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Evaluation of the behaviour and constructability of Slotted-Hidden-Gap HSS brace connections

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ABSTRACT

Steel square hollow structural section (HSS) brace members are typically connected to a braced frame using a slotted tube-to-gusset plate (conventional) connection. When only the HSS is slotted to accept the gusset plate, a net section exists in the brace, which without reinforcement tends to concentrate inelastic behaviour in the tube near the slot region; as a result, net-section fracture may occur before the tube has yielded along its full length. The "Slotted-Hidden-Gap" (SHG) connection represents an attractive alternative to connection reinforcement, whereby the brace is able to yield along its length during repeated tension cycles without any reinforcement. Researchers in Japan and Canada have demonstrated the effectiveness of this connection detail for HSS braces, however, no encompassing seismic design or detailing rules exist for this SHG connection for square HSS members that can be applied in a general sense. Thus, a finite element study of SHG connections of square HSS brace members when subjected to monotonic tensile loading was carried out to evaluate the influence of parameters, including; the overlap length, weld length and weld size. Constructability of the SHG connection was also investigated; two paddle-gusset connection scenarios were examined and their effect on the performance of the SHG connection was evaluated. Results have shown that the overlap length, weld length and weld size contribute significantly to the inelastic response of the SHG connection.

Keywords: Brace, Connection, Hollow Structural Section (HSS), Slotted-Hidden-Gap (SHG), finite element analysis.

INTRODUCTION

Concentrically braced frames (CBFs) are among the common choices for the seismic force resisting systems (SFRS) for low-to medium-rise steel buildings in Canada. Hollow structural sections (HSS) typically form the braces of these CBFs because of their high resistance in compression, as well as their aesthetic appeal [1]. A slotted tube-to-gusset plate connection or a knife-plate welded connection, herein referred to as a conventional connection, is often utilized to connect the HSS braces to the beam-to-column joints in a bracing-bent frame. This detail involves inserting one end of the brace onto the gusset plate by means of the slot in the HSS, which is then field welded to the gusset plate using fillet welds. This detail, although highly favoured by fabricators and designers due to its simplicity, suffers major downsides; the reduced net section due to the slots, and the uneven tensile stress distribution due to the shear lag effects. The reduced net-section area of the brace and the well-known conservatism of existing design shear lag factors [2-4] usually lead an engineer to specify some type of connection reinforcement at the net section of the brace when trying to satisfy the seismic capacity based design requirements of CSA S16 [5]. However, connection reinforcement schemes typically prove to be either uneconomic or unsuitable [2-8].

Therefore, to avoid having to reinforce the conventional end connections of an HSS brace, the Slotted Hidden Gap (SHG) connection was developed. Although a design approach was published by the Architectural Institute of Japan [9], based on the results of and limited to the scope of study of a laboratory test program by Mitsui et al. [10], no encompassing seismic design or detailing rules exist for this connection for square HSS members used in seismic applications. Thus, a finite element (FE) parametric study was carried using ABAQUS to understand the geometric and material properties that influence the SHG connection response. This paper presents a brief review of past studies on the topic and then describes the FE model and the parameters used, as well as the preliminary findings.

LITERATURE REVIEW

In a conventional HSS brace connection, there is a stress concentration in the tube at the end of the gusset plate where the welds terminate, which can lead to subsequent cracks at this location [11]. Thus, the Slotted-Hidden-Gap (SHG) connection was developed to avoid net-section fracture without having to reinforce the connection (Figure 1). It was adopted from the AIJ recommendations [9] based on work by Mitsui et al. [10], and was further studied by Martinez-Saucedo [8], Packer et al. [12] and Moreau et al. [1]. The SHG connection is constructed by inserting the slotted end of the HSS brace onto a slotted gusset plate (Figure 1); a gap is left between the end of the slot in the gusset plate and the end of the slot in the HSS, which cannot be seen once the connection has been fully fabricated. The SHG connection detail allows the fillet weld to start on the gross area of the HSS, thus moving stress concentrations away from the net section region of the brace.

Martinez-Saucedo et al. [13, 14] conducted laboratory tests and FE simulation of two CHS braces with SHG connections subjected to reversed-cyclic loading. Further, Packer et al. [12] conducted reversed-cyclic testing of four CHS braces using the SHG connection. These studies proved the merits of the SHG connection, and its ability to distribute inelastic demands away from the connection region. No parametric studies were carried out on rectangular or square HSS. Moreau et al. [1] conducted laboratory tests and FE modeling of two square HSS brace sizes (HSS152×152×9.5 and HSS203×203×13) to determine the minimum overlap length required to develop the yield resistance of the braces. This study led to the recommendation that an overlap length of 5% of the weld length in the SHG connection is sufficient to develop the yield resistance of the HSS brace. Overall design and detailing rules were not developed from these past research projects. Thus, a research program was initiated to develop general design and detailing rules for the SHG HSS brace connection.

