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John Enright

Robert Harriss

Gregory J. Hancock

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STRUCTURAL STABILITY OF BRACED SCAFFOLDING AND FORMWORK WITH SPIGOT JOINTS

John Enright*, Robert Harriss** and Gregory J Hancock***

ABSTRACT

Steel Scaffolding systems are often constructed from cold-formed circular hollow sections. The beams of this system are normally called "ledgers" and the columns are normally called "standards". To allow the system to be quickly erected on site, "spigot joints" are inserted in the standards. The spigot joints consist of smaller diameter tubes which slide into the larger diameter tubes to provide a safe connection under gravity load. However, the spigot joints may have a lack of fit, and when located midway between the ledgers, they can cause significant out-of-straightness in a standard. This PΔ effect may weaken the standard as a column and lead to a reduced load capacity of the scaffold system.

The paper describes tests on sub-assemblages of scaffolding with and without spigot joints. Concentric and eccentric loading eccentricity was also investigated. The results are compared with a nonlinear inelastic finite element frame analysis (program NIFA) developed at the University of Sydney. The nonlinear analysis included special modelling of the spigot joints. The results are also compared with design capacities computed using the Australian Steel Structures standard AS 4100-1998.

Conclusions are given regarding the modelling of the spigot joints and the effect of the spigot joints on the strength of scaffolding systems.

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* Toll Logistics, Level 1, 32 Walker Street, North Sydney, Australia, ** A.T. Kearney, Level 44, 1 Farrer Place Sydney, Australia, *** Department of Civil Engineering, University of Sydney

1. INTRODUCTION

Scaffolding and Formwork systems constructed from steel structural members are used widely in the construction industry. Scaffolding is generally a light framework attached to the outside of a building under construction and normally only carries its own weight plus the working loads of equipment and labourers such as bricklayers and other trades along with appropriate materials, as well as wind loading. The stability of scaffolding systems is closely linked to its attachment to the building under construction. Formwork, on the other hand, is the structure used to support wet concrete. The direct retainment of the wet concrete is usually by timber bearers and panelling which often sits on steel frameworks of a similar form to conventional scaffolding. The structural stability of formwork is often more at risk due to the heavier loads and the decreased degree of restraint when compared with scaffolding systems. The assessment of the structural stability of scaffolding and formwork systems is similar due to the use of similar components in both, especially semi-rigid connections at joints (called couplers) and flexible connections within members (called spigot joints) both of which are used for rapid assembly and disassembly. In both cases, cold-formed tubular members are commonly used. Failures of these assemblies due to instability is not uncommon although not widely reported unless there is loss of life involved. The main objective of this paper is to assess the effect of spigot joints on the structural strength of these systems.

The structural design of scaffolding and formwork systems in Australia is covered by Australian Standards, AS/NZS 1576 (scaffolding) Standards Australia (1995a) and AS 3610 (formwork for concrete) Standards Australia (1995b). Both of these standards make reference to the Australian Steel Structures Design Standard AS 4100 (Standards Australia 1998). However, the nature of scaffolding and formwork, with its semi-rigid connections, is not adequately covered by AS 4100 (Standards Australia 1998), or in fact any structural steel design standard in the world.

A simplified 2D model of a scaffolding formwork system is shown in Fig. 1. In this figure, the nomenclature used for systems of this type is shown. Of particular importance are the top and bottom sections (called "top jack" and "base jack"). These sections are variable in length depending upon the unevenness of the ground on which the structure sits and the variable height of the timber formwork at the top. They are also loaded eccentrically at the top depending upon the arrangement of the timber formwork support. They are often loaded eccentrically at the bottom as well as shown in Fig. 1 depending upon the base plate and its location on uneven ground. Assessment of the stability of the top and bottom jacks alone presents several challenges due to the fact that these levels in the structure are normally unbraced although the intermediate lifts are normally braced. The bracing itself is often eccentrically connected and not as effective as may be assumed in conventional structural steel design. The spigot joint, used for rapid assembly, is also shown in Fig. 1 in the main lift.

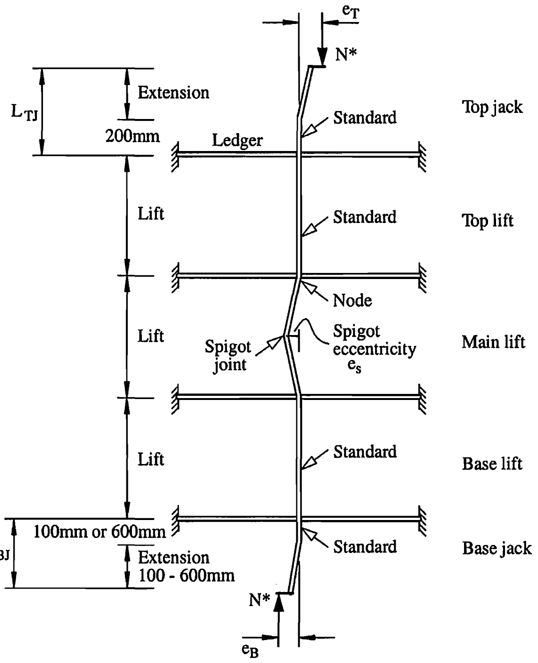

Figure 1: Simplified 2D Model of a Scaffolding or Formwork System

In practice, the systems are three dimensional with a series of frames of the type shown in Fig. 1. In the case of scaffolding, there are normally two planes with the inner plane propped from the façade of the building under construction. Scaffolding systems normally extend along the face of the buildings to which they are attached. However, in formwork systems, the configuration may contain many planes and extend significantly in 2 orthogonal directions.

