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Teoman Pekoz

Ali Karakaplan

Ali Koç

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FRAME ANALYSIS AND DESIGN OF INDUSTRIAL COLD-FORMED STEEL RACKS

Teoman Peköz, PhD[1], Ali Karakaplan, Eng.Sc.D[2], Ali Koç[3],

Abstract

Industrial cold-formed steel racks have semi-rigid joints between the columns and beams. Frame analysis of such structures call for special considerations that are studied in this paper. The current design approach uses a linear idealization of the moment-rotation relation relationship based on an empirically decided secant to the nonlinear moment rotation curve.

This study presents a refined analytical approach to the analysis such frames using the state-of-art finite element based nonlinear analysis program LARSA 4D. Parametric studies are carried out to obtain an accurate design approach for using computer programs that treat linear moment-rotation relationships.

INTRODUCTION

Beams and columns of cold-formed steel industrial racks shown in Fig. 1 have mechanical connections. When loaded, the moment-rotation relationship at these joints is nonlinear. In this paper rotation is defined as the change in angle between a beam and a column. The Rack Manufacturers Institute Specification for The Design, Testing And Utilization Of Industrial Steel Storage Racks (to be referred to herein as the RMI Specification) [Rack Manufacturers Institute, 2010] idealizes the moment-rotation relationship as linear. The linearization obtained by taking a secant to the moment-rotation curve for all levels of loading can be quite inaccurate as will be shown in this paper. This study is aimed at exploring the accuracy of such approaches and reaching a more accurate basis for analysis.

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[1] Professor Emeritus, Cornell University, Ithaca, NY USA
[2] President, LARSA, Inc, Melville, NY USA
[3] Director, Research, Development and Support, LARSA, Inc, Melville, NY USA

Fig. 1 Examples of Pallet Racks

MOMENT-ROTATION RELATIONSHIP

Moment-rotation relationship at the joint between the columns and the beams are determined by three different types of tests according to the RMI Specification. Each type is preferable depending on the information required. The three types of tests are:

- Portal test illustrated in Fig. 2 is stated in the RMI Specification to be appropriate for getting the moment-rotation behavior to evaluate the sidesway behavior and stability. This is a rather difficult test to run.

- Cantilever test illustrated in Fig. 3 is specified for determining the moment capacity and according to the RMI Specification Commentary rigidity of the connection. The rigidity obtained from this test is lower than that obtained by portal tests.

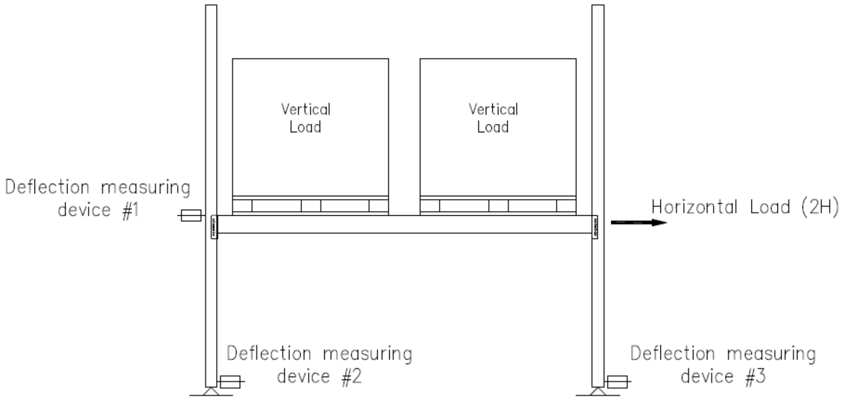


Fig. 2 Portal test Setup

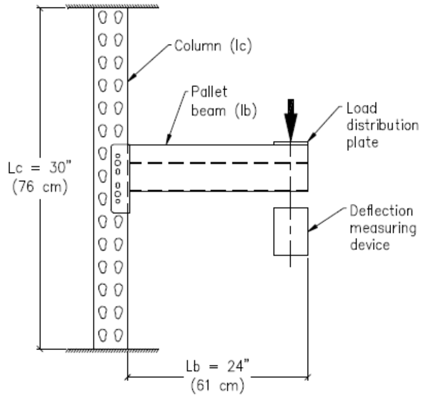


Fig. 3 Cantilever Test Setup

- Cyclic test illustrated in Fig. 4 is specified to determine the moment-rotation characteristics of the beam-to-column connections. This type of test is new in the RMI Specification and could be the most accurate type of testing to obtain moment-rotation relationship.

