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Finite Element Simulation of Stiffened Top-and-Seat Angles for Self-Centering Connections

Md. Arman Chowdhury[1], Ahmad Rahmzadeh[2], M. Shahria Alam[3]

[1] MASc. Student, School of Engineering, University of British Columbia - Kelowna, BC, Canada.
[2] Ph.D. Student, School of Engineering, University of British Columbia - Kelowna, BC, Canada.
[3] Associate Professor, School of Engineering, University of British Columbia - Kelowna, BC, Canada.

ABSTRACT

The use of post-tensioning strands is a proven technique to enhance the seismic performance of moment resisting frames. As opposed to conventional moment connections, in which structural components are bonded to each other, in post-tensioned connections they are pre-compressed together, allowing the formation of a gap under lateral loads. During gap opening, replaceable sacrificial elements can dissipate energy through plastic deformation. In this paper, test results of bolted top-and-seat angles from previous experimental studies are validated using three-dimensional finite element (FE) models. Then, the behavior of stiffened angle is investigated numerically by modifying the validated models. The purpose of this investigation is to determine how the stiffener thickness, yield strength, angle size, and gage length affect the connection stiffness, strength, and energy dissipation capacity. The results show that the stiffened angles are capable of dissipating a considerable amount of energy with moderately thick stiffeners. The bolt gage length greatly influences all the studied characteristics of the connection. Design recommendations are also provided based on the parametric study presented herein.

Keywords: Top-and-seat angle, Energy dissipation, Self-centering, Stiffener, Finite element.

INTRODUCTION

Moment resisting frames designed with welded beam to column connections form plastic hinges in the beams to dissipate energy by accumulating residual deformation. During the 1960s, welded steel beam-column connections were considered to be the most ductile system against earthquakes [1]. In these connections, the beam web and flanges are welded to the column flange to get maximum plastic moment [2]. However, the 1994 Northridge earthquake indicated that welded connections were susceptible to brittle fracture at the beam-column joints. This failure mode was observed even for structures subjected to a moderate level of ground shaking.

Instead of the welded connection, bolted connection with the sacrificial element can dissipate energy by isolating all the damages in that element which can be replaced after the earthquake. Plastic hinge relocation can also be achieved by reducing the beam section (RBS) close to the joint [3], adding reinforcing cover plates on beam flanges close to the joint [4] and applying haunches at the joint [5].

An extensive amount of research has been conducted on the cyclic behavior of bolted top-and-seat angle connections. Most previous research aimed at determining the cyclic response of steel moment resisting frames with bolted connections. FEMA [6] indicated the energy dissipation capability of the bolted connection. Shen and Astaneh-Asl [7] studied the top-and-seat angle connection experimentally both under monotonic and cyclic loading protocol. The results indicated identical response under both loading conditions. Based on the experimental observation, Shen and Astaneh-Asl [8] proposed a hysteretic model for thick and thin angles, respectively.

The use of post-tensioning strands is now a proven technique to enhance the seismic performance of moment resisting frames. Energy-dissipating element is an important component in self-centering structures. Although a number of researchers focused on top-and-seat angles, Garlock et al. [9] specifically focused on the specific requirements on the properties of top-and-seat angles for SC structures. This paper focuses on investigating the cyclic response of top-and-seat angles with an additional stiffener between the legs. To simulate the behaviour, three-dimensional FE models are developed and validated with previous experimental results.

FE MODELING

Model development

The performance of bolted top-and-seat angle connections was investigated by [9] in terms of stiffness, strength, energy dissipation capacity, and resistance to low cycle fatigue. Although several other researchers investigated the behavior of bolted angles before, the angle properties used in those studies were not appropriate (i.e., the legs were too short, the thickness were insufficient, or the material strength was too low) for post-tensioned connections. Therefore, the specimen used in Garlock et al. [9] was redesigned with a stiffener to investigate in this study.

Two angles were placed back to back and were connected to the beam flange and column section as shown in Figure 1. The whole section was rotated 90° counterclockwise so that the strong column is horizontal to the floor. A T-stub section connected to the actuator and the angles legs were used to simulate a beam flange. The column section was strong enough (W360 x 262/ W14 x 176) to avoid any plastic deformation during the tests. This test setup does not account for the rotation that can be generated in the angle legs due to the relative rotation of the beam and column section. However, this rotational effect can be neglected since it is only about 10% of the total rotation of the connection.

