International Specialty Conference on Cold-Formed Steel Structures

(2010) - 20th International Specialty Conference on Cold-Formed Steel Structures

Nov 3rd, 12:00 AM

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Recommended Citation

Sajja, S. R.; Beale, R. G.; and Godley, M. H. R., "Cross-aisle Stiffness Tests on Rack Upright Frames" (2010). *International Specialty Conference on Cold-Formed Steel Structures*. 1.
https://scholarsmine.mst.edu/isccss/20iccfss/20iccfss-session8/1

Twentieth International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri, U.S.A., November 3 & 4, 2010

Cross-aisle Shear Stiffness Tests on Rack Upright Frames

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Abstract

The US Rack Manufacturers Institution (RMI) code uses a theoretical formula derived by Timoshenko and the new Eurocode EN15512 requires testing. There is a considerable difference in the stiffness values determined by two approaches. This paper describes the experiments conducted on 80 full sized upright frames at Oxford Brookes University varying upright size, number of panels in the frame, aspect ratio of the panel (panel length/depth), restraints at the intermediate nodes of the frame, loading pattern, lacing pattern (channels back to back or front to front) and bolt tightness. The experimental data reported can be used in proposing revised design procedures.

1. Introduction

The cross-aisle shear stiffness of upright pallet rack frames is determined in Europe by testing using BS EN15512 (2009) whereas the US Rack Manufacturer's code (RMI, 2005) uses a theoretical method proposed by Timoshenko (Timoshenko and Gere, 1961). A pilot test program conducted at Oxford Brookes University by Chwan (2001) revealed that there was

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considerable difference in the shear stiffness values obtained by the two methods, showing that the international codes for the evaluation of shear stiffness are not consistent and at least one not accurate. Chwan's tests were based on provisions of the code derived by the Federation Europeene de la Manutention (FEM 2000) which was used as the basis for BS EN 15512 (2009). A review of the literature (Rao et al 2004) indicated that the number of test results available was not enough to find the reasons for the difference in shear stiffness values determined by the two methods. Hence, a detailed experimental study was undertaken to identify the factors affecting the shear stiffness, which could be used for developing accurate and more rational design method. The test data were also used as a basis for generating numerical models using LUSAS that helped to quantify the affect of various parameters.

In the test program, experiments were conducted on full sized upright frames. In a preliminary study, three tests were carried out to check the repeatability of experiments and to confirm earlier findings from Chwan. Later a detailed test program was designed by varying the following parameters: upright size, number of panels in the frame, aspect ratio of the panel (panel length/depth), restraints at intermediate nodes of the frame, loading pattern and the lacing pattern (channels back-to-back or lip-to-lip). The affect of bolt tightness was also studied. In total, 80 tests were conducted at the detailed stage.

2. Shear Stiffness Tests

The test program was aimed at the following objectives and scope:

- To confirm the findings from previous research.
- To find the effect of the number of panels in the frame or length of upright, the aspect ratio of the panels, the boundary conditions and the influence of half-panels, on the shear stiffness of upright frames.
- To study the connection behaviour.
- To study the behaviour of different types of lacing patterns.
- To generate more experimental data that can be used in proposing a rational design method for industry practice.

3. Test specimens

Tests were conducted on full sized upright frames made of cold formed steel sections conforming to BS EN 10147 (2000). The uprights were open perforated lipped channels with additional bends and the bracing members were lipped channels. Typical upright and bracing members used in testing are shown in Fig.1.

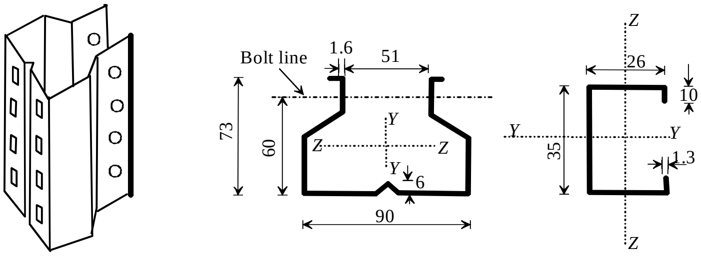


Fig.1: Upright and bracing layout

In the experimental programme, two different sizes of uprights and bracing members were used; one in the preliminary study (Series 1) and the other in the extended series (Series 2) of tests. Cross-sectional properties of upright and bracing members that were used for testing are presented in Table 1. 1.8 mm thick bracing members were used in series 1 tests, whereas 1.5 mm thick bracing members were used in series 2 tests. In Table 1, G_Y is the distance of the centroid of the upright from its back face centre line. The upright frames used in testing varied in size as the number of panels and aspect ratio of the panels (panel length/depth) were changed. The panel length (i.e. centre-to-centre distance between joints, where diagonals intersect) was kept as 1200mm and the depth of the frame varied from 605mm to 1050mm leading to panel aspect ratios ranging from 1.14 to 1.98. The test frames were 1200mm to 3600mm long with 1, 1.5, 2, 2.5 and 3 panels.

