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Determination of column base-plate connection flexibility in low-rise metal buildings

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ABSTRACT: Low-rise metal building systems are used in various applications such as complex production facilities and warehouses, retail stores, shopping centers, schools, libraries and medical facilities. Cost effectiveness of metal building systems is the major reason for their widespread adoption in the U.S. and around the world. The current practice for most low-rise metal building frames is to model the column bases as pinned for strength and serviceability design. For strength limit state design, the pin connection assumption gives a conservative estimate, which is accepted for safety considerations. Preliminary research findings indicate that even the smallest column bases provide a rotational stiffness and the pinned assumption is very conservative when evaluating frame drift due to lateral loads, which can significantly increase the cost. Therefore, there is a need to quantify the rotational stiffness of the column base-plate connections in low-rise metal buildings. This paper describes an experimental program which examines the rotational stiffness of base-plate connections. The experimental program includes testing of a total of nine columns base-plate connections with various base-plate dimensions, number of anchor rods, anchor rod diameters and locations, and taper of the column sections. The connections are selected from actual building designs that are representative of the typical metal buildings in the U.S. It is expected that the data from this study will result in development of new or modification of existing design guidelines for metal buildings and result in more cost effective solutions. This study is in starting phase and this paper summarizes the research problem and the planned experimental work.

1 INTRODUCTION

Several researchers investigated the moment-rotation relationship of semi-rigid connections which are commonly used at foundation-column joints of low-rise metal buildings systems. Specifically, the “pinned (or moment free)” foundation connection assumption which underestimates the moment resistance can lead to highly conservative design and to an overestimation of the cost of the structure. The main purpose of this research is to obtain experimental moment-rotation relationships for different base-plate connection configurations; thereby developing a better understanding of the flexibility of the column base plates under the combined flexural and axial loads.

For this reason, nine full-scale column base-plate connections are designed and constructed to be tested at the Structural Research Laboratory of the Civil and Environmental Engineering Department at the University of Houston. The specimens will be subjected to reversed cyclic horizontal displacements under axial loads to explore the effect of several parameters including the base-plate dimensions, number of anchor rods, anchor rod diameter and layout, and the taper of column sections. Typical configurations of the base plates are shown in Figure 1.

The connections studied here (shown in Figure 1) are commonly used in metal building systems (1-2 story). The main characteristic of these metal buildings is the utilization of web-tapered sections which offer cost efficiency, easy fabrication and longer spans. Although, design concepts were proposed based on experimental data (Hong, 2007), the absence of explicit design guidelines for serviceability limit states of foundation-column connections is a strong justification for this study.

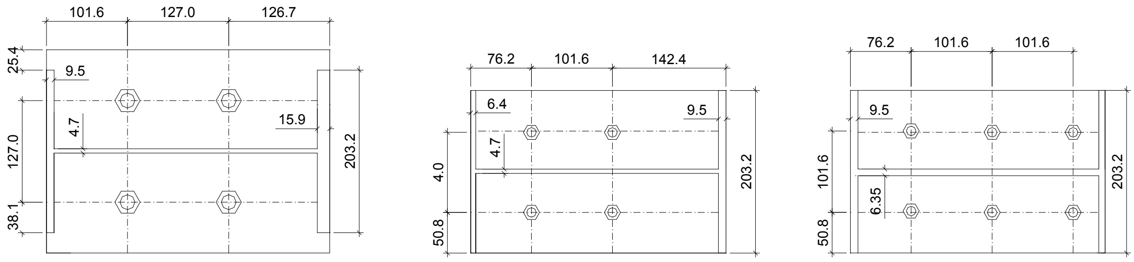

Figure 1.Typical configuration of base plates (all dimensions are in mm)