Since the objective of the study was to obtain a general approach, several moment-rotation relationships were used. The study covered a wide range of parameters, but this paper will demonstrate only one case. However, the conclusions were applicable to other cases studied as well.

The relationship between the moment and the angular change at a joint is not linear. The RMI Specification Commentary states that in evaluating cantilever tests it appears reasonable to use constant value, F for relating moment, M , to angular change, θ, between the members at a joint.

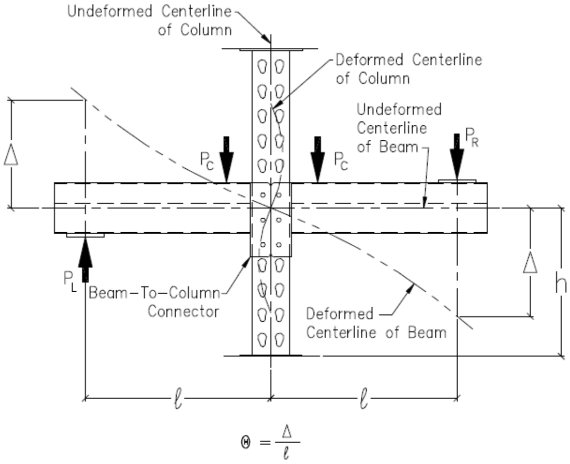


Fig.4 Cyclic test Setup

The value of M used for the determination of F is 85% of the ultimate moment, $M_{.85}$, and the value of θ is the rotation at $M_{.85}$. A reduction factor of 2/3 is applied to determine $F_{.85}$ the value of F to use in design of beams. No reduction factor is used for design of columns.

The RMI Specification states that “the portal test is to be performed when the value of F is be used to obtain a joint spring constant needed for a semi-rigid frame analysis”. In the portal test the tightening of the joint due to vertical loads in the actual rack is better represented. A reduction factor of 2/3 is applied to the value of F determined for design of beams as well as columns.

According to the RMI Specification “a horizontal force equal to the horizontal design load corresponding to the vertical load on the assembly shall be applied to the assembly, equally distributed between the two columns, at the level of the top of the beams, and in the direction of the beams. Deflection due to the horizontal loading shall be measured at the level of the top of the beams. The procedure shall be repeated at a load twice the design load." To determine the design load one needs the spring constant F . To determine the load to apply in the portal frame test one needs the design load. The process is thus an iterative one.

The portal test is difficult to run and get consistent reproducible results. The cyclic load tests that is included in the 2010 edition of the RMI Specification appears to be the most reasonable test to obtain the spring constant F . There are many cycles of loading involved in this test procedure. Thus one has to select the most relevant stress cycle for the purpose of determining the spring constant F .

The possibility of using one value of F, for example, $F_{.85}$, for all load levels was studied and the results are discussed below.

TYPES OF RACKS AND LOADINGS STUDIED

Several numerical examples were studied to see the implications of using various ways of determining frame load carrying capacity. Two types of racks were studied as numerical examples. One was a rack having cold-formed steel members (designated CF Rack), the other was a rack having hot-rolled steel members. Only the results on CF rack will be discussed here.

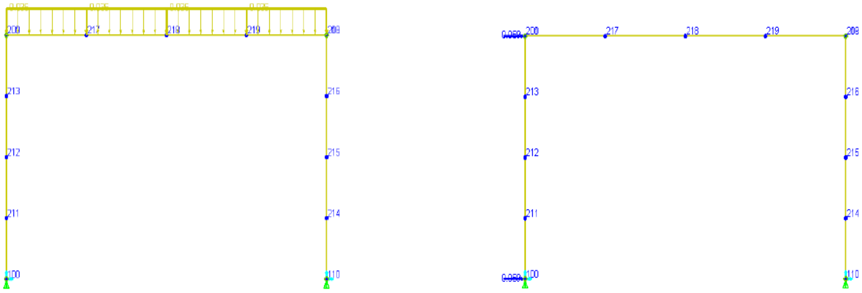


Fig. 5 Portal Frame Studied

Two rack frame configurations were studied. These were the portal frame shown in Fig. 5 and the multistory frame shown in Fig. 6. These figures are from the LARSA 4D Models which will be described below. Load cases and the node numbers are also shown on these figures.

