6th International Conference on Advances in Experimental Structural Engineering
11th International Workshop on Advanced Smart Materials and Smart Structures Technology
August 1-2, 2015, University of Illinois, Urbana-Champaign, United States

Experimental Investigation of the Cyclic Response of Bolted Angles in Gravity Beam-Column Connections for Enhanced Seismic Performance

T. Beland[1], R. Tremblay[2], L.A. Fahnestock[3], E.M. Hines[4], C.R. Bradley[5], J.G Sizemore[6], A. Davaran[7]

1 *Ph.D. Candidate, Group for Research in Structural Engineering, Department of Civil Geological and Mining Engineering Polytechnique Montreal, Canada. E-mail: thierry.beland@polymtl.ca*
2 *Professor, Group for Research in Structural Engineering, Department of Civil Geological and Mining Engineering, Polytechnique Montreal, Canada. E-mail: robert.tremblay@polymtl.ca*
3 *Associate Professor, Department of Civil and Environmental Engineering, University of Illinois, Urbana-Champaign, United States. E-mail: fhnstck@illinois.edu*
4 *Professor of Practice, Department of Civil and Environmental Engineering, Tufts University; Principal, LeMessurier Consultants, United States. E-mail: ehines@lemessurier.com*
5 *M.S. Candidate, Department of Civil and Environmental Engineering, Tufts University, United States. E-mail: cbradley@lemessurier.com*
6 *Ph.D. Candidate, Department of Civil and Environmental Engineering, University of Illinois, Urbana-Champaign, United States. E-mail: sizemor2@illinois.edu*
7 *Visiting Researcher, Group for Research in Structural Engineering, Department of Civil Geological and Mining Engineering, Polytechnique Montreal, Canada. E-mail: ali.davaran@polymtl.ca*

ABSTRACT
This paper presents work that is in progress towards developing a better understanding of beam-column connection behavior in conventional steel buildings in which bolted top and seat angles are used to enhance the contribution of the gravity system for seismic response. An extensive experimental program investigating the nonlinear behavior of 140 bolted angles to examine the influence of several geometrical parameters is described, as well as an upcoming experimental program of 22 full-scale beam-column connections under combined gravity and cyclic loads. The experimental results are used to develop and calibrate nonlinear models in order to estimate the contribution of the gravity system in the building's reserve capacity under seismic load through numerical simulations. An example of numerical simulation using the OpenSEES software is also presented to illustrate the gravity connection influence as well as the potential of adding bolted top and seat angles to the connections to further enhance the building's reserve capacity.

KEYWORDS: *Gravity connection, bolted angles, numerical modeling, seismic load, reserve capacity*

1. INTRODUCTION

In conventional steel buildings, gravity beam-column connections are generally assumed pinned and their effect on the resistance to lateral loads is neglected in the building design. However, the frame action resulting from rotational stiffness and strength of gravity beam-column connections can provide lateral resistance to buildings (Flores and Charney, 2014; Shen and Astaneh-Asl, 2000; Wang, Yin et al., 2006; Yang and Tan, 2013). In addition, the redundancy brought from these connections could form a reserve capacity system to enhance the seismic performance and robustness of the structure.

The use of top and seat angles with double web clip angles appears to be an economically viable option to increase the strength and ductility of the gravity connections. Several past experimental programs (Kishi and Chen, 1990; Shen and Astaneh-Asl, 1999; Garlock, Ricles et al., 2003; Yang and Tan, 2013) have been conducted on bolted angle connections to characterize the nonlinear behavior of their components. Those studies identified the most influential parameters to be the angle thickness and the distance between the column bolts and the angle corner. However, the limited scope of these test programs could not allow for a comprehensive analysis of each parameter. To resolve this issue, an extensive experimental program has been developed to characterize the influence of the loading conditions, bolt detailing, and geometrical parameters such as the column bolt gauge and the angle thickness. These parameters were investigated through monotonic and cyclic loadings, with 19 different angle geometries, for a total of 140 tests conducted at Polytechnique Montreal from June to October 2013 and March to July 2014.

The results of this comprehensive experimental investigation are used to calibrate and improve numerical models of beam-column connections using the OpenSEES software (Mazzoni, McKenna et al., 2006). An experimental program of 22 full-scale beam-column connections, under gravity and cyclic loads to be conducted at Polytechnique Montreal will allow for the validation of the connection modeling. These models are intended to be incorporated in building seismic simulations to estimate the influence of the gravity system on the reserve capacity. An example of enhanced connection performance is presented herein through numerical simulations.