2 RESEARCH PROBLEM

Current provisions of the American Institute of Steel Construction (AISC), allow a straightforward evaluation of the moment resistance of web-tapered elements and fixed base plate connections (Fisher, 2006; Kaehler, 2011). However, design provisions for semi-rigid connections under flexural loading is not specified; therefore, there are no guidelines that can be readily used in an engineering office. Because of these reasons, semi-rigid base-plate connection behavior has been investigated in a number of studies in the past (Murray, 1983; Penserini-Colson, 1989). In addition, research studies explicitly examining the moment rotation relationship of column base plates under flexural and axial loads have been conducted that considered anchor rod strength, column sectional dimensions, presence/non-presence of a grout, base plate thickness and yield strength of anchor rods (Li, 2000; Gomez, 2010; Stamatopoulos, 2011). However, limited test data exist where the effect of numerous parameters such as plate thickness, anchor rod gage, anchor rod diameter, and column dimensions are considered consistently in a single study.

In order to account for the above mentioned parameters, testing of nine web-tapered steel columns, under the combination of flexural and compressive loads will be performed to predict the moment rotation relationship of the base plates. The experimental study is going to be followed by a finite element analysis of the column base-plate connections under investigation. The effect of the selected parameters on the moment-rotation relationship will be investigated. In this paper, only the experimental program and some material tests are presented in addition to preliminary finite element simulation results; while, the results from the tests will be reported elsewhere.

3 EXPERIMENTAL PROGRAM

3.1 Specimen design and test matrix

The following are selected as test parameters: number of the anchor rods, anchor rod diameter and layout, base plate thickness and the cross-sectional dimensions of the web-tapered column. Additionally, the two flanges of the web-tapered columns differ in thickness. The base plate dimensions vary from 152.4 mm x 254 mm to 254 mm x 356 mm and plate thickness changes from 12.7 mm to 19 mm. The anchor rod gage is between 100 mm and 127 mm and four to six anchor rods with 19 mm to 32 mm diameter are used. The test matrix is provided in Table 1.

It is important to note that specimens eight and nine are identical except for their foundations. Specimen eight will be tested on a steel foundation while specimen will be tested on a reinforced concrete foundation with embedded anchor rods. A steel foundation is used in testing the majority of the beams in order to reduce the cost and expedite the testing. While a concrete foundation is considered to assess the effects of this simplification on the member behavior.

Table 1. Test matrix

Specimen No.	Base plate thickness (mm)	Base plate width (mm)	Column flange thickness (mm)	Anchor rod diameter (mm)	Number of anchor rods	Concrete (C) or steel (S) foundation
1	12.7	152.4	8-9.5	19	4	S
2	16	203.2	9.5-8	19	6	S
3	16	203.2	6.4-9.5	19	4	S
4	16	203.2	12.7-16	19	4	S
5	16	203.2	6.4-6.4	25.4	4	S
6	10	152.4	6.4-9.5	19	4	S
7	16	203.2	9.5-9.5	19	4	S
8	19	254	9.5-16	32	4	S
9	19	254	9.5-16	32	4	C

3.2 Test setup

The test setup is designed for the highest loads expected during the tests. A schematic illustration is provided in Figure 2. Three built–up steel foundation beams, which are connected with four channels, form the foundation which is fixed to the strong floor. A 490 kN capacity actuator is connected to a "transfer beam" which is in turn bolted to the top of the test articles. The servo-controlled hydraulic actuator will be used to apply a cyclic flexural load in the column and a hydraulic jack atop the "transfer beam" will be used to apply a constant compressive load in the columns ranging from 50 kN to 300 kN. Two post-tensioning bars connect the transverse beam with the pin connections attached to the foundation, transferring the axial load applied on the specimens using the hydraulic jack. To prevent out-of-plane movement of the specimens, a portal frame is built on each side and fixed to the strong floor. The lateral support beams are positioned 5 mm away from the test specimen and are designed to resist out-of-plane movement. The test specimens are

