Effects of Different Support Conditions on Experimental Bending Strength of Thin Walled Cold Formed Steel Storage Upright Frames

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Abstract: Design computations of industrial storage racks in accordance with current industry standards rely in part on laboratory testing. One of these tests is for determining the bending strength of upright sections. When testing the bending strength about the axis of symmetry of the upright, a four-point bending test of the assembled upright frame is mandated. The test arrangement prescribed by the standard must permit free twisting of the section at the supports, while the applied loads and their reactions for each upright may be applied in the plane of the section's shear centre. A test arrangement that provides free twisting of the upright section at the supports is more complex and difficult to set up compared with a simple support. This paper examines if the condition of free twisting at supports is necessary in the case of shear centre loading, especially that relaxing this particular code requirement would lead to a simpler test arrangement. Laboratory testing of two sets of upright frames, loaded through the upright's shear centre but with each set having a different support condition indicated that free twisting at the supports had no effect on the bending capacity of the upright members tested. The paper outlines the test setup and reports the results in form of characteristic load deformation curves of the tested specimen.

Keywords: *Four-point Bending Test, Upright Bending Strength, Support Conditions, Load Deformation Curves, Free Twisting*

1. Introduction and Background

Industrial racks are the most common structures for the storage of palletised goods. The behaviour of these structures, which are built-up from thin-walled cold-formed steel profiles, is quite complex [1]. Upright frames are primary structural components in industrial racking systems. They typically consist of two perforated thin-walled members that are linked together by a bracing system [2] as depicted in Figure 1. The sensitivity of the uprights to buckling, the presence of the perforations on the uprights, the non-linearity of the connections, the frame sensitivity to the second-order effects and the influence of the imperfections are the main sources of complexity [3, 4].

Several numerical and experimental studies (e.g. Michael et al. 1997 [5]; Crisan et al. 2014 [6]; Bertoccia et al. 2017 [7]; Zhao et al. 2017 [8]) have been carried out on bending capacity and different buckling modes of perforated thin-walled cold-formed steel upright

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frames in order to understand the complex structural behaviour of those steel members. The large variability in terms of geometry of the profiles, of the joints and of the perforations, and the complexity of the phenomena which affects the member behaviour, do not yet allow performing a pure numerical design, but call for tests aimed at the characterisation of the structural components [9]. One of the important tests, which is the subject of this study, is focused on determining the bending strength of upright sections. When testing the moment resistance about the axis of symmetry of the upright, EN 15512 (2009) [10] and Australian Standard AS 4084 (2012) [11] both require a four-point bending test of the assembled upright frame with a test arrangement as depicted in Figure 2.

Bernuzzi & Maxenti (2015) [12] have employed the mentioned four-point test setup to study the performance of uprights under axial load and gradient moment. They pointed out that when investigating the flexural member behavior about the axis of symmetry, a complete upright frame has to be tested instead of an isolated upright. In this case, four-point tests allow for the prediction of the upright flexural performance about major and minor axes of bending properly [12]. Trouncer & Rasmussen (2014) [13] tested 16 nominally concentrically loaded upright frames in order to capture the interactive buckling effects of local, distortional and overall buckling. A comparison of the experimental ultimate loads with strength determinations by the AS/NZS 4084 (2012) [11], EN15512 (2009) [10] and RMI (2008) [14] steel storage rack specifications was also conducted, highlighting the differences between each. The comparison indicated that EN 15512 (2009) [10] specification is more accurate in establishing the ultimate capacities of upright sections than the other two examined specifications. Therefore, it can be concluded that for experimental investigation, four-point bending test of the assembled upright frames based on EN 15512 (2009) [10] can render the most accurate outcomes.

2. Test Configurations

The four-point bending test arrangement in EN 15512 (2009) [10] stipulates that "the applied loads and their reactions for each upright shall always be in the same vertical plane and that this plane may be defined by the shear centre or the centroid of the section". Furthermore, EN 15512 (2009) prescribes free twisting of the section at the supports in order to allow the lateral torsional buckling effects to be developed by the uprights in their normal mode of use. An experimental setup in which the web of the upright section is used to apply the loads and their reactions will inevitably lead to twisting of the upright axis due to the eccentricity between the planes of loading and corresponding upright shear centre. As a result, the twisting action that will develop during the test may undesirably influence the bending strength of the specimen and therefore the code requirement of free twisting of supports is justified. However, if in the experimental setup loads and support reactions were to be applied through the shear centre of the upright section then, twisting of the upright will be minimal and cross-sectional distortion insignificant. If furthermore it can be demonstrated that the upright's bending strength remains unaffected, then the code requirement of free twisting at the supports may be considered as too conservative or even redundant. The effect of this particular requirement on the accuracy and reliability of the final test outcomes has not been examined in the literature. Therefore, as a first step to investigate this effect, six upright frames with different support conditions were tested. The uprights of the tested frames were Dexion's Keylock-Mk6-90R sections, which had a painted finish and a measured average metal thickness of 1.51 mm. Based on tensile tests taken from the parent upright material, the elastic modulus and proof stress were 200,000 N/mm^2 and of 538 N/mm^2, respectively.