The CF Rack members had the following properties:
Column $A_g = 0.936 in^2$, $I_x = 1.27 in^4$, $S_x = 0.8647 in^3$, Beam $A_g = 0.78 in^2$, $I_x = 1.701 in^4$.

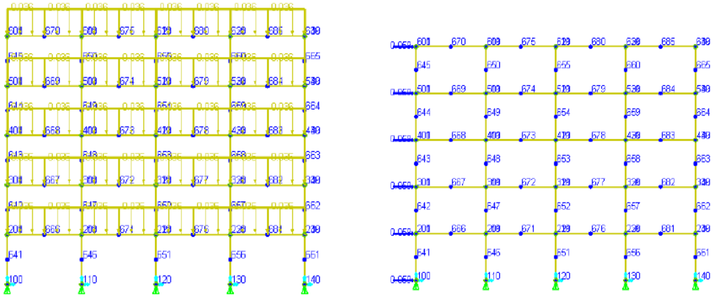


Fig. 6 Multi Story Frame Studied

Bending axis is the x axis of the members.

The beam center line to beam centerline dimension as well as the distance from the first level beam centerline to floor distance was 60 inches. Centerline to centerline dimension of columns was 99 inches.

Loading is applied as follows:

- Stage 1: Vertical load are applied in increments of 0.1 times the typical total factored load of 3.53 k per beam applied uniformly in 10 increments.

- Stage 2: While the total vertical load is on the rack, horizontal load is applied in increments of 0.1 times the vertical load divided by 240. The horizontal loads are applied up to 30 increments. The combination of the vertical load and horizontal load is intended to simulate earth quake loading. In the Tables the parameters are in general reported for the increment 10 of the horizontal loads since this corresponds to the intended design load.

The modulus of elasticity is reduced by 80 percent as required by the AISI Specification [American Iron and Steel Institute, 2007] to a value of 23,600 ksi for second order analysis.

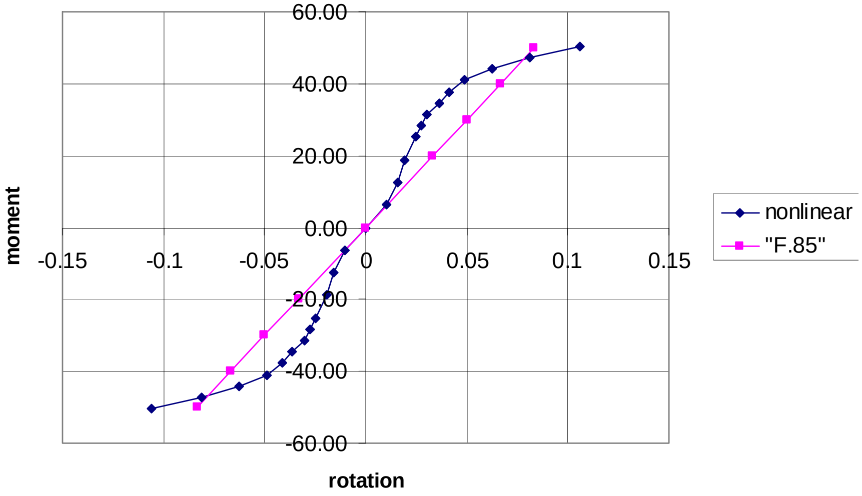


Fig. 7 Moment-Rotation curve for the CF steel rack studied

TYPES OF JOINT PROPERTIES STUDIED

Moment-rotation curve of the cold-formed steel rack joint was assumed to be as shown in Figs. 7 and 8. This curve was a modified version of a cantilever test result. A typical cantilever test result was made stiffer to represent the tightening due to vertical loads. The line designated F.85 is a secant drawn from the origin to the nonlinear curve where the moment reaches 0.85 times the maximum value of the moment obtained in the test.