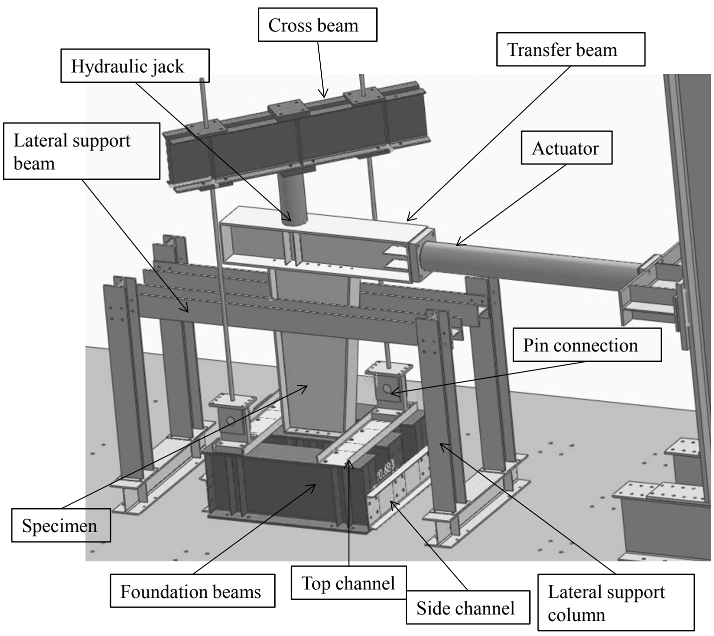

Figure 2. Test setup.

1.9 m tall built-up from Grade 50 steel sheets (where 50 indicates the yield strength of the steel in ksi). As mentioned earlier, the columns are connected with the central steel foundation beam and the transfer loading beam.

3.3 Instrumentation

The global and local deformations of the specimens will be measured using both conventional instrumentation and a state-of-the art digital image correlation-based non-contact measurement technique. The global response measurements include the deflection of the column at various locations along the height (using linear potentiometers), and deflection and load at the tip of the column using actuator LVDT and load cell. On one side of the columns, local deformations of the base-plate (uplift and in-plane and out-of plane movements) will also be measured with the help of linear potentiometers. In order to measure the strain and (calculate the stress) in the anchor rods, bolt strain gauges will be installed inside the rods by drilling a hole with a diameter of 2 mm.

The other side of the specimens will be kept clear of any conventional instrumentation and it will be dedicated to DIC-based non-contact measurements. A random contrasting speckle pattern of black and white dots will be applied on the measurement surface. Digital images of the specimens will be continuously collected throughout the tests and processed to obtain the full-field 3D deformations. This data will be unique in terms of providing detailed deformation response of base-plate connections.

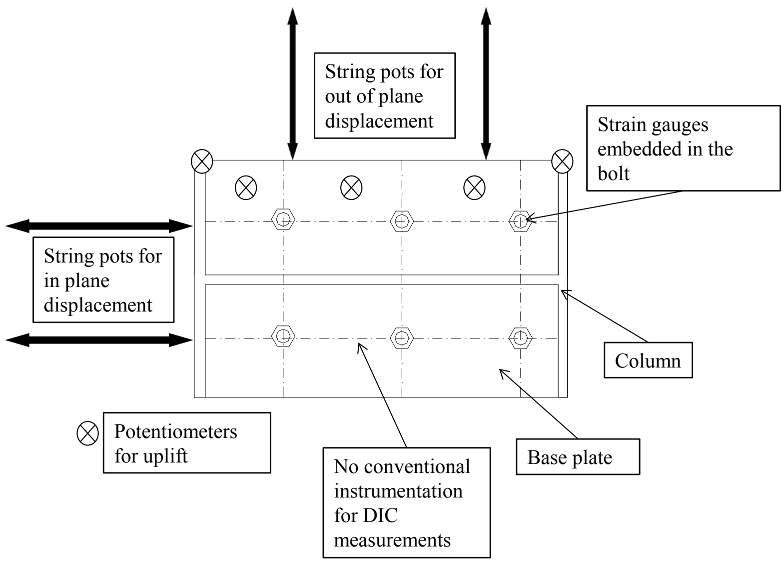

Figure 3. In plane and out of plane measurements

4 RESULTS AND DISCUSSION

Tensile tests have been conducted on anchor rods to determine the stress strain relationship. Sample specimens were taken from batches of rods with 19 mm, 25.4 mm and 36 mm diameter and tested under monotonically increasing displacement until rupture. An extensometer was attached in the mid-length gage of the samples for measuring the deformation of the rods. Steel couplers were threaded on both sides of the specimens for proper gripping using the wedge grips of the load frame. The results of the tension tests are shown in Figure 4.

