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Design of Industrial Cold-Formed Steel Rack Upright Frames for Loads in Cross-Aisle Direction

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Abstract

This paper summarizes research on the cross-aisle stiffness and strength of industrial cold-formed steel rack upright frames for loads in cross-aisle direction. Tests were carried out at the Universitat Politècnica de Catalunya, Barcelona, Spain on joints as well as entire upright frames. A possible rather simple analysis procedure is developed and described.

Introduction

In general, industrial cold-formed steel pallet racks consist of upright frames and pallet beams. Upright frames consist of columns, column base plates and bracing members. In the United States, typically, base plates and braces are welded to the columns.

The stiffness of the upright frame is important for design in the cross aisle direction, namely in the plane of the upright frames. The stiffness in the cross aisle is important in determining the earthquake performance of racks. At the moment some design are made using a rigid frame analysis which as will be shown results in a very significantly larger stiffness than if the semirigid nature of the joints is considered. Semirigid nature of the joints results from the distortions of the column at the connections to the braces.

Rotational flexibility at the joints does not have as significant effect as the stiffness in the axial direction of the braces. The stiffness and strength of the joints between the braces and columns were studied experimentally and analytically and reported in Roure, F., et al [1].

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To develop a simple and more accurate approach to the design of upright frames as rigid frames tests were carried out at LERMA (Laboratory of Elasticity and Resistance of Materials), Universitat Politècnica de Catalunya, Barcelona, Spain.

The tested upright frame configuration as well as the section geometries and photographs are shown in Fig. 1. The frames had two different column thicknesses of 0.07 inch (Type A Columns) and 0.105 inch (Type B Columns) inch. Same brace was used for both types of frames. Each frame was also subjected to two types of loading, one that will cause tension in the diagonal and the other compression. Tests were done on three identical frames for each type of upright frames and loading. Thus there were 12 tests in total. Though the tests were done on rather low height upright frames, it is expected the developed methodology will be applicable to higher upright frames.

Tests on the joints between columns and braces

Special test fixtures and procedure were developed for getting a spring coefficient for the restraining of the braces in the axial direction as described in detail in Roure, et al. [1]. Test fixtures, views of failed specimens and a sample of finite element modelling result are shown in Figs. 2 through 4. As shown in Fig. 2 test were carried out on joints with braces at right angles and at 45 degrees to the columns. The finite element modeling has shown to be feasible for connections between other types of columns and braces.

The stiffness for the joints are given in Table 1 obtained from tests where the braces are in tension and compression. The stiffness is the slope of the regression line obtained from the initial linear part of the experimental curves, up to a value that varies between 0.3 and 0.6 of the ultimate force at the joint. Table 1 also has “adjusted brace area” to be used in frame analysis as described below. The regression lines are shown in Fig. 4 for joints of between Type A columns and braces.

Frame Tests

The frames tested are illustrated in Fig. 1. The frames were tested in a horizontal position as shown in Figs. 6 and 8. Bases were fixed and typical base plates were used. Out of plane displacement of the frames was restrained. Loads were applied at the joints shown in the figures. The loads were applied in two directions, in a direction that causes tension and in a direction that causes compression in the diagonal braces. The tests were carried out in triplicate for each direction and for each column geometry.

Frame Test results and their evaluation

Deflections observed and calculated at the points of application are plotted in Figs. 5, 7, 9 and 10. Deflections were calculated using MASTAN2 [2]] frame analysis program. In MASTAN2 (which will be referred to as MASTAN), the semirigid nature of the joints were idealized by reducing the area of the horizontal and diagonal braces in the element adjacent braces to the columns in such a way that the axial stiffness of the braces are reduced to the stiffness values observed in joint tests. These areas are listed in Table 1 as "adjusted brace area". Stiffness is different depending on the thickness of the column and whether the brace is in compression or tension. The elements whose areas are modified 1.9 inches and 2.687 inches long for horizontal and diagonal braces, respectively.