The 2D and 3D stability of scaffolding systems has been investigated by Godley and Beale (1997) who reported the importance of sway modes even for structures attached to the face of a building by props. Further, Godley and Beale also reported that the sway stability was found to be sensitive to the connection (coupler) semi-rigid stiffness. However, in the Godley and Beale study, the predicted deflections were approximately half those measured in prototype tests using either 2D or 3D analyses. As stated by Godley and Beale, "there are significant discrepancies between the observed deflections and the experimental results. It is thought that the reason for this is the looseness at the joints, and in particular at the upright splices (spigot joints) which have not been taken into account".

The Super Cuplok scaffolding/formwork support system has been developed by Boral Building Services in Australia. It is based on the Cuplok system developed in the United Kingdom, with the difference being that Super Cuplok is made of high strength steel, compared with mild steel as is the case with Cuplok. Both Cuplok and Super Cuplok are unique in that their assembly requires no nuts, bolts or specialised types of tools. Connections between vertical members, called standards, are made using a spigot joint. Nodal connections are made by means of a cup joint, hence the name Cuplok. The cup joint is capable of connecting four members into a standard within a single connection. These members can be horizontal members or diagonal bracing members.

A spigot joint is a type of joint in which two tubular members are connected by a smaller diameter tubular section. The smaller section sits inside the two larger sections, and holds them together if subjected to tension via locking pins. The joint can also resist bending via the flexural action of the spigot. For reasons of practicality and robustness, it is essential that there is a small difference between the internal diameter of the standards and the external diameter of the spigot. The problem with the spigot joint is that there is the tendency for the connected elements to become out-of-plumb, due to the necessary difference in diameter between the standards and the spigot. It is believed that the lateral displacement which is a result of this could have a significant effect on the strength and stability of a frame incorporating spigot joints. Specifically, the difference between the outside diameter of the spigot and the inside diameter of the standards allows some horizontal movement in the joint, which translates into an eccentricity in the vertical standards. It is believed that this eccentricity will, under loading, lead to second-order bending moments in the standards and spigot. These bending moments could be significant, and hence could have a substantial effect on the strength and stability of scaffolding and formwork systems based on the Cuplok system. This expected effect is the primary focus of this paper.

2. METHODS

This paper quantifies the effects of spigot joints within the Cuplok formwork and scaffolding system. Three basic methods are used in order to determine ultimate working loads for various frame structures. These methods are:

1. Linear-elastic analysis based on the Australian Steel Structures Standard AS 4100-1998 (Standards Australia 1998).
2. Advanced elastic-plastic analysis using the computer program NIFA (Non-linear Inelastic Frame Analysis) (Clarke 1994).
3. Tests conducted on frames.

2.1 Linear-elastic Analysis

The method involves analysing a standard bay of the scaffold structure using a linear-elastic analysis as specified in AS 4100-1998. This stage was completed as part of a consultancy for Boral Building Services by the University of Sydney (CASE, 1998). Design charts were produced, showing the maximum allowable working load for each scaffolding configuration. Second-order moments were accounted for by using the moment amplification factor for a sway member, δ_{sway}, as specified in Clause 4.4.2.3 of AS 4100-1998. The maximum allowable load (equivalent to the computed ultimate load/1.5) was calculated as the minimum of the maximum loads determined in the following calculations:

1. Column capacity of standard.
2. Beam-column capacity of standard (at end and centre).
3. Bending capacity of spigot.
4. Column capacity of jack (threaded section and at standard).
5. Beam-column capacity of jack (threaded section and at standard).

The calculations were undertaken using the computer program Mathcad and will be referred to later in this paper.

2.2 Advanced Elastic-plastic Analysis

The method looks at the strength and stability of a standard bay of the Cuplok system. The computer program NIFA (Non-linear Inelastic Frame Analysis) (Clarke, 1994) is used for this purpose. NIFA is capable of undertaking a two-dimensional advanced analysis as described in AS 4100-1998 Appendix D. It accounts for member cross-section geometry, imperfections within a frame, various stress-strain curves, concentrated elastic restraints and residual stresses. By using the method of finite elements, it is able to accurately determine forces within the elements of a structure, to a greater degree of precision than both first- and second-order linear elastic analysis.

2.3 Full-scale Tests

The final method for determining the failure load of the Super Cuplok formwork/scaffolding system was by physically testing a number of standards as part of sub-assemblages. The sub-assemblages were braced so that sway deflections were not considered. The base jacks and top jacks were kept short deliberately so that Items 4 and 5 in Section 2.1 above were not the controlling limit states.

3. SPIGOT JOINTS

3.1 Spigot Geometry and Eccentricity

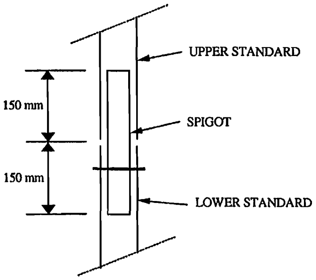

Figure 2: Components of a Spigot Joint

For the Super Cuplok system, the upper and lower standards are 48.3 x 4.0 CHS (Circular Hollow Section), and the spigot is a 38.2 x 3.2 CHS as shown in Figure 2. The spigot section, which is 300 mm long, sits in the middle of the two larger diameter hollow sections, with 150 mm embedded in each of the standards. Both tubes are connected to the spigot by locking pins, the upper side of the joint having a removable pin and the lower side having a fixed pin. The locking pins and associated holes have not been designed to take any of the axial load.

