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DEVELOPMENT OF A PORTAL FRAME SYSTEM ON THE BASIS OF COMPONENT TESTING

J. Rhodes[1] and R. Burns[2]

Abstract

This paper describes tests carried out on various components of a cold formed steel portal frame system. The main aims were to validate the design, initially set up on the basis of finite element software, to check and modify connection details if required, and to obtain experimental stiffness values which could be incorporated into the design software. Test series were carried out to determine the strength and stiffness of Stanchion bases, Rafter and Apex layouts and haunch configurations, and these tests are described in the paper together with the test results.

Introduction

Metspec PLC manufacture a wide range of cold-formed steel products, and have interacted with the University of Strathclyde for many years on development and testing of a variety of components and systems. In this paper a number of tests carried out on components of cold-formed steel portal frames at the University of Strathclyde for Metsec PLC , with the aims of assisting the development of the system, checking connection details and modifying these if required, and validating the design software.

The portal frame system examined is produced using pairs of Metsec standard channel sections bolted back to back for stanchions , rafters and knee braces

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together with plates and angles to form the connections between members. A general layout of a portal frame in the range is shown in Figure 1.
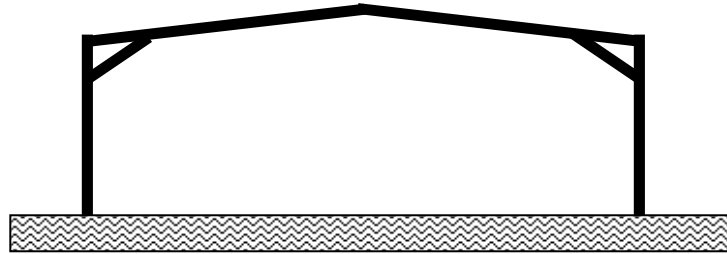

Figure 1. General Layout of Portal Frame under Consideration

The base-plate connections are angle sections which may or not have stiffeners attached. The rafters are connected to knee braces and haunches using angles and plates. The rafters are connected at the apex through a plate with 8 bolts in each rafter/plate connection.

All of these connection areas are potential sources of weakness in the system and one major aim of the testing process was to examine the behaviour of the connections and modify these if necessary.

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Tests on Stanchion Bases

A series of 6 tests were carried out on stanchion bases. The aims of these tests were to determine the capacities of the base plates in bending. The relevant design specification states that the base plates should be able to withstand a moment equal to 25% of the capacity of the Stanchions.

Sets of two tests were carried out on each of three different stanchion sections. For each base two alternative designs were tested, one which consisted of basic angle sections which bolted to the webs of the stanchion channels, and another which had stiffeners attached to the angles to prevent any opening or closing of the 90° angle between the legs of the angle sections.

To facilitate testing each set-up had two bases connected together to provide a symmetrical layout The elements tested consisted of two stanchions connected at the bases and extending over a total span between end supports of 3.5 metres (i.e.

1.75 metres per stanchion). The end supports were designed to provide pin-end conditions while permitting free axial movement and preventing any tendency for the stanchions to twist or rotate at the supports. These conditions were produced via a cradle arrangement for each end support. The cradle arrangement was initially designed for the apex tests, in which it was imperative that free axial displacements were allowed, but it was decided that they would be equally useful for the stanchion base tests, in which the applied loading will cause secondary axial movement effects. A central load applied to the bases then produced a simple three point bending situation from which the base moment could easily be determined. A diagrammatic layout of the test set-up is shown in Figure 2 together with details of the cradle supports (as set-up for apex tests). The tests were carried out on a Tinius Olsen electromechanical test machine.
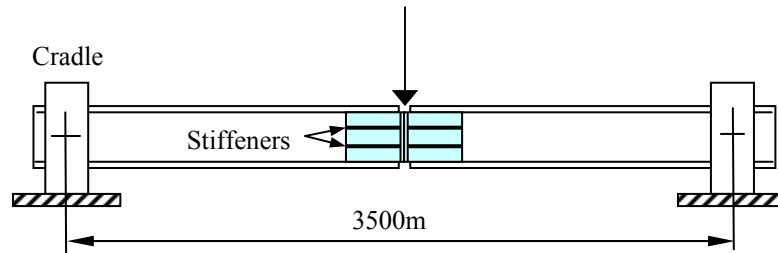