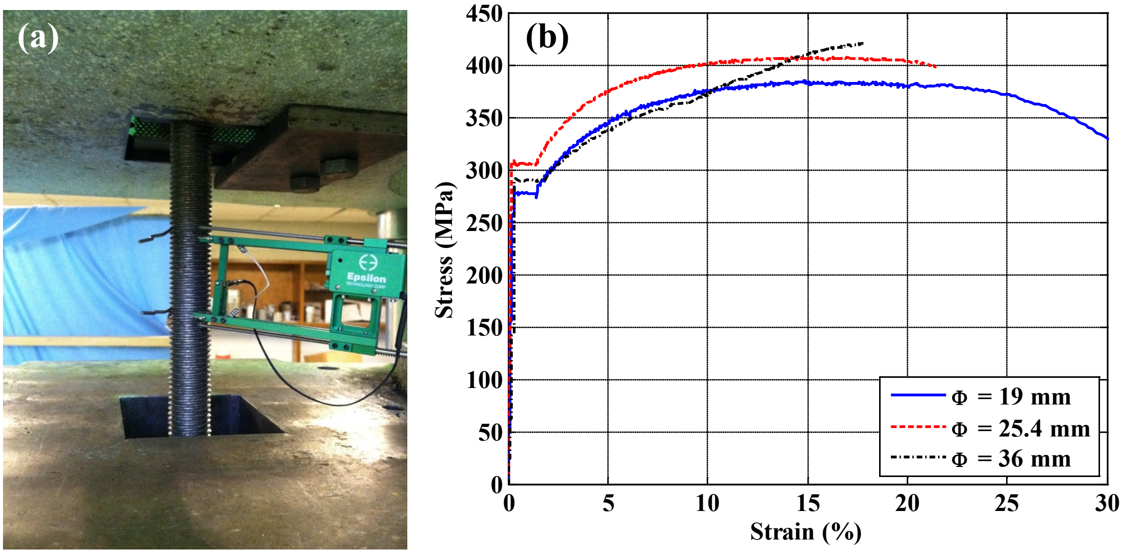

Figure 4. (a) Tensile testing of anchor rods, (b) stress-strain curves for different diameter anchor rods

Additionally, static pushover analysis has been conducted for gabled frames with tapered sections (Figure 5) by varying fixity of the base connections (pinned, semi-rigid and pinned). From the base shear- interstory drift curves (Figure 6) it is seen that the flexibility of the base-plate connection has a significant influence on the lateral response of the frames both from a stiffness and strength perspective. A typical frame which is designed with the "pinned connection" assumption can lead to significant overdesign. This simple analysis illustrates the motivation for this study.

The results from the testing of the columns are not reported in this paper; however, a brief snapshot from earlier studies regarding the moment-rotation response of certain base-plate connections is provided here. Previous analytical and experimental studies have proposed formulas to predict the moment-rotation response and rotational flexibility. An example is that by Melchers (1992) that used results from testing of ten specimens under flexural loads and proposed a procedure for calculating the elastic stifness of pinned connections by altering the thickness of the base plates, and the number and diameter of the anchor rods.

Furthermore, ten specimens of base plate connections are tested under axial and flexural loads from in Ermopoulos and Stamatopoulos (1996) and Stamatopoulos Ermopoulos (2011) verified the analytical expression of Eqn. (1) for the moment rotation relationship of the base plates:

$$M = \alpha M_0 \frac{\varphi}{\varphi_0+\varphi} \tag{1}$$

where α is the curve fitting coefficient and M_0 and φ_0 are estimated according as shown in Figure 7. Finally, the comparison between the results for the moment-rotation relationship obtained by the analytical formula of Eqn. (1) and those which derived from the FEM models were found to be satisfactory as shown in Figure 8 (Stamatopoulos Ermopoulos, 2011).