The dimension of the specimens used by Garlock et al. [9] was used in this study. The specimens were named according to their length, thickness and gage length to thickness (g/t) ratio. In total seven (07) angle with three different thickness that is 7.9 mm, 15.9 mm, and 19.0 mm were used. All specimens were 178 mm wide. To provide a distinct boundary for the plastic hinge and to reduce the prying force on the column bolt, an ASTM Gr 50 steel washer plate (i.e., 12 × 57 × 178) was used for all specimen except for one.

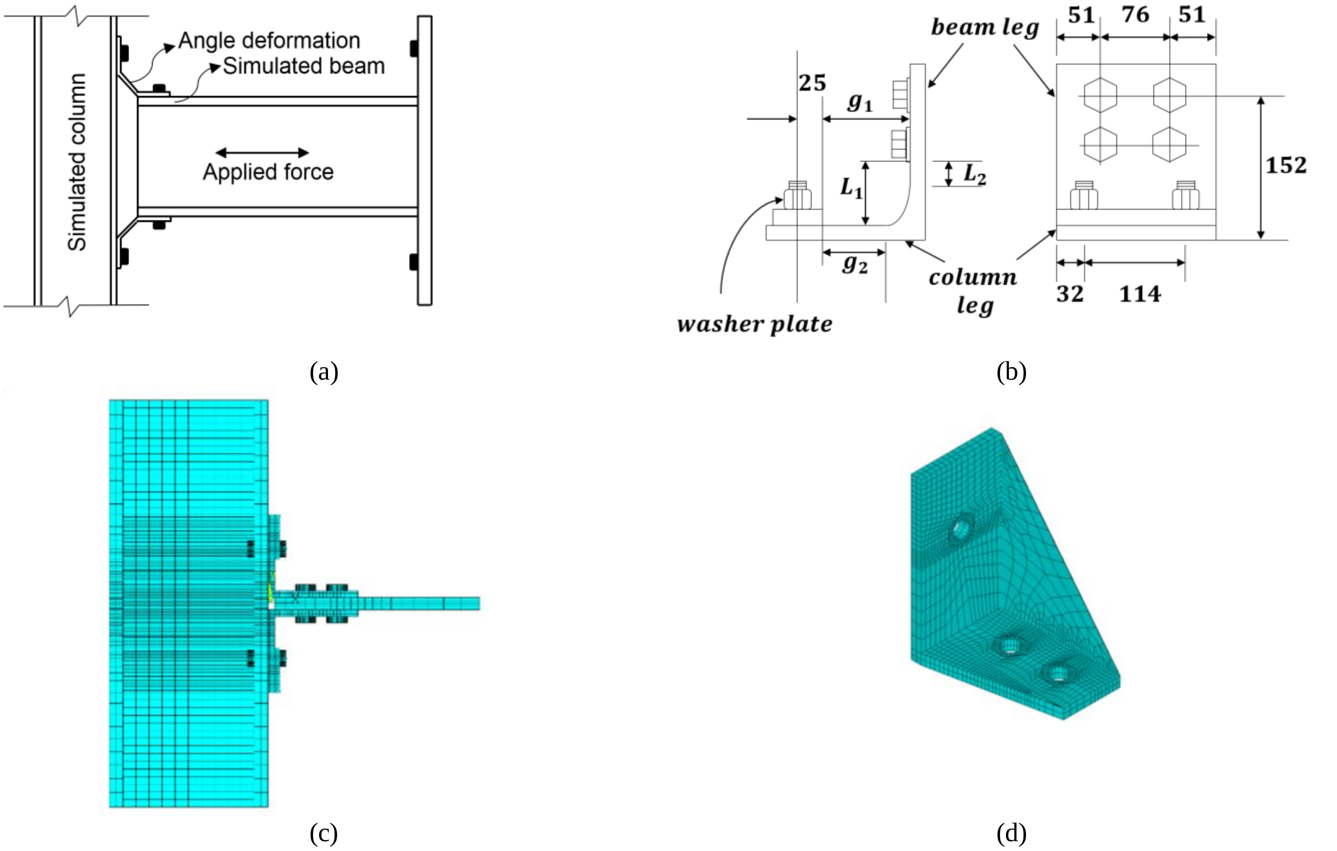


Figure 1. (a) experimental specimen, (b) geometric details of angle, (c) FE model, and (d) FE model of stiffened angle.