Figure 2(a) Set-up for Stanchion base tests
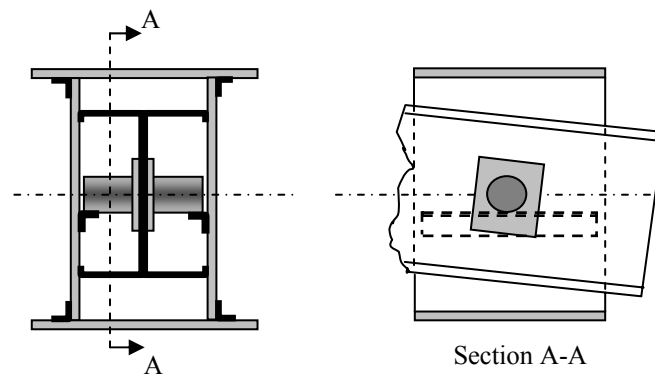

Figure 2(b) Diagrammatic set-up of cradle supports

The stanchion bases tested and the failure loads sustained, are specified in Table 1, together with the failure loads required to attain 25% of the stanchion moment capacity. In the table the 6 digit codes for the stanchion specify the C section depth in mm, followed by C to denote a channel section, followed by a two digit

number specifying the nominal material thickness in mm times 10. For example "302C29" describes a 302mm deep channel of 2.9mm thick material.

Table 1. Details of Specimens for Stanchion Base Tests

Test No.	Stanchion	Base Configuration	Failure Load kN	Required failure load kN
1	302C29	Unstiffened	34.49	23.4
2	302C29	Stiffened	70.76	23.4
3	342C32	Unstiffened	40.50	32.2
4	342C32	Stiffened	74.32	32.2
5	402C32	Unstiffened	53.58	39.2
6	402C32	Stiffened	97.01	39.2

Typical load - central deflection curves for tests on stiffened and unstiffened base plates are shown in Figure 3.
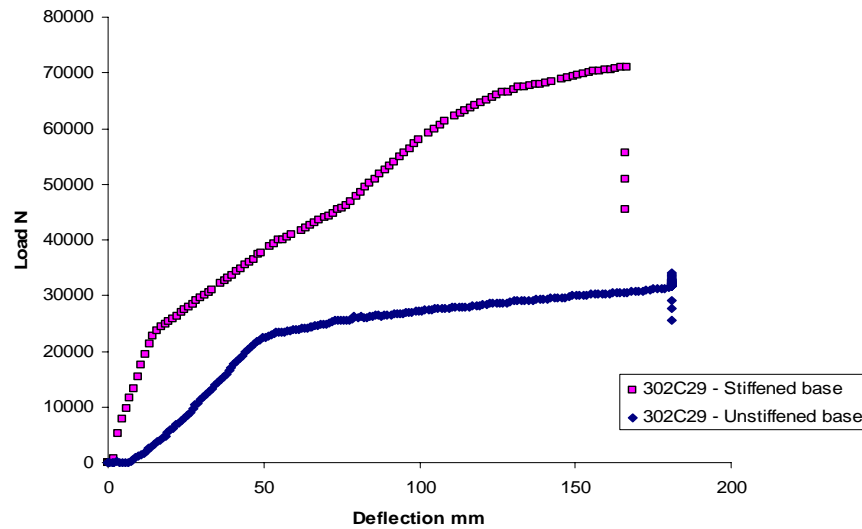

Figure 3. Load-deflection behaviour under stanchion base tests

In this case the stiffened base took more than twice the loading taken by the unstiffened base, and was also substantially more efficient in resisting rotation, as witnessed by the load-deflection behaviour. The same type of behaviour was observed in all tests. The modes of failure for stiffened and unstiffened bases were completely different. All unstiffened bases failed very gradually with gross

deformation of all the angles. For all stiffened bases the stiffeners reduced the gross deformation possibilities and in all cases this resulted in failure arising by sudden fracture of the bolts connecting the bases. This type of behaviour was somewhat frightening by its suddenness and its dynamic onset, but it did not occur until high loads had been obtained From Table 1, however, it may be observed that all the unstiffened bases, while less strong than the stiffened bases, superceded their design requirement by at least 25%. Since the frame design procedure treats the stanchion bases as simply supported the unstiffened bases are perfectly adequate for their specified purpose.