Table 1: Sectional properties of upright and bracing members

Member	**Ser-ies**	**Net Area (mm^2)**	**Second Moment of Area (mm^4)**		**Centroid (mm)**	**Torsion constant (mm^4)**
			I_Y	I_Z	G_Y	J
Upright	1	324.0	372205	163060	22.91	294
	2	788.9	522444	1.02×10^9	33.96	2062
Bracing member	1	167.1	30879	14307	9.73	180
	2	139.5	27187	10923	8.87	105

The lacing patterns of the frames used in the testing were single layer diagonal, X and N. As the lacing members in the frames were channels, they can either be connected lip-to-lip or back-to-back to the uprights. Frames with both these connection patterns were studied even though a lip-to-lip lacing pattern is not now used commonly in the industry. This pattern was chosen to enhance eccentricity effects.

The test layout and arrangement of displacement transducers (LVDTs) are shown schematically in Fig. 2 and a typical arrangement of a frame under test at Oxford Brookes University laboratory can be seen in Fig. 3.

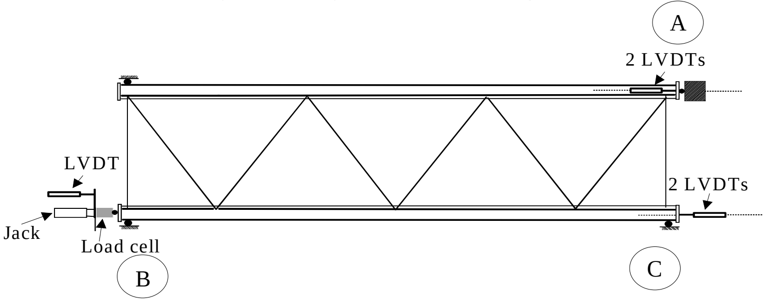


Fig.2: Schematic of test arrangement

Fig. 3: Frame under test

The positions of the rollers were adjusted so that the frame just fitted snugly between them with no looseness. The roller condition at the nodes was achieved by putting two PVC sheets in between the uprights and packing the test rig. This arrangement led to an upright frame with restraints at all nodes (RAN) and satisfied the FEM code provisions (FEM, 2000). But in practice, cross-aisle frames have limited restraint from beams. Hence frames were also tested with only corner restraints (OCR) to reflect actual conditions of the frames during their usage.

The pinned support achieved at point A in the frame (Fig. 2), by using ball type arrangement, restrained all three translational displacements but allowed upright sections to rotate freely in all three directions. The FEM code procedure assumed that the out-of-plane rotation of the frame would be negligible and hence would not affect the shear stiffness in the cross-aisle direction. However, there might have been some movement at the support under the application of load. Therefore, two displacement transducers were placed at A in the direction of the upright to determine any movement of the support. The load was applied along the centroid of the other leg, at point B in Fig. 2. A load cell of 6 kN capacity was connected to a 230 kN jack and an LVDT was placed there to control the loading. Load was applied gradually using the jack at the rate of 0.1 kN/sec. The maximum load applied in the test was kept low (approximately 5 kN) so that there was no visible damage to the specimens. After reaching the maximum load, the frames were unloaded to approximately 0.5 kN. The frames were reloaded and unloaded between loads 0.5 kN and 5 kN for 5 to 6 cycles in each test. This was carried out to avoid any error in evaluating shear stiffness due to bolt slip at the joints connecting diagonal bracing members and upright sections. Two LVDTs were placed at point C as shown in Fig. 2 to measure the displacement of the loaded upright along its own axis. LVDTs were placed at bottom and top of the upright base plate to measure any difference in displacements. In some of the tests LVDTs were also placed at the four corners of the frame to measure any horizontal movement of the frame and also to capture out-of-plane deformations of uprights, if any. The data obtained was used to plot a load-deformation curve and then to calculate the shear stiffness of the frame.

