Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.IV)

6-3-1

EFFECT OF JOINT FLEXIBILITY ON SEISMIC RESPONSE OF LOW-RISE STEEL FRAMES

Wael YOUSSEF-AGHA[1] and Haluk AKTAN[2]

[1]Department of Civil Engineering, Wayne State University, Detroit, MI 48202

[2]Department of Civil Engineering, Wayne State University, Detroit, MI 48202

SUMMARY

Joint flexibility significantly influences the drift of low-rise steel frame buildings in low seismicity zones. However, lateral actions are not considered critical in the design of such buildings by assuming rigid joints will generate sufficient lateral stiffness. An analytical model for obtaining the flexibility properties of semi-rigid bolted connections is presented and compared with experimental data obtained by other investigators (Ref. 6,7). The joint model is incorporated in a computer program for predicting the drift of low-rise steel frames under seismic action.

INTRODUCTION

Low-rise moment-resisting steel frame buildings with bolted connections in low seismicity zones undergo larger than anticipated drift under seismic actions. This is because the lateral actions are not considered critical for the design and, hence, the lateral stiffness characteristics of the building are not evaluated assuming that the moment connections will generate sufficient lateral stiffness. An example is the Ohio earthquake of January 31, 1986, which caused damage to several low-rise buildings in the area (Ref. 1). Subsequent investigations show that the primary reason for the earthquake damage was due to excessive drift, and that was simply because lateral stiffness evaluations of low-rise frames were ignored.

For commonly-used bolted connection details, the assumption of perfectly rigid joint is not valid. Therefore, deformations of bolted frames attributable to joint flexibility should be the main criterion for evaluation of the lateral drift of low-rise moment-resisting frame buildings (Ref. 2). Since this excessive drift during low levels of seismic action causes damage to walls, windows, partitions, etc., resulting in a building unfit for use, it is necessary to obtain a method that includes the effect of joint flexibility in the analysis of buildings under lateral load. One way to incorporate joint flexibility in the analysis is to obtain the joint stiffness, (M-θ curve) of the joint, and model the steel frame as an assemblage of beams, columns and semi-rigid joint elements.

For certain types of connections, (M-θ curves) are available from prototype experiments as presented, e.g., in (Ref. 2,3,4,5) and more recently (Ref. 6,7).

However, it is not practical to carry out extensive testing for each connection size and type to assess the joint stiffness accurately. Moreover, the tests are expensive and time-consuming. This study will present an analytical procedure for determining the (M-θ curve) for bolted moment-resisting connections. The analytical joint model presented in this study is for the analysis of top and seat angle. The modeling parameters are components of a general joint and the model is applicable for generation of moment rotation characteristics of all bolted joints such as the inclusion of the web angle in addition to the top and seat angles. It is important to note that every connection exhibits some flexibility, and hence it is important to include the effect of joint flexibility to assure serviceability in every structure.

Computer programs used for the analysis of steel frames with semi-rigid joint elements are DRAIN-2D (Ref. 8), to verify the experimental and analytical correlation, and ABAQUS for the serviceability response state analysis under seismic action.

Top and Seat Angle Connection Analytical Model In developing the relationship between the moment acting at the end of the beam and the corresponding rotation for top and seat angle bolted connections it is assumed that the joint rotation is primarily due to the deformation at the flange of the column and the top and bottom angles as shown in Fig. 1.

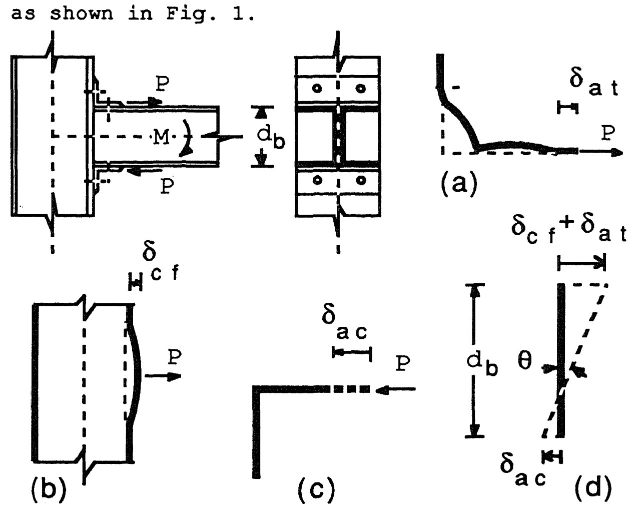


Fig. 1 Deformation of top and seat angle connection. (a) Angle deformation under tensile force. (b) Column flange deformation. (c) Angle under compressive force. (d) Rotation of connection due to applied moment M