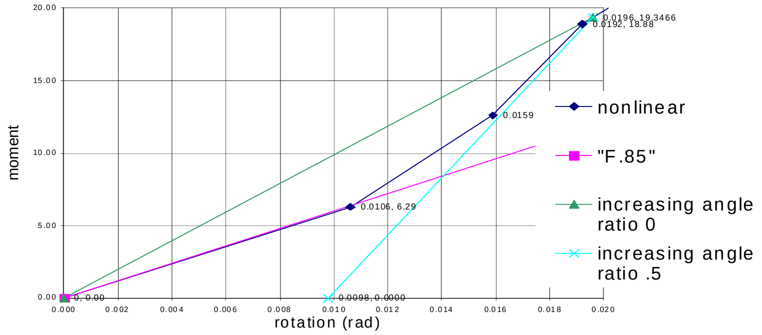


Fig. 8 Joint idealization

Cyclic testing data is shown for a series of tests in Fig. 9. The process of extraction of the moment-rotation curves to be used for semi-rigid frame analysis requires careful study.

Column base fixity was considered for two reduced values of 2,400 and 600 in-k/rad. In this paper the results for the former value are discussed.

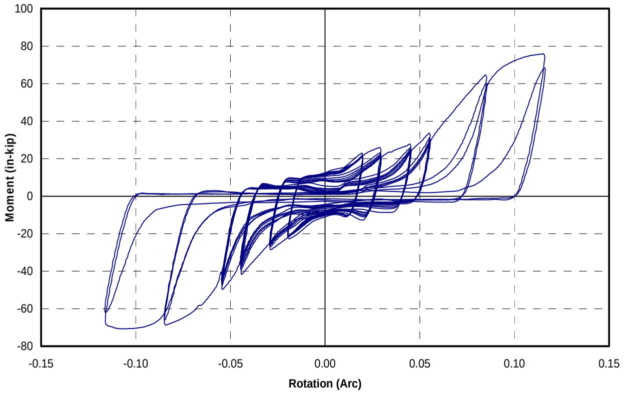


Fig. 9 Cyclic Test Results for a Rack Joint

ANALYSIS METHODS

Computer programs MASTAN and LARSA 4D were used for the analyses. MASTAN analyzes frames only with linear semi-rigid joints. As will be shown later this is a serious limitation for racks and the procedure developed here need to be used to apply to nonlinear semi-rigid joints. However, this procedure may lead to results that are quite conservative.

LARSA 4D is a state of the art finite element based nonlinear analysis program described at the site http://www.larsausa.com/ . This program was used for the parametric studies described in this report. This program enables the modeling of semi-rigid joints by true nonlinear springs characterized by moment-rotation values obtained by tests. This program also has a “staged construction” capability which makes it possible to change the spring properties between stages. As described in the next section this was used when the spring characteristics needed to be changed after vertical loads are applied and the application of horizontal loads starts. The loading in any stage can be applied incrementally. Increments are also referred to as Steps.

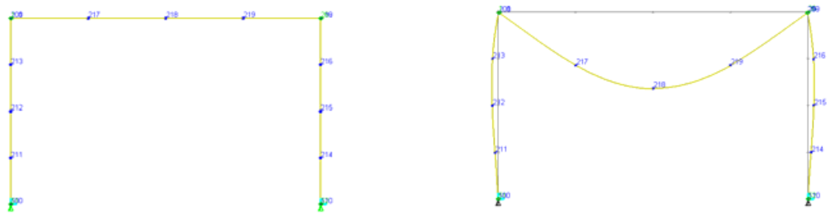
PORTAL FRAME ANALYSIS

First the portal frame shown in Fig. 5 was analyzed for the loads mentioned above. Deflected shapes of the frame are shown in Fig. 10. During the application of the vertical loads (gravity loads) the angle between the columns and the beam decreases. When the horizontal load is subsequently applied, the angle on the left side begins to increase and the angle on the right side continues to decrease. This is shown in Fig. 10 as well as the plot in Fig. 11.