2. EXPERIMENTAL PROGRAMS

2.1. Bolted Angles Experimental Program

2.1.1. Experimental Setup

The main objective of this experimental program is to characterize the inelastic behavior of beam-column joints made from bolted angles when subjected to reversed cyclic rotation demands under seismic loading. The bending moment caused by the rotations translates into alternate tensile and compressive forces in the top and bottom angles, as shown in Figure 2.1a). Most of the deformations experienced by the angles occur during tension excursions, as the gap between the beam and the column is increasing, and then during compression excursions, when the gap is closing. In order to create a similar behavior, the experimental setup has been simplified to an angle bolted to a plate, which is in turn bolted to the actuator. The actuator is then used to impose a displacement demand similar to the one caused by the beam rotation, as seen in Figure 2.1b). Both monotonic tension tests and cyclic tension-compression tests were performed. To avoid flexural effects caused by the eccentricity between the column bolts and the plate and the setup asymmetry, a second angle has been added under the plate. A similar test setup has already been used by Shen and Astaneh-Asl (1999), Garlock, Ricles et al. (2003) and Yang and Tan (2013). Experimental angle behavior obtained in this fashion is also applicable for characterizing response of double web angle connections. Since the behavior of the angles is the focus of the testing program, the bolts were overdesigned to avoid as much as possible bolt failure.

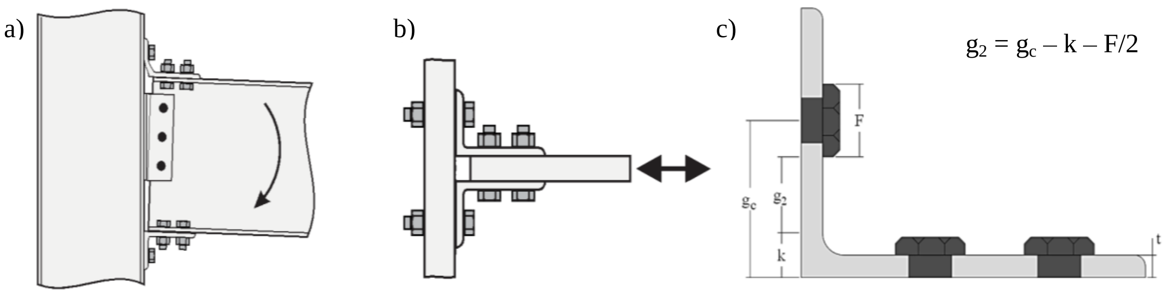


Figure 2.1 a) Typical deformation of a beam-column joint made of bolted angles b) Schematic experimental setup c) Geometric parameters of bolted angles specimens

2.1.2. Test Matrix

The inelastic behavior of bolted angles depends greatly on various geometric parameters such as the distance between the angle corner and the column bolts and the angle thickness. An objective of this experimental study was to characterize the influence of those aforementioned dimensions. Therefore, a parametric study was conducted by varying the thickness from 8 to 19 mm (5/16" to 3/4") and the column bolt gauge from 64 to 114 mm (2.5" to 4.5"). The test matrix of the 19 different cases studied is presented in Table 2.1. A total of 140 specimens were tested.

Table 2.1 Test matrix of the bolted angles experimental program

t / g_c	7.9 mm		9.5 mm		12.7 mm		15.9 mm		19.1 mm	
	Test Case	g_2/t	Test Case	g_2/t	Test Case	g_2/t	Test Case	g_2/t	Test Case	g_2/t
64 mm	19	3.80	1	2.67	3	1.38	-	-	-	-
76 mm	-	-	2	4.00	4	2.38	5	1.70	6	1.25
89 mm	-	-	7	5.33	9	3.38	11	2.50	13	1.92
102 mm	-	-	8	6.67	10	4.38	12	3.30	14	2.58
114 mm	-	-	15	8.00	16	5.38	17	4.10	18	3.25

Most of the displacements were observed on the column leg of the angles, between the bolt and the corner. This part of the angle is characterized by the length g_2, which, as shown in Figure 2.1c), corresponds to the distance between the end of the fillet and the edge of the bolt head. To establish a comparative basis between the several test cases, the ratio of g_2/t was used. For the different angle configurations studied, this ratio varies from 1.25 to 8.00. A small ratio is associated with a thick stocky angle while a large ratio represents a thin slender angle.