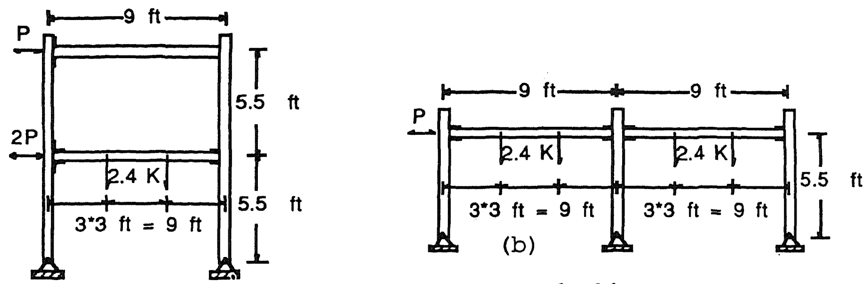
The bending moment at the joint is resolved to a couple "P" with arm equal to the depth of the beam section as shown in Fig. 1 and represented in Eq. (1). The joint rotation is defined as the summation of column flange and top and seat angle deformations divided by the depth of the beam section as shown in Fig. 1-d and represented in Eq. (2). Where M is the resisting moment at the beam end, d_b is the depth of the beam section, θ is the joint rotation due to the applied moment M, δ_{cf} is the column flange deformation, δ_{at} is the angle deformation under tensile force and δ_{ac} is the angle deformation under compressive force.

$$M = P * d_b \quad (1)$$

$$\theta = (\delta_{cf}+\delta_{at}+\delta_{ac})/d_b \quad (2)$$

The analytical procedure presented here is the calculation of the deformation components of the column flange, which is idealized as a cantilever plate, and the top and seat angle including the bolts. The joint deformation model is represented in a nonlinear M-θ relationship which is later simplified to a bi-linear form for use in computer simulation. Details of the analytical model are discussed in (Ref. 9).

Comparison With Existing Experimental Data Results of experimental tests conducted by Stelmack (Ref. 7) and Marley (Ref. 10) are used for the purpose of comparison with the analytical model. The frames tested by Stelmack and Marley consisted of a one-story, two-bay frame and a two-story, one-bay frame, as shown in Fig. 2.



All Members are W 5*16 A36 Steel

Fig.2 (a) Two-story, one-bay frame details. (b) One-story, two-bay frame details

The frames were constructed for both 1/4 inch and 1/2 inch thick top and seat angle connections, shown in Fig.3, and were subjected to various combinations of gravity and cyclic lateral load histories (Ref. 7).

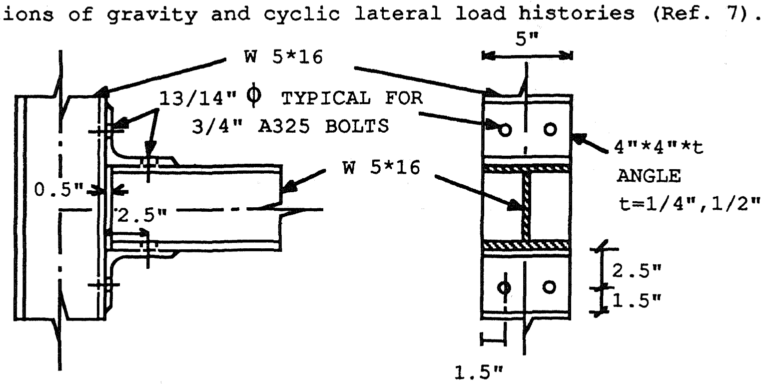
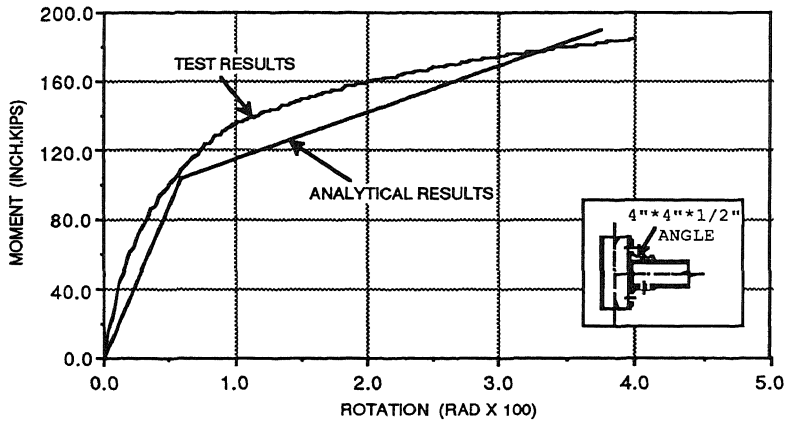
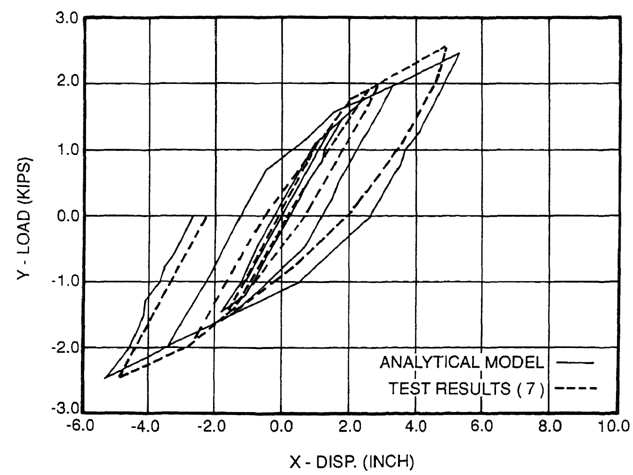