For increasing rotations, the spring moment-rotation curve is nonlinear as seen in Fig. 7. Though the moment rotation curve for the increasing rotations is determined in the tests, the tests do not show exactly what the decreasing curve should be for an arbitrary point on the increasing rotation curve. For this study, it was assumed that the decreasing moment rotation relationship is linear. When the moment becomes zero, there could be a residual rotation as seen in Fig. 8. This residual rotation can be defined as a percentage of the rotation at which the rotation began to decrease. The percentage is designated “ratio”. If the “ratio” is zero then there is no residual rotation. If the “ratio” is 1.00 then the residual rotation is equal to the rotation at which rotation began to increase. This is illustrated in Fig. 8 for ratios equal to 0 and 0.5. Analyses were carried out for various values of “ratio”. Highest deflection and moment is obtained for “ratio”=0. Very significant decrease in deflections and moments were observed when nonlinear moment rotation relationships are used. Results are discussed more in detail for multistory frames, but the conclusions are valid for this portal frame as well.

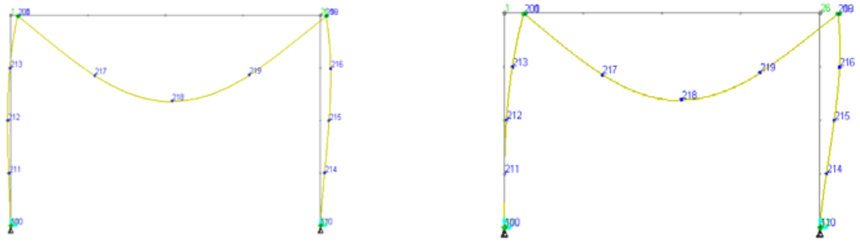
MULTISTORY FRAME ANALYIS

The overall frame configuration and the deflected shapes of the multistory rack studied are shown in Fig. 11 for various stages of loading.
The spring rotations obtained by LARSA 4D are plotted in Fig. 12. It is seen that the rotations at these lateral loads are much smaller than the rotations corresponding to $F_{.85}$; namely when the moment is 85% of the



Initial shape

Stage 1 Step 10



Stage 2 Step 10

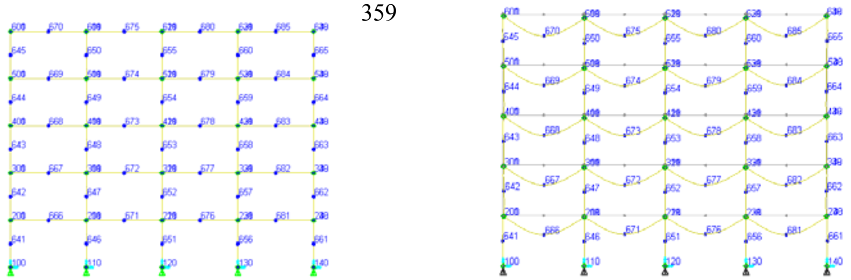
Stage 2 Step 30

Fig. 10 Portal Frame deflected shapes

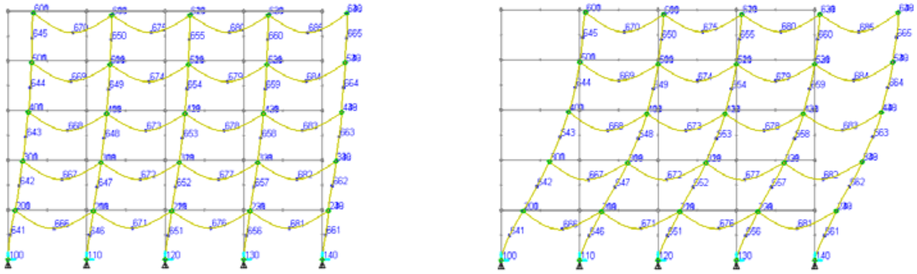
maximum moment obtained in a joint test. The rotation at each joint is different when the horizontal load is applied. Determining the rotations at all joints when the horizontal loads start to be applied is tedious but essential for the decreasing rotation behavior of each spring where the angle between the columns and beams starts to increase. The solution for this difficult task was made possible by a special macro prepared for LARSA 4D which determined the rotation at each joint on the left end of each beam when the horizontal load was applied. The macro also inserted a different linear spring value F for the moment-rotation for the left end of each beam.

For second order analysis the values of F as well as the column base fixity was reduced by a factor of 0.85 in as required by the AISI Specification [American Iron and Steel Institute, 2007].