The rotational flexibility of exposed column base connections was also studied by Kanvinde (2012) in an experimental study involving testing of nine specimens. A simple method to describe the nonlinear response of the base plate connection under flexural and axial load was proposed. The parameters considered by Kanvinde (2012) are the base plate dimensions, the yielding of the anchor rods in tension, concrete strength and the level of axial load. Despite the limitations due to the complexity of the connection response (e.g. grout-plate interaction, rod deformation, etc.) a very detailed methodology for calculating the connection stiffness was proposed.

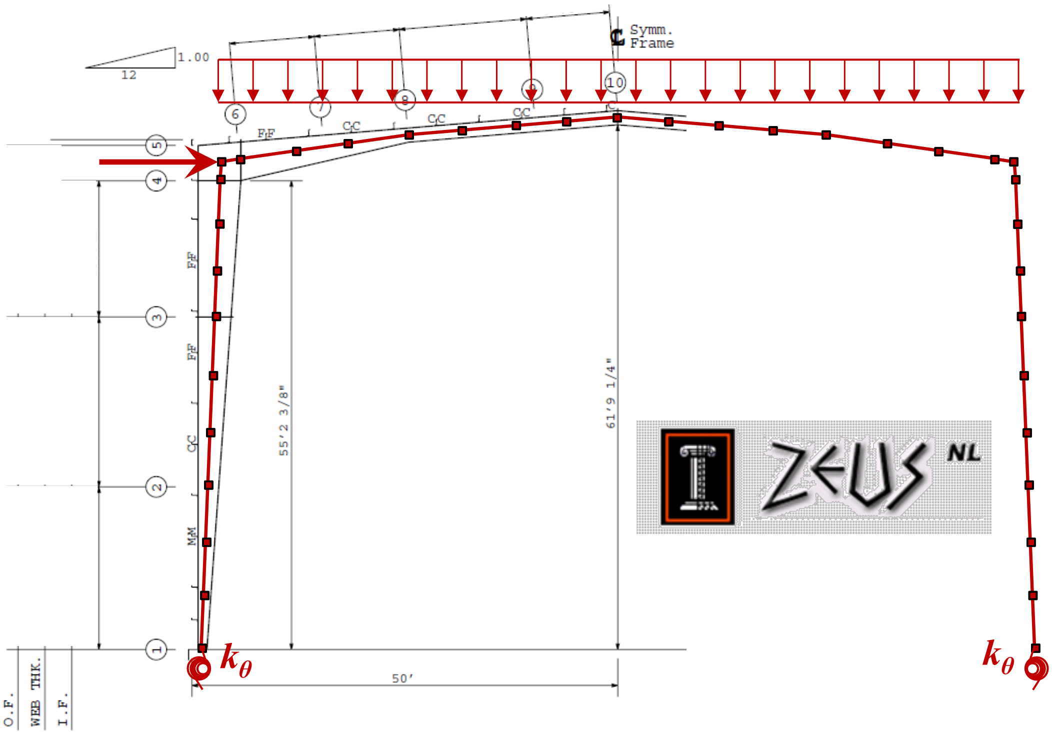

Figure 5. Long span steel tapered section frame models for finite element analysis using ZEUS NL (Elnashai et al., 2010).