Fig. 3 Top and seat angle connection details

The analytical joint model results are compared with the experimental results for the two connections described above. The results obtained from the analysis of the joint are used to generate a comparable computer model for the analysis of the frames shown in Fig. 2. The analytical and experimental results for the frames are compared in the form of lateral load vs. lateral displacement at each floor level. Fig. 4 shows comparison examples between the developed analytical model and the experimental results. For more details refer to (Ref.9). The results of the comparison are the following: 1) Experimental and analytical initial stiffness correlates well. 2) Under low levels of load cycles just beyond yield, the analytical model hysteretic energy dissipation is more than the experimental hysteresis. 3) The analytical model correlates better with the experimental results under large load cycles near the limit state response.



(a)



(b)

Fig. 4 (a) Comparison of the analytical and experimental results of 1/2 inch thick connection. (b) Comparison of the analytical and experimental results of second story displacement of test # 9

The analytical model is intended for serviceability considerations in low-rise steel frames. However, the joint model can also be used to simulate the limit state response accurately.

<u>Seismic Response of Low-Rise Steel Frame</u> A dynamic nonlinear analysis of the two-story one-bay steel frame shown in Fig.2-a with 1/2-inch angle shown in Fig.3 is performed using the ABAQUS computer program. Although the scaling of the frame was not described by Stelmack (Ref. 7), for the purposes of this paper it is assumed to represent a 1/3-scale two story industrial building. Representative mass calculations are based on this scaling assumption. The frame is subjected to a low seismic ground acceleration and gravity loading to

simulate a realistic load condition. The procedure described earlier is used in the analysis and the results are compared with those obtained using the assumption of a rigid joint model.

The earthquake acceleration record used in this analysis is shown in Fig. 5 with a maximum peak acceleration of 0.05 g and an effective peak acceleration of 0.036 g.The comparison between the maximum drift of the frame with variable mass for the rigid and flexible connection models is shown in Fig.6. For convenience, the structural mass is represented in terms of total load to dead load ratio.