3. Experimental Investigation

Four-point bending tests on six upright frames were conducted in this study in accordance with EN 15512 (2009) [10]. The frames were divided into two sets, whereby one set was supported by spherical seats that allow free twisting and bending rotations while the other set had cylindrical supports to provide only free bending rotations. In the experimental investigation, all frames were tested to failure and the load-deformation responses associated with the two support types were compared. The frames, which were tested at the Structures Testing Laboratory of the University of Technology Sydney were supplied by Dexion Australia. All frame uprights had a Keylock-Mk6-90R cross-section made of painted material. The frames were assembled using Dexion's standard bracing system. Figure 3 illustrates a general view of the test rig. The sketch of the test arrangement in plan and side view can be seen in Figure 4. In the test, the load was applied by means of two synchronised hydraulic jacks acting at quarter points of the upright spans. Two spreader beams transfer the loads to the upright sections. As depicted in Figure 5, the load of the transfer beam was applied to the upright section using a spherical seat and an L-shaped bracket to position the load at the shear centre of the upright. A similar arrangement was used at the supports to transfer the reactions through the shear centre. To enable testing of the frames, both with and without free torsion at the supports, two different support arrangements were used. In the first arrangement, shown in Figure 6, spherical seats were used to allow rotations for both bending and torsion to take place. In the second arrangement, the cylindrical bearings depicted in Figure 7 were employed. In addition, roller skates were used at one end of the frames to permit displacement in direction of upright axis. The vertical deformation of the uprights was logged using linear variable displacement transducers (LVDT's) which were placed at six points of interest. These points are identified in Figure 4 using the labels NW, NC, NE, SW, SC and SE. At each point, two LVDT's were used to record both the top flange vertical displacement and its rotation about the axis of the upright. The arrangement of the utilised LVDTs is illustrated in Figure 8.

4. Results and Discussion

The six upright frames were divided into two groups. As per Tables 1 and 2, three frames (S1, S2, S3) were tested using supports with spherical seats and three frames (C1, C2, C3) were tested using supports with cylindrical seats. During the test, the vertical displacement at mid-span of the frame was recorded, while the load was gradually increased up to failure. The attained ultimate loads and corresponding mid-span moments are given in Tables 1 and 2. With reference to the test arrangement in Figure 4, the load (*P*) tabulated for each test, represents the average of the two load cell readings. The mid-span moments (*M*) in Tables 1 and 2 are computed by simple statics, the load (*P*) and the frame geometry. Moment-deformation curves are shown in Figures 9 to 13. In all curves, a moment offset of approximately 0.16 kNm can be seen. The offset accounts for the weight of spreader beams, which was not recorded by the load cells.

Figure 9 shows the moment versus vertical mid-span deformation. For each frame, the displacement plotted represents the average of the two frame upright displacements. Considering the moment-deformation curves presented in Figure 9, it is apparent that regardless of support type, all curves are similar in shape showing little difference in ultimate moments. A comparison of the results in Tables 1 and 2, shows that the average ultimate load values differ by less than 0.5% whereby the average of the specimen with cylindrical supports was slightly lower. In order to compare the cross-section deformation and twisting of the upright sections, the top flange rotation about the upright axis was recorded at the supports and at mid-span of the frame. In all tests, as shown in the moment rotation curves of Figures 10 and 11, the largest rotation at supports was below 2.5^{o} (0.04rad) at ultimate. No observable difference or trend could be attributed to the different support types. While in the case of general loading cylindrical supports would be expected to provide torsional restraint, for the special case of shear centre loading, twisting of the cross section and hence torsional moments at the supports should not take place according to theory. Visual inspection during the test did not reveal any tendency of the cylindrical support itself for twisting by partial uplifting. It is noted that the brackets used to transfer the support force were connected to the web of the uprights and thereby allowed for cross section distortion at the supports to take place. It is also noted that, since the rotations were measured at the top flange, the values plotted in Figures 10-13 may include a component attributed to section distortion, however due to the bracing connection close to the supports, the effect of section distortion may be assumed to be minimal. In addition, the observed mode of failure in all tests was by local buckling of the upright section in the zone of maximum bending moment as expected. A typical example is shown in Figure 14.

In summary, the observed twist rotations at supports remained insignificantly small throughout all tests. The small rotations that took place were likely due to inevitable imperfections in the assembled upright frame and other minor experimental setup inaccuracies. It is also hypothesised that bracing members of the frame may provide some degree of twist restraint that counters the effects of imperfections on torsional rotation especially near the supports where bracing members are usually attached. Furthermore, bracing members are typically bolted to the flanges of the upright section and thereby resist any tendency for the upright's cross-section to become distorted.

Other common bracing configurations as shown in the examples of Figure 15 and referred to by EN 15512 (2009) [10], have bracing elements connected near the supports. The test results presented demonstrate that in the case of shear centre loading, twist rotations will remain minimal and will not affect the measured bending strength of the frame. Subject to further testing to confirm the applicability of the above finding to other bracing configuration, which were not examined in this study, dropping the code requirement of free twisting at supports should be considered. In practice, ensuring a free twisting condition at supports requires a more complex experimental setup compared with a setup for a simply supported four-point bending test of the frame. Relaxing the code requirement of free twisting in the case of shear centre loading would therefore simplify the test setup and speed up the test procedure.