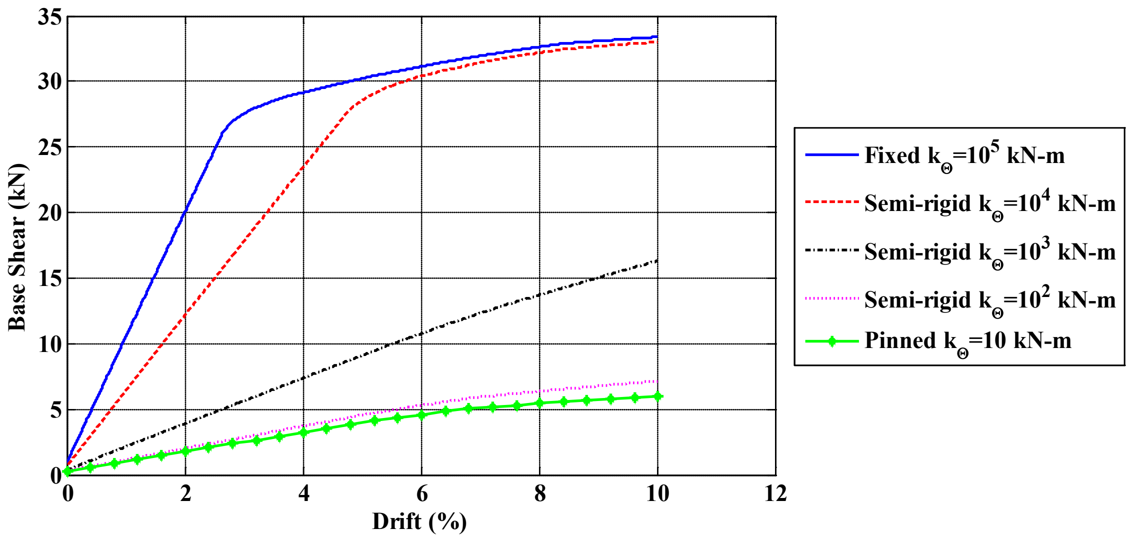

Figure 6. Base shear vs. interstory drift curves for rigid, semi-rigid and pinned base connections.

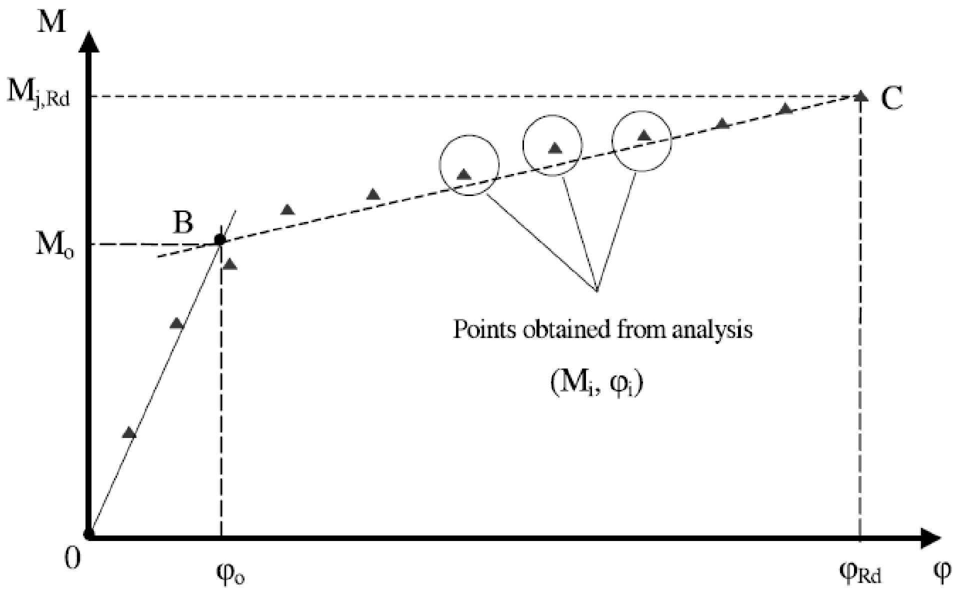

Figure 7. Moment-rotation curve obtained using Eqn. (1) [Ermopoulos, 1996]

