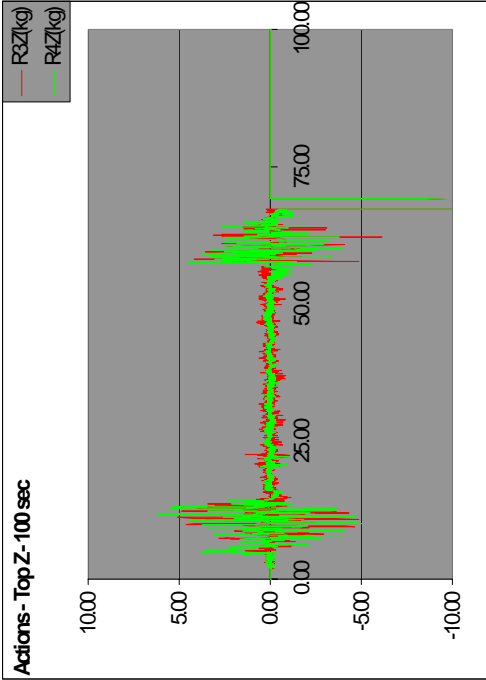


Figure 6 – Output from Trial 3B2

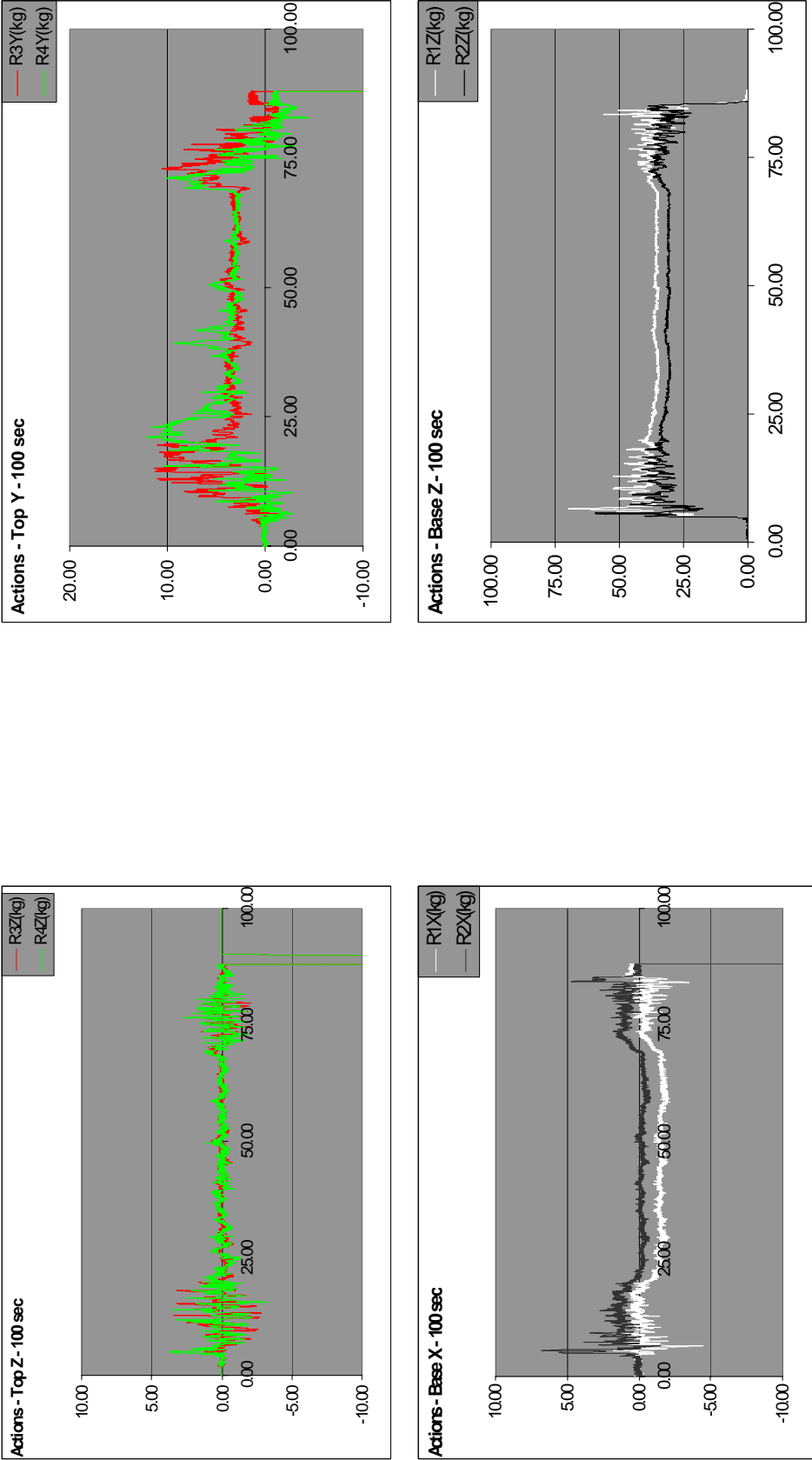
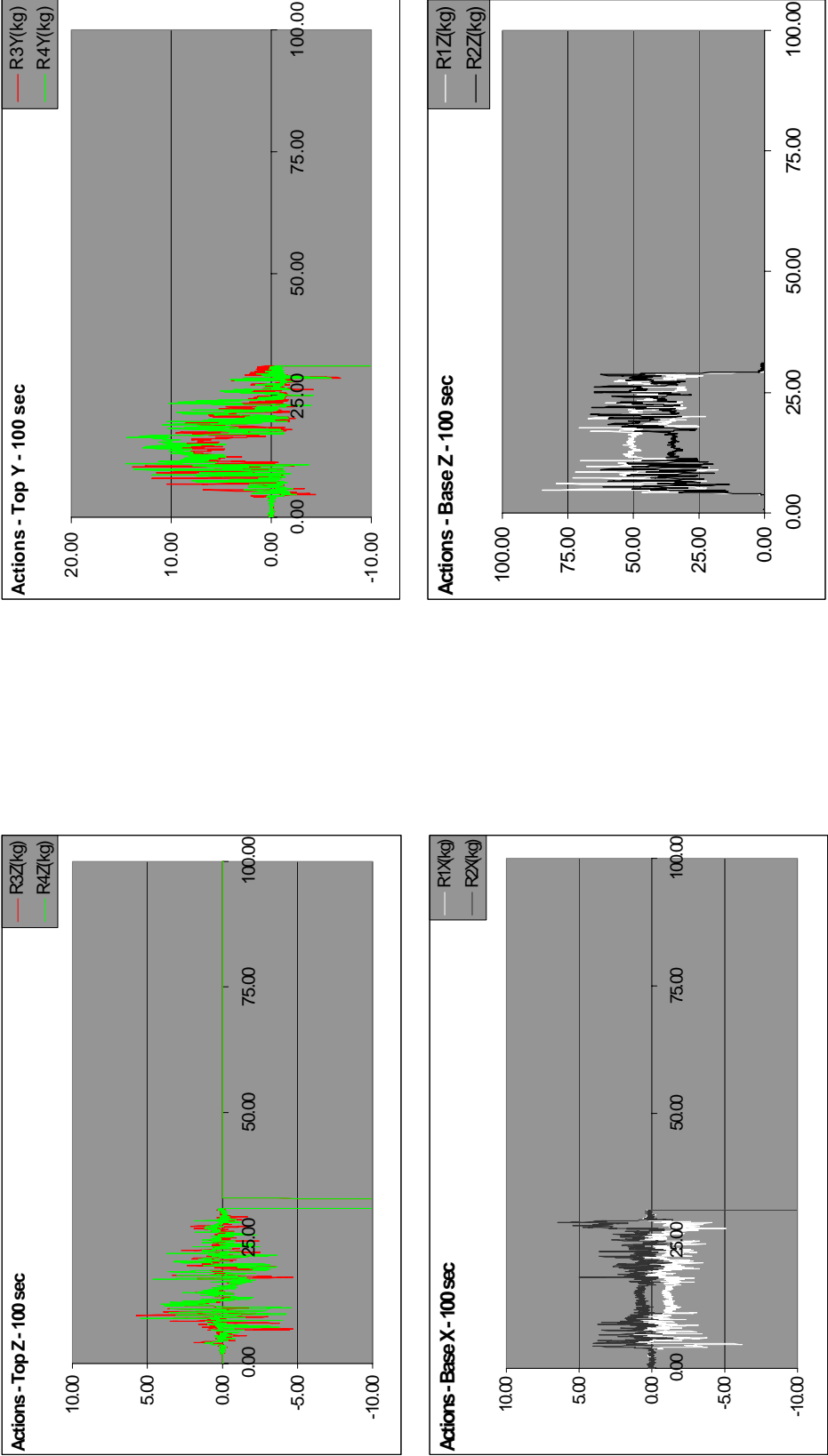


Figure 7 – Output from Trial 4F1



8 Analysis

8.1 $R_{top}Z(kg)$ results

When the graphical results for $R_{top}Z(kg)$ – constituting $R3Z(kg)$ and $R4Z(kg)$, are evaluated it is possible to observe a number of features. For the trial ascent and decent phases, there is usually transient activity, typically peaking at about 5kg, and is clearly symmetric about zero. There is no evidence at this time of any medium term standing load being generated, the decay rate to zero being measured in periods of low seconds. Immediately and thereafter during the task phase, there is consistently low level transient activity, very definitely driven to and centred at precisely zero load. This is typically of order 1 kg amplitude , but can reach about 3 kg for oscillatory tasks like sawing.