2.1.3. Connection Behavior

All specimens exhibited a bilinear response under monotonic tension loading and two distinct failure modes were observed. The first failure mode is illustrated in Figure 2.2a) for Specimen TC10 (g_2/t = 4.38). It is characterized by a fracture in the column leg, above the fillet, where the first plastic hinge appeared. At large displacements, uplift of the beam leg can also be observed. This uplift is caused by an increasing demand on the axial stiffness of the column leg and is generally accompanied by geometrical hardening, as can be seen starting at a displacement of approximately 15 mm in Figure 2.2b). This failure mode happened primarily on slender angles with a g_2/t larger than 2.5. The second failure mode is shown in Figure 2.2c) for Specimen TC4 (g_2/t = 2.38). It was observed mainly on stockier angles with a g_2/t ratio lower than 3.0. The fracture occurred on the beam leg, where the section is subjected to both tension and bending due to the stiff region of the fillet.

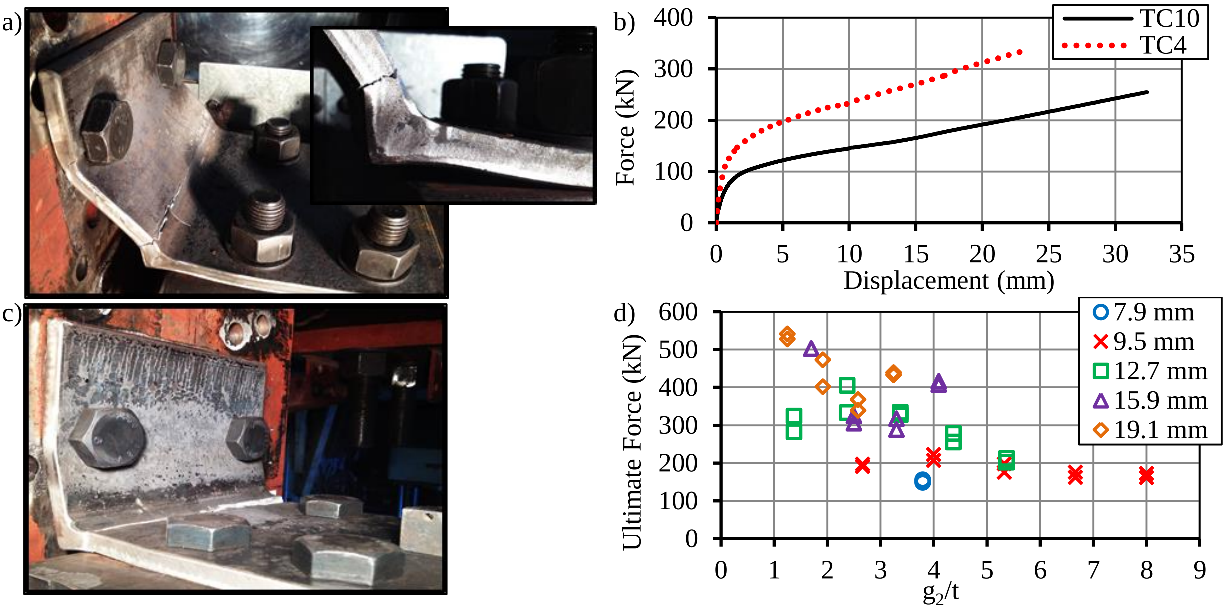


Figure 2.2 a) Failure of Specimen TC10 (g_2/t = 4.38); b) Force-Displacement response of Specimens TC4 and TC10 ;c) Failure of Specimen TC4 (g_2/t = 2.38); and d) Ultimate force vs. g_2/t ratio

As shown on Figure 2.2b), Specimen TC4, which has a smaller g_2/t ratio than TC10, presents a larger ultimate strength but a reduced inelastic deformation capacity. Examination of the test results indicated that these trends could be generalized: for a given thickness, as the ultimate strength generally decreased while the ultimate displacement generally increased with an increase of the g_2/t ratio. The first trend is illustrated in Figure 2.2d).

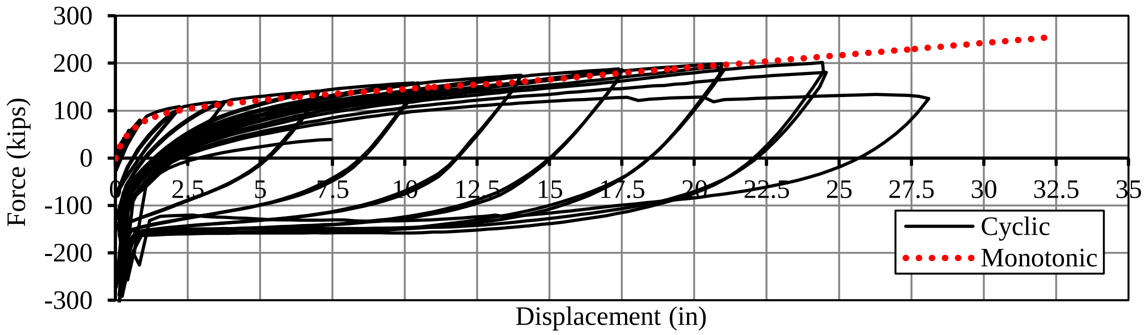


Figure 2.3 Cyclic and monotonic force-displacement curves of TC10 (g_2/t = 4.38)