The lateral deflections at the point of loading calculated using MASTAN and observed in the tests are plotted in Figs. 5, 7, 9 and 10. In these figures the deflected shapes of the frames are also shown. Photographs of the tested specimens are shown in Figs. 6 and 8. It can be seen in Figs. 5, 7, 9 and 10 that assuming the joints to be rigid (MASTAN rigid) results in in very significantly smaller deflections than deflections assuming semirigid joints (MASTAN semirigid). MASTAN semirigid analysis results were obtained using the stiffness values based on Table 1 as described above.

In general the observed and calculated deflections (MASTAN semirigid) are seen to agree reasonably well. Since the MASTAN analyses uses linear axial stiffness, the agreement in the early stages of loading, for instance up to lateral loads of 1.5 kips to 2 kips range, appear to be satisfactory,. The largest discrepancy between the observed and calculated values obtained using the stiffnesses shown in Table 1 appears to be for frames with Type A columns loaded such that the diagonals are in tension. In Fig. 5 two more cases are shown with stiffnesses obtained at a lower load level. These are designated "K at 1.5" and "K at 1". These predictions are based on axial joint stiffnesses for all the members obtained from regression analysis fit to the deflections in the joint tests at axial load levels from zero to 1.5 kip and 1.0 kips, respectively. It is seen that these latter k values give calculated deflection values in better agreement with the tests results.

It is possible to improve the accuracy of the predictions by selecting the stiffness values obtained from joint tests on each member according to the forces in the members. This would lead to an iterative approach which would be more tedious than the simple approach aimed at in this study for design applications. Developing general criteria for specifying joint stiffness in the axial direction of the braces to be used in frame analysis based on tests is in progress.

Summary and conclusions

Tests and analytical studies were carried out on upright frames to study the effect of axial stiffness of the braces affected by local distortions at the joints. The comparison of the calculated and observed results indicates the feasibility of the procedure developed.

Ignoring the effect of the local distortions on the axial stiffness of the braces gives grossly erroneous results. Studies conducted but not reported here have shown that the effect of the semirigidty for moment fixity at the joints is smaller.

The approach developed is expected to be applicable to upright frames higher than those tested.

Acknowledgements

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References

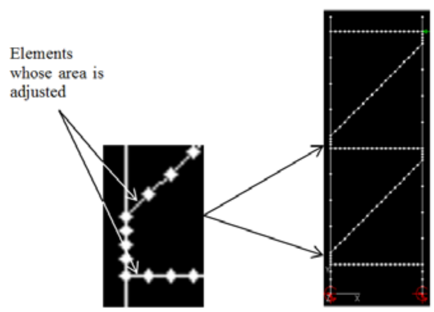
1. Roure, F., Peköz, T., Bonada, J, Somalo, M. R. Pastor, M.M. Casafont, M. "Stiffness of Welded Brace to Lipped Channel Column Joints: An Experimental and Numerical Approach", The International Colloquium on Stability and Ductility of Steel Structures, Timisoara, Romania, 2016

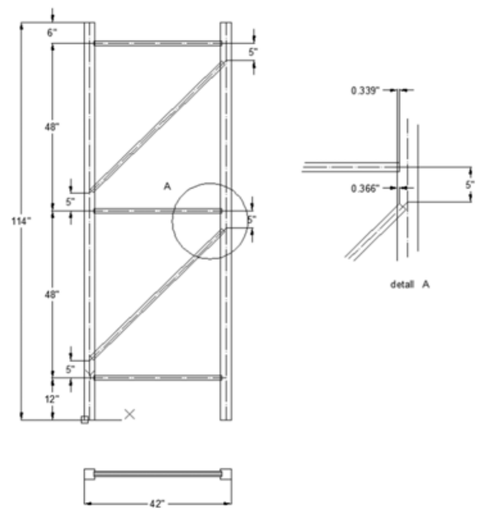
2. Ziemian, R., "MASTAN2" Program
Source for free download: http://www.mastan2.com/download.html

