Pallet Racking Using Cold-reduced Steel

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Introduction

Codes of practice for the design of cold-formed sections have generally included a requirement for the coil material to possess a specified amount of ductility prior to forming. The scientific basis for such ductility requirements is shrouded in historical mystery but code drafting committees have been reluctant to remove these requirements in the absence of good reason. However, very low ductility steels have been used for the manufacture of cold-formed steel components for many years by the two leading UK manufacturers of storage racks without this lack of ductility giving rise to any problems during either manufacture or service. This relatively hard material is produced by taking conventional coil material and cold-reducing it prior to forming it into beam, column and other components. The advantage gained by this procedure is a significant increase in the yield stress but the penalty is a considerable reduction in the ductility. As, up to the present time, storage racking has not been subject to formal approval procedures, the absence of clauses in UK or European Codes of Practice allowing the use of these hard steels has not caused any problems. However, this situation is now changing and it has become necessary to justify their performance in comparison with material of more usual ductility.

It may be noted here that the use of low ductility steel is not unique to storage racking because very hard steels have been also used successfully in Europe for the manufacture of profiled steel cladding. Galvanised coil is available with a guaranteed yield stress of 550 N/mm^2 and several manufacturers successfully form this material. Indeed, the first author[(1)] has tested roof sheeting made from material which had a measured yield stress in excess of 700 N/mm^2 together with zero elongation in a conventional tensile test. The buckling-yielding failure modes observed in both single and two-span tests to failure showed no evidence of the influence of reduced ductility.

In this paper, the justification for the use of low-yield stress steel is taken a stage further by describing a series of tests on racking components made from both cold-reduced steel and an equivalent hot-rolled steel of similar yield stress but much greater ductility. It is shown that the use of hard steel has no adverse effect on performance. The paper concludes by describing a test to failure of a full scale rack structure fabricated using components made from cold-reduced steel.

Design of pallet racks

Pallet racks are typically framed structures fabricated from cold-formed sections. The main components are the uprights, the beams and the beam to upright connectors. There are also

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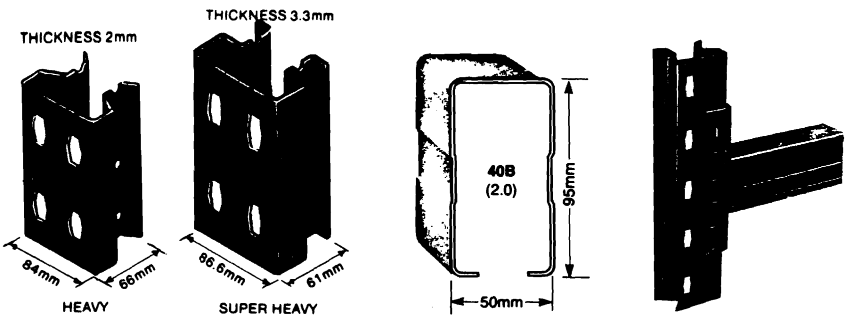
diagonal bracing members in the cross-aisle direction and possibly in the down-aisle direction as well. A particular feature of pallet rack construction is the use of clipped joints between the beams and the uprights. This results in joints of significant flexibility which must be taken into account in the design. Indeed, the performance of the beam to upright connector is crucial in the design of a pallet rack system and will feature prominently in the tests described later in this paper. The uprights are generally cold-formed sections of singly symmetric open cross-section which contain regular arrays of perforations in order to accommodate the clip systems. They carry large axial loads together with bending moments about both axes. Such sections generally fail by lateral torsional buckling and it follows that the design of the heavily loaded uprights of a pallet rack system is one of the more difficult design problems encountered by structural engineers.

As a consequence of the relatively light construction and the use of flexible connections, pallet rack structures are subject to significant second-order effects. This will be apparent in the discussion of the full scale tests later in this paper.

Components Tested

The components tested were all from the standard range of components in the Link 51 "Stormor XL" range. They comprised the 2mm thick "heavy" and 3.3mm thick "super heavy" uprights, the 2mm thick 40B beam and the standard beam end connector as shown in Fig. 1.



(a) uprights (b) beam (c) connector

Fig.1 Components tested

Materials

The primary components which were tested were all the standard cold-reduced production of the manufacturer and were taken from two coils, one for material of nominal thickness 2mm and one for material of 3.3mm thickness. For the comparison, a similar set of components were made from hot-rolled material with a yield stress as near as possible to that of the primary components.