5. Conclusions and Recommendations

In this study, the bending strength of six uprights frames was tested using a four-point bending test in accordance with EN 15512 (2009) [10]. The frames were loaded to failure, whereby the load was applied in the shear centre plane of the uprights. Three frames were supported using spherical seats that allow free twisting and bending to take place while the other three frames had cylindrical supports. Load-deformation curves at mid-span and at supports indicated that no observable difference or trend could be attributed to the different support types. Additionally, torsion of the uprights at supports was examined and the observed results corresponding to the two support types were very similar.

The experimental outcomes of this study clearly imply that when the frames are loaded in the shear centre plane of the upright section, allowing free twisting at the supports has little influence on the bending capacity of the upright member. As a result, it is recommended to consider dropping the code requirement according to EN 15512 (2009) [10] for providing free twisting at the supports when loads and reactions are made to act through the shear centre of the upright section. This requirement adds complexity to the test setup, but it does not appear to influence the accuracy of the experimental four-point bending tests.

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Figure1: Typical upright frames

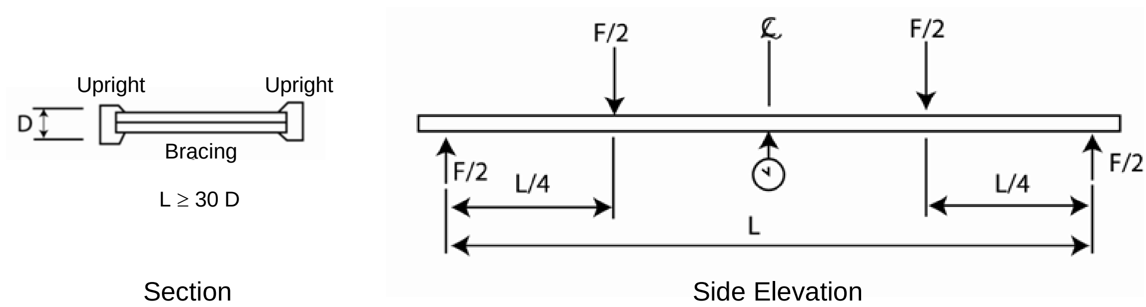

Figure 2: Test arrangement for the major axis bending test on upright sections [10]