Table 1 Joint test results

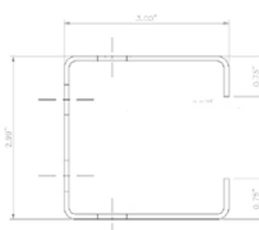
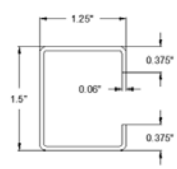
Column (thickness)	Angle	Test (force in diagonal)	stiffness	stiffness	adjusted diagonal brace area (*)	adjusted horizontal brace area (*)	Upper limit for regression line (**)
	degrees		(kN/mm)	k/in	in2	in2	k
A	90	tension	5.75	32.8333	0.00299	0.00211	1.50
(1.78 mm)	90	compression	3.44	19.6429	0.00179	0.00127	1.75
	45	tension	7.65	43.6826	0.00398	0.00281	2.25
	45	compression	5.67	32.3765	0.00295	0.00209	3.00
B	90	tension	14.77	84.3389	0.00768	0.00543	3.00
(2.67 mm)	90	compression	8.97	51.2200	0.00467	0.00330	3.25
	45	tension	20.31	115.9731	0.01056	0.00747	3.25
	45	compression	14.79	84.4531	0.00769	0.00544	4.75

(*) Elements with adjusted brace areas shown below
(**) Upper limit for the force for the regression line, the lower limit is 0 k