The properties of the materials were determined by standard tensile tests and are summarised by the average values given in Table 1.

source of sample	cold-reduced or hot-rolled	core thickness (mm)	yield stress (N/mm^2)	ultimate stress (N/mm^2)	elongation %
2mm uprights	CR	2.02	474.3	474.3	*
2mm uprights	HR	2.07	492.9	498.9	20
3mm uprights	CR	3.27	504.8	511.6	10
3mm uprights	HR	3.25	409.8	477.1	31

* specimens failed outside gauge length

Table 1 **Properties of the materials used in the tests**

In the case of the 2mm uprights, the difference in yield stress between the cold-reduced and hot-rolled material was small (approximately 4%) and the test results can be considered to be directly comparable. In the case of the 3mm materials, the cold reduced steel was approximately 23% stronger than the hot-rolled material and this must be born in mind when comparing the test results.

Lengths of beam were supplied for the testing with the connector already welded in position by the manufacturer. The material for the connector itself was the manufacturer's standard hot-rolled with no special provisions being made for the test programme.

Component test procedures

The various component tests were all carried out in accordance with the provisions of the Storage Equipment Manufacturers Association (SEMA) Code of Practice for the Design of Static Racking, 1980[2], as follows:

(a) connector looseness (clause 4.2.1)
   6 tests with cold-reduced material
   6 tests with hot-rolled material

(b) moment capacity and moment/rotation characteristic of connector (clause 4.2.2)
   6 tests with cold-reduced material
   6 tests with hot-rolled material

(c) compression test on upright members (clause 3.4)
   24 tests with cold-reduced material
   24 tests with hot-rolled material

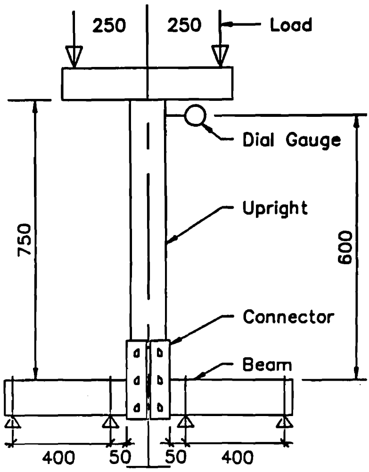


Fig.2 Connector looseness test

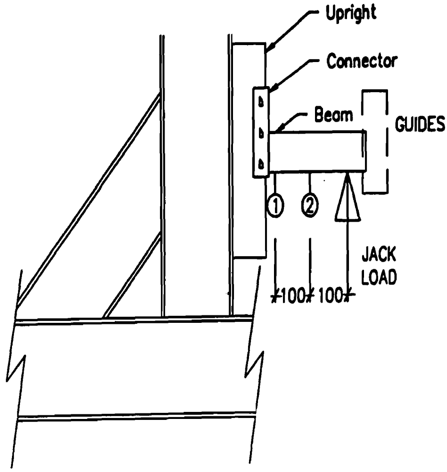


Fig.3 Moment capacity test

Figs.2 and 3 show schematically the apparatus for the connector looseness and moment capacity tests respectively. The self-stressing arrangement for the compression tests is shown in Fig.4. The specimen was loaded through balls located at the calculated centroid of the gross cross-section. Minor axis deflection was restrained at the third points of the length in order to take approximate account of the restraining effect of the bracing members in the plane of the upright frame. Deflections were measured at five positions around the profile of the member at mid-span using displacement transducers.

It may be noted here that more recent thinking, as expressed in the European (FEM) Recommendations for the design of racking[3], is to test the upright as part of the complete upright frame in order to take more accurate account of both the lateral and torsional restraint provided by the bracing members.

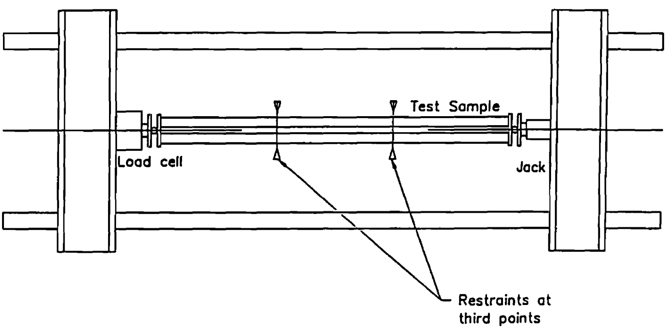


Fig.4 Axial load test on upright

A compression test in progress is shown in Fig.5. The compression tests at short length are similar to "stub column" tests.