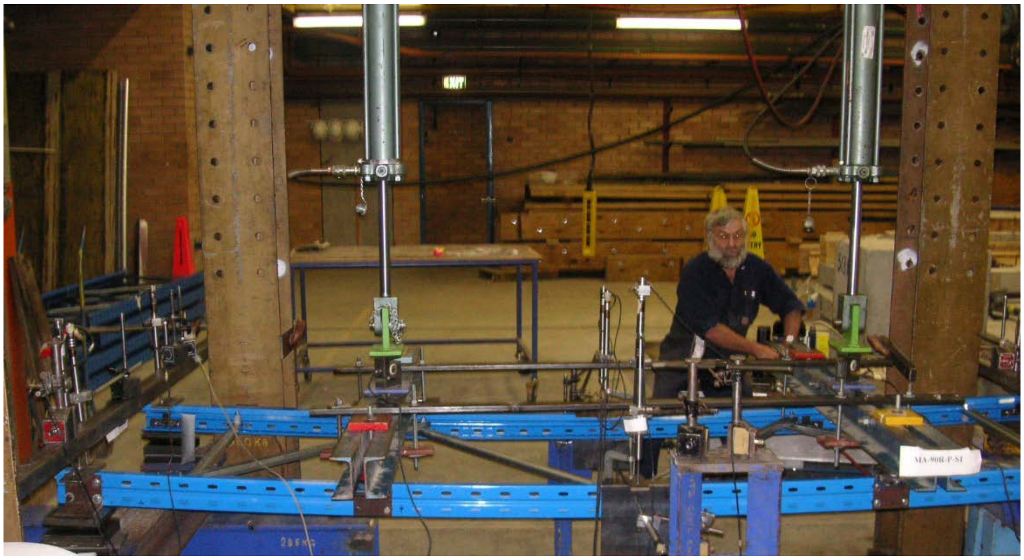

Figure 3: General view of the test rig

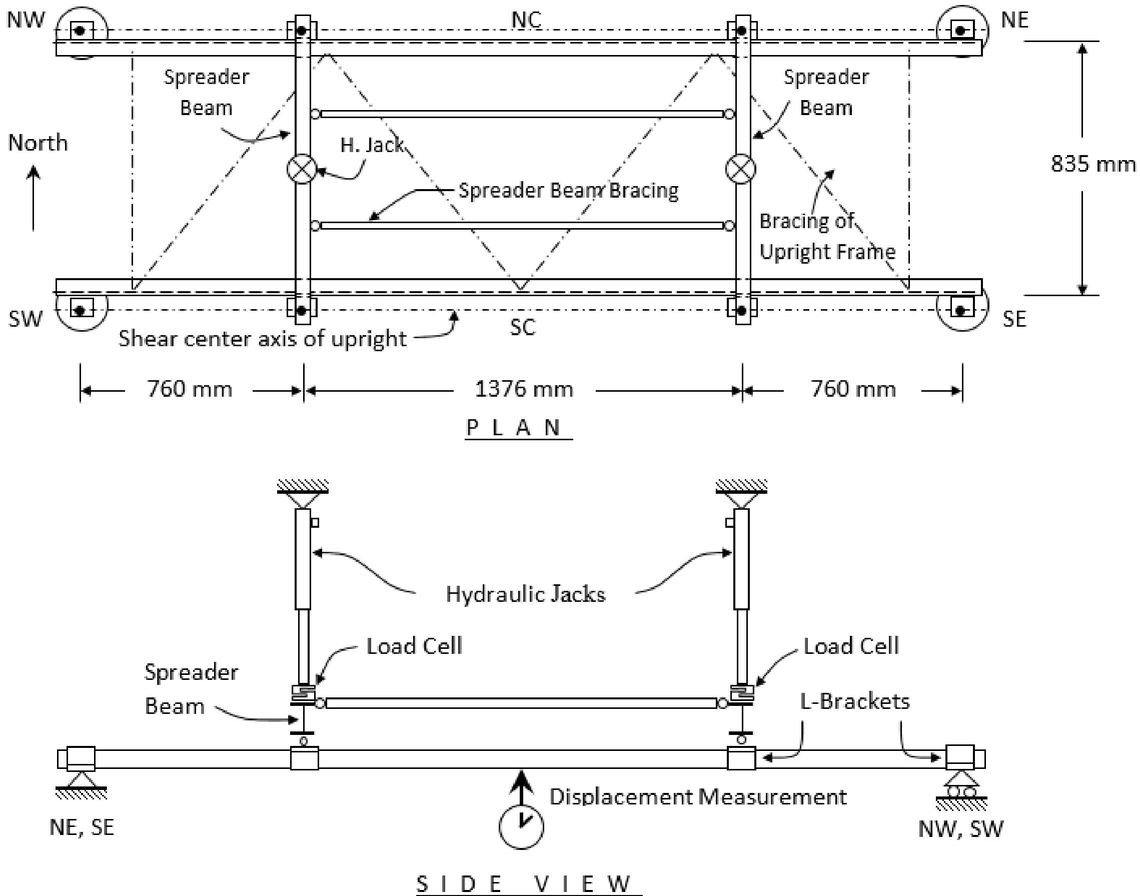

Figure 4: Test arrangement

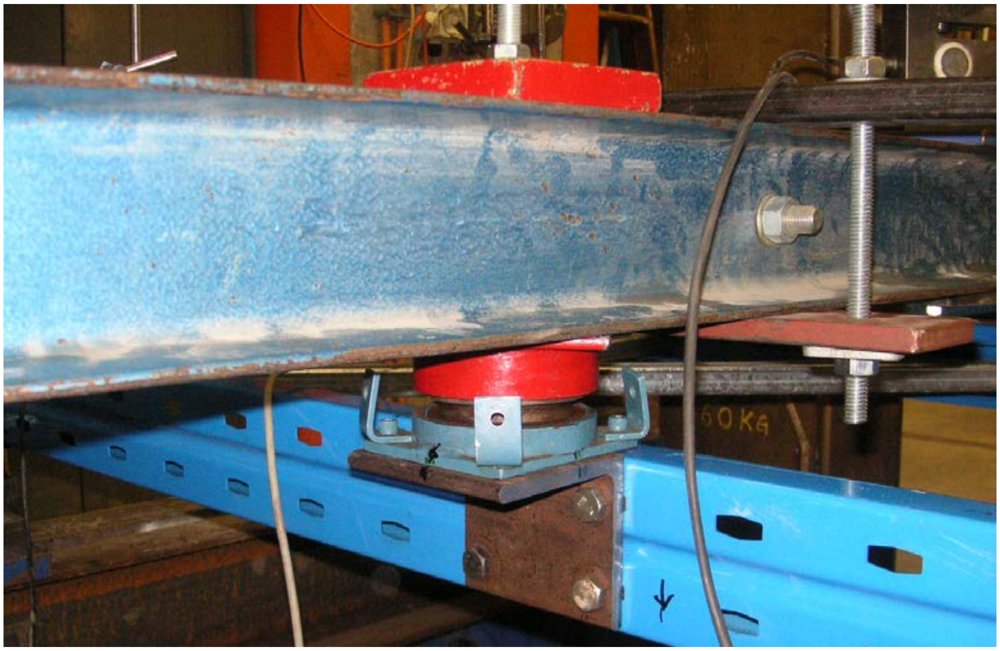

Figure 5: Load applied at 1/4 point

a) Spherical Seat & skate **b)** Spherical Seat only **c)** Section