To avoid failure of bolts due to prying force, A325 and A490 bolts were used. The column and beam bolts were 25 mm and 32 mm, respectively. A325 bolts were used for 7.9 mm and 15.9 mm bolts where A490 bolts were used for 19.0 mm diameter. For specimen L6-516-4 and L6-516-9, A36 steel was used. All other specimens were of ASTM A572 Grade 50 steel.

The loading history applied on bolted top-and-seat angle connection was determined from the experimental study on PT steel beam-column connection by Ricles et al. [10]. The angle displacement corresponding to the story drift was recorded and modified according to the SAC joint venture testing protocol [11].

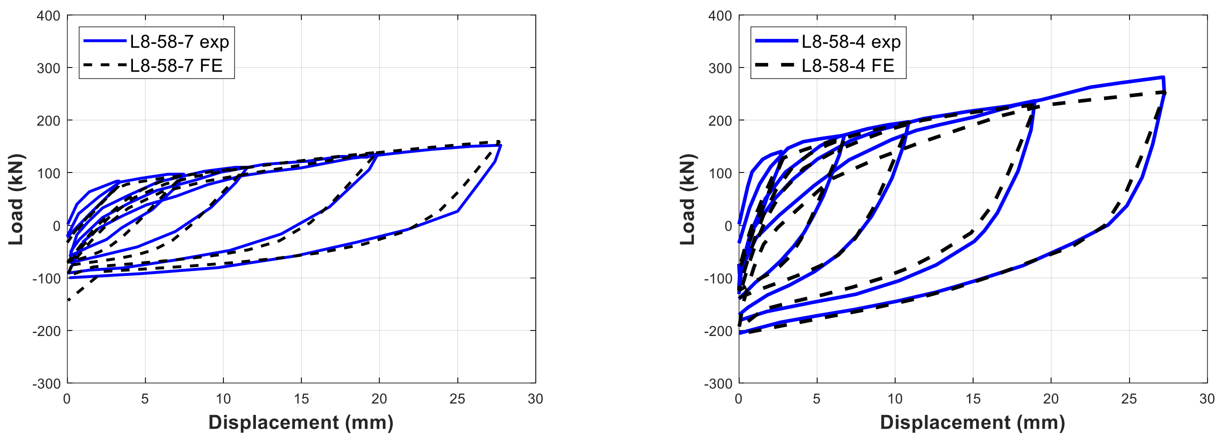
Validation study

The experimental setup of top-and-seat angle connection in Figure 1 (a-b) represents the actual self-centering beam-column connection. The load-deformation behavior of the angle is similar to the previously tested PC4 specimen [10]. However, top-and-seat angle in PC4 connection experience additional moment due to rotation which was neglected in this setup.

To reduce the computational time, only half of the model was developed, and the symmetry condition was applied to restrain any movement in the horizontal direction [12]. In the experimental setup, column section was horizontal to the ground and considered fixed, therefore, fixed boundary condition was applied in the FE model. The mesh density was controlled in the angle section to capture accurate load-deformation behavior. MESH200 and SOLID185 element were used to develop the meshed area and solid volumes, respectively.

Instead of engineering stress-strain, true stress-strain of steel materials was used. The modulus of elasticity and strain hardening ratio was 200 GPa and 0.05, respectively. The developed model is shown in Figure 1 (c-d). The total number of nodes, areas, volumes, and elements generated were 106612, 1514, 334, and 117827, respectively.

Two experimental specimens tested by Garlock et al. [9] was developed FE analysis platform. In order to assess the accuracy of the FE analysis, the numerical results for the bolted angle models were compared with the experimental results. Figure 2 (a-b) shows the load-displacement behavior of the experimental specimen alongside the experimental test results. These comparisons indicate that the FE analysis can accurately capture the cyclic response of bolted angle connection in terms of initial stiffness, strength, and dissipated energy.