A typical response from a cyclic test under stepwise incremented deformations is illustrated in Figure 2.3. Stable response was observed although the stiffness upon loading gradually decreased as larger deformations were imposed. Eventually, low cycle fatigue caused cracking and fracture of the specimen. This behavior resulted in progressive loss in strength near failure. It was also observed that monotonic curves provide a good approximation of the backbone curve of cyclic plots, particularly at smaller displacements. Specimens typically showed smaller deformation capacities under cyclic loading compared to monotonic loading.

2.2. Upcoming Beam-Column Connection Experimental Program

The bolted angles experimental program will be followed by a series of 22 beam-column connection tests on 8 configurations. The effect of top and seat angles will be investigated as some tests will be performed on double web angles only, while others on slender and stocky top and seat with web clip angles. The influence of the beam depth and the column section will also be investigated. Table 2.2 presents the joint test matrix. This experimental investigation is planned to take place at Polytechnique Montreal in the fall of 2015.

Table 2.2 Test matrix of the beam-column joint experimental program

Beam			W310x39		W410x67	
Column			W360x347	W250x49	W360x347	W250x49
Top & Seat Angles	-	Test Case	1	-	4	-
		Web angle length	140	-	216	-
	L152 x 102 x 9.5	Test Case	2	-	5	-
		Web angle length	140	-	216	-
	L204 x 152 x 19.1	Test Case	3	3B	6	6B
		Web angle length	140	140	216	216
Web angle section: L102x102x7.9						

The main objective of this second experimental program is to characterize the behavior of partially-restrained connections made of bolted top and seat with web clip angles. It will also serve to observe the behavior of the top and seat angles in a joint connection under rotational demands to complement the bolted angle parametric study. The setup of the joint connection test is illustrated in Figure 2.4. It consists of a single beam-column connection rotated 90° and loaded with two actuators on the beam. The top actuator is used to apply a cyclic load in order to create a flexural moment in the connection generated by a moment frame action under seismic loading, while the second actuator applies a constant force to mimic the gravity load.