Figure 6: Spherical Support – with and without roller skate

a) Cylindrical support & skate **b)** Cylindrical support only **c)** Section

Figure 7: Cylindrical Support – with and without roller skate

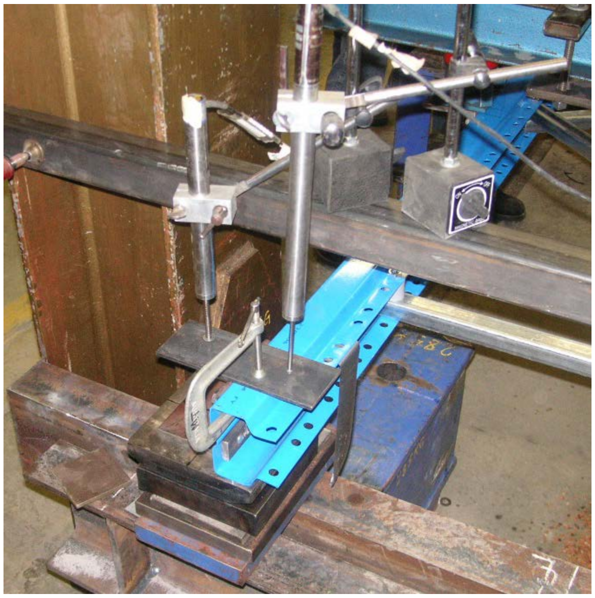

Figure 8: Arrangement of linear variable displacement transducers (LVDTs) in the tests