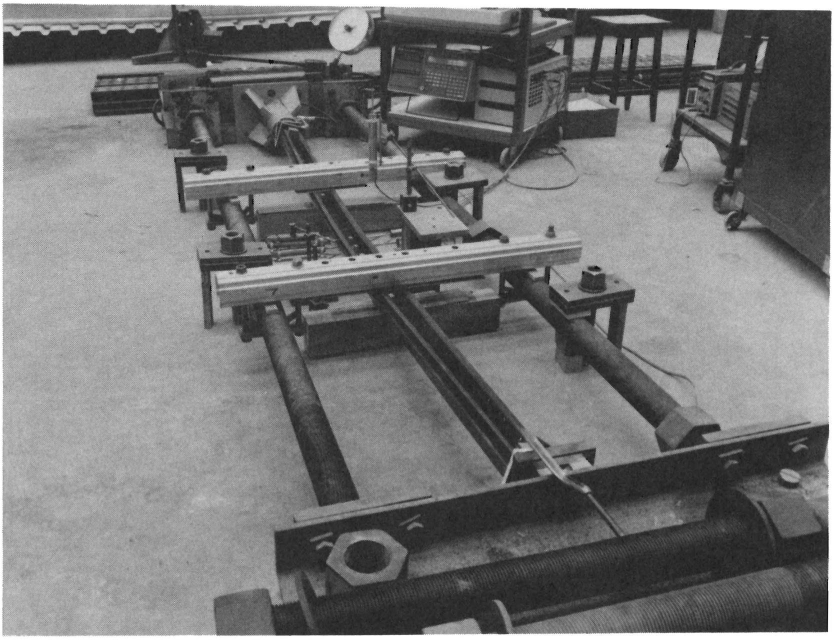


Fig.5 Compression test on upright

Results of component tests

(a) connector looseness

The results of the connector looseness tests are summarised in Table 2. In each case, the quoted result is an average of three tests.

upright material	average R_0 (radians)	standard deviation (radians)
2mm CR	0.51×10^{-3}	0.076×10^{-3}
2mm HR	1.25×10^{-3}	0.39×10^{-3}
3mm CR	0.44×10^{-3}	0.079×10^{-3}
3mm HR	0.91×10^{-3}	0.16×10^{-3}

Table 2 Results of connector looseness tests

Evidently the use of cold-reduced material reduces considerably the looseness of the connections. It also appears to give rise to greater scatter of the results, as evidenced by the larger values of the standard deviation.

(b) moment-rotation characteristics

Fig.6 shows the average moment-rotation relationships from the four series of tests using cold-reduced and hot-rolled material for the upright. The individual series were internally consistent and there was little variation between the individual curves. The shape of the curves is entirely characteristic of this type of test. The results for the complete series are summarised in Table 3.

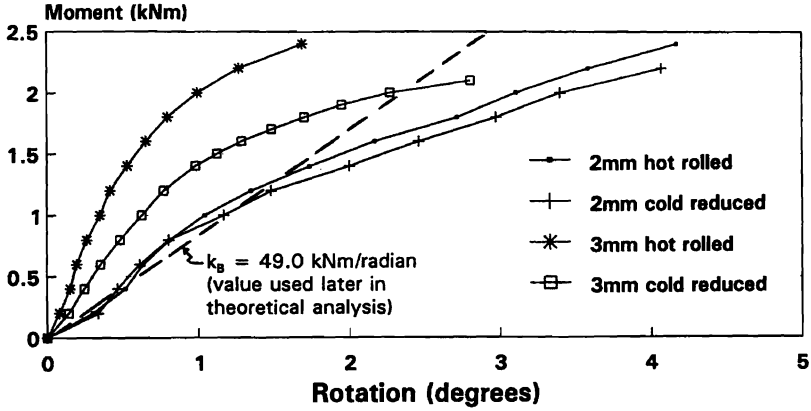


Fig.6 Moment-rotation characteristics from tests on beam to upright connectors

upright material	ultimate moment (kNm)	rotational stiffness (kNm/rad)
2mm CR	2.2 (SD = 0.2)	49.0 (SD = 8.5)
2mm HR	2.4 (SD = 0.2)	51.7 (SD = 2.9)
3mm CR	2.2 (SD = 0.26)	90.6 (SD = 8.3)
3mm HR	2.5 (SD = 0.1)	164.5 (SD = 11.0)

Table 3 Results of connector moment-rotation tests

The hot-rolled material gave rise to slightly stronger connections than the cold-rolled material. The stiffnesses of the connections were similar for the alternative 2mm materials but, in the case of the 3mm material, the hot-rolled connections were considerably stiffer than their cold-rolled equivalent.