The load – displacement curves of upright frames in shear stiffness testing have two slopes (k_{ti}); one during initial loading (0 – 5 kN, *OP* portion in the graph) and the other during remaining cycles. The slope for the second portion was obtained by fitting a linear trend line to the cyclic loading applied in the test omitting the first cycle.

For example, in the case of the graph shown in Fig. 4, the slope of line *OP* is 1.49 and the slope of trend line is 6.14. The difference in the slopes is about four in the chosen test and can be attributed to initial settlement, bedding of the joints and bolt slip during the first cycle of loading. The slope of *OP* yields conservative results and was recommended by the FEM code for shear stiffness calculation. But, the slope of *OP* depends on the looseness of joint, which was considered in the paper by Godley and Beale (2008). Hence, the data from initial loading was omitted hereafter. The slope was calculated from trend line. In this case, the slope of trend line is 6.14 and hence k_{ti} is 6.14. Note that the shear stiffness is often influenced by joint looseness.

After getting k_{ti} values from graphs, shear stiffness values can be easily determined using equation 1

$$S_{ti} = k_{ti} D^2 / H \qquad (1)$$

For the case considered, the length of the frame (H) was 3600 mm and the distance between the centroidal axes of the upright sections (D) was 1050 mm. Hence, the experimental shear stiffness value for this case is 1880 kN. Once the procedure for testing and derivation of results was established, tests were carried out to confirm findings of earlier research and to fill gaps in the research, by varying the different parameters mentioned earlier. Results of these tests are given in Table 2 and discussed below.

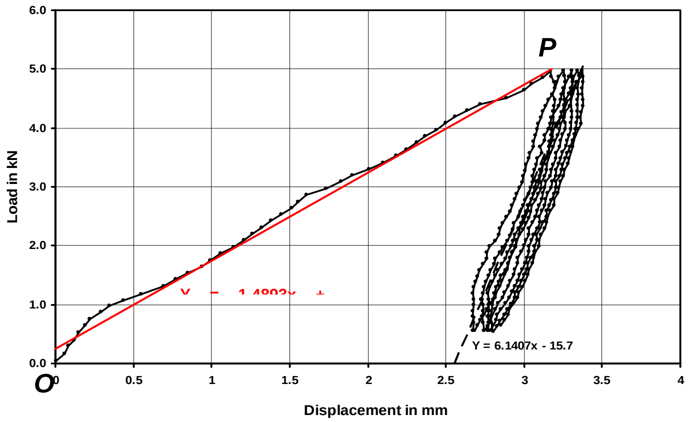


Fig. 4: A typical load-deformation curve

The mean value of the three frames tested in the preliminary study was 1808 kN. The results suggest that the repeated tests will yield results within 10% range from the mean value. Results from testing are compared against the RMI values (calculated based on Timoshenko's theory) and it can be noticed that the RMI values are approximately eight times higher than the test values.

4. Test results

4.1 Effect of lacing pattern or eccentricity

In Europe, cross-aisle frames are constructed by bolting bracing sections to uprights. Generally, channel sections are used as bracing members no consideration is given to the way they connect i.e. lip-to-lip or back-to-back. However tests show that frames with a back-to-back bracing pattern have almost double the stiffness values compared to similar size lip-to-lip panel frames due to the larger eccentricity in load transfer between upright members and bracing sections.

Hence, this factor was considered and both lacing patterns were tested. Fig. 5 shows the two configurations. In the results in Table 2, for frames restrained at corners only for size 1 frames (centre-centre distance of 1032 mm) the mean stiffness for the back-to-back configuration was 1718 kN and for the front-to-front case was 644 kN.