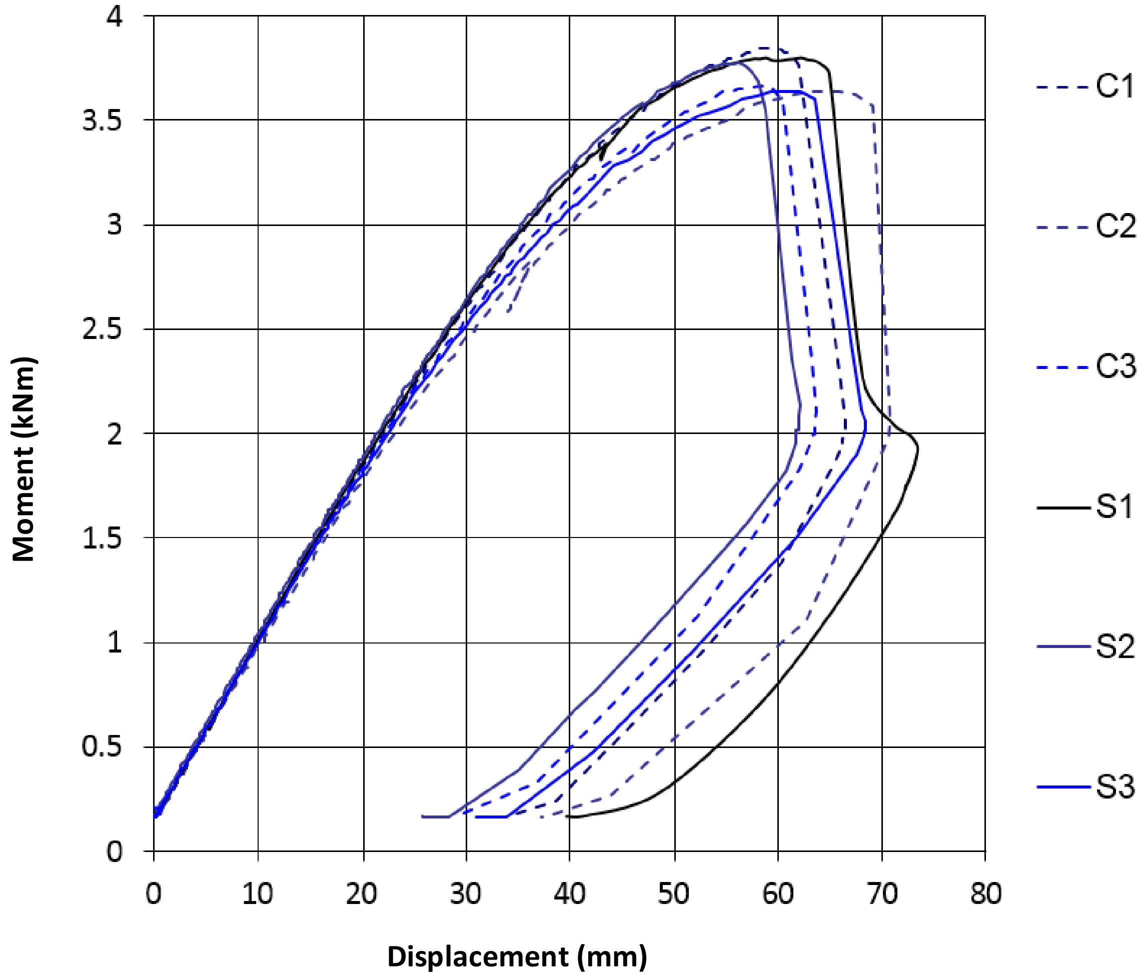

Figure 9: Mid-span moment vs mid-span vertical displacement

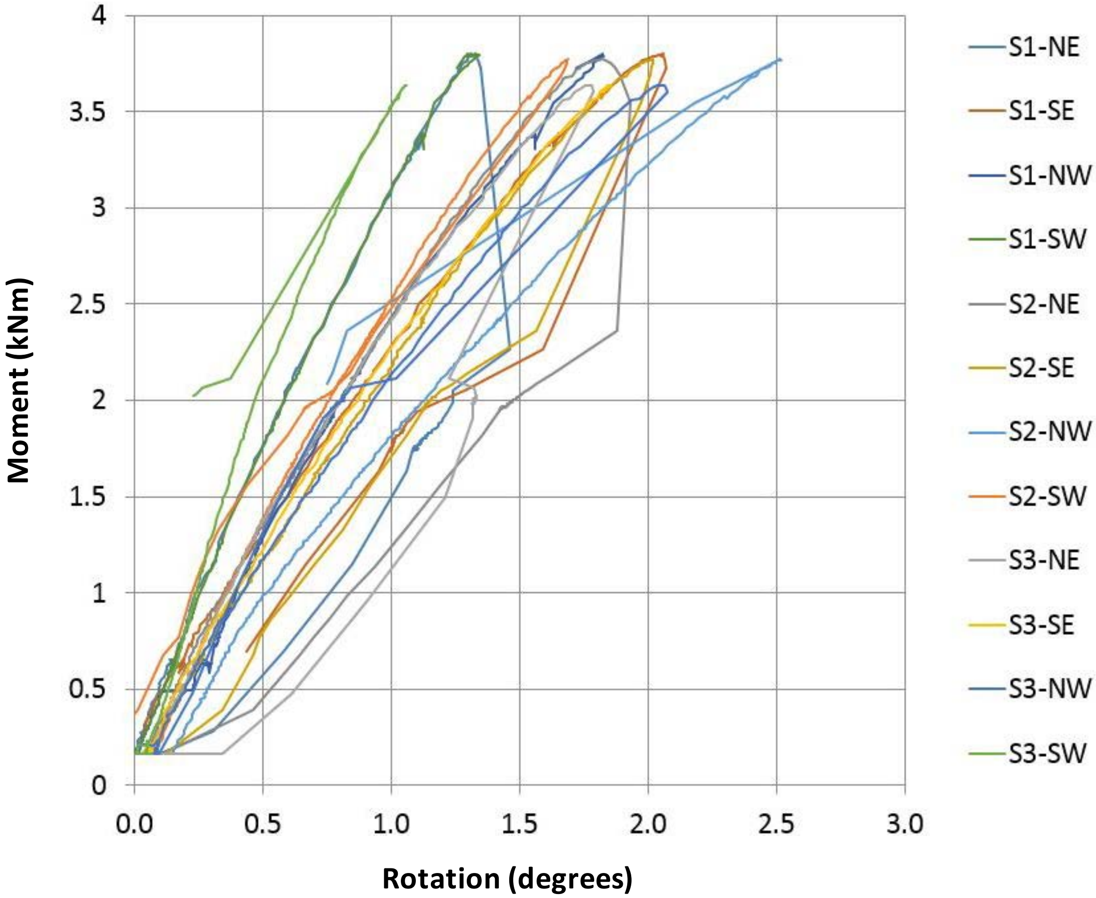

Figure 10: Moments vs top flange twist rotation for uprights with spherical supports