Tests on Rafter Strength and   Stiffness

A series of six tests were carried out on rafter components to determine the strength and stiffness of the apex connection. Three sets of two tests were carried out on different rafter sizes. For each set one test was carried out to apply moment to the apex which would be caused by download and one test to apply apex moment due to uplift. The tests were carried out on the Tinius Olsen testing machine using the same cradle supports which were employed for the stanchion base tests. In all tests a span of 3.5 metres, 1.75 metres each side of the apex, was tested. A diagrammatic arrangement of the set-up for download testing is shown in Figure 4. For uplift tests the cradle supports were raised from the Tinius Olsen table and the system laid in the inverted position.
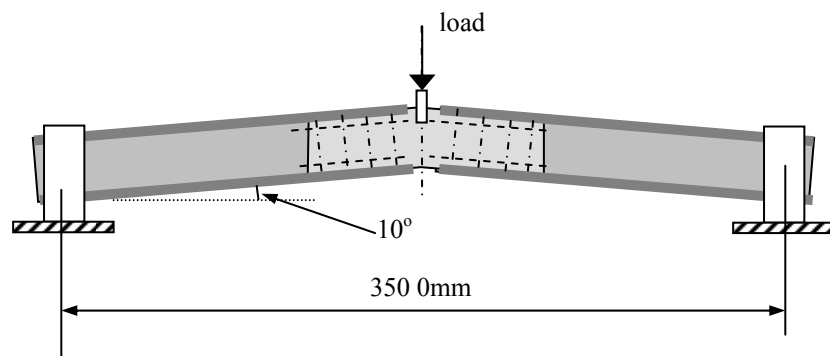

load

10°

350 0mm

Figure 4. Set-up for Apex Tests

In all tests, loading was applied via a plate connected to the Tinius Olsen loading head which incorporated a slot which straddled the apex plate to ensure that torsional deformation at the loading point was restrained. In the first test, however, it was observed that torsional deformations did occur, and indeed contributed to failure. In view of this the plate thickness was increased substantially to provide a greater degree of torsional restraint. Subsequent tests showed no evidence of torsional deformations. In all subsequent tests failure was accompanied by local buckling in the channels close to the connection to the apex plates, but it is almost certain that the primary cause of failure in all cases was the attainment of the plastic moment capacity of the apex plates.

Typical graphs of apex deflection against applied load for download and uplift conditions are shown in Figure 5 .
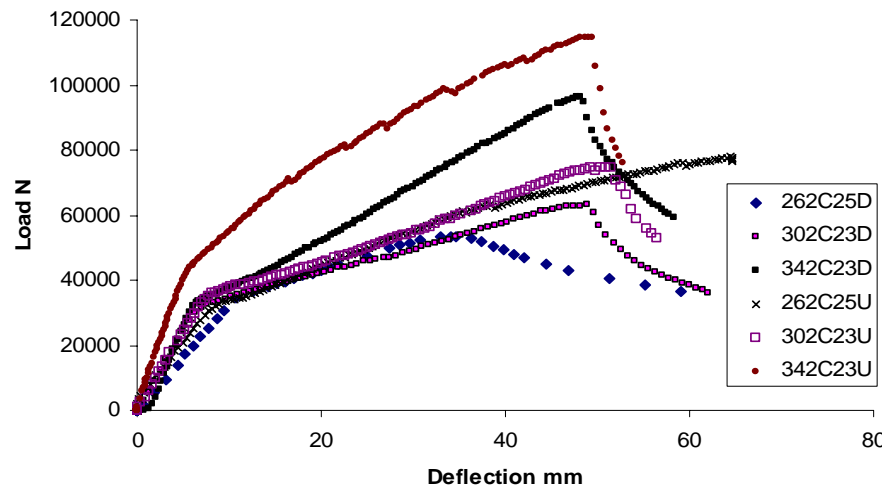

Figure 5. Load - deflection curves for apex tests

In all three sets of tests the uplift tests produced higher failure loads and moments than the download tests. This was essentially due to the greater degree of stability present in these tests as (1) the inverted apex is naturally more stable with no tendency for the apex to move laterally and (2) the length of the unrestrained compression region of the apex plates is substantially shorter than in the download case, reducing the tendency for this region to display instability.

The results of all 6 tests are shown in Table 2. The letter U or D after the test number indicates download or uplift loading. In the table the failure load is converted to the corresponding moment at the apex.

Table 2. Test results for apex load tests

Test No.	Rafter	Stiffness KNm/rad.	Failure Moment. kNm	Apex Plastic Mom. kNm
1-D	262C25	22750	46.7	51.08
2-U	262C25	19504	71.06	51.08
3-D	302C23	31135	55.1	60.03
4-U	302C23	19344	65.2	60.03
5-D	342C23	21617	84.1	81.23
6-U	342C23	40438	100.26	81.23

In all cases the failure moment was close to the fully plastic capacity of the apex plates. All the uplift cases showed failure loads greater than the calculated apex plate fully plastic moment, in two cases substantially greater, and the download cases showed on average only slightly less than the fully plastic apex plate moment. The calculated apex plate capacities were derived considering one pair of 8mm thickness apex plates of steel with yield strength 250 N/mm^2 and depth equal to channel web depth minus s mm, where s=36 for webs less than 300mm and s=57 for webs greater than 300mm depth.