Table 2: Geometric properties and test results of the upright frames tested

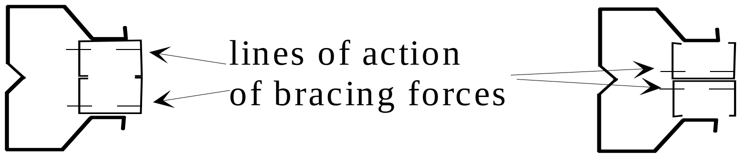
Reference to Experiments	Panel Depth (mm) c/c	Length of frame (mm)	No. of Panels	Bracing Pattern	Support conditions	Test Stiffness (kN)	RMI stiffness (kN)	Comments
Preliminary Study	1050	3600	3	B/B	RAN	1881	14070	Hi - Lo Frames Repeatability
	1050	3600	3	B/B	RAN	1606	14070	
	1050	3600	3	B/B	RAN	1937	14070	
Single Layer Diagonal Bracing	1032	3600	3	F/F	OCR	963	11005	Horizontal displacement
	1032	3600	3	F/F	RAN	1210	11005	
	1032	3600	3	B/B	OCR	1566	11005	
	1032	3600	3	B/B	RAN	1683	11005	
Tests for Bolt Looseness (Single Layer Diagonal Bracing)	1032	3600	3	F/F	RAN	643	11005	Torque = 20Nm
	1032	3600	3	F/F	OCR	554	11005	
	1032	3600	3	F/F	OCR	263	11005	Torque = 10Nm
	1032	3600	3	F/F	RAN	387	11005	
	1032	3600	3	F/F	OCR	589	11005	Torque = 15Nm
	1032	3600	3	F/F	RAN	702	11005	
	1032	3600	3	F/F	RAN	363	11005	Torque = 5Nm
	1032	3600	3	F/F	OCR	294	11005	
	1032	3600	3	F/F	RAN	589	11005	Torque = 12.5Nm
	1032	3600	3	F/F	OCR	409	11005	
	1032	3600	3	F/F	RAN	1043	11005	Torque =17.5Nm
	1032	3600	3	F/F	OCR	674	11005	
Size 2 (Single Layer Diagonal Bracing)	902	3600	3	B/B	OCR	1974	11248	
	902	3600	3	B/B	RAN	2790	11248	
	902	3600	3	F/F	OCR	896	11248	
	902	3600	3	F/F	RAN	1204	11248	
	902	3000	2.5	F/F	OCR	624	11248	
	902	3000	2.5	F/F	RAN	949	11248	
	902	3000	2.5	B/B	RAN	1143	11248	
	902	3000	2.5	B/B	OCR	1003	11248	
Size 1 (Single Layer Diagonal Bracing)	1032	3000	2.5	B/B	RAN	1255	11005	
	1032	3000	2.5	B/B	OCR	1179	11005	
	1032	3000	2.5	F/F	RAN	887	11005	
	1032	3000	2.5	F/F	OCR	667	11005	
	1032	2400	2	B/B	RAN	1585	11005	
	1032	2400	2	B/B	OCR	1192	11005	

Reference to Experiments	**Panel Depth (mm) c/c**	**Length of frame (mm)**	**No. of Panels**	**Bracing Pattern**	**Support conditions**	**Test Stiffness (kN)**	**RMI stiffness (kN)**	**Comments**
	1032	2400	2	F/F	OCR	623	11005	
Size 2	902	2400	2	B/B	OCR	1653	11248	
	902	2400	2	B/B	RAN	1011	11248	
	1032	2400	2	F/F	RAN	754	11005	
Size 2	902	2400	2	F/F	OCR	761	11248	
	902	2400	2		RAN	874	11248	
Size 1, 1.5 Panel Frame	1032	1800	1.5	B/B	OCR	1339	11005	
	1032	1800	1.5	B/B	RAN	2600	11005	
	1032	1800	1.5	F/F	OCR	425	11005	
	1032	1800	1.5	F/F	RAN	580	11005	
Size 2 (Single Layer Diagonal Bracing)	902	1800	1.5	F/F	OCR	741	11248	
	902	1800	1.5	F/F	RAN	847	11248	
	902	1800	1.5	B/B	OCR	1007	11248	
	902	1800	1.5	B/B	RAN	1175	11248	
	902	1200	1	B/B	OCR	1264	11248	
	902	1200	1	B/B	RAN	1286	11248	
Size 1, 1 Panel Frame	1032	1200	1	B/B	OCR	1223	11005	
	1032	1200	1	B/B	RAN	1272	11005	
Size 2	902	1200	1	F/F	OCR	601	11248	
	902	1200	1	F/F	RAN	545	11248	
Size 1, 1 Panel Frame	1032	1200	1	F/F	OCR	762	11005	
	1032	1200	1	F/F	RAN	578	11005	
Loading Pattern tests	1032	1200	1	F/F	OCR	461	11005	Load Pattern 1
	1032	1200	1	B/B	OCR	1207	11005	
	1032	1200	1	B/B	OCR	1279	11005	Load Pattern 2
	1032	1200	1	F/F	OCR	799	11005	
Tests for Joint rotation	1032	1200	1	F/F	OCR	Not measured	11005	distortion of joint studied
	1032	1200	1	B/B	OCR		11005	
	1032	1200	1	B/B	OCR		11005	
	1032	1200	1	F/F	OCR		11005	
X bracing Frames	1032	1200	1	B/B	OCR	1207	11005	
	1032	1200	1	F/F	OCR	976	11005	
N bracing Frames	1032	1200	1	F/F	OCR	683	11000	Loading Pattern 2
	1032	1200	1	B/B	OCR	976	11000	