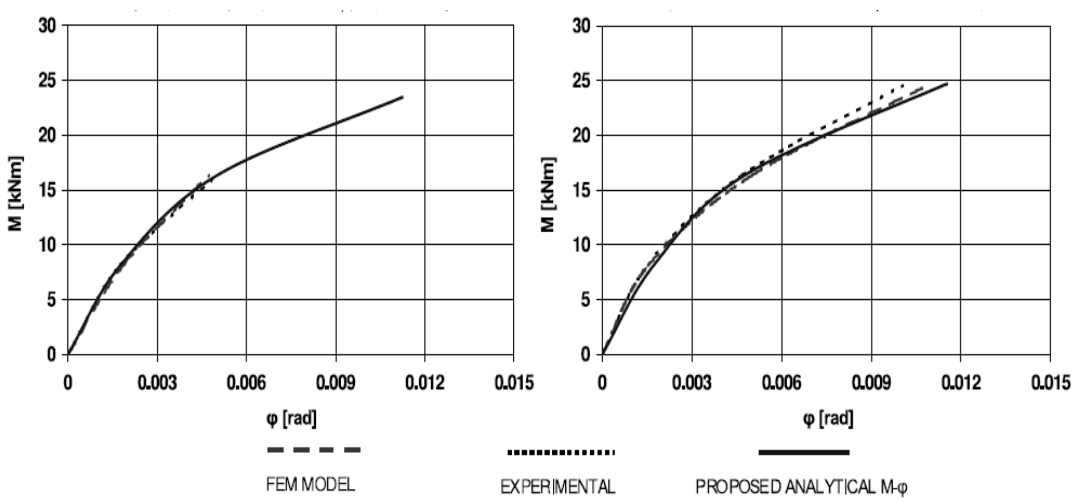

Figure 8. A comparison of moment-rotation curves of two specimens based on analytical formulas given in Eqn (1), FEM models and experiments (Stamatopoulos, 2011)

5 CONCLUSIONS

This paper summarizes the research plan of an ongoing project on testing of column base-plate connections. The main motivation for this study is the lack of design guidelines for quantifying the flexibility of foundation-column connections in low-rise metal buildings. As illustrated in the paper, preliminary results from finite element analysis indicate that the connection flexibility has a significant influence on the lateral response of these buildings and the currently used “pinned” connection assumption is overly conservative.

6 REFERENCES

Ermopoulos, J. Ch. and Stamatopoulos, G. N. 1996. Mathematical modelling of column base plate connection. *Journal of constructional steel research*, 36(2): 79-100.

Fisher, J K. 2006. *Base Plate and Anchor Rod Design,* American Institute of Steel Construction, Chicago, IL: Steel Design Guide Series No. 1.

Gomez, I. 2010. Behavior and design of column base connections. Ph.D. Thesis, Department of Civil and Environmental Engineering, University of California, California, USA.

Elnashai, A. S., Papanikolaou, V. K. and Lee, D. 2010. "ZEUS NL - A System for Inelastic Analysis of Structures," Mid-America Earthquake (MAE) Center, Department of Civil and Environmental Engineeering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA.

Hong, J-K. 2007. Developlment of A Seismic Design Procedure for Metal Building Systems. Ph.D. Thesis, Department of Civil and Environmental Engineering,University of California, San Diego, USA.

Kaehler, R. C., White, D. W., and Kim, Y. D. 2011. *Frame Design Using Web-Tapered Members.* American Institute of Steel Construction, Chicago, IL: Steel Design Guide Series No. 25.

Kanvinde, A M. 2012. Rotational stifness of exposed base plate connections:Experiments and analytical model. *Journal of structural engineering*, Vol. 138(5), 549-560.

Li, T., Sakai, J., and Matsui, C. 2000. Seismic behavior of steel-concrete composite column bases, 12th World Conference on Earthquake Engineering, Auckland, New Zealand, January 20-February 4, paper no. 1072.

Melchers, R. 1992. Column-base response under applied moment. *Journal of Constructional Steel Research*, Vol. 23(1-3), 127-143.

Murray, T. 1983. Design of lightly loaded steel column base plates*.* *Engineering Journal*, 20:(4th Quarter), 143-152.

Penserini, P. and Colson A. 1989. Ultimate limit strength of column-base connections. *J. Constructional Steel Research*, Vol. 14(4), 301-320.

Stamatopoulos, G.N. and Ermopoulos, J. Ch. 2011. Experimental and analytical analytical investigation of steel column bases. *Journal of Constructional Steel Research*, Vol. 67(9), 1341-1357.