In each case, the failure mode involved local distortion of the upright and eventually tearing of the upright material around the perforations. Fig. 7 shows a typical failure in cold-reduced material. The hardness of the material evidently has no adverse effect.

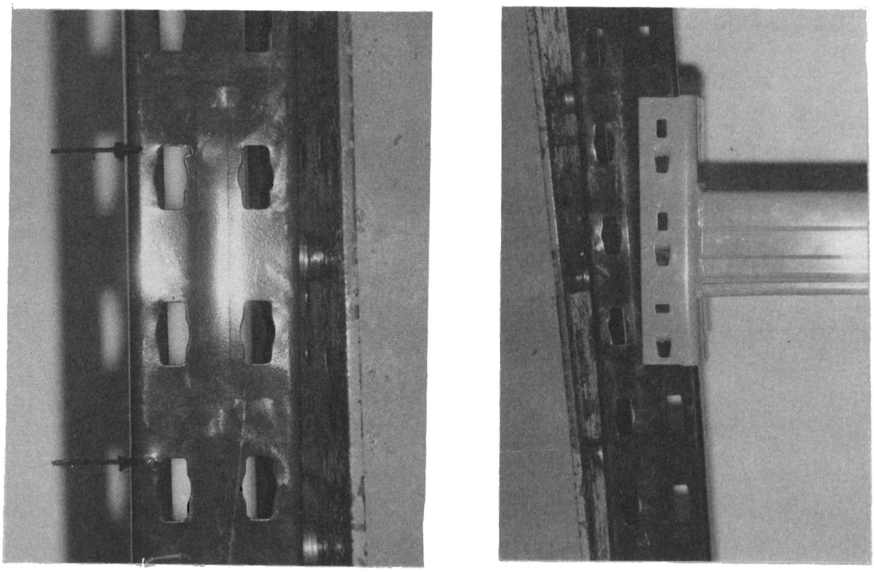


Fig.7 Failure mode of beam to upright connector - cold-reduced material

(c) compression tests

The results of the compression tests are summarised in Table 4 and Fig.8. Short columns failed in distortional buckling. As a consequence of the minor axis restraint, longer columns failed in major axis buckling with some evidence of torsion and distortion of the cross-section. The difference between the two materials is small with the cold-reduced material performing slightly better at longer lengths.

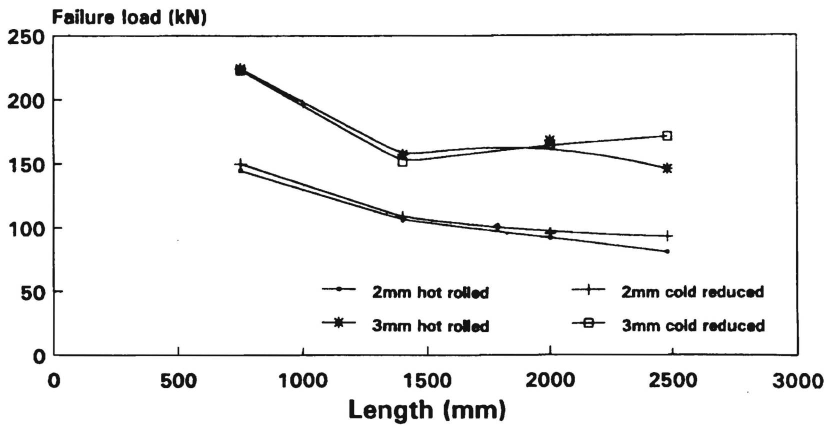


Fig.8 Failure loads of uprights in axial compression

upright material	length (mm)	failure load (kN)	
		mean	standard dev.
2mm CR	750	150.0	2.6
2mm HR	750	144.7	4.7
2mm CR	1400	108.7	5.9
2mm HR	1400	106.5	0.9
2mm CR	2000	95.7	4.4
2mm HR	2000	92.4	8.0
2mm CR	2480	93.0	8.7
2mm HR	2480	80.9	6.5
3mm CR	750	223.0	10.8
3mm HR	750	224.3	8.3
3mm CR	1400	151.7	3.8
3mm HR	1400	157.2	5.8
3mm CR	2000	165.0	2.6
3mm HR	2000	168.0	4.4
3mm CR	2480	171.0	14.7
3mm HR	2480	145.6	4.9