The nature of the spigot joint is such that there is the potential for movement of one vertical element relative to the other. In the context of a frame, this means that the connected standards, at the location of the joint, will experience lateral movement when subjected to even a minor load. The magnitude of this displacement depends upon the diameters of the standards and spigot, height of the lift (that is, the length of the standard from ledger to ledger), and the position of the spigot joint within the lift. For the standard and spigot sizes specified above, the maximum spigot eccentricities, assuming that the spigot joint is in the centre of the lift, have been determined as set out in Table 1.

LIFT (metres)	ECCENTRICITY e_s (mm)
1.0	6.17
1.5	7.66
2.0	12.59

Table 1: Assumed Spigot Eccentricities

Theory suggests that an axial load applied through a standard (containing a spigot joint) will cause the joint to assume the position of maximum eccentricity. It is not possible to predict which direction the spigot will move, because of the fact that the connection is tubular. It is then predicted that the induced eccentricity will lead to second-order moments due to the PΔ effect. A bending moment of magnitude Pe_s will be added to the pre-existing bending moment caused by the eccentric loading at the ends. This additional moment will in turn will be transferred to adjoining ledgers according to the relative flexural stiffness of these members.

It is believed that the additional PΔ bending moment will reduce the axial loading capacity of the frame. The purpose of these investigations is to determine how much the load capacity is reduced for a given frame configuration.

3.2 Load Transfer at Spigot

Before it is possible to accurately model a frame containing a spigot joint, it is necessary to determine the behaviour of the joint. This has been achieved by drawing free-body diagrams which show the forces acting on each component of the joint as shown in Figure 3.

The nature of the spigot joint is such that all axial load is transmitted through the standards and not the spigot. This means that, in theory, the pins do not carry any load under normal service conditions. This is achieved by ensuring that the holes for the pins are large enough so that at no stage does the loading cause the pins to bear on any of the elements. Instead, axial load is transmitted by the upper standard bearing directly on the lower standard. The resulting free body diagrams are shown in Fig. 3.

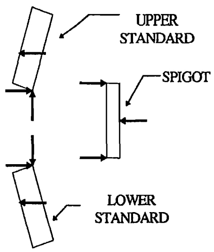

Figure 3: Free-Body Diagram of Spigot Joint

3.3 Development of the Spigot Joint Model

In order to be able to effectively analyse the basic frame incorporating a mid-height spigot joint, it was necessary to devise a way of modelling the spigot joint for use in the computer program NIFA. The main difficulty in developing a model for the spigot joint for use in the NIFA computer model was the fact that the load transfer at the joint is not fully continuous through any element. Vertical load is transferred through the standards, but bending is taken through the spigot. This presented the challenge of how to represent the joint while at the same time providing accurate load paths for the axial force and bending moment acting on the joint.

The model adopted contained two members connected by a pin joint, which represented the standards as shown in Figure 4. Alongside these members was a single member, connected to the standards at the top, centre and bottom, to represent the spigot.

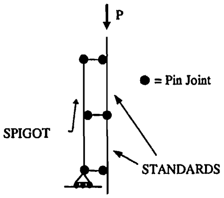

Figure 4: Spigot Joint NIFA Model

As Figure 4 shows, the spigot element is entirely rigid. It is connected to the standards by short, high EI and EA members which are only capable of transferring lateral force to the spigot. The only force transfer is horizontally through the short connecting elements, and vertically through the standard at the pin joint. As the standards bend relative to each other due to a vertical load P, the spigot is placed into bending due to the opposite lateral forces acting on it at the top/bottom and centre. At the same time, all of the vertical load P is being transferred directly from one standard to the other. The partial pin connections between the standards and the spigot ensure that none of the vertical load is passed over to the spigot. The level of bending force acting on the spigot depends on the degree to which the standards are out of plumb, and the value of the force P.

4. Testing

4.1 Test Rig Configuration

The test rig itself was designed with two considerations. Firstly, it was believed that a full frame rather than a single isolated standard would produce results more directly applicable to service conditions. Secondly, the size of the scaffold was limited by the available space and also by the size of the loading frame to which the hydraulic jack was mounted.

The scaffold frame, when viewed in plan, was 2.44 metres square as shown in Figure 5. One of the corners was placed under a hydraulic loading jack. At this corner, there was a threaded top jack at the top and a threaded base jack at the bottom and either a spigotted standard or a spigotless standard, depending on the test being undertaken. The other three corners stood on base jacks and were comprised of spigotless standards. The threaded base jack below the loaded standard and the one opposite were located on a steel support beam embedded in the floor of the laboratory. The other two threaded base jacks sat on the concrete floor of the laboratory. Each side of the frame had a top and bottom 2.44 metre ledger connected into the upper and lower cup joints. Each plane frame was braced with a 3.16 metre diagonal element. Once fully constructed, the frame was self supporting and did not require any additional propping.

In order to ensure that the frame was sturdy, all cup joints were knocked closed using a hammer. Ledgers and braces were hit firmly into position to ensure each joint was as rigid as possible. The four standards were simply placed over the bottom jacks. They provided no upward vertical restraint, which meant that the standards were capable of lifting off the jacks if the uplift force was sufficient. The jacks were all fully adjustable using a large wingnut.