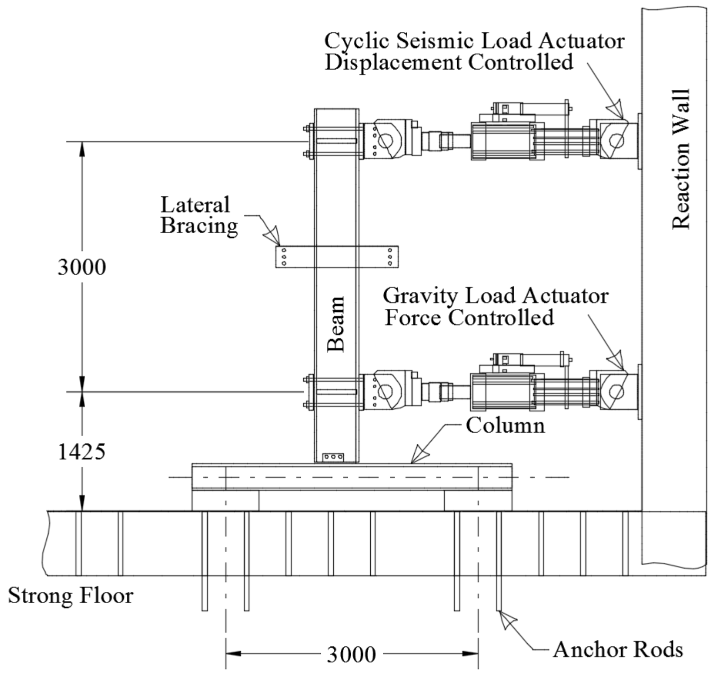


Figure 2.4 Test setup of beam-coluumn joint experimental program

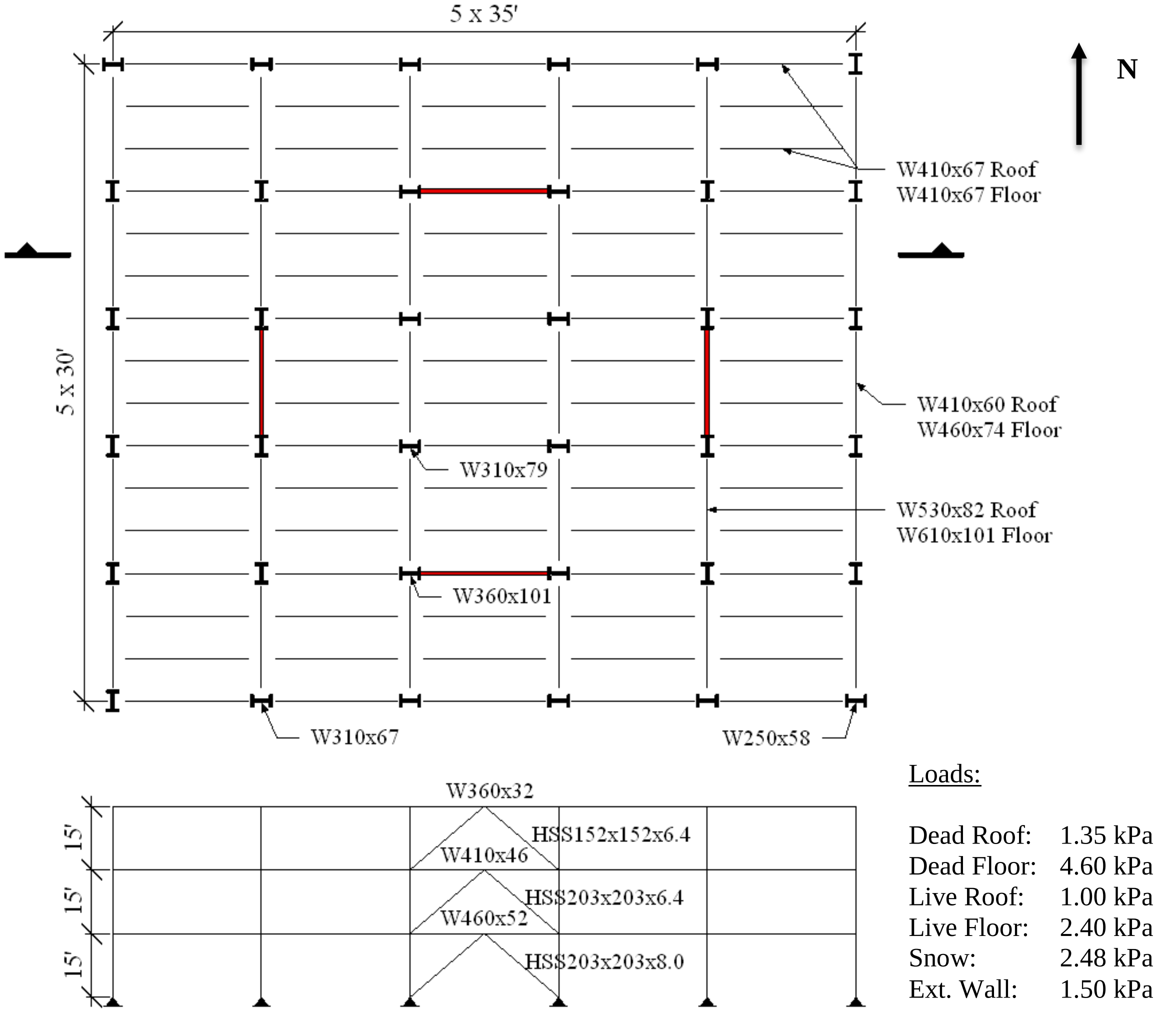
3. EXAMPLE OF ENHANCED SEISMIC PERFORMANCE

An example of numerical analysis of a low-ductility braced frame building is presented to illustrate the influence of the gravity system in the reserve capacity and the potential enhancement of the seismic performance. The building is first modeled according to current design practices, i.e. by considering the gravity beam-column joints as pinned and assuming that the entire lateral stiffness is provided by the braced frames. A second analysis of the same building is then performed using the results of cyclic angle tests to define the nonlinear behavior of gravity beam-column bolted top and seat with double clip angles connections, qualified as partially restrained. The influence of the gravity framing in the seismic performance is then observed by comparing the two models. Both models are solicited with the same ground motion developed for Eastern North America by Atkinson (2009). This ground motion has been filtered and scaled to correspond to the Montreal design acceleration spectra with a 5% damping ratio. The peak ground acceleration of the signal is 0.274g.

3.1. Prototype Building

The building studied is a 3-story concentrically braced frame located in Montreal, QC, and designed according to the provisions for Conventional Construction (Type CC, R_d = 1.5 R_o = 1.3) of the Canadian standards (CSA S16-09, 2009; NBCC, 2010). This type of lateral force resisting system is essentially strength designed and the design load of the connections is amplified to avoid brittle failure. Since no capacity design is required, Type CC systems are widely used for low-rise steel buildings.