Upright frame

Column section Brace section

Joint details

Fig. 1 Test specimen details

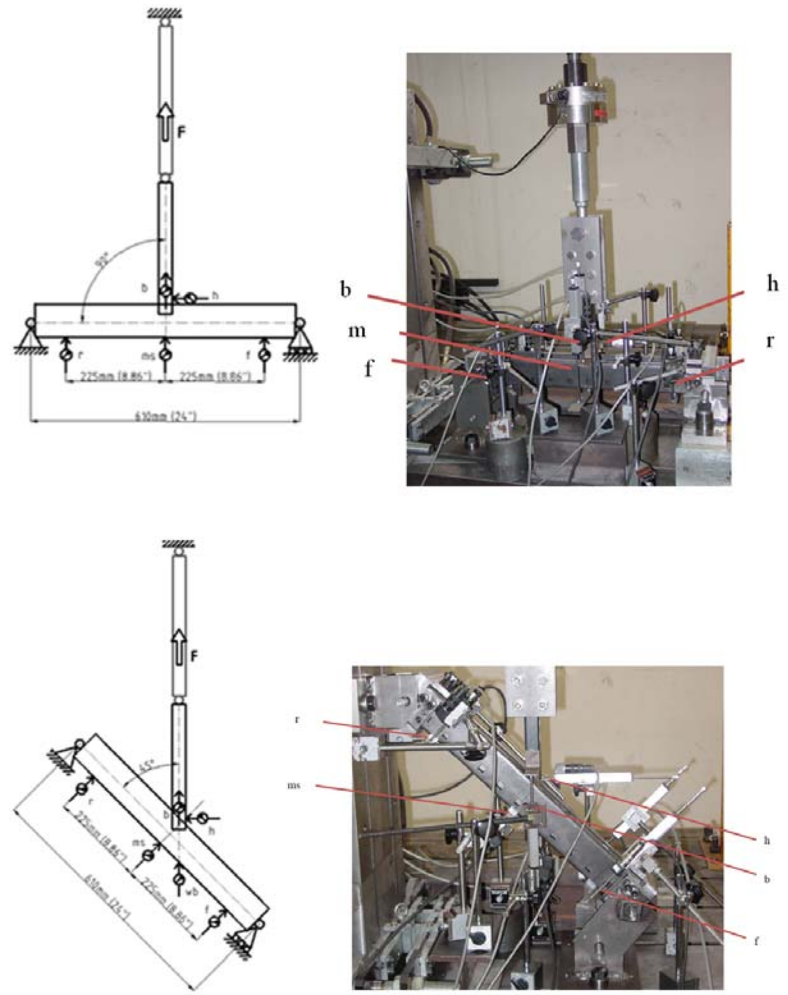


Fig. 2 Test set-ups

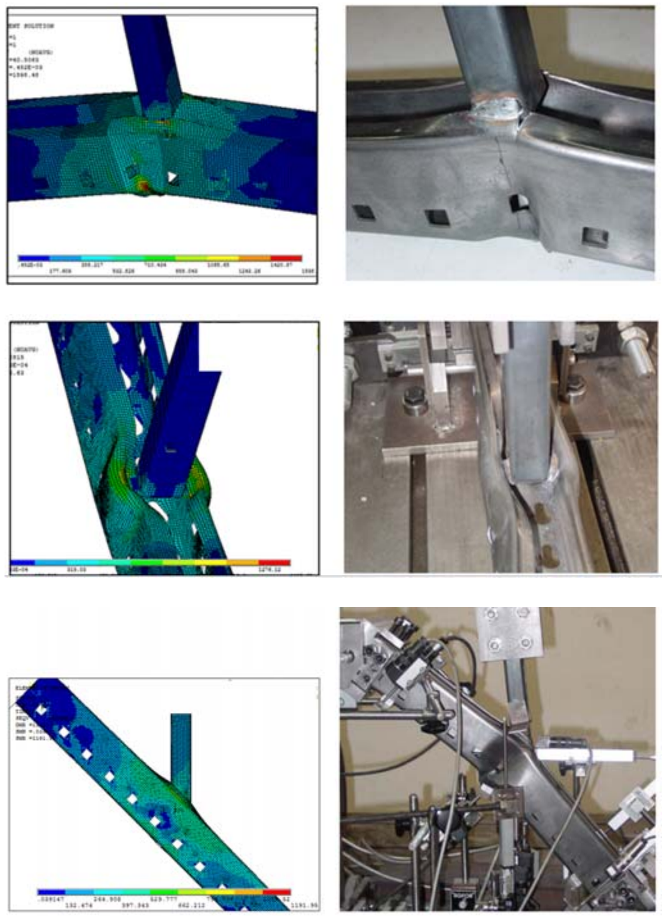


Fig. 3 Test fixtures, views of failed specimens ant finite element modelling

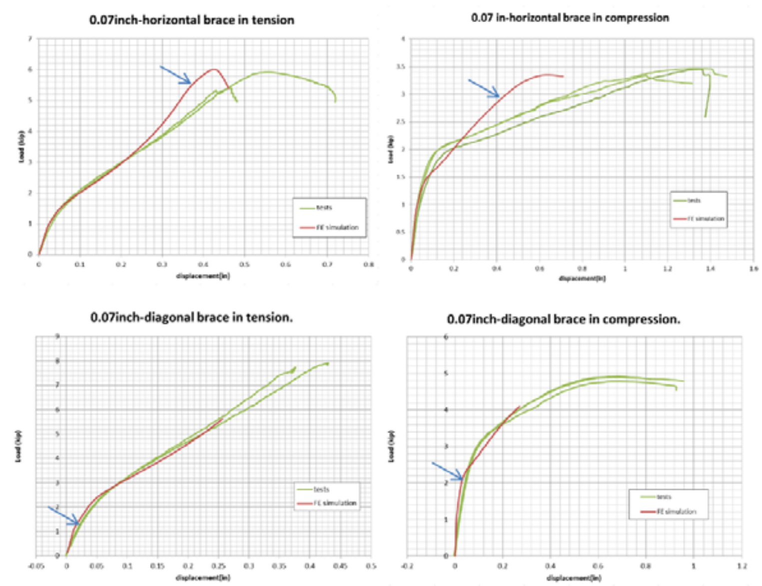
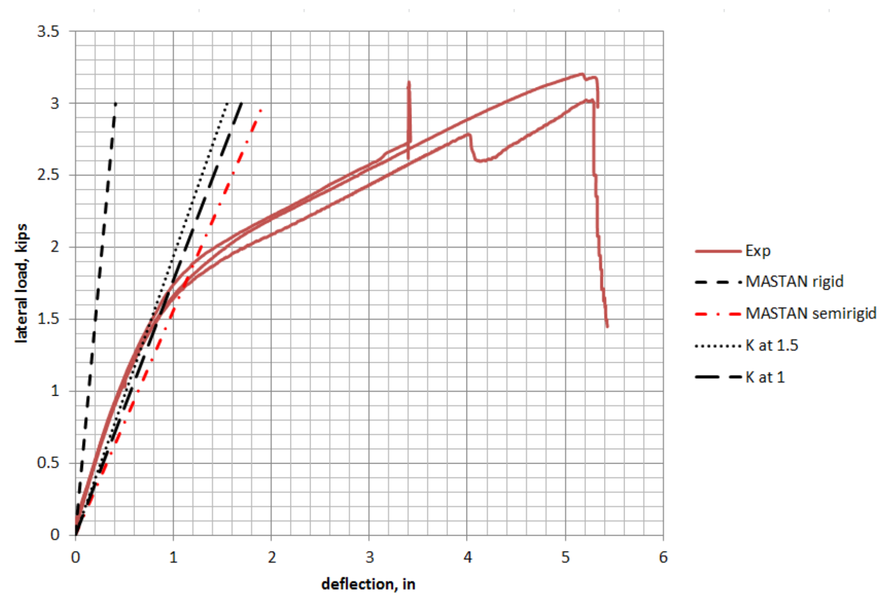