The stiffness values specified in Table 2 give the connection rotational stiffness for the initial parts of the load-deflection curves. The initial steep slopes of the curves take place within the load range which was used for bedding down. As the British Standard, BS5950:Part 5 (1), suggests the application of a bedding load not greater than the unfactored loads it may be assumed that the stiffness measured in this region is suitable for use in design analysis.

In evaluation of the connection rotational stiffness the theoretical ratio of load/deflection for a fully continuous system is determined from the expression, obtained using simple beam analysis:-

$$K_T = \frac{48EI\cos10^o}{L^3}$$

The experimental stiffness, K_E can be obtained from the experimental load - deflection curves, and the connection rotational stiffness can be obtained as:-

$$\frac{M}{\theta} = \frac{L^2}{8} \frac{K_E K_T}{\left(K_T - K_E\right)} \, N \, mm / rad$$

The values so determined, but converted to kNm magnitudes, are shown in Table 2. As may be observed, for each rafter the lower value of rotational stiffness obtained was close to 20,000 kNm/rad. Observing that even relatively large changes in the apex stiffness have little effect on overall frame design it would seem that accepting a stiffness value of 20,000 kNm/rad for design calculations would adequately portray the real situation.

Tests on Portal Frame Haunches

Two series of tests were carried out on haunch layouts incorporating knee braces to examine different connection details, select the best arrangement, and to ensure that the system tested performed as predicted by the design software.

First test series

The first test series, involving 8 tests on part portal frames, each consisting of full length stanchion of overall height 5 metres and rafter of length such that the loading applied to the rafter would be situated at a point coincident with the point of inflection of the full length rafter under download conditions on site. This series was exploratory in nature, with the aim of eliminating weaknesses in the connection design and the testing procedure before proceeding to the second test series. The tests were carried out on the strong floor in the structures laboratory

The layout of the first two specimens tested is shown in Figure 6. In this particular case the rafter is of section 262C20, the stanchion is of section 302C29 and the brace of section 202C20. The connections between brace and rafter and brace and haunch utilised thick plates which were fitted between the channel sections of all members. Tests on these specimens were carried out for comparison purposes only, as it was expected that the connection method would be efficient and give good results under test conditions, but the layout had some undesirable features, e.g. the two channels comprising each member could not be bolted directly together as they had to be separated to allow for the thick plate connection.
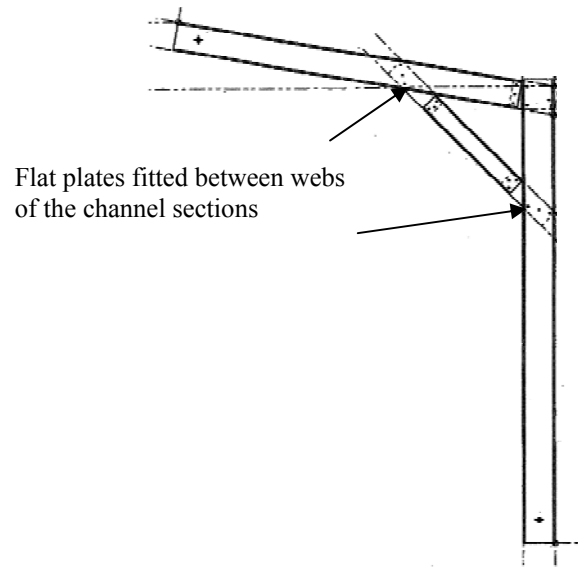
Flat plates fitted between webs
of the channel sections

Figure 6. Test specimens with thick-plate connections

To avoid these undesireable features connections in which the thick plate
attachment through the brace but had had flat plates welded to the plates to butt
onto the flanges of rafter and stanchion were designed and manufactured for
examination in the first series of tests. It was realised that this would result in the
application of very high transverse compression loads in stanchion and rafter and
give rise to possibilities of web crushing in these members, so to reduce such
possibilities angle sections were incorporated in the connection design, these
being bolted through the channel webs and connected, by bolts through the
flanges, through the flanges to the flat plate from the brace.