8.2 $R_{base}X(kg)$ results

When the results for $R_{base}X(kg)$ - constituting $R1X(kg)$ and $R2X(kg)$, are examined it is evident that moderate level transients are generated during ascent and decent. The task phase is generally quiescent, with low level holding reactions developing in the region of 3 kg maximum.

8.3 $R_{top}Y(kg)$ and $R_{base}Z(kg)$ results

The remaining data sets contain signals for both $R_{top}Y(kg)$ and $R_{base}Z(kg)$ which are the major supporting vectors being normal to the ground contact planes. In these cases it is possible to observe the internal stability of the system. The erratic interchange between load bearing contact point pairs at the top and base, is quite clearly evident. Close analysis reveals that the controlling vectors in the modelling regime, which are constituted by sums of these vector pairs, is itself a more predictable and less volatile parameter.

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9 Conclusion

The evidence derived from these trials indicates that the amplitudes of the vectors in question, specifically $R_{top}Z(kg)$ and $R_{base}X(kg)$ are consistently at very low level during all task phases. The upper vector is clearly driven consistently to zero load through a natural kinematic and frictional degeneration process. It does however exist as a low amplitude deviation of order 1 kg but maximal at about 3 kg.

A review of the modes of failure, in particular the underlying dynamic mechanism, will show that $R_{top}X(kg)$ is uncoupled to three of the stability modes, but can effect base frictional demand and hence $S_{int}Base(\#)$. The decrease in value of this index through a correction for $R_{top}X(kg)$ is maximal at 0.3 %.

The lower vector $R_{base}X(kg)$ is seen to exist, and at an order of 1 kg as predicted. There is a theoretical coupling to base frictional demand, and hence to the index $S_{int}Base(\#)$. This is consistently below 0.3 % reduction during task phases.

Through the generation of this data it is patent that our modelling assumptions and methods of analysis forming the basis of the main research project findings, are fully justified. A natural decay process in $R_{top}Z(kg)$ has been demonstrated, which drives this vector inexorably and quickly towards a null condition, where there is no standing load or stress in the support system. There is logically no element of coupling into the mechanical system, and cannot be involved in the stability regime.

The existence of low amplitude transient activity is acknowledged, and it is accepted that there is an effect upon base slip mode. However, it is shown that the modification to the pertinent stability index would be numerically minor. Likewise the modelling choice to ignore $R_{base}X(kg)$ is argued and proven to be minuscule.

The original modelling doctrine is based on the theorems of kinematic mounting and are developed more fully in the main Contract Research Report. However, these trials and this report demonstrates that this analytic structure correctly concords with reality, and in particular that the elastic properties of ladders do not effectively modify this analysis.

The propensity to an active 3 point support is manifestly evident, and certainly so during high duress asymmetric loading situations which represent the periods of greatest interest throughout this work.

This being so, there is an evident formal problem with the existence of $R_{top}Z(kg)$. This vector is non existent in the model, and is not sought or necessary by the real standing structure. Yet, small erratic transients are measurable and arise in practice.

However, this should not be confused with inaccuracies in the model. These transients are due to compression or structural distortions within the ladder frame, where small linear alterations perhaps of millimetre size, are calling into play internal system forces, through a coupling effect acting counter to the greater dynamic.

Put simply, vertical frictional capability at the ladder top is acting against the natural registration physics, giving rise to high frequency chatter type activity where none is desirable. There is every argument to require that a ladder should be free moving in a vertical direction at the top. This could be easily achieved with free running high friction wheels. Such a ladder would be perfectly stable within the definitions given in the main report, and would be entirely equivalent to a simple ladder employing solid end pieces. However, the vibration component will be entirely eliminated, and the small contribution to the detriment of $S_{int}Base(\#)$ will be likewise eliminated. If then these wheels are spaced outward by some nominal distance, additional safety is afforded to $S_{int}Flip(\#)$, with no detriment to the other indices.

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