Fig. 4 Connection test results and finite element correlations for frames with Type A columns

- FEM simulations are indicated by the arrows



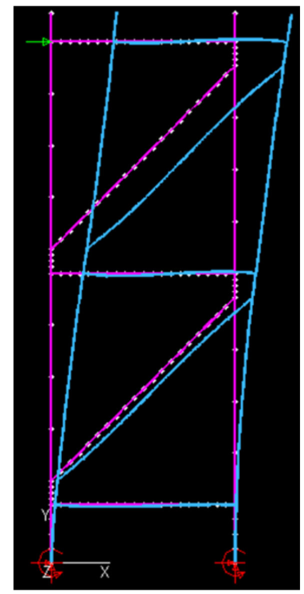


Fig. 5 Frame type A column test with diagonal in tension

Fig. 6 Frame type A column test set-up - diagonal in tension

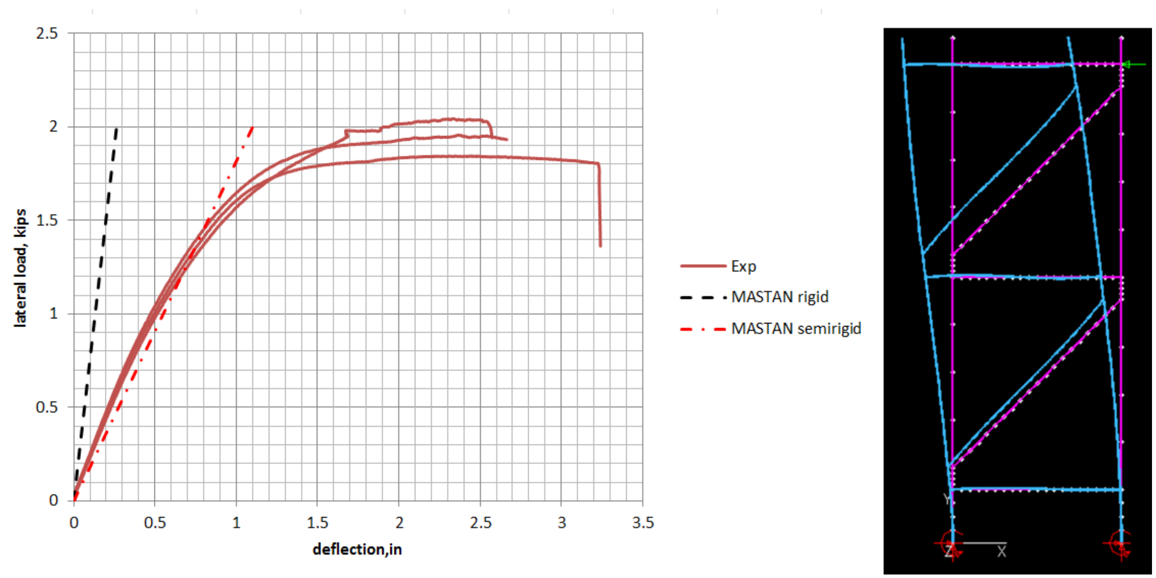
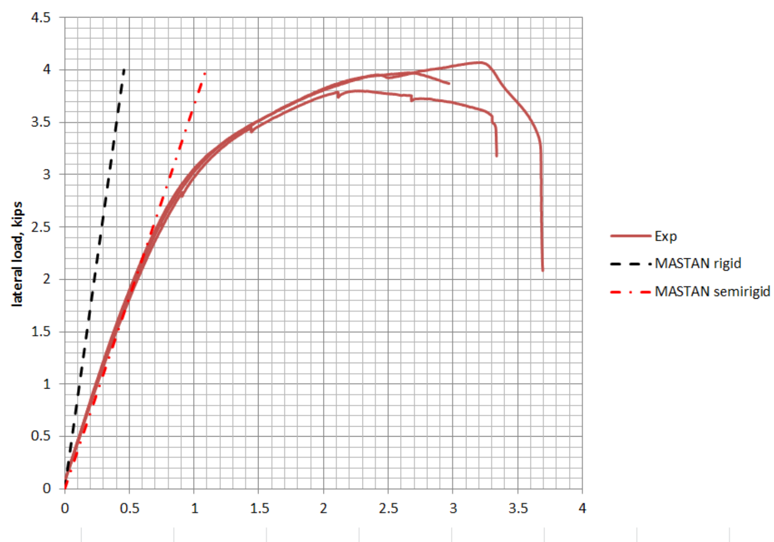