4.2 Test Procedure

Testing of frames was undertaken by loading the standard axially using the hydraulic jack mounted on the loading frame. All measurements of horizontal deflections were achieved using two electronic theodolites positioned in an orthogonal coordinate frame as shown in Figure 5. One instrument was located perpendicular to the test rig frame, and the other to the side of the frame, at an angle of 90 degrees relative to the loaded standard. These instruments were capable of taking angular measurements to an accuracy of one second of arc. The angle readings, when combined with the known distances from the instruments to the loaded standard, enabled the calculation of a deflection perpendicular to the line of sight of the instrument. The distance from each theodolite to the standard was measured by taking multiple readings using a tape measure.

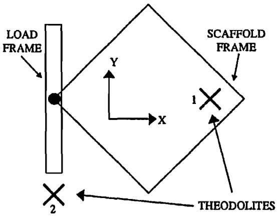

Figure 5: Test Arrangement, Viewed in Plan

The standards were loaded in increments of 2.3 kN in the early stages of the tests, and as deflections became noticeably larger this was decreased to 1.1 kN. Deflection angles at the spigot were recorded at each load increment. One assumption made here was that the change in distance from the theodolites to the loaded standard (due to lateral movement of the spigot) did not significantly impact upon the accuracy of the results. After each test, photographs of failed components were taken, and relevant observations made regarding the behaviour of the frames before, at and after failure. These will be presented with the discussion of results in a later section.

4.3 Test Specimen Configuration

Five tests were conducted on both spigotted and spigotless standards. The first three tests were on spigotted standards, and the final two were on spigotless standards. Table 2 summarises the testing program.

Test	Test Specimen Configuration	Load Eccentricity (mm)	Maximum Test Load (kN)	NIFA (kN)
1	Spigotted standard, concentrically loaded	0	78.41	-
2	As for Test 1, but supported on pin at base	0	72.37	73.09
3	As for Test 2, but eccentrically loaded at base frame	27	52.27	56.24
4	As for Test 2, but with spigotless standard	0	72.73	72.63
5	As for Test 4, but eccentrically loaded	27	54.55	60.52

Table 2: Test Program, Results and Theoretical Comparisons

Test 1 was conducted on a concentrically loaded spigotted standard. The bottom jack supporting the loaded standard was placed square on the supporting beam, with no ball-and-plate system to idealise the reaction force. As a result, the bottom jack acted as a semi-rigid restraint. The purpose of this test was to gain an indication of the behaviour of the frame system, and to give an indication as to the probable mode of failure of the standard. The results of this test provided guidance for subsequent tests.

Test 2 was the same as Test 1 except that the bottom jack was supported on a ball-and-plate joint. This meant that the jack acted as a pin at its base. No moment transfer was possible at this joint. This situation could be called the ideal situation because there are no external moments acting. The only load acting on the standard was the vertical axial load at the top plate. Any internal moments are the result of the P-Δ effect, caused by an eccentricity in the standard.

Test 3 was significantly different to Tests 1 and 2 because the vertical load was applied at an offset to the standard's centreline. In this test, the eccentricity was 27 mm. This value was used instead of a larger value (such as 55 mm, as specified by AS 3610-1995) because of the concern that the top plate might bend before the standard failed. Again, in this test, the bottom jack was supported on a ball-and-plate arrangement.

Test 4 was conducted on a spigotless standard. It was identical to Test 2 in all other respects. Test 5 was also on a spigotless standard and was identical to Test 3 in all other respects.

4.4 Test Results

The results of each of the five tests conducted are presented separately. For each test, an overall load vs total lateral deflection graph is shown, as well as details of the initial deflection and mode of failure. The full results of each test can be found in Enright (1998) and Harriss (1998).

4.4.1 Test 1

Figure 6 below shows the load vs deflection relationship for Test 1. It can be seen that after an initial large deflection, movements settled down until just prior to failure. It also shows that a deflection of 2 mm occurred as a result of the initial small load which was generated when the hydraulic jack and the top jack of the scaffold came into contact. This is in addition to the approximately 12 mm eccentricity which existed before *any* loading was applied to the standard. Taking this one step further, the spigot did not clearly stabilise until a deflection of about 7 mm was recorded, at a load of 10 kN. Again, this is in addition to the initial 12 mm eccentricity. It could be said therefore that the actual "initial" eccentricity of this standard was in the order of 19 mm.