(a) (b)

Figure 2. Comparison of the load-deformation behavior between experimental and FE model: (a) L8-58-7, and (b) L8-58-4

PARAMETRIC STUDY ON STIFFENED ANGLE

In the current literature, to the best of the knowledge of the author, no parametric study on stiffened angle connection was found. To optimize the performance of the energy dissipating element in SC-PT connection, a full factorial design approach was used. Four parameters such as (a) gage length, (b) angle thickness, (c) yield strength of angle material, and (d) stiffener thickness were considered to evaluate the performance in terms of initial stiffness, load capacity and energy dissipation capacity. For each parameter, one high value (denoted as "+") and one low value (denoted as "-") was considered (Table 1).

Table 1. Factor selection for factorial analysis.

Factor	Parameter name	High (+1)	Low (-1)	Units
A	Stiffener thickness	10	3	mm
B	Yield strength	690	250	MPa
C	Gage length	114	90	mm
D	Angle thickness	25.4	12.7	mm

To determine the minimum and maximum thickness of stiffener, L8-58-4 NW specimen was modified with three different thickness such as 5 mm, 8 mm, and 10 mm. From Figure 3, it was evident that the effect of stiffener decreases with increasing thickness. Therefore, increasing the thickness after that will increase the cost without contributing to the capacity of the connection. On the other hand, a thickness less than 3 mm will initiate plate buckling during the welding process. To this end, stiffener thickness between 3 mm and 10 mm was considered and recommended for stiffened angle connection.

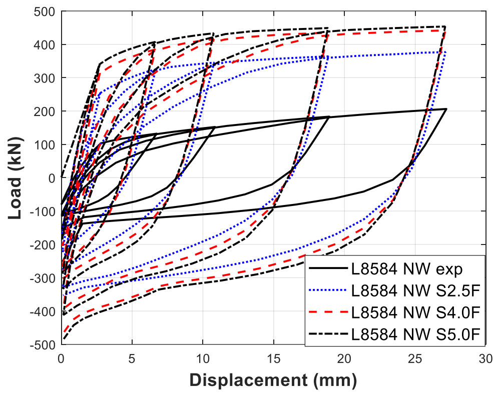


Figure 3. Effect of stiffener thickness on load-displacement behavior

RESULT AND DISCUSSION

Based on four factors, in total, 16 models were developed and analyzed to investigate the cyclic behavior. For each factor combination, the load-deformation response is presented in Figure 4. A wide range of cyclic response was observed for these models. Model responses in terms of initial stiffness, load capacity and energy dissipation capacity are presented in Table 2. The angle thickness was the same (i.e., 25.4 mm) for the first eight models, whereas, stiffener thickness, material yield strength, and gage length were varied.

Table 2. Factorial analysis results

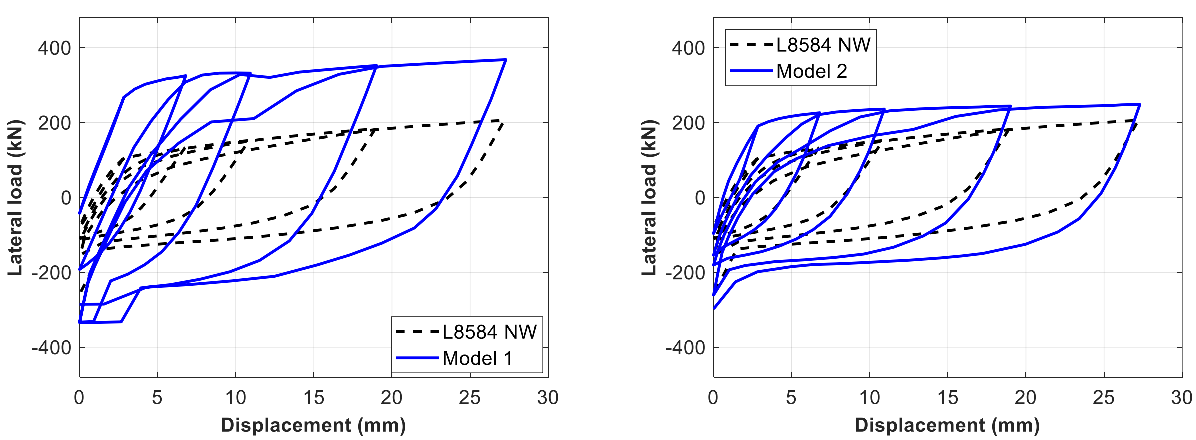
SL No	Run	Factors					
		A (mm)	B (N/mm^2)	C (mm)	D (mm)	F_{max} (kN)	E_d (kN.m)
1	2	3	690	90	25.4	368	20.63
2	3	3	250	90	25.4	248	16.52
3	4	10	250	90	25.4	303	21.13
4	5	10	690	120	25.4	391	18.65
5	8	10	690	90	25.4	458	23.60
6	10	3	250	120	25.4	205	12.53
7	13	3	690	120	25.4	311	16.50
8	15	10	250	120	25.4	254	17.27
9	1	10	690	120	12.7	266	14.81
10	6	10	250	90	12.7	166	11.72
11	7	10	690	90	12.7	293	16.81
12	9	3	250	120	12.7	104	7.720
13	11	10	250	120	12.7	146	10.43
14	12	3	250	90	12.7	124	9.330
15	14	3	690	120	12.7	180	12.33
16	16	3	690	90	12.7	213	14.77