Figure 3.1 shows a plan and elevation view of the building, including the member sections and the loads. The risk category of the building is considered normal (I_E = 1.0) and site class C was considered. The seismic loading is applied along the E-W direction.



Loads:

Dead Roof:	1.35 kPa
Dead Floor:	4.60 kPa
Live Roof:	1.00 kPa
Live Floor:	2.40 kPa
Snow:	2.48 kPa
Ext. Wall:	1.50 kPa

Figure 3.1 Plan and Elevation views of prototype building

3.2. Numerical Modeling

3.2.1 Building Model

Nonlinear response analysis is performed using the software OpenSEES (Mazzoni, McKenna et al., 2006). Since the prototype building is symmetric, only half is modeled to reduce the computational time. The first model considering pinned beam-column connections is simply constituted of a braced frame with a leaning column to account for the second-order (P-delta) effects. The gusset plates are modeled as rigid elements to reduce the effective length of the braces. The critical limit state for this structure is rupture of the welds between the braces and the gusset plates. The welds are modeled as uniaxial spring elements associated to a rigid elastic material wrapped with a Min-Max material to represent the fracture. The material properties were defined using experimental data on welds by Lesik and Kennedy (1990).

The second model accounting for the moment frame action of the gravity system consists of three full frames in parallel. Every beams and columns are modeled to account for the various cross sections of the columns forming the gravity frame and their orientation with respect to the loading direction. Since every column is modeled, each of those elements supports the gravity load according to their tributary area and is subjected to the second-order P-delta effects. As in the first model, the gusset plates and brace weld fracture are modeled.

Since the building has only three stories, the columns are likely to be continuous over the entire height of the structure. The benefits of considering column continuity have been investigated through several inelastic pushover and dynamic time history analyses (Tremblay and Stiemer, 1994; MacRae, Kimura et al., 2004; Ji, Kato et al., 2009; Flores, Charney et al., 2014). This contribution can mitigate soft story collapse by creating a more uniform story drift distribution along the building height and avoid structural instability. To obtain a more realistic building response, column continuity is therefore considered in the second model.

3.2.2 Gravity System Connection Modeling

As illustrated in Figure 3.2 a), beam-column connections in the gravity system are modeled using zero-length section elements with a fiber defined at each bolt location on the column leg,. For the web angles, the area of each fiber is equal to the tributary width (height) of the bolts, while the top and seat angles are assigned an area corresponding to the entire angle width.

A hysteretic material developed from cyclic results of the bolted angles experimental program is assigned to each fiber of the section. This material represents the behavior of a unitary strip of angle in the connection. While being simple to use, the hysteretic material offers a good approximation of the stiffness degradation as the maximum displacement experienced by the angle increases, as well as of the unloading stiffness. Figure 3.2b) presents the force-displacement curve of this material developed from the experimental results of TC10 (g_2/t = 4.38) for a 25.4 mm (1") strip, which is also the material used in the numerical model. A stiff elastic no tension material is assigned in parallel to the hysteretic material to represent the contact between the angle and the column flange and a Min-Max material is assigned to represent the angle fracture in tension.

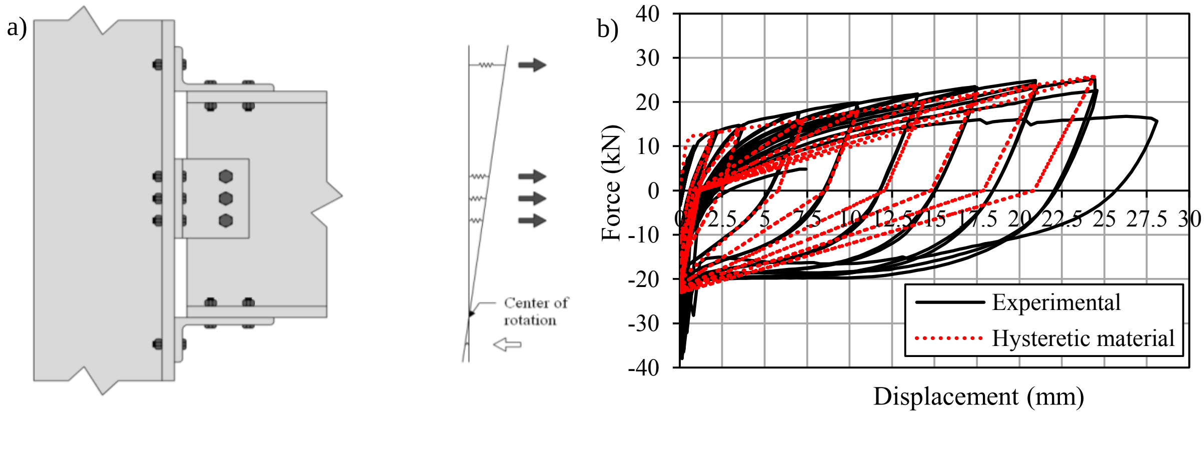


Figure 3.2 a) Spring model of gravity connection b) Force-displacement curve of hysteretic material based on the experimental cyclic results of TC10 (g_2/t = 4.38) for a 25.4 mm (1") strip