The set-up for testing was as shown in Figure 7. the frame was laid on wooden
blocks, spaced approximately 1.5 metres apart on the the laboratory strong floor
to minimise any frictional effects, and pinned to the strong floor through a hole
drilled near the stanchion base. Loading was applied through a jack connected
through a pin to the rafter and fixed to the strong floor in alignment with an axis
between the two pinned points. In this way the tested configuration produced a
moment distribution substantially similar to that existing under download
conditions between the point of inflection on the rafter and the pinned base of the
stanchion on site. Under uplift conditions the jack was moved to the outside of

the rafter and aligned along the same axis to produce an increase in distance between the pinned points under load.
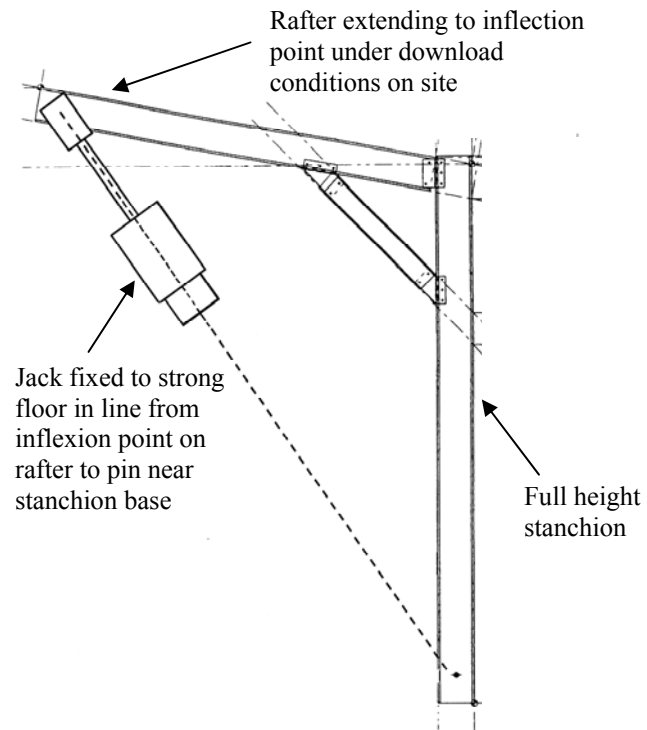
Some findings from these tests were as follows:-

Rafter extending to inflection point under download conditions on site

Jack fixed to strong floor in line from inflexion point on rafter to pin near stanchion base

Full height stanchion

Figure 7. Set-up for haunch tests

(1) The thick plate connections produced good results as expected. With no surprising or unexpected deformations. The load capacities attained were as expected

(2) When these connections were replaced by angle type connections as shown in Figure 7, which permitted rafter and stanchion channels to be bolted directly together , complications arose.

(3) For the connection type displayed in Figure 7 substantial problems resulted. The load capacity under download compared to that of the flat plate connection on a similar frame reduced by 30%. Examination of the connections showed that the resistance to twisting at the flanges of the channels was poor and more substantial connections were required. As a result the angle connections were increased in depth to cover most of the web. The new connection detail is shown in Figure 8(b), and these changes were introduced for both rafters and haunches.
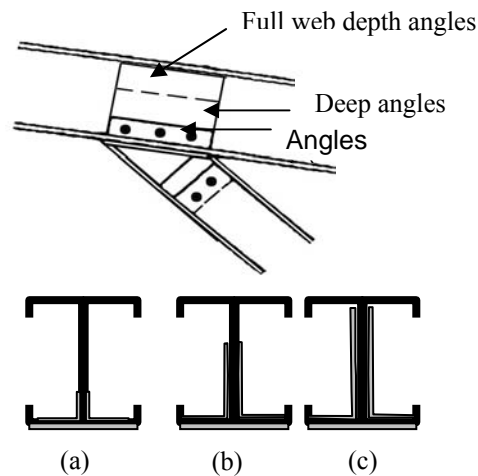

Figure 8. Angle connections

(4) It was also realised that a set-up which gave absolutely no support against lateral-torsional buckling would not model the practical situation in which a degree of support is given by adjacent building frame components, and would give over-conservative results. To take this into account a laterally stabilising member was connected through the test floor to bear lightly on the frame close to the rafter-brace connection during test. This member was held by a light screwed rod of 10mm diameter which passed through a 50mm diameter hole in the test floor and was lightly hand tightened to produce no resistance to deformation of the frame in the plane of the floor, and some light resistance to lifting of the frame from the plane of the floor, giving some simulation of the on-site situation.