Table 4 Compression test results

Evidently, the use of cold-reduced material of low ductility has no detrimental effect on the performance of uprights in compression.

Test on a complete rack structure

The complete test frame and loading system is shown diagrammatically in Fig.9 and also in Fig 10. It consisted of three upright frames of total height 3.15 metres together with a total of eight beams of 2.4 metre span. The beams were set at heights of 1.4 and 2.8 metres above the floor.

The columns in the upright frames were of the 2mm thick 'heavy' type and 3.15m length with steel baseplates. The columns and diagonal bracing were fabricated using cold reduced mild steel as described earlier. The beams were of type 40B (95 x 50mm x 2mm thick) and 2.4 metres span. They were also fabricated using cold-reduced material but had end connectors of standard hot-rolled material welded to them. These components are shown in Fig. 1 and their material was as described in Table 1.

The two bay test frame was positioned on two 150 x 150 Universal Column sections which were placed on the laboratory floor and acted as supporting beams. The base plates of the test frame columns were not fixed to these beams but they butted against steel plates which were fixed to the top flanges of the beams, thus preventing slip from occurring in the direction of the horizontal loading which was applied to the frame.

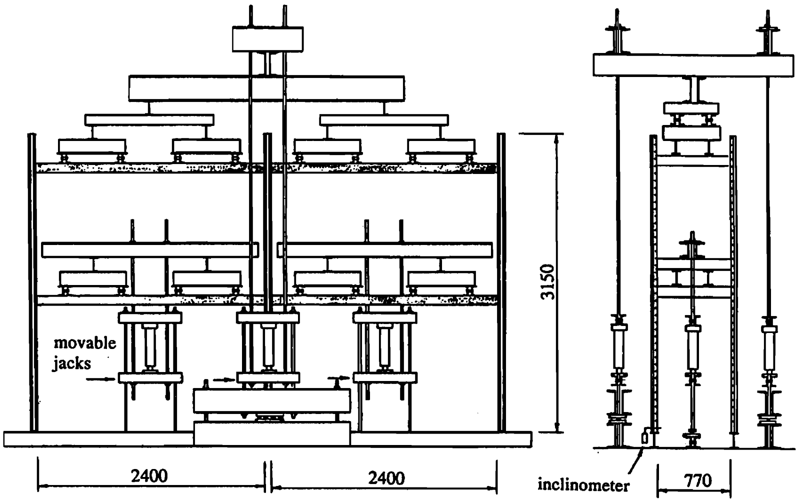


Fig.9 Tested rack with loading system

Loading system

The applied loading was a combination of vertical and horizontal load reflecting the design requirements of the Storage Equipment Manufacturer Association's (SEMA) Code of Practice for the design of static racking, 1980. Vertical load from pallet racks was simulated by an arrangement of spreader beams and tie rods loaded by four hydraulic jacks which were anchored to the strong floor of the laboratory. Two jacks applied load to the upper beams and two to the lower beams, the load application points being the normal resting points of typical pallets. The dead load of the spreader beams was 3.38 kN per beam at upper level and 2.0 kN per beam at lower level. Therefore an additional load of 1.38 kN per beam was imposed at the lower level in order to bring the loadings at both levels equal before increasing the vertical load in increments. The vertical loading system is shown in Fig. 9.

A horizontal load of 0.5% of the vertical load was applied at each beam level by means of weights which were carried on hangers attached to steel cables. These cables passed over pulleys supported by an 'A' frame. Fig. 10 is a photograph showing the complete frame and test arrangement.

The vertical load was applied in increments of 2.0 kN per beam together with a proportional increase in the horizontal loads until failure of the rack took place.