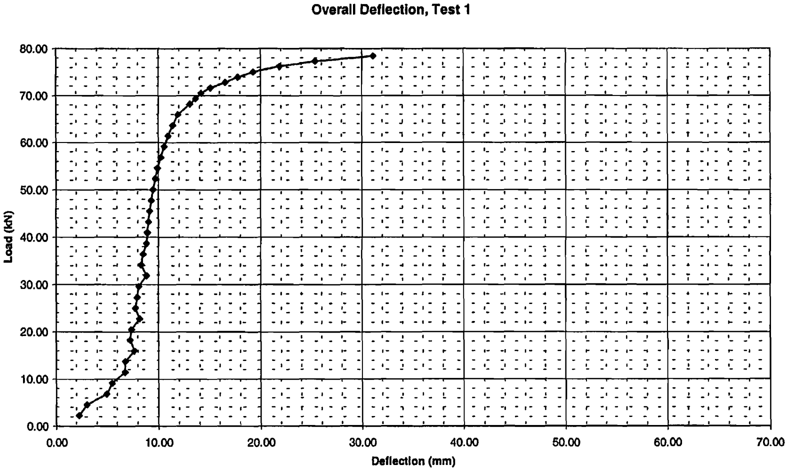

Figure 6: Load-Deflection Graph for Test 1

Upon loading, the standard moved laterally by about 5 mm, most of this occurring before 15 kN was reached. It is thought that this happened because the standard moved to assume its most rigid position under load. In the load range 15-35 kN, the standard experienced some instability, with lateral movements in the order of +/- 1 mm in the x-axis of the test coordinate frame (refer Figure 12). In itself this movement is small, but in comparison with the stability shown at loads above 35 kN, its significance becomes apparent. It is believed that the instability was caused by the fact that because the standard was loaded concentrically, it was possible for it to deflect in virtually any direction. The instability was in effect the standard determining which way it should deflect as the load increased.

Above a load of 35 kN, lateral deflections became quite stable. In the x-axis direction the standard continued to deflect in the same direction as it had been, but in the y-axis direction the deflections reversed direction, passing through the initial zero point. Once the load passed about 65 kN, deflections in both axes became considerably more significant. Past 75 kN they accelerated dramatically, until failure occurred at 78.41 kN.

The mode of failure was bending failure of the spigot element at the point where the upper and lower standards meet. Failure was in the direction parallel to the ledger aligned in the (+x, +y) quadrant of the test coordinate frame (see Figure 5). In addition to the yielding of the spigot, the top and bottom ledgers yielded in bending at the standard-ledger joint. This was not a direct result of the loading, however, Rather, the excessive lateral deflections of the standard caused by the yielding of the spigot led to the ledgers deforming plastically.

4.4.2 Test 2

The load vs deflection relationship for Test 2 is shown below in Figure 6. After an initial deflection of 2.5 to 3 mm, lateral movements settled down until just prior to failure. This is in addition to the 6 mm eccentricity which existed before the standard was loaded.

Once loading was applied, the standard moved to assume a deflected position at about 2.5 mm from the initial position. This deflection stabilised at about 5 kN. In the load range 5-50 kN, deflections remained stable. Above 50 kN, the rate of deflection accelerated to failure at 72.73 kN.

It is interesting to note that deflections in the x-axis are significantly less than those in the y-axis. In addition, the direction of failure was identical to that in Test 1. This has no implications for the results of these tests, other than they show that the standards seem to prefer to fail in the direction of the ledgers. These are the weakest directions because torsional restraint from the perpendicular ledgers is at a minimum.

Like Test 1, failure occurred when the spigot element yielded. As a result of excessive lateral deflections at failure, both the top and bottom ledger in the plane of failure yielded in bending at the nodes on the failed standard. In all respects failure was identical to Test 1.

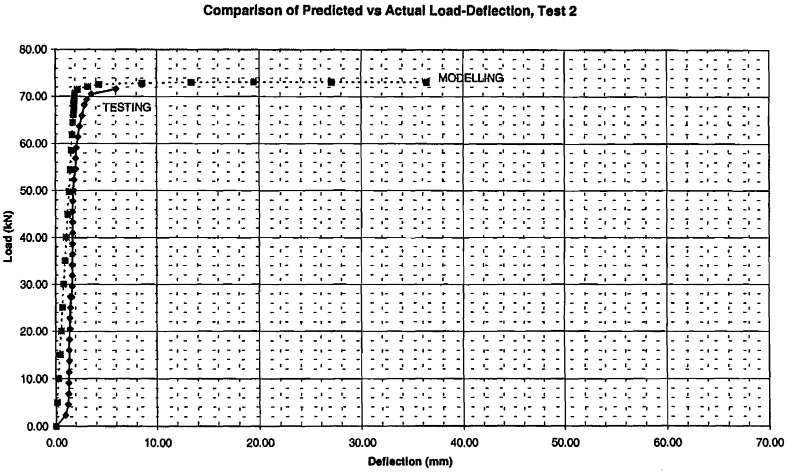

Figure 7: Comparison of Load-Deflection Curves - Test 2

4.4.3 Test 3

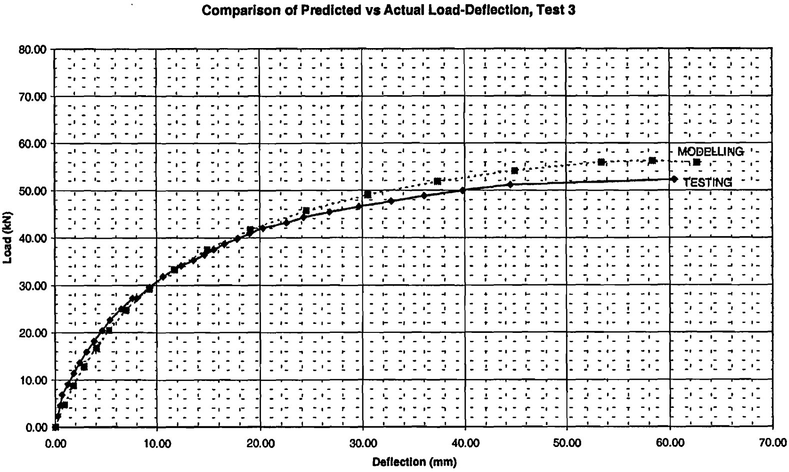

Figure 8: Comparison of Load-Deflection Curves - Test 3

The mode of failure of Test 3 was the same as Tests 1 and 2, the only difference being that the process was accelerated due to the eccentricity of the load. Failure occurred due to yielding of the spigot at 52.27 kN, which is approximately 30% below that of the concentrically loaded cases. A comparison of two of the failed spigots shows that the type of failure was virtually identical in both cases. The axis of the holes designed for the locking pins had no effect on the ultimate direction of failure.