(5) These changes produced substantial improvements, and the new connections were found to produce results equal to the thick plate connections. It was then decided to build on this finding and increase the depth of the angle connections to cover the full web in rafters and haunches as shown in Figure 8(c). This resulted in further improvements in load capacity and the connections originally envisaged for the second test series were changed to this design.

Some photographs of the test layout are shown in Figures 9 to 12 to illustrate the arrangements more clearly. Figure 9 shows the layout viewed from a position beyond the load point on the rafter, showing a laterally restraining bar situated near the rafter-brace connection.
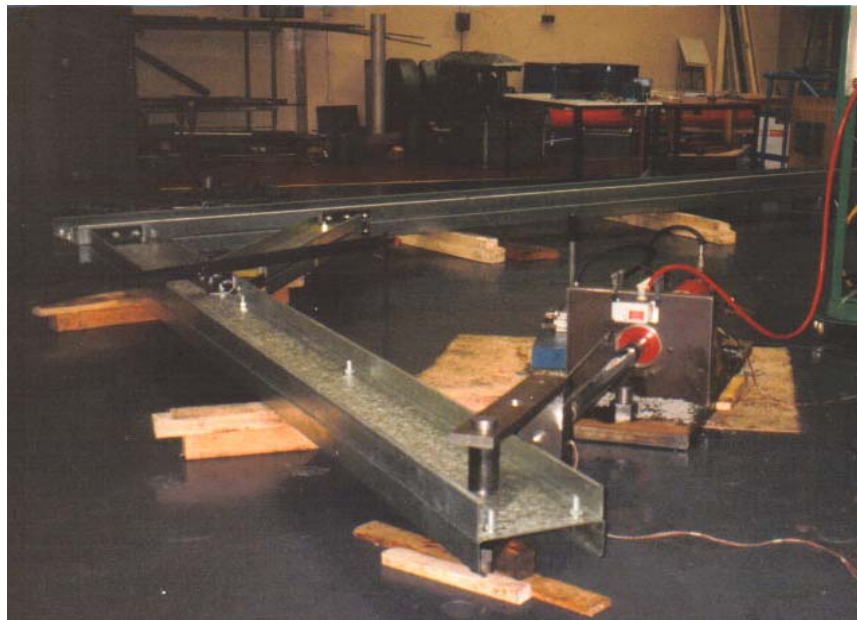

Figure 9. View of test frame from the rafter end

Figure 10 shows the pin arrangement at the stanchion end, and figure 11 shows the stanchion/rafter brace, with the lateral restraint.
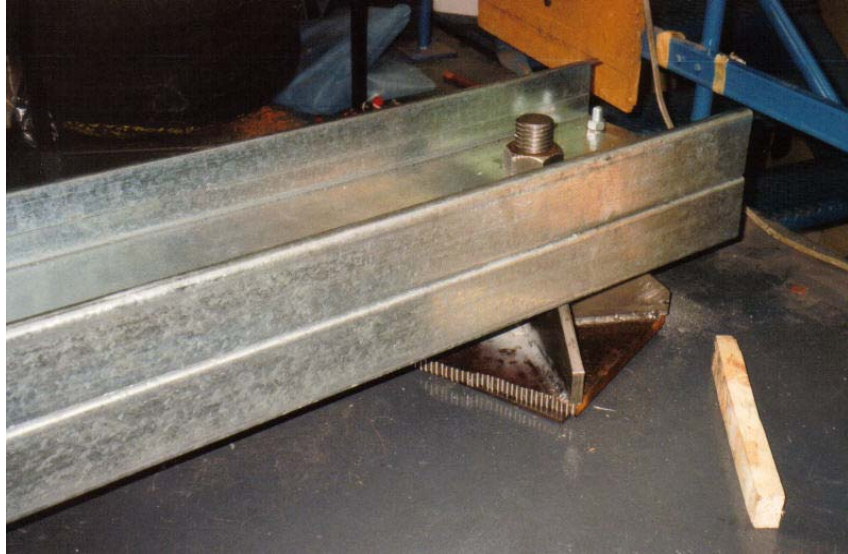
Figure 10. Pin arrangement at stanchion end