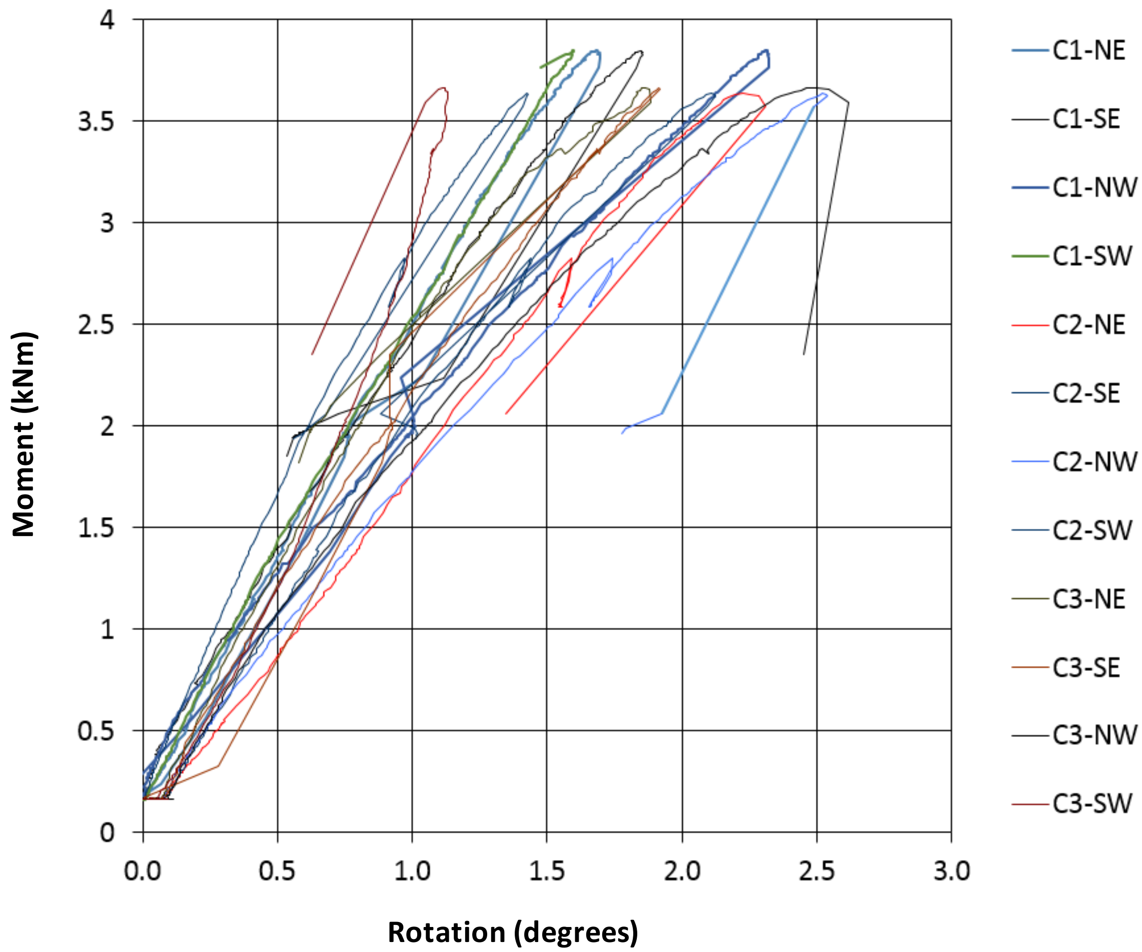

Figure11: Moments vs top flange twist rotation for uprights with cylindrical supports