4.4.4 Test 4

Deflection readings were taken at the centre of the standard and are shown in Figure 9. Since there was no spigot, there is no initial lateral deflection to report. Deflection readings recorded during the test indicated a relatively consistent increase in the eccentricity. A sharp change occurred at about 64 kN. Deflections increased rapidly, and failure occurred at mid height at 72.73 kN. Failure was through yielding at mid-height of the standard.

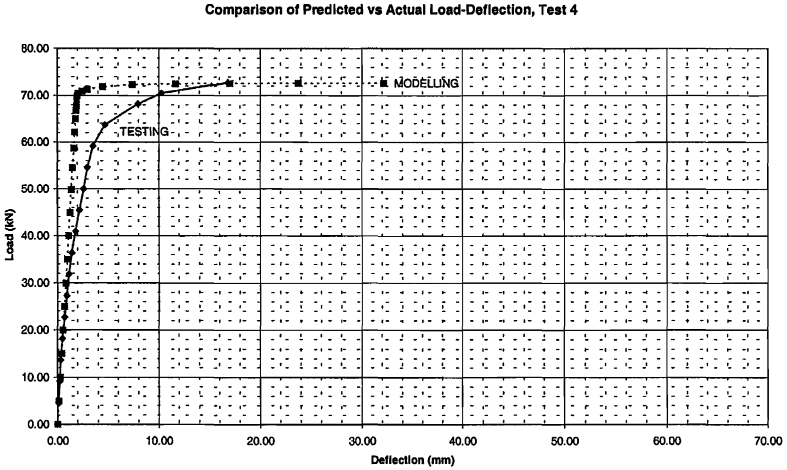

Figure 9: Comparison of Load-Deflection Curves - Test 4

4.4.5 Test 5

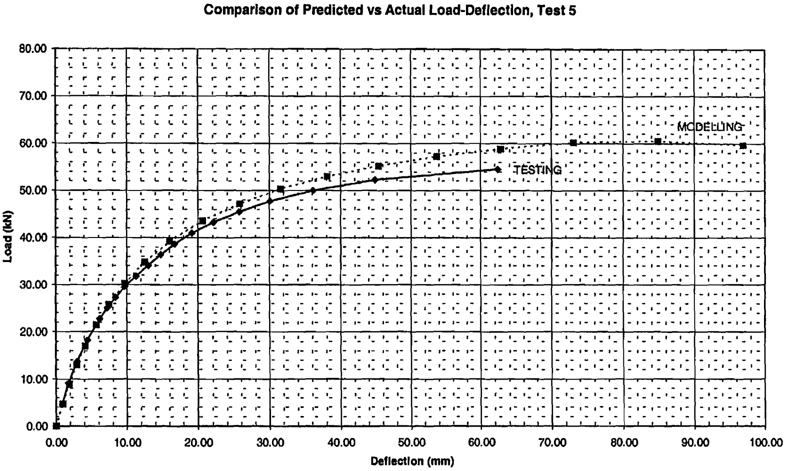

Figure 10: Comparison of Load-Deflection Curves - Test 5

In Test 5, large deflections were observed from the start. Consistent with these results, this standard failed at a load of 54.55 kN, slightly above that at which the spigotted standard failed in the third test. Failure occurred when the standard yielded just above mid-height.

4.4.6 Coupon Tests

Coupon tests were conducted on specimens cut out of the various elements of the Cuplok system. The table below shows the eight tests undertaken, and where the particular specimens were taken from. It also shows the nominal and actual yield stresses obtained from the tests.

	ELEMENT	NOMINAL f_y (MPa)	ACTUAL f_y (MPa)
1	Ledger	350	435
2	Upper Standard	450	510
3	Lower Standard	450	500
4	Spigot 1	400	496
5	Spigot 2	400	500
6	Spigot 3	400	497
7	Spigotless Standard 1	450	515
8	Spigotless Standard 2	450	521

Table 3: Results of Tensile Coupon Tests

5. Computer Modelling

The results achieved in computer modelling have been divided into two sections. The first compares the results of the NIFA analyses with each of the scaffold tests previously described. The computer modelling for each test are based on the frames shown in Figure 11 and represent as closely as possible the actual test conditions. The second section (5.2) is a sensitivity analysis of significant variables within the system, the major ones having already been described. These were load eccentricity, spigot eccentricity, frame configuration and jack length.