Reference to Experiments	Panel Depth (mm) c/c	Length of frame (mm)	No. of Panels	Bracing Pattern	Support conditions	Test Stiffness (kN)	RMI stiffness (kN)	Comments
	1032	1200	1	B/B	OCR	1029	11000	Loading Pattern 1
	1032	1200	1	F/F	OCR	692	11000	
Single Layer Diagonal Bracing	1032	3600	3	F/F	OCR	434	11005	Loading Pattern 2
	1032	3600	3	F/F	OCR	443	11005	
	1032	3600	3	F/F	OCR	508	11005	Repeatability of Loading Pattern 2
	1032	3600	3	B/B	OCR	730	11005	
	1032	3600	3	B/B	OCR	757	11005	
	1032	3600	3	B/B	OCR	723	11005	Repeatability
Size 3 (Single Layer Diagonal Bracing)	1032	3600	3	F/F	OCR	582	11005	Loading Pattern 1
	1032	3600	3	B/B	OCR	897	11005	
	605	3600	3	F/F	OCR	390	10400	
	605	3600	3	B/B	OCR	373	10400	

Notes: B/B = Back-to-Back bracing pattern; F/F = Front-to-Front or Lip-to-Lip bracing pattern; OCR = Only Corner Restraints; and RAN = Restraints at All Nodes

For the size 2 frames (centre-centre distance of 902 mm) the corresponding mean values were 1380 kN for the back-to-back case and 725 kN for the lip-to-lip case. Hence the authors' recommendation is that all rack frames should be constructed with faces in the back-to-back configuration.



(a) 2 lipped channels face-to-face

(b) 2 lipped channels back-to-back

Fig. 5: Bracing configurations

4.2 Effect of external restraints at joint (RAN vs OCR)

The experimental study was started with conducting tests on frames with both external support conditions i.e. restraints at all the nodes (intersection of bracing members and upright sections and with supports at corner nodes only.

The restraints at the nodes were achieved by placing PVC sheets between upright section and either the testing frame or packing. Two PVC sheets were used at each location to simulate roller behavior at the joints. As can be seen from Table 2, shear stiffness values for frames with restraints at all nodes were higher than the shear stiffness values for frames with restraints at corner nodes only. The variability in the two values ranges from 10 to 50%.

The external supports were achieved with the help of packing where the amount of fixity was not quantified. This resulted in uncontrolled and additional frictional resistance on the test frames and thus in larger stiffness values for frames with restraints at all nodes compared to the frames with only corner restraints. Therefore, in 2004 (Ra et al, 2004) the authors recommended that shear stiffness tests be carried out with only corner restraints (OCR). This recommendation has been included in the Eurocode (BS EN 15512, 2009). The assumption may be conservative as there will be some amount of restraint from the down-aisle beams. However the results will be consistent and indeterminate stiffness will not be introduced.

4.3 Effect of bolt torque

In the experimental program, tests were carried out to find the significance of bolt tightness (connection between bracing members and uprights) on shear stiffness of upright frames.

It was concluded from the experimental results (Tests 12-23) that a bolt torque above 12.5 Nm would produce consistent results for the specimens tested. Hence, a bolt torque of 15 Nm was used in all further experiments. Further details of these tests are given in Rao et al (2004). The authors also recommend that when testing frames preliminary bolt tightness tests be undertaken to ensure consistency of results.

4.4 Effect of horizontal movements

The test frames were supported at nodes. However there is a possibility of frames undergoing rigid body motion due to looseness in the test set up. This could influence shear deformations and hence the effect has been studied to measure the difference in shear stiffness values. The horizontal displacements were measured by placing LVDTs parallel to the frame at the four corners as shown in Fig. 6. The change in displacements measured at the free end of the loaded upright can be either additive or subtractive depending upon the rotation of the frame. If the frame rotates anti-clockwise as shown in Fig. 6 the difference to be subtracted from actual measurements at the free end or vice versa.