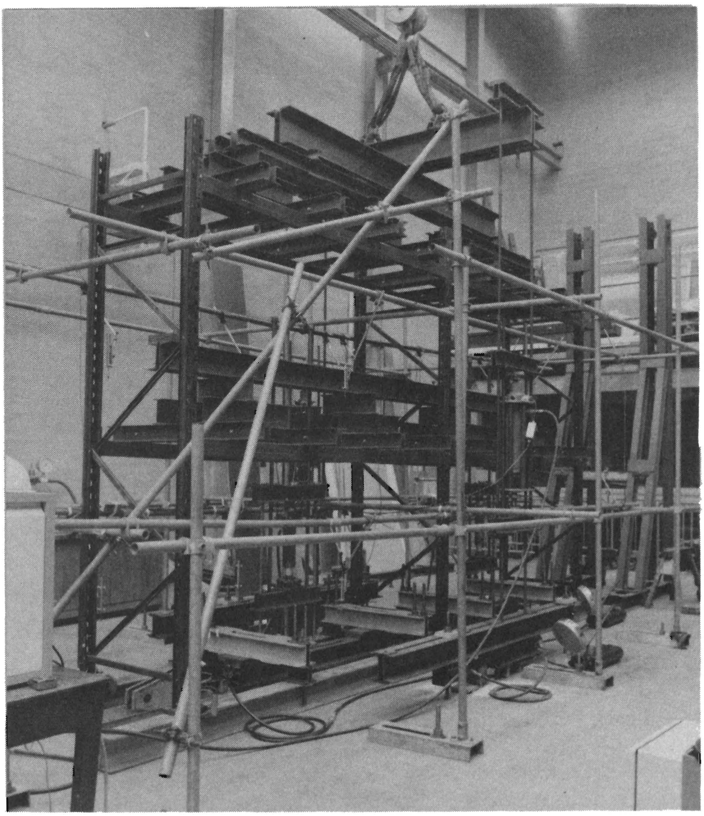


Fig.10 Rack under test

In order to ensure that the simulated pallet loads remained truly vertical as the frame swayed under the influence of the horizontal loads, the jacks were moved horizontally at each load increment. Rollers were placed between the jack reaction beams and their floor anchors and after the horizontal movement of the frame had been measured, the reaction beams were moved by a similar amount so that the tie rods remained vertical.

Instrumentation

Horizontal movement of the frame was monitored at the upper and lower beam levels using four dial gauges reading to an accuracy of 0.01mm. Deflections of the beams were measured using a total of sixteen displacement transducers connected to an Orion Data Logger. Out of the sixteen transducers, twelve were used to monitor the end and central deflections of the four beams on one side of the frame including both bays. The other four transducers measured the central deflections only of the four beams on the opposite side of the frame.

The three columns on one side of the structure were also fitted with a total of six strain gauges positioned as shown in Fig. 11 and three inclinometers positioned at a height of 70mm above the base of the columns. From these gauges the level of strain in the columns and the base rotations could be measured during the loading process.

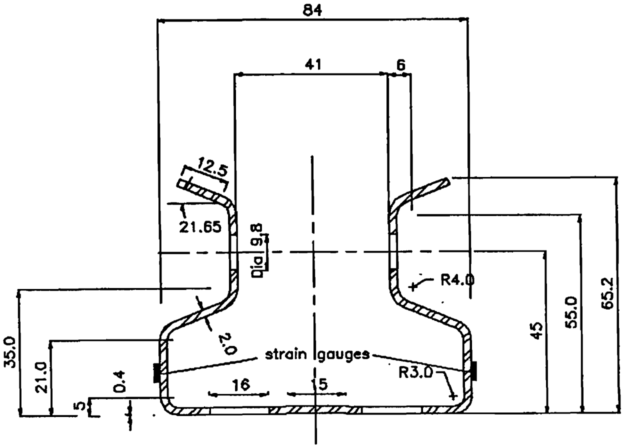


Fig.11 Cross section of upright showing strain gauge positions

Analysis of the tested rack

The rack was analyzed in the down-aisle direction using an elastic-plastic second-order plane frame computer package in which both the beam to column connections and the bases of the uprights were treated as semi-rigid. An elastic critical load analysis was also carried out in order to quantify the significance of second-order effects.