FINITE ELEMENT MODEL

Overview

A numerical parametric study was conducted to better understand the different geometric properties that influence the behaviour of a SHG connection. Monotonic tensile loading of the connection was investigated for this parametric study because the conventional connection often fails in tension at the net-sectional area of the brace. Hence, monotonic loading represents an extreme loading case; it also gives an opportunity to study the stress-strain distribution of the connection before proceeding into the reversed-cyclic loading routine.

Methodology

The brace configurations from Moreau et al. [1] were used as the starting point for this study. In all FE models, the HSS size, gusset plate thickness and width were kept constant. The overlap length, L_{wg}, weld length, L_w, and weld size D_w (Figure 1) were varied; their effects on the connection response were investigated. The global load-displacement response and stress-strain distribution at critical points were evaluated. The ratio of load attained to the yielding load (P/P_y) was used to compare the performance of the different models, where P_y was calculated using the product of the gross area (A_g) and the measured material yielding strength (F_y) of the HSS braces tested by Moreau at al.

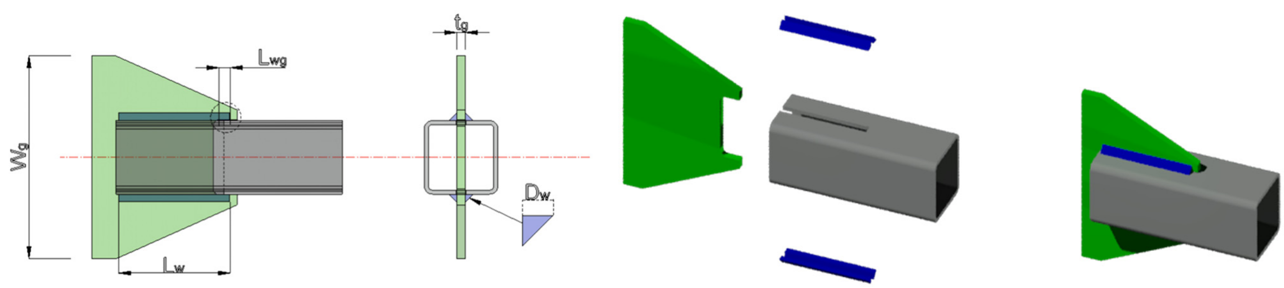


Figure 1. Details of SHG HSS brace connection and assembly of parts.

The overlap length, L_{wg}, is defined as the length of weld on the gross cross-sectional area of the tube (Figure 1). It is believed to be one of the most important parameters influencing the response to loading of the SHG connection. Thus, in the first part of the study, three overlap lengths were investigated; 20 mm, 10 mm and 0 mm. In the second part of the study, the weld details were examined through varying the weld length from 390 mm to 620 mm and decreasing the weld size from 29 mm to 19 mm. Welds start at distance of L_{tol}=10-15mm, commonly found in practice. All HSS tubes were grade CSA G40.20-21 350W Class C, and plates were ASTM A572-50. The Slot created in HSS has a rounded end to match the common practice. The material properties used in the modeling were those obtained through measurement in the test program by Moreau et al. [1]. A summary of the models and corresponding geometric aspects is found in Table 1.

FE Model Properties

The parametric study was conducted using the finite element software ABAQUS 2017 [15]. A 3D drawing of the assembled brace connection was first created in AutoCAD 2017 [16], which was subsequently imported into Abaqus. This procedure was chosen for all connection types because of its simplicity, but more importantly it allows Abaqus to recognize the entire assembly as one entity, which leads to improved meshing of the geometry at the connection. Also, there was no need to create tie constraints to join the brace, weld and gusset plate. Symmetry was utilized to model one-quarter of the geometry as shown in Figure 2. This is acceptable since buckling is not expected under tension loading. A displacement loading of 140mm was applied at the gusset end, while the reaction forces were measured at the other end of the tube. A tube length of 1000 mm was used to minimize computational time and to ensure that an overly short length of brace would not influence the distribution of strain and stress in the connection.

Table 1. Summary of finite element model