The deflections and moments are obtained by LARSA 4D analysis are given in Table 1. Linear joint results by MASTAN analysis are given in Table 2.



Initial shape Stage 1 Step 10



Stage 2 Step 10 Stage 2 Step 30

Fig. 11 Multistory Rack Deflected Shapes

The following are some additional observations and conclusions based on the results:

- Assuming “ratio” = 0 gives more conservative results than assuming “ratio” greater than zero. Definition of “ratio” is given in previous section. Determining ratio or the exact shape of the reducing branch of the moment curve for all values of maximum moment experimentally is not practical or possible. It is certain that “ratio” should be greater than 0. For the sake of comparison, the numbers given below are based on “ratio”=0. Similar comparisons were made for other values of “ratio” and column base fixity.

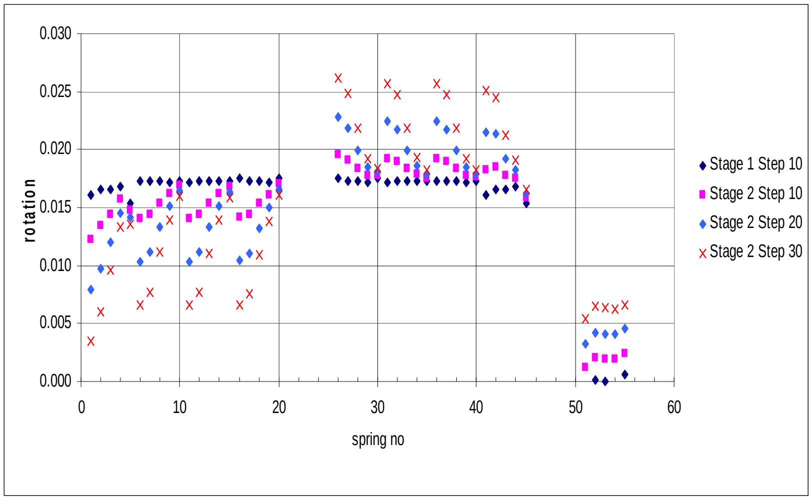


Fig. 12 Multistory Rack Spring Rotations

(Note: Springs 1 through 20 are on the right end of the beams where the rotation is increased with horizontal load. Springs 26 through 45 are on the left end of the beams where rotation is decreased with horizontal load. Springs 51 through 55 are column base springs)

- From Table 1, it is seen that assuming rigid joints in the analysis is grossly unconservative. A maximum horizontal deflection of 0.3768 in is determined for rigid frame compared to 1.005 in for the semi-rigid frame determined as explained in the Note 3 this Table.

- There are significant benefits of using the nonlinear joint characteristics of joints. For the maximum moment is 8.879 in-k for linear semi-rigid joints using $F_{.85}$ versus 4.912 in-k for non-linear semi-rigid joints with “ratio”= 0 and 3.801 in-k for “ratio”=0.8.

ratio	Deflection top beam	M_{max} 2nd column base	P_{max} 2^{nd} column base	Note
Na	0.3768	3.100	18.13	6
Na	2.4239	8.879	17.79	1
Na	0.7811	4.291	17.75	2
0	1.0050	4.912	17.76	3
0	2.4697	9.004	17.70	4
0	1.2531	5.600	17.74	5
0.4	0.8240	4.386	17.76	3
0.8	0.6306	3.801	17.76	3

Note:

1	For linear left and right joints using F=750 ($F_{reduced}$=600k-in/rad)
2	For nonlinear both ends beams for vertical and horizontal loads
3	For nonlinear for vertical loads for both ends of beams For horizontal loads applied subsequently, springs nonlinear for right end linear for left end
4	All Linear springs with right and left stiffer spring const 6.293/0.0106 (=593.68) . For these values see Fig. 8.
5	All linear springs with right and left stiffer spring const 18.88/0.0193 (978.24). For these values see Fig. 8.
6	Rigid joints by MASTAN Analysis
Na	not applicable

Table 1 Multistory frame LARSA 4D analysis results

- The use of $F_{0.85}$ also gives very conservative results. For example a deflection of 2.424 in is obtained using $F_{0.85}$ versus 1.005 in using the nonlinear moment rotation curve.