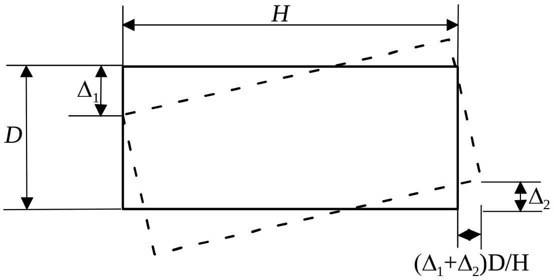


Fig. 6: Schematic showing rigid body motion of the frame

The results were sensitive to rigid body rotation. For example, a 3-panel back-to-back braced frame with centre-to-centre distance of uprights of 902 mm (3PBS2OCR) had a slope without considering horizontal displacements of 8.33 resulting in a shear stiffness value of 1882 kN. But the slope of the curve when the contribution to the total longitudinal displacement due to rigid body rotation was subtracted was 8.73, which resulted in shear stiffness value of 1974 kN. The error in estimate of shear stiffness due to neglecting rigid body rotation in this case was approximately 5%. Variations from other experiments where horizontal displacements were measured were approximately 5 – 15 %. However the horizontal displacements were not measured in some of the experiments as the number of LVDTs was limited in the laboratory. In these cases a correction of 10% was applied to the test results.

4.5 Effect of aspect ratio of frame

In Timoshenko’s theory shear stiffness is influenced by the aspect ratio (defined as the ratio of the total length of the panels to the centre-to-centre distance of uprights) of the panel and remains constant irrespective of the length of the frame. Tests were carried out to check if there was any variation in the results.

The aspect ratio of the frame increases as the number of panels increases for a given depth and hence this effect was studied in terms of number of panels. As it had been previously concluded that frames with restraints at all nodes resulted in inconsistent high values (see section 4.2), test results with only corner restraints were used for comparison. The general trend noted was that shear stiffness values increased with increased length of the frame. This could be due to reduced impact of local effects. However the test results for the half panel cases appear anomalous.

At the time of testing the effect of the asymmetry of the half panel configuration was unknown and hence further tests were carried out to study this effect by loading the frame in two alternative patterns, which is discussed in the next section.

4.6 Effect of loading pattern

Diagonal bracing in the frames results in unsymmetrical frames. For example, a one panel frame can be loaded in two different patterns. In one case, the diagonal and upright meet at the loading point (loading pattern 1) and in other case the diagonal member will not be there (loading pattern 2), which will influence load transfer in the frames leading to a variation in shear deformations. The internal force distribution and reactions are shown in Fig. 7. Note that the restraints used at the load point and at the two corner nodes not loaded with horizontal restraint can only take compressive loadings into the restraint. Tensile reactions were not supported by the restraint applied. This effect has been studied on one panel and three panel frames with only corner restraints.

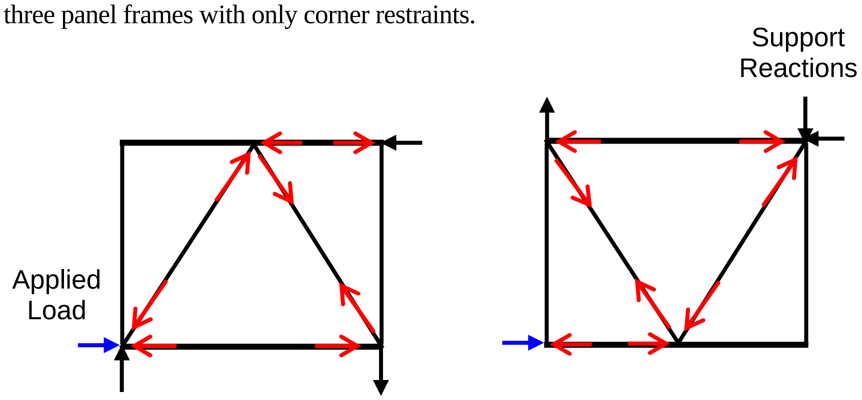


Fig. 7: Force distribution

The shear stiffness values determined by tests with load pattern 2 were consistently larger than the load pattern 1 test results. The difference becomes less important when number of panels in frames is high. But normally frames consisting of 2.5 to 3 panels only will be tested due to costs and difficulties involved with large frames. There are considerable differences in the load distributions between frames with panels with a whole number of panels and those with frames with half panels at one end. Hence care should be taken while testing frames for shear stiffness and both load patterns must be tested or full cyclic loading used. It is recommended that if the difference between the two values is not more than 10%

then the average of the two values can be taken as shear stiffness. Otherwise the lowest value should be taken as the shear stiffness of the frame.