Figure 11 View of stanchion-rafter brace

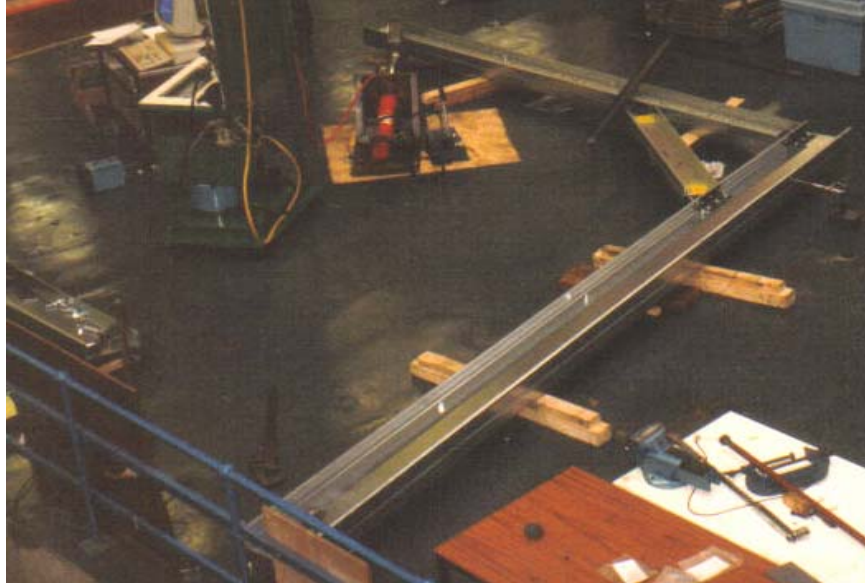Figure 12 shows the test set-up viewed from above.

Figure 12. View of test set-up from above

The photographs shown were taken during the first series of tests, but the set-up for the second series was essentially the same, apart from the use of full web depth angles at the connections between rafter and brace and stanchion and brace.

Second Test Series

This test series consisted of 8 tests on a variety of stanchion/rafter combinations using the connections ultimately decided upon, with the twin aims of ensuring that the design calculations were accurate in assessment of the load capacity, and of examining experimentally the behaviour of different stanchion-rafter combinations. The design calculations are not detailed here, although predicted failure loads are given. The capacity is based on consideration of the interaction of moment with axial forces and with shear forces at the most critical points on rafters and stanchions.

250mm

C

1800mm

A

W = Jack Load

B

250mm
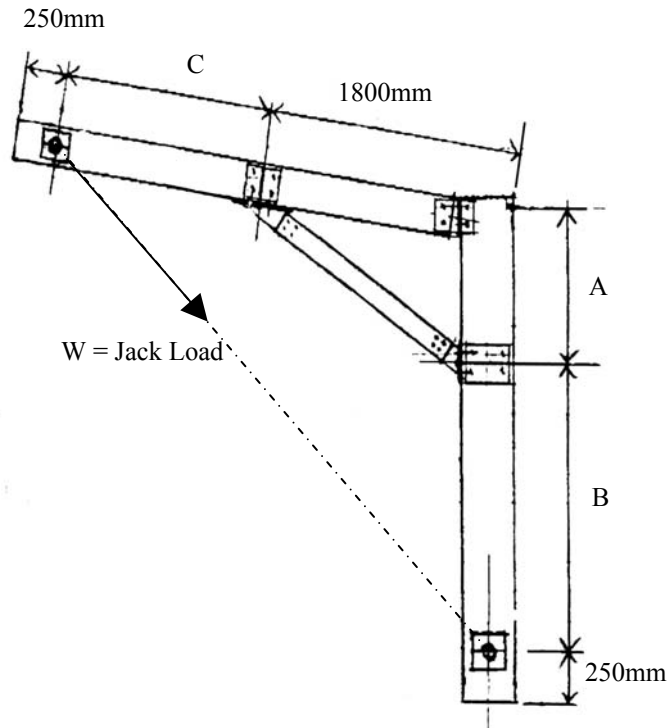
Figure 13 Test dimensions for haunch tests-Series 2

A diagrammatic arrangement of the test set-up, showing the chosen connection system is illustrated in Figure 13, and the member sizes, test frame dimensions and load direction are given in Table 3, together with initially calculated load capacities of the test frames. These capacities were based on nominal thicknesses and yield strengths and only gave a rough estimate of the capacities to be expected.