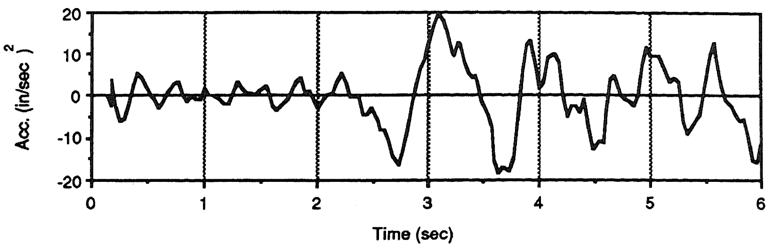


Fig. 5 Earthquake acceleration record used in the analysis

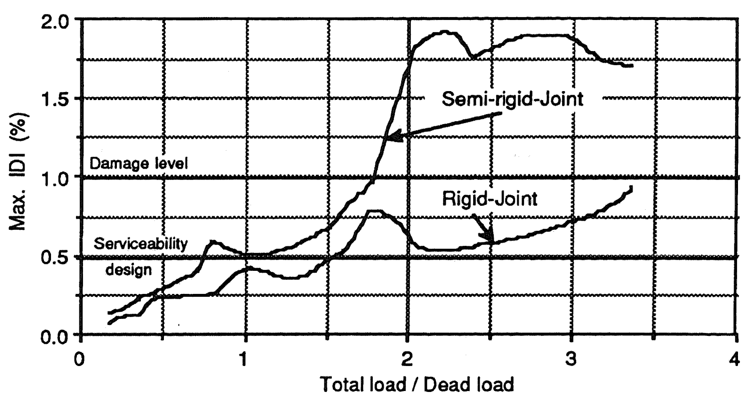


Fig. 6 Comparison of seismic response of the two-story frame

As seen in Fig. 6, the designer's assumption of rigid joints satisfies serviceability in the case of realistic gravity load. However, when joint flexibility is incorporated, serviceability requirements are not satisfied and in certain cases significant damage will be observed for inter-story drift ranges above 1%. It is important to note that this comparison is valid for the ground motion used in this study, yet the study verifies that low-rise frames with bolted moment connections that comply with state-of-the-practice design and detailing requirements will not provide the required stiffness for serviceability in low seismicity zones. The designer should evaluate the lateral drift of such classes of structures, and the moment-resisting joint design should be controlled by lateral stiffness requirements.

It is clear that the flexibility of the joint plays a significant role as regards the drift of the frame. A level of drift which is acceptable using rigid joint assumption becomes unacceptable if flexible joint behavior is included in the analysis; the latter represents the real behavior of the structure.

CONCLUSIONS

The purpose of this study was to develop a practical analytical method to obtain the moment-rotation relationship for semi-rigid bolted connections. The moment-rotation relation was developed to be suitable for use in a computer program to evaluate the response of low-rise steel frame buildings under low levels of seismic action. An analytical model for semi-rigid bolted connections is presented. The model was compared with experimental results obtained by other investigators and was found satisfactory.

Joint flexibility has a large effect on the drift of low-rise steel frame buildings in low seismicity zones. For such buildings lateral actions are not even considered critical for the design; thus evaluation of the lateral stiffness characteristics of the buildings is ignored.

Methods for incorporating joint flexibility in the design of low-rise industrial buildings with moment connections should be developed. Two methods to be explored are: Reduction coefficients for the beam moment of inertia and amplification coefficients for drift calculated from the rigid joint assumption. Other research on joints is related to modeling fabrication errors for joint flexibility calculations.

REFERENCES

1. Neil J. Monroe, M. EERI, and John D. Stevenson, M. EERI, "Preliminary Report on the Ohio Earthquake of January 31, 1986," Proceedings of Workshop on Engineering Characterization of Small Magnitude Earthquake. EPRI. Palo Alto, Jan., 1987.
2. Fry, M.J., and Morris, G.A., "Analysis of Flexibly Connected Steel Frames," Canadian. Journal of Civil Engineering. 2(3),pp. 280-291, 1975.
3. Krawinkler, H., and Popov, E.P., "Seismic Behavior of Moment Connections and Joints," Journal of the Structural Division, ASCE, Vol. 108, No. ST2, February, 1982, pp. 372-391.
4. Popov, E.P., and Pinkney, R.B., "Cyclic Yield Reversal in Steel Building Connections," Journal of the Structural Division, ASCE, Vol. 95, No. ST3, Mar., 1969, pp. 327-353.
5. Wilson, W.M., and Moore, H.F., "Tests to Determine the Rigidity of Riveted Joints in Steel Structures," Bulletin No. 104, Engineering Experiment Station, University of Illinois, 1917.
6. Stelmack, T.W., Marley, M.J., and Gerstle, K.H., "Analysis and Tests of Flexibly Connected Steel Frames," Journal of Structural Engineering, ASCE, July, 1986, Vol. 112, No. 7, pp. 1573-1586.
7. Stelmack, T.W., "Analytical and Experimental Response of Flexibly-Connected Steel Frames," Report to AISI CEAE Department, University of Colorado, Boulder, 1983.
8. Powell, G.H., Kannan, A.E., "DRAIN-2D" A computer program distributed by NISEE/Computer Applications, Reports No. EERC 73-6 and EERC 73-22,Apr., 1973, Revised Sep., 1973 and Aug., 1975.
9. Youssef-Agha, W., Aktan, H.M., Olowokere O.D., "Seismic Response of Low-Rise Steel Frames," to appear, Journal of the Structural Division, ASCE, 1988.
10. Marley, J.J.,"Comparison of Analytical and Measured Flexibly-connected Frame Response," Master of Science Thesis, University of Colorado, Boulder, 1981.