$F_{.85}$	$.8\ F_{.85}$	Horizontal Deflection at top beam level, in.	Maximum Column Moment, in-k.	Maximum Column axial Load, k.	Deflection at bottom beam level, in	Maximum Beam end Moment, in-k
rigid		0.377	3.074	18.13	0.124	
1200	960	1.278	5.688	17.74	0.327	19.67
1125	900	1.370	5.954	17.73	0.346	19.27
1000	800	1.574	6.536	17.72	0.387	18.59
875	700	1.883	7.406	17.71	0.448	17.92
750	600	2.408	8.861	17.71	0.551	17.36

Table 2 Multistory frame MASTAN analysis results

- The significant difference between using linear semi-rigid joints with $F_{0.85}$ and using the non-linear moment rotation relationship can be explained as follows: using $F_{0.85}$ assumes that the moments and rotations are much larger than the analysis would show. It can be seen in Fig. 7 that $F_{0.85}$ line crosses the nonlinear moment-rotation curve between a moment between 47.20-50.35 in-k and between a rotation between 0.0809-0.1062 rad. However the non-linear analysis with the non-linear moment rotation curves shows rotations plotted in Fig. 12 around 0.017 rad.

- The range of rotations and moments obtained by the nonlinear analysis with the nonlinear moment-rotation curves are shown in Fig. 7. In this range, it is interesting to see in Table 1 that the analyses carried out with linear joint rotation spring constant 18.88/0.0192 (Note 5 in the Table) give better results than $F_{0.85}$ or a spring constant 6.293/0.0106 (Note 4 in the Table). The slope of the moment-rotation curve to the left of 6.293/0.0106 is almost identical with the $F_{0.85}$ where as the slope to the left of 18.88/0.0192 is significantly different.

- These conclusions apply to other the moment-rotation curves used in this study. The results were sensitive to the shape of moment rotation curves. It is necessary to look at data for other joints before general conclusions are drawn.

- If the moments at the beam ends due to vertical loads are closer to the ultimate moments of the joints the benefits obtained by using an analysis that includes the nonlinearity of the joints may not be as large as demonstrated in this study.

A POSSIBLE DESIGN APPROACH

Analytically it is most accurate and proper to use a program such as LARSA 4D that accounts for nonlinear moment-rotation behavior of joints. The following is a conservative procedure to use a computer program as MASTAN which applies to frames with joints linear moment-rotation relationship:

- Based on the moment-rotation relationship draw a moment versus secant plot as shown in Fig. 13.

- Based on MASTAN analysis results given in Table 2, plot a maximum beam end moment versus 0.8 $F_{.85}$ as shown in Fig. 14.

- Based on MASTAN analysis results given in Table 2, plot a maximum column moment versus 0.8 $F_{.85}$ as shown in Fig. 15.

- Start the analysis of the frame by MASTAN using 0.8 $F_{.85}$. In the case of the frame being analyzed here for beam end fixity coefficient of 0.8 $F_{.85}$ = 600 in k/rad and determine maximum beam end moment anywhere in the frame. In the case of the frame being analyzed the maximum beam end moment is 17.36 in-k.

- The value of the secant to the moment-rotation curve at a moment of 17.36 is approximately 960 as seen in Fig. 13.

- Analyze the frame by MASTAN using a beam end fixity coefficient of 960.

- The maximum end moment obtained is about 19.67 in-k as seen in Table 2.

- Fig. 13 indicates that the secant value or the beam end fixity coefficient should be 900 thus the process has converged and the end moment is 19.27 in k.

- Determine maximum column moment anywhere in the frame for beam end fixity coefficient of 900 in-k/rad. This can be determined from Table 2 or plot of Fig. 15. The value of the maximum column moment is 5.964 in-k.