The rotational stiffness at the base of the uprights was, of course, not known. Analyses were therefore carried out with the following values of this stiffness so that the influence of the (probably non-linear) base stiffness could be investigated:

Run 1:	k_c = 20000 kNmm/radian
Run 2:	k_c = 40000 kNmm/radian
Run 2:	k_c = 80000 kNmm/radian

The remaining data for the analyses were as follows:

Spans etc:	See Fig. 9.		
Beam levels:	1400 and 2800 mm		
Upright properties:	Area = 493 mm^2,	I = 415000 mm^4	(gross section)
Beam properties:	Area = 516 mm^2,	I = 570000 mm^4,	M_p = 7210 kNmm
Beam/upright connector:	Rotn. stiff. k_b	= 49000 kNmm/rad,	M_p = 2200 kNmm

The detailed results are given later in the form of load-deflection curves. The predicted failure loads from the three analyses were as follows:

Run 1:	Failure load 25.1 kN/beam:	Partially plastic sway failure with "plastic hinges" at the leeward ends of the beams.
	Elastic critical load 36.5 kN/beam:	
Run 2:	Failure load 27.3 kN/beam:	Partially plastic combined mode with "plastic hinges" in the middle and at the leeward ends of the beams.
	Elastic critical load 44.6 kN/beam:	
Run 3:	Failure load 28.3 kN/beam:	Partially plastic combined mode with "plastic hinges" in the middle and at the leeward ends of the beams.
	Elastic critical load 56.0 kN/beam:	

As indicated by the proximity of the elastic critical load to the failure load, and as also evidenced by a comparison of first and second-order analyses, even in the low-rise rack that was tested, the sway deflections were strongly influenced by second-order effects.

Test results

(a) failure load of complete structure

The working load of the beams in the arrangement tested was 10 kN per beam. The small size of the arrangement prevented the columns from being fully stressed.

The results of the load test may be summarised as follows:

self weight + weight of loading system	=	3.40 kN/beam
applied jack load at failure	=	26.50 kN/beam
Total load at failure:		29.90 kN/beam

The mode of failure was sway accompanied by the sudden shearing of the lugs in one of the leeward beam to upright connectors. There was adequate warning of impending failure as the connectors had been observed to distort and rotate as the failure load was approached. This was interpreted as a ductile moment failure in the beam to upright connectors as predicted by the theoretical analysis. The observed failure load was a little higher than any of the alternative analyses but within normal experimental limits.

(b) sway stiffness

The experimental and theoretical curves for sway at the upper and lower beam levels are given in Figs. 12 and 13. It can be seen that these are commensurate with a gradually reducing base stiffness within the range considered. However, it must also be born in mind that the beam end connector stiffness is also highly non-linear (see Fig. 6) so that it is not possible to come to precise conclusions from the shape of these curves.