The results indicate that the load capacity and energy dissipation capacity of angle connection can be increased by increasing the stiffener thickness or material yield strength. At the same time, the gage length should be lower. From previous literature, it was observed that lower gage length can lead to early fatigue failure of the specimen. This study shows that higher capacity is also achievable with higher gage length by adding thick stiffener plate.

Gage length (g) is defined as the distance between the bottom edge of the angle leg to the edge of the hole in the angle. The ratio of the gage length over the thickness of a bolted angle (g/t) is an important parameter to illustrate its load-deformation behavior. By decreasing g/t ratio, the energy dissipation as well as the strength and stiffness increases, however, the angle is prone to early fatigue failure [9]. Therefore, g/t ratio should be carefully chosen so that the required amount of energy is dissipated while avoiding the early fatigue failure. This study considered two different gage length of 90 mm and 114 mm for the stiffened angles. If the angle thickness is kept at its higher limit such as 25.4 mm for this study, maximum load capacity can be achieved by lowering the gage length.

To examine the effect of the stiffener thickness, two different thicknesses of 10 mm, and 3 mm are considered. Table 2 lists these models and associated response parameters. The validated FE model is modified accordingly to accommodate additional stiffeners. The FE results of the stiffened angles in terms of load-displacement hysteresis are shown in Figure 4 (*a*)-(*f*). The energy dissipation capacity of the connection with a higher thickness of stiffener was larger than the control specimen (L8584 NW). The energy dissipation capacity (E_d) increased by about 52% when the thickness of stiffener was 10 mm. Although higher energy dissipation capacity (E_d) can be achieved, using thicker stiffeners affects the self-centering capacity of the connection. The residual deformation of the stiffened angle connection increases significantly with increased thickness of the stiffener. High accumulated plastic deformations in the beam flanges are the reason for the reduction in self-centering capability. The maximum load capacity increases with the increase in the stiffener thickness. For the considered cases, the load capacity (F_{max}) increased up to 458 kN for the specimens with 10 mm stiffener. In all cases, the capacity is about 20 to 34% higher than that of the original specimen (L8584 NW).

Models 8 to 16 consist of angles with smaller thickness (i.e., 12.7 mm). The load capacity ranges from 124 kN to 293 kN. The energy dissipation capacity can reach up to 16.81 kN.m. All model's responses were compared with the experimentally tested specimen L8-58-4-NW. The angle thickness was about 15.9 mm for this specimen. From Figure 4, it is evident that even with smaller angles higher capacity can be achieved by adding stiffener into the angles.