3.3. Seismic Performance of Frames with Enhanced Connections

The three vibration periods of the building for each connection assumption are presented in Table 3.1. These values do not vary significantly because the lateral stiffness contributed by the partially restrained connections of the gravity is small compared to the lateral stiffness of the braced frame. Therefore, as shown in Figure 3.3, the two models experienced the same elastic response at the beginning of the ground motion and, eventually, the same brace weld fracture in the first story at approximately the same base shear.

Table 3.1 Vibration periods of prototype building

Period	T1 (s)	T2 (s)	T3 (s)
Pinned	0.761	0.309	0.230
Partially restrained	0.746	0.302	0.226

The Base shear versus first story drift of this simulation is plotted in Figure 3.3a). As shown, the benefits from the gravity frame occur after failure of the main lateral force resisting system. The numerical model with pinned beam-to-column connections experienced weld fracture at a base shear of 2981 kN in the compression brace. As a result, the structure could not remain stable and the P-delta effects created large displacements which led to a soft-story mechanism at the first story. The weld fracture occurred at a base shear of 3023 kN in the case of the building with enhanced gravity connections. After this point, the moment frame action created by the partially-restrained beam-column connections was able to limit the first-story drift to 3.43% and keep the structure from collapsing throughout the ground motion. After the weld failure, the building exhibited a residual base shear capacity of 387 kN.

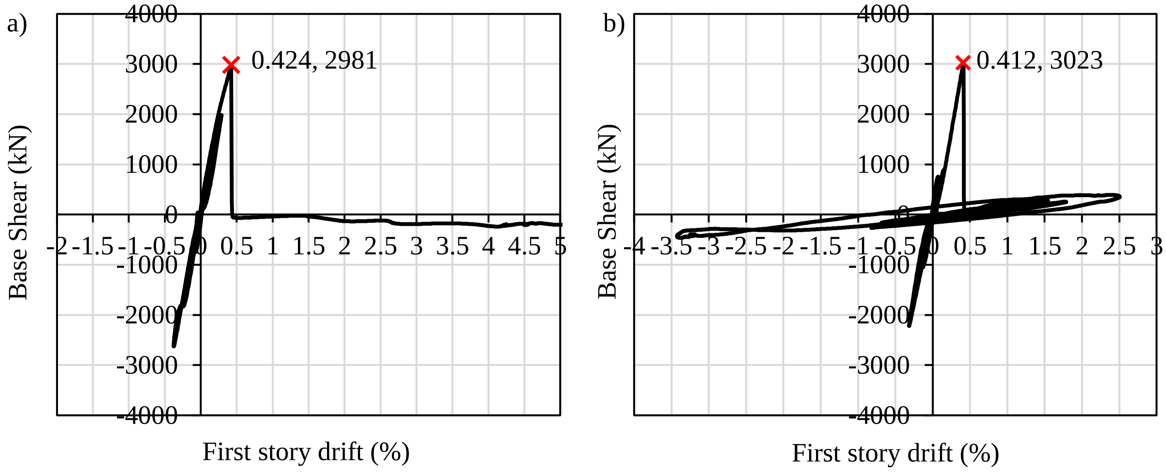


Figure 3.3 Base Shear vs. First story drift of model with a) Pinned beam-column connections
b) Partially restrained beam-column connections

Although the scope of the numerical investigation presented herein is limited to a single example, the case studied showed that considering the gravity framing in the seismic response of a steel building can result in enhanced seismic robustness and better performance after a failure in the main lateral force resisting system.

The numerical simulations presented herein give an example of the potential influence of the gravity system on the reserve capacity and of the improvement of the seismic performance of low-ductility steel braced frames. Several other elements should be included in the model to obtain a more realistic structural response, such as the stiffness provided by column base plates, column panel zone deformations, material and geometrical nonlinearities (residual stresses and misalignment defaults) and composite action of the concrete slabs. Also, the geometrical properties of the building, such as the number of stories, the bracing configuration and the number of gravity columns can influence significantly the contribution of the gravity frame to the reserve capacity.