Table 3. Details of specimens for haunch tests-2nd series

Test No.	Rafter	Stanchion	Load Direction	A mm	B mm	C mm	W kN
1	262C18	302C25	Down	1218	3729	1427	33
2	262C23	342C25	Down	1185	4255	1651	35
3	262C29	342C25	Up	1185	4255	1651	35
4	262C25	342C29	Down	1185	4255	1854	40
5	302C23	342C32	Down	1230	4710	1977	40
6	342C25	342C32	Down	1276	4664	1999	45
7	342C25	342C32	Up	1276	4664	1999	45
8	342C25	402C32	Down	1225	4704	2385	48

Sets of two tensile tests were carried out on the members which failed in each test and used , together with the measured material thickness for the individual specimens, to provide accurate calculated failure loads for each system tested. Details of the tensile test results are given in Table 4

Table 4. Tensile test results for failed members of 2nd Test series

*Test no.	Specimen No.	Thickness mm	Yield stress N/mm^2	Ultimate stress N/mm^2
1	262C18	1.99	399	475
2	262C23	2.22	418	496
3	342C25	3.12	343	465
4	262C25	2.45	355	460
5	302C23	2.22	337	405
6	342C32	3.15	358	451
7	342C32	3.15	358	452
8	402C32	3.22	352	469

In all tests the variation of horizontal deflection at the eaves and load point deflection in the direction of the load was measured using electronic transducers. For all tests the load-deflection behaviour followed a similar pattern, with the load point deflection increasing to 60-80mm at ultimate load and the eaves horizontal deflection reaching 20-40 mm at ultimate load. A typical load-deflection graph is shown in Figure 14.   .
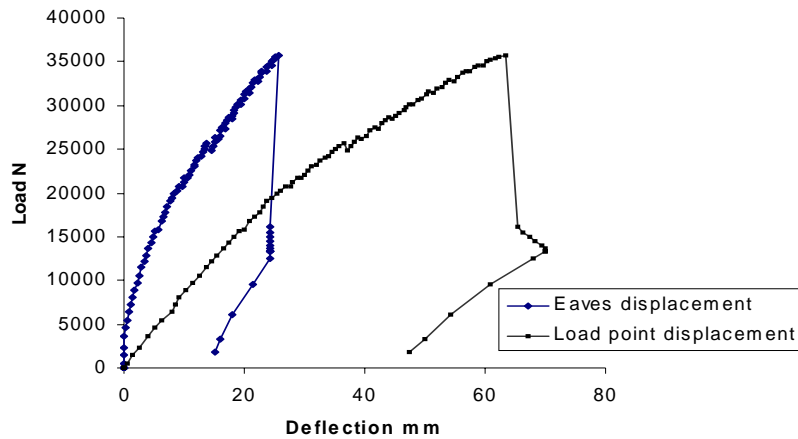
Figure 14 Load-deflection variation for Haunch test No. 1

The failure loads for all tests are shown in Table 5, with re-calculated load capacities taking the measured thicknesses and yield stresses into account and taking interaction of the different load in the same way as the design software.

Table 5. Failure loads for Haunch tests - 2nd Series

Test No.	Rafter	Stanchion	Load dir.	Exp. failure load kN	Calculated Load kN
1	262C18	302C25	Down	35.75	34.51
2	262C23	342C25	Down	37.07	37.24
3	262C29	342C25	Up	49.00	46.70
4	262C25	342C29	Down	35.22	35.56
5	302C23	342C32	Down	29.82	31.41
6	342C25	342C32	Down	48.54	43.24
7	342C25	342C32	Up	43.60	43.24
8	342C25	402C32	Down	53.60	48.62

Discussion of the results of the 2nd test series on haunches

The results given in Table 5 show in general good agreement between the design software predictions based on frame finite element analysis together with the interaction criteria specified in BS5950:Part 5. The average ratio of experimental strength/design strength was 1.0317, with a standard deviation of 0.0547.

In all cases except one the theoretical cause of failure was the interaction of bending and shear near the brace-rafter or brace-stanchion connection. For all of these cases except for test no. 1 the area of failure was within the portion of rafter or stanchion between the brace and the rafter-stanchion junction, due to the high shear forces in this area.

Summary and Conclusions

Overall the aims of the tests. i.e to validate the stanchion base capacities, to obtain an evaluation of the apex stiffness and capacity and to verify that the BS 5950 interaction formulae combined with relatively simple frame finite element analysis accurately depicted the load capacity of the portal frame system, were fulfilled. The load capacities obtained using this approach were in general accurate and slightly conservative despite the lack of any restraint on lateral displacement of the stanchion a very light restraint at the rafter-brace joint.

Metsec Plc. Has since produced a number of Portal frame installations using the connection methods examined here. Typical examples are shown in Figure 15 with the top picture showing a set up using the full depth angle brace connections and the bottom photograph a set up using thick plate connections.

Figure 15. Frame systems with (top) full depth angle connections and (bottom) thick plate connections

Reference

British Standards Institution. BS 5950:Part 5. Code of Practice for design of cold formed sections, 1998