(a) (b)

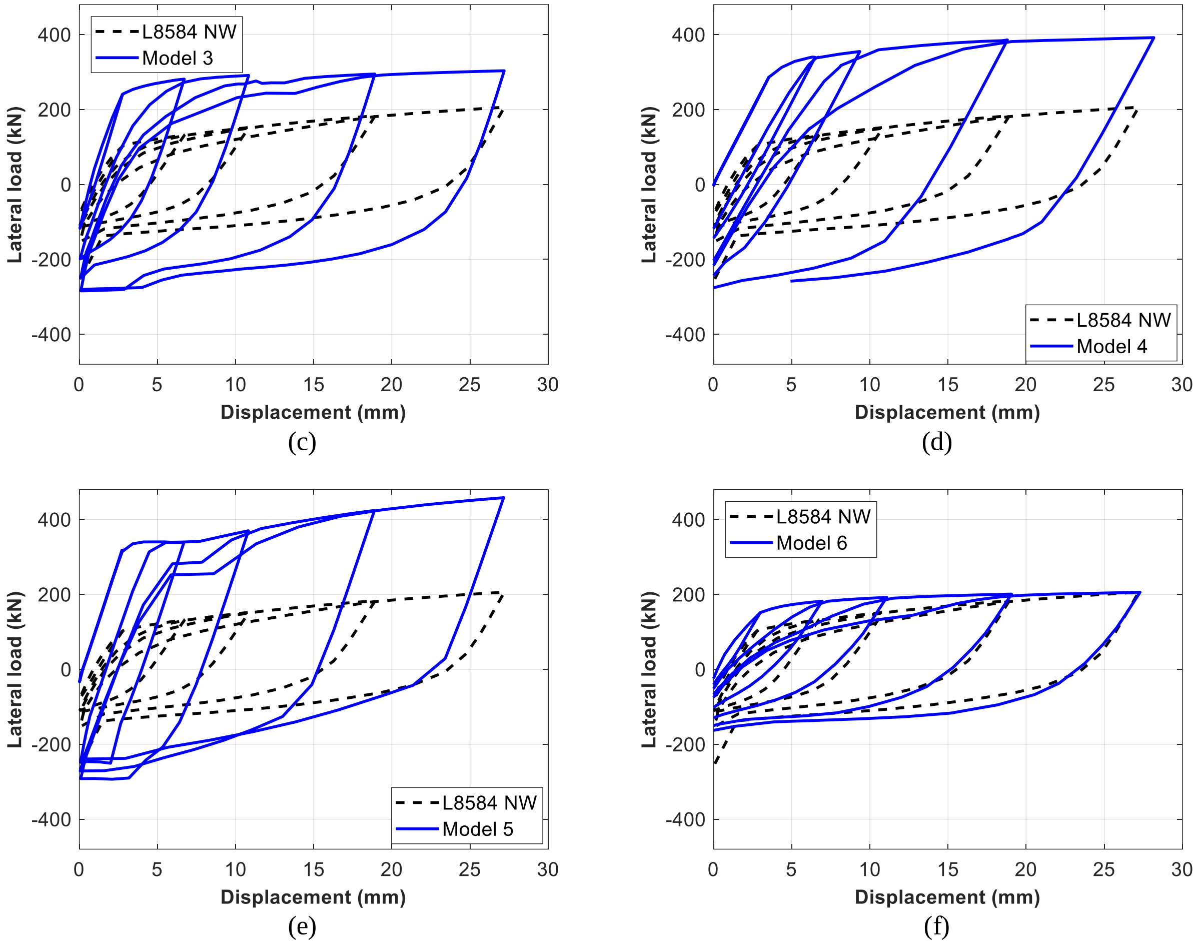


Figure 4. (a-f) Load-deflection behavior of model 1-6

CONCLUSIONS

Adding stiffener enhanced the behavior of the bolted top-and-seat angle. After developing a 3D FE model, a parametric study was carried out to examine the effects of four controlling factors. An increase in stiffener thickness leads to higher capacity and higher energy dissipation, however, residual deformation of the connection increases as well. Increasing the gage length can have a negative effect on the energy dissipation capacity but it removes the residual deformation. In order to optimize the top-and-seat angle connection with different stiffener thickness, gage length, and angle sizes, a full factorial analysis was conducted. Higher load capacity and energy dissipation capacity can be achieved by using smaller angle with stiffener. Smaller gage length can help the angle to increase the load carrying capacity, but might result in early fatigue failure. Therefore, the gage length of the stiffened angle connection can be used to improve the load capacity and prevent the early fatigue failure.

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