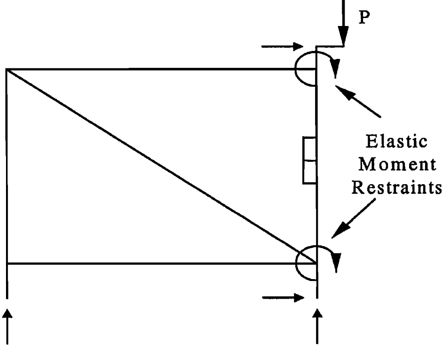

Figure 11: Frame for Computer Modelling

5.1 Comparison with Test Results

NIFA has been used to model Tests 2 to 5, using actual yield stresses (Table 3), actual jack lengths and with all other dimensional data identical. Load-deflection curves for the NIFA predictions are plotted in Figures 6-10. These graphs allow a direct comparison between the observed load-deflection relationship and those predicted by NIFA. The failure loads predicted by NIFA are given in Table 2.

When the load-deflection curves of the tests are compared with those obtained from the computer modelling, it is apparent that there is a high degree of correlation, to a lesser extent in Test 4 than in the others. Failure loads have been matched reasonably accurately, as have deflections over most of the load range.

5.2 Sensitivity Analysis

Once it was ensured that the computer models were of sufficient accuracy for prediction purposes, a sensitivity analysis using NIFA was conducted in order to illustrate the effects of altering key variables within the frame. The frame used as a base for this purpose was identical to that used in Test 2, shown in detail as Figure 11. That is, all results of the sensitivity analysis refer to the difference between the modified frame and the frame used in Test 2. This is referred to as the base case. All variables were modified one at a time so as to give an accurate representation of what effect each change has. The results of this analysis are presented below. The frame model used for internal standards is shown in Fig. 12.

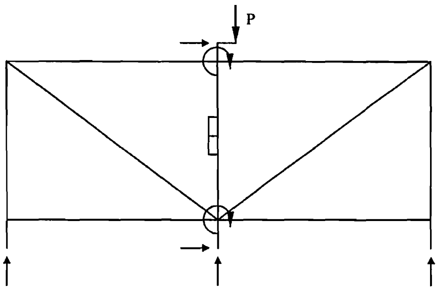

Figure 12: Final Frame for Internal Standard

	Failure Load (kilonewtons)	Change (%)	Deflection (mm)	Change (%)
Base Case (Corner Standard)	73.09	**0.00**	27.02	**0.00**
Removal of Spigot Joint	75.38	**+3.13**	26.86	**-0.01**
27 mm Load Eccentricity	59.67	**-18.36**	28.00	**+3.63**
Edge Standard	79.43	**+8.67**	27.07	**+0.19**
Internal Standard	102.73	**+40.55**	5.20	**-80.75**
No Torsional Restraint	66.33	**-9.25**	26.95	**-0.26**
100 mm Jack Extension (minimum)	78.39	**+7.25**	20.20	**-25.24**
600 mm Jack Extension (maximum)	41.44	**-43.30**	66.66	**+146.71**
6 mm Spigot Eccentricity	65.34	**-10.60**	44.28	**+63.88**
12 mm Spigot Eccentricity	58.85	**-19.48**	43.37	**+60.51**
No Lateral Restraint at Point of Load	64.83	**-11.30**	26.81	**-0.78**

Table 4: Results of Sensitivity Analysis

6. DISCUSSION

6.1 Comparison of Test Results with NIFA Predictions

The comparison of the load-deflection curves indicates that NIFA is significantly more accurate in predicting failure loads than it is in deflection, in particular deflections at failure. Prior to failure, however, the correlation between test deflections and predicted deflections is good. It is only in the final stages of loading that NIFA tends to have difficulty in predicting deflections. There is no obvious trend suggested by the results, that is, the program does not regularly overestimate or underestimate deflections. The sample size of four is too small to draw definite conclusions, however, in the case of predicting failure loads, NIFA is reasonably accurate. In all four tests, it manages to predict the failure load within 11.0% of the measured value, in one case within less than 1%. Again, it does not consistently overestimate or underestimate failure loads. It is expected that the causes of the errors are due to factors which cannot easily be controlled. These include initial out-of-straightness of standards, imperceptible variations in load eccentricity and possible variations in both the geometrical and material properties of the elements within the frames. Any or all of these could have been present in the tests, and any one of them is capable of having an effect on the results. That is, the computer program is providing the best prediction it can given the assumptions the model is based on. If the initial assumptions are incorrect, these will flow through and have an effect on the final results. The magnitude of the errors suggests that the initial assumptions were quite accurate.

Having said that, in general the correlation between the computer modelling and the test results is good. If only failure loads are to be considered, the correlation is very good. The computer models appear to be accurate enough for the purposes of determining the effects of altering key variables on the strength and stability of the Super Cuplok system.

6.2 Sensitivity Analysis

The results of the sensitivity analysis (shown in Table 4) indicate that the system is highly susceptible to some variables but barely susceptible to others. For instance, it is highly sensitive to jack length, less so to load eccentricity, and only slightly affected by frame configuration, in particular the removal and addition of torsional restraints at the top and bottom nodes. The most significant result is that the inclusion of a spigot joint has an almost negligible effect on both the strength and stability of the system. Taking the spigot joint out of a standard only increases the load capacity by 3.13%, with no significant change in deflections. This is believed to be so because the spigot itself does not have to carry any axial load. Instead, it is in pure bending. As a result, even though the spigot is a weaker section than the standards it joins, because it does not have to take any of the axial load which the standards *do* have to take, it can withstand a significantly higher bending moment.