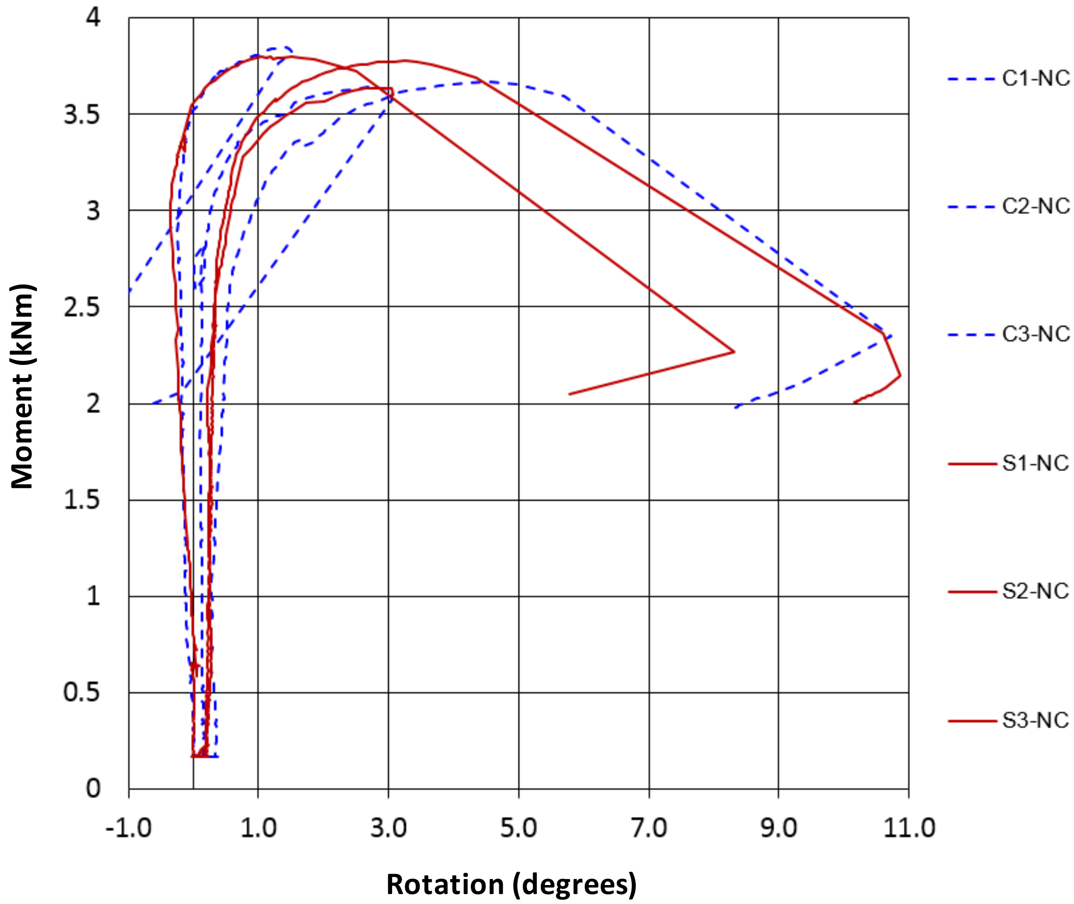

Figure 12: Upright top flange rotation at mid-span – north side

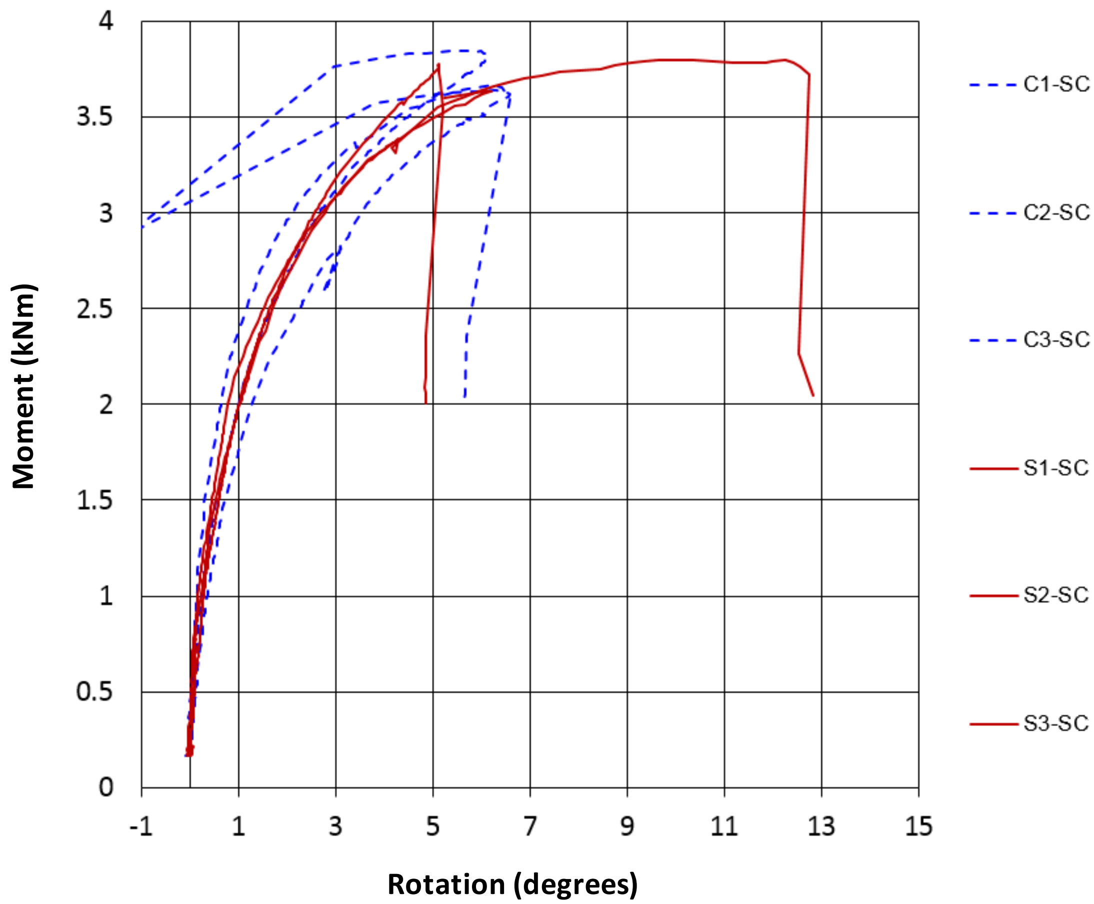

Figure 13: Upright top flange rotation at mid-span – south side

Figure14: Typical failure mode

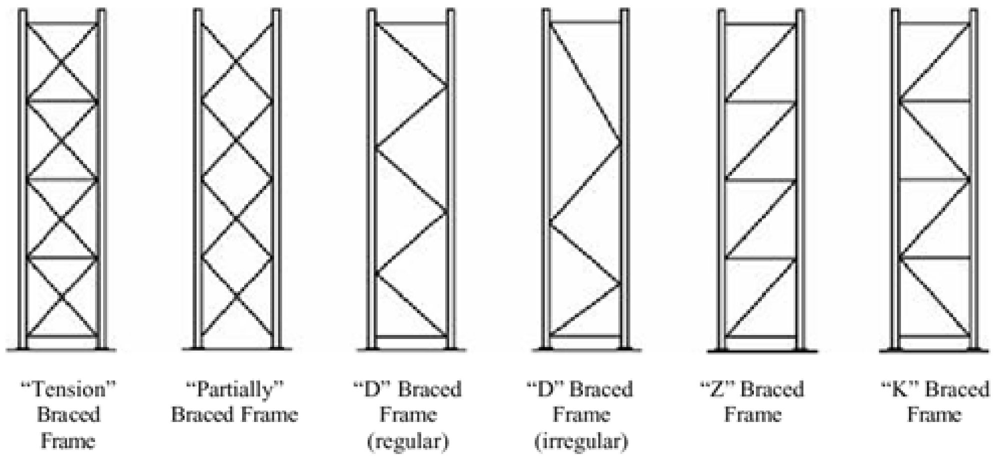

Figure 15: Typical upright frame bracing configurations [10]

Table 1: Average ultimate loads and mid-span moments in upright frames with spherical seats

Test ID	Max *P* (kN)	Max *M* (kNm)
S1	10.00	3.80
S2	9.93	3.78
S3	9.57	3.63
Average	**9.83**	**3.74**

Table 2: Average ultimate loads and mid-span moments in upright frames with cylindrical seats

Test ID	Max P (kN)	Max M (kNm)
C1	10.13	3.85
C2	9.58	3.64
C3	9.65	3.67
Average	**9.78**	**3.72**