Fig. 7 Frame type A column test with diagonal in compression

Fig. 8 Frame type A column Test Set-up – Diagonal in compression



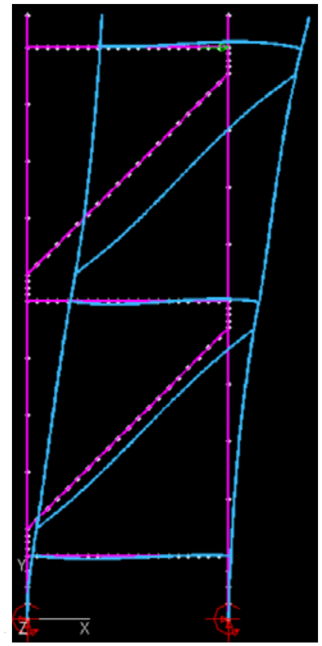
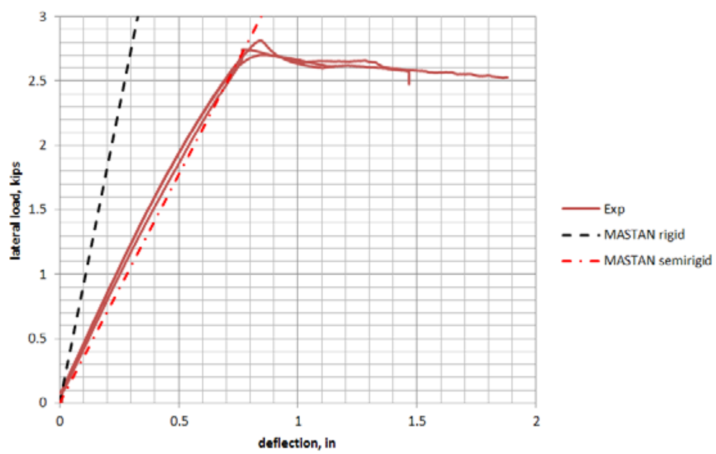


Fig. 9 Frame type B column test with diagonal in tension



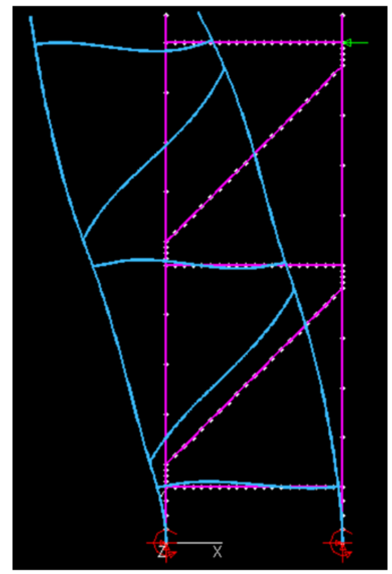


Fig. 10 Frame type B column test with diagonal in compression