4. CONCLUSION

Combining top and seat with double web clip angles represents an economically viable option to increase the strength and ductility of beam-column connections of the gravity system and, thereby, enhance the seismic robustness of low-ductility steel braced frame buildings. The impact of using this type of partially restrained connections is assessed through an example of numerical simulations of a 3-story concentrically braced frame of the conventional construction category designed according to the Canadian standards. Although the observations are limited to a single building, the partially restrained beam-column connections were able to control the lateral displacements and mitigate second order effects to keep the structure stable after brace failure.

To obtain more realistic results from nonlinear building analyses, experimental programs concerning bolted angles and partially restrained connections are developed. Each component will be individually modeled and calibrated with experimental results to accurately and efficiently characterize its nonlinear behavior. Those individual models will then be integrated in nonlinear dynamic simulations to assess the contribution of the gravity system to the seismic resistance and performance of multi-story braced frame buildings.

AKCNOWLEDGEMENT

This study is supported by the United States National Science Foundation (Grant No. CMMI-1207976), the American Institute of Steel Construction and the Natural Sciences and Engineering Research Council (NSERC) of Canada. The contribution of the technical staff of the Structural Engineering laboratory of Polytechnique Montreal is acknowledged by the authors, as well as the participation of Nucor, ADF Group and Unytite for providing the materials required for testing. The opinions, findings, and conclusions of this paper are those of the authors and do not necessarily reflect the views of those acknowledged here.

REFERENCES

1. Shen, J., and Astaneh-Asl, A. (2000). Hysteresis model of bolted-angle connections. *Journal of Constructional Steel Research.* **54:3**, 317-343.
2. Wang, X.L., and Yin, Z.Z., Shen, S.Z., Li, Q.F. (2006). Experimental Research on Stiffness of Semi-Rigid Connection in Beam-Column and Effect on Steel Frame Ductility. Science Press Beijing, Beijing.
3. Flores, F., and Charney, F. (2014). The Influence of Gravity Column Continuity on the Collapse Performance of Special Steel Moment Frames *Tenth U.S. National Conference on Earthquake Engineering Frontiers of Earthquake Engineering.* Anchorage, AK, United States.
4. Kishi, N. and Chen, W (1990). Moment-Rotation Relations of Semirigid Connections with Angles. *Journal of Structural Engineering*. **116**:**7**, 1813-1834.
5. Shen, J. and Astaneh-Asl, A. (1999). Hysteretic behavior of bolted-angle connections. *Journal of Constructional Steel Research*. **51:3**, 201-218.
6. Garlock, M.M., and Ricles, J.M., Sause, R. (2003). Cyclic Load Tests and Analysis of Bolted Top-and-Seat Angle Connections. *Journal of Structural Engineering*. **129:12**, 1615-1625.
7. Yang, B. and Tan, K.H. (2013). Robustness of Bolted-Angle Connections against Progressive Collapse: Experimental Tests of Beam-Column Joints and Development of Component-Based Models. *Journal of Structural Engineering* **139:9**, 1498-1514.
8. CSA-S16-09. (2009). Design of steel structures, 7th Edition. Canadian Standards Association, Mississauga, ON.
9. NBCC. (2010). National Building code of Canada, 13th Edition. National Research Council of Canada, Ottawa, ON.
10. Atkinson, G.M. (2009). Earthquake time histories compatible with the 2005 National building code of Canada uniform hazard spectrum. *Canadian Journal of Civil Engineering***. 36:6**, 991-1000.
11. Lesik, D.F., and Kennedy, D.J. (1990). Ultimate strength of fillet welded connections loaded in plane. *Canadian Journal of Civil Engineering*. **17:1**, 55-67.
12. Tremblay, R., and Stiemer, S.F. (1994). Back-up stiffness for improving the stability of multi-storey braced frames under seismic loading. *1994 SSRC Annual Task Group Technical Session, Structural Stability Research Council*. Bethlehem, PA, United States.
13. MacRae, G., and Kimura, Y., Roeder, C. (2004). Effect of column stiffness on braced frame seismic behavior. *Journal of Structural Engineering*. **130:3**, 381-391.
14. Ji, X., and Kato, M., Wang, T., Hitaka, T., Nakashima, M. (2009). Effect of gravity columns on mitigation of drift concentration for braced frames. *Journal of Constructional Steel Research*. **65**:**12**, 2148-2156.
15. Flores, F.X., and Charney, F.A., Lopez-Garcia, D. (2014). Influence of the gravity framing system on the collapse performance of special steel moment frames. *Journal of Constructional Steel Research*. **101**, 351-362
16. Mazzoni, S., McKenna, F., Scott, M. H., and Fenves, G. L. (2006). “Open system for earthquake engineering simulation, user command-language manual.” Software Version 2.4.6. Pacific Earthquake Engineering Research Center, Univ. of California, Berkeley, CA.