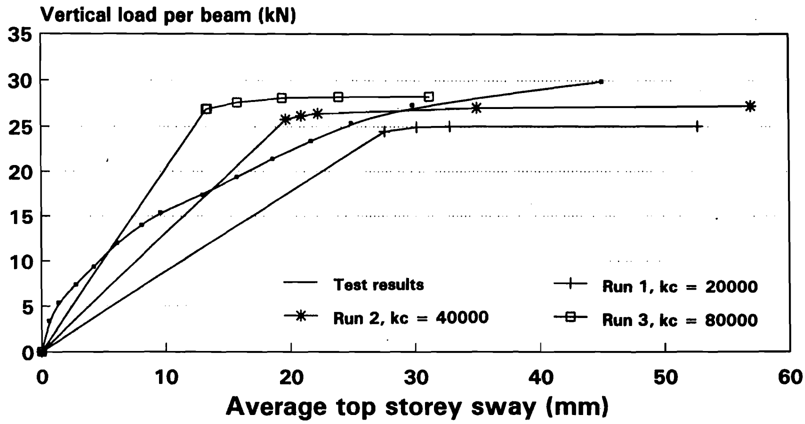


Fig.12 Load-deflection curves for top storey sway

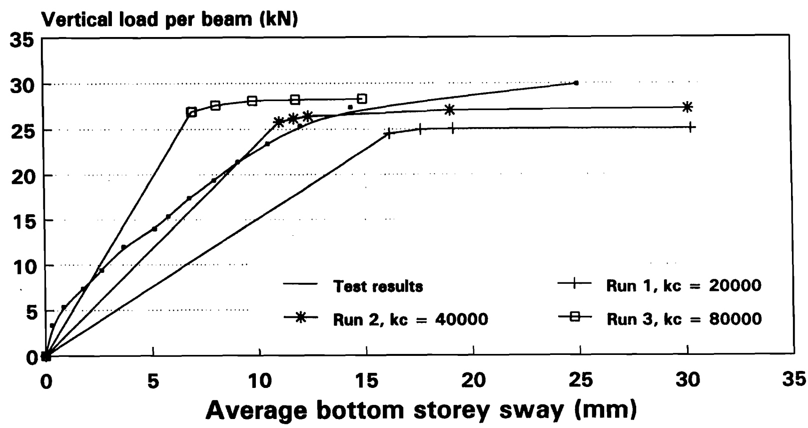


Fig.13 Load-deflection curves for bottom storey sway

The inclinometer readings indicated base rotations that agreed well with each other. Comparison with the predicted values was, however, inconclusive as the measured values were relatively large up to a load of about 12 kN per beam at which point the rate of rotation reduced to a value commensurate with a base stiffness of about 80000 kNmm/radian.

(c) beam deflections

Because of the danger of disturbance while setting up the loading equipment, zero readings of the deflection measuring equipment were taken once the loading equipment was in position. The measured deflections were then adjusted to give zero deflection under zero applied load. The central deflections were also corrected to give a true deflection relative to the ends of the beams. It is the average of these central deflections which is considered here.

The experimental and theoretical beam deflections are shown in Fig. 14. These are strongly influenced by the beam end connector stiffness but the base stiffness has much less effect. There is good agreement between the test and theory.

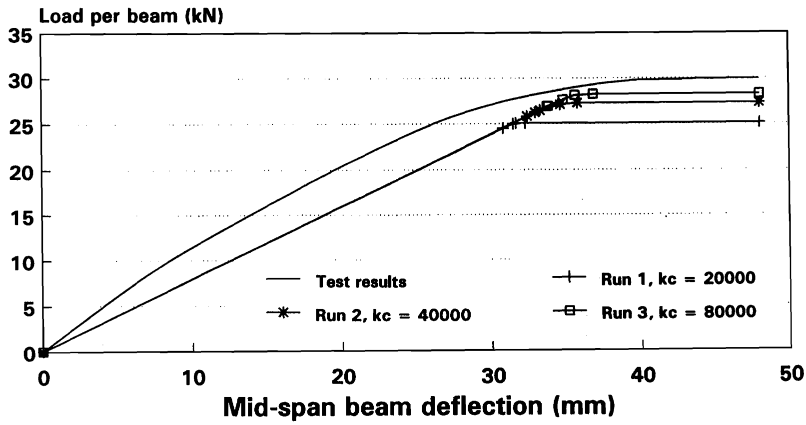


Fig. 14 Curves of load versus average beam deflection

Conclusions

The full scale test, together with the component tests which preceded it, were designed to demonstrate that components formed from cold-reduced steel perform satisfactorily up to ultimate load conditions and in a manner similar to more ductile hot-rolled components. This has clearly been achieved.

The various load-deflection curves all indicate that the performance of the complete rack was normal and satisfactory. A comparison of the test results with an appropriate theoretical analysis indicates that the behaviour is entirely consistent with the theoretical predictions.

In particular, the experimental failure load of 29.9 kN per beam was slightly higher than the theoretical value of approximately 28 kN per beam. The theoretical results also indicate that, when the lugs in the beam to upright connectors failed, the entire frame was close to failure in a combined beam and sway mode.

This, together with other similar experiences, lead the authors to the conclusion that there is no need for a formal ductility requirement in cold-formed section specifications. If a member can be cold-formed without longitudinal cracking, it will perform satisfactorily in service. If a safeguard is required, it should be in the nature of a bend test according to ISO 7438-1985 *Metallic Materials - Bend Test* rather than a requirement for a specified elongation in a tensile test or a particular ratio between the yield and ultimate stresses.

References

1. J M Davies "Loading tests on 35mm deep profiled steel sheets" University of Salford, Dept. of Civil Engineering, Report Ref. 82/175, 1982.

2. "Code of Practice for the Design of Static Racking", Storage Equipment Manufacturers Association", June 1980.

3. "Recommendations for the Design of Steel Static Pallet Racking and Shelving", Federation Europeenne de la Manutention, Section X, Final Draft, March 1994.