4.7 Effect of bracing shape

Three different bracing shapes i.e. X – bracing, diagonal bracing and N – bracing, were tested. These tests were carried out to compare test results with different formulae proposed by Timoshenko. These are shown in Fig. 7.

(a) Diagonal bracing (b) X bracing

(c) N bracing

Figure 7: Bracing configurations

Different brace shapes were treated by the ratios of their areas of the cross-sections of the bracing sections and to that of the upright in one panel. Note that in these ratios the area of the bracing at the end of each frame was not considered. These ratios give an indication of the material used per panel and the corresponding shear stiffness values. Hence, bracing values for the frames were 0.35 (diagonal bracing) and 0.70 (for both X – bracing and N - bracing). The results of tests carried out on X-braced frames and on N – braced frames of depth 1032mm test

68-73) are given in Table 2. Note that these tests were carried out on single panel frames. The results presented in Table 2 clearly demonstrate that N – braced frames are not efficient in resisting shear for given material. Theoretically X – braced frames should have double the shear stiffness values to diagonal braced frames but this was not observed in practice.

5 Conclusions

Based on the test results, the following can be concluded:

- Test results do not compare with theoretical values of Timoshenko (1961) and they differ by between 5 to 25 times.
- Frames with a back-to-back bracing pattern have almost double the stiffness values compared to similar size lip-to-lip panel frames. It is due to the larger eccentricity in load transfer between upright members and bracing sections.
- Frames with external supports at all the nodes produced larger stiffness values compared to the frames with only corner restraints. However these are not consistent and do not represent true behavior.
- Frames with an N-bracing configuration are inefficient and do not have any better performance than a diagonally braced frame of the same dimensions.
- Shear stiffness values of the same frames were also affected by loading arrangement during testing and hence full cyclic loading through zero should be undertaken to get representative values.

References

BS EN10147, (2000), *Continuously hot-dip zinc coated structural steels strip and sheet. Technical delivery conditions*, British Standards Institute, London.

BS EN 15512 (2009), *Steel Static Storage Systems – Adjustable pallet racking systems – Principles for Structural Design*, British Standards Institute, London.

Chwan K, (2001), *Investigations into the Shear Stiffness of Pallet Rack Uprights*, BEng. Thesis, School of Architecture, Oxford Brookes University.

FEM 10.2.02 (2000), T*he Design of Steel Pallet Racking*, Section X of the Equipement et Proceeds de Stockage, Federation Europeénne de la Manutention.

Godley, M H R, Beale, R G, (2008), Investigation of the effects of looseness of bracing components in the cross-aisle direction on the ultimate load-carrying capacity of pallet rack frames, *Thin-walled Structures*, 46 (7-9), 848-854.

Rao S S, Beale R G, Godley M H R, (2004), Shear stiffness of pallet rack upright frames. *Proceedings of 17th International Specialty Conference on Cold-formed Steel Structures*, Orlando, USA, 295–311.

RMI (2005), The Rack Manufacturers' Institute: *Specification for the design, testing and utilisation of industrial steel storage racks.*

Sajja S R, Beale R G, Godley M H R, (2008), Shear stiffness of pallet rack upright frames, *Journal of Constructional Steel Research*, 64, 867–874.

Timoshenko, S P, Gere J M, (1961), *Theory of Elastic Stability*, 2nd Edition, McGraw-Hill Book Company Inc., New York.

Appendix: notation

D	Distance between centroidal axes of the uprights
G_y	Distance of centroid of upright from back face centre line
H	Length of frame
I_y	Moment of inertia of upright about minor axis
I_z	Moment of inertia of upright about major axis
J	Torsion constant
OCR	Restraints applied at corner nodes only
RAN	Restraints applied at all nodes
S_{ti}	Shear stiffness of frame
YY	Principal major bending axes of sections
ZZ	Principal minor bending axes of sections
k_{ti}	Slope of regression line (Load against displacement)
Δ_1	Horizontal displacement of frame in the cross-aisle direction at one end of frame
Δ_2	Horizontal displacement of frame in the cross-aisle direction at the other end of frame