The situation becomes more complex, however, when an initial spigot eccentricity is considered. An initial spigot eccentricity of only 6 mm leads to a predicted reduction in load carrying capacity of 10.60%, and an increase in deflections of 63.88%. Increasing this initial eccentricity to 12 mm gives figures of -19.48% and +60.51% for load capacity and deflections, respectively. Measurements made prior to testing each frame showed that an initial spigot eccentricity of 6 mm is possible in a practical situation. These large reductions in strength capacity are the direct result of the increased second-order moments induced by the eccentricity. Interestingly, though, no such reduction in capacity was observed during testing.

The results also indicated a high degree of sensitivity to top and bottom jack length. Changing the jack extensions from their minimum value of 100 mm to their maximum value of 600 mm has the cumulative effect of lowering load capacity by 47.14% and increasing mid-height lateral deflections by 230%. This is due to the increased effective length of a standard with its jacks extended.

Load eccentricity also had a substantial effect on the system. A 27 mm load eccentricity had the effect of lowering load capacity by 18.36% and increasing deflections by 3.63%. Again, this is due to second-order bending moments induced by the off-centre loading. Frame configuration also has an effect. Changing a standard from a corner standard to an edge standard provides an increase in strength of 8.67%, and a negligible effect on deflections. Changing from a corner to an internal standard increases load capacity by 40.55% and decreases mid-height deflections by a large 80.75%. These effects can be explained by the restraint provided to the standard in each of the three cases. The results show that connecting ledgers in bending provide much more restraint than connecting ledgers in torsion. It has been of interest to note that in the three tests where the standard potentially could have failed in any direction, all three tests produced a consistent direction of failure. This indicates that, in the configuration tested, the system has a significant weakness in one plane of the frame.

Returning to the most significant result of this paper, it appears that the spigot joint within the Super Cuplok system is very well designed. Its addition has a very small effect on the strength of a standard, and virtually no effect on its deflections. This means that the spigot joint does not have as much of an effect as was first expected.

6.3 Comparison with Linear-Elastic Analysis

Comparison with the results obtained in the linear-elastic analysis showed that designing in accordance with AS 4100-1990 is, in general, conservative. Predictions of working load capacity range from 30 to 50 kN, with most lying closer to the lower end of the range. This corresponds to an ultimate load of 45 to 75 kN, depending on the frame configuration (because ultimate load = 1.5 x working load). The results also indicated that jack extension had a relatively minor effect on load capacity. Table 5 below shows predicted ultimate failure loads (in kilonewtons) as given by AS 4100-1998.

	AS 4100 (kN)	**NIFA (kN)**
Edge Standard	47.10	79.43
Internal Standard	53.70	102.73

Table 5: Comparison of NIFA and AS 4100 Predictions

The two cases above are the only two cases which can be compared directly. The reason for this is that the NIFA analysis is based on a corner standard, but the linear-elastic AS 4100 analysis is based on edge and internal standards. In the two cases which can be compared, it can be seen that the AS 4100 predicted failure loads are substantially below the loads predicted by NIFA.

Another aspect of the AS 4100 predictions which can be examined are the sensitivities suggested by the linear-elastic analyses. According to AS 4100, jack extension has virtually no effect on failure load. It predicts a capacity of 47.1 kN with a top jack extension of 100 mm, which is only decreased to 46.5 kN at 600 mm. A change in load eccentricity has a similarly small effect. A concentrically loaded edge standard has a capacity of 47.1 kN, while moving the load out to 25 mm eccentricity reduces it to 43.05 kN, a reduction of 8.6%. This compares with an 18.36% reduction predicted by NIFA for a corner standard (see Table 5).

In summary it appears that the linear-elastic analysis is significantly more conservative than the NIFA analysis for the system with a spigot joint. This is a direct consequence of the fact that the AS 4100 analysis assumes the maximum spigot eccentricity in Table 1. In the tests, the eccentricity was minimal.

7. CONCLUSIONS

These investigations conducted on the Super Cuplok scaffolding and formwork system aimed to determine the effect of spigot joints on the strength and stability of members subject to combined bending and compression. Five tests were completed, three on spigotted standards and two on spigotless standards. In addition, the computer program NIFA (Non-linear Inelastic Frame Analysis) was used to model a number of cases where key variables were altered.

The testing program showed that the mode of failure for all three spigotted standard tests was through yielding of the spigot in bending. In the standards without a spigot, failure occurred when the standard yielded in bending. It was also observed that framing ledgers bent at failure, however this was a result of excessive deformations of the standard during failure.

A model for the spigot joint was developed and implemented within the NIFA program. It was found to work quite well in simulating the forces acting on both the standards and the spigot as loading was applied. Coupon tests were conducted to determine the actual yield stresses of the elements of the test frame. These results were used in the computer analysis.

The computer models were found to be quite accurate when compared to the test results. Predicted failure loads were within 11% of the observed load, but deflections were found to differ significantly from those observed. Computer modelling was used to determine the effect of modifying key variables within the system. The factors which had the greatest effect were jack length, spigot eccentricity and load eccentricity. Frame configuration was found to have a minor effect in general. The most important result, however, was that the inclusion of a spigot within a standard had only a minor effect on the strength of the standard, and no effect on its deflections.

It can be concluded from these investigations that spigot joints, under ideal conditions, do not present a problem with regard to either the strength or stability of the Super Cuplok system. However, it has been found that an initial spigot eccentricity can have a substantial effect on both the failure load and deflections of a standard. Under practical operating conditions, it is possible that a spigotted standard might be erected in such a way that there is such an initial spigot eccentricity. In this case, it is expected that the capacity of the system will be reduced.

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