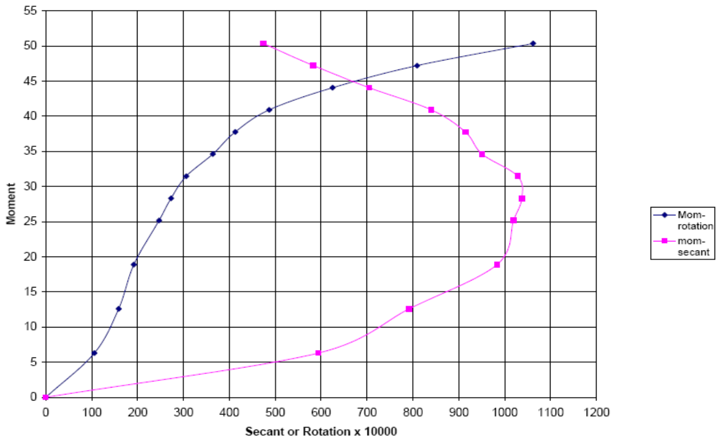


Fig. 13 Moment-rotation and moment-secant curves
Note: Moment-secant curve is based on the moment-rotation curve

- The value of the secant to the moment rotation curve at a moment of 8.861 is approximately 600 as seen in Fig. 14.

- Analyze the frame by MASTAN using a beam end fixity coefficient of 960. The maximum beam end moment obtained is about 19.27 in k

- Fig. 14 shows that the secant value or the beam end fixity coefficient should be 900 in-k/rad, thus the process has converged and the beam end moment is determined to be 19.27 in k and the maximum column moment is 5.964 in-k. These values are conservative compared to the maximum beam end moment of 17.76 in-k and maximum column moment 4.912 in-k by LARSA 4D analysis given in Table 1 with Note 2. The degree of conservatism for this example is 21.4% for the column moment and 8.5% for the column moment.

- It may be possible to reduce the degree of conservatism of the procedure above by taking other values of the moments rather than the maximums in the above procedure. This will be studied in future.

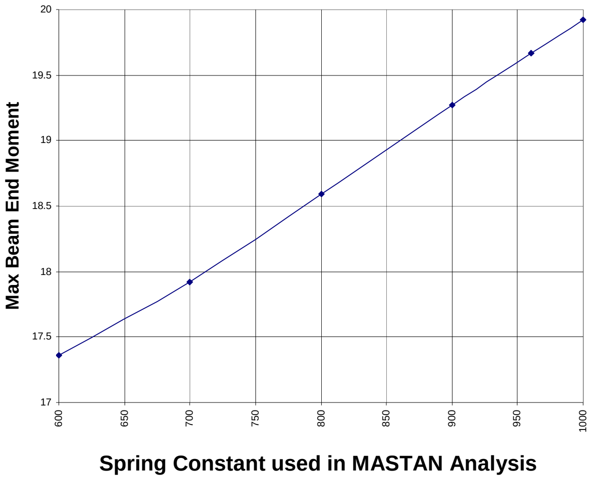


Fig. 14 Maximum beam end moment in the frame versus spring constant used in MASTAN analysis based on Table 2.

- Other moment rotation curves were tried and similar results were obtained.

CONCLUSIONS

A study of industrial rack frames with nonlinearly semi-rigid joints was carried out. The results show that care must be used to treat the moment-rotation relationship as linear. The LARSA 4D program was found to be particularly suitable to treat the nonlinear nature of the moment-rotation relationship of the joints. A procedure for using idealizing the joint moment-rotation relationship as linear was developed. This approach may be too conservative for certain range of parameters.

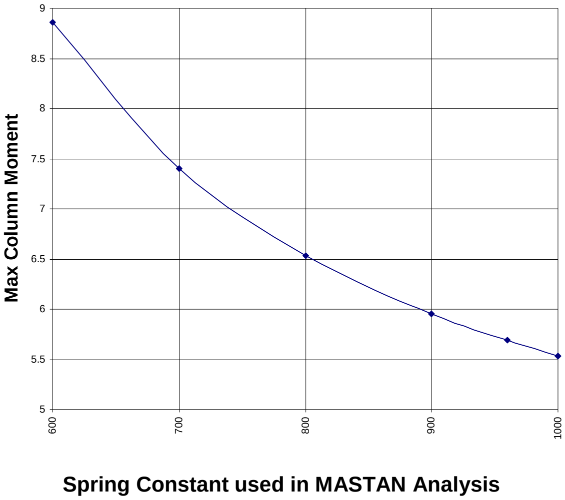


Fig. 15 Maximum column moment in the frame versus spring constant used in MASTAN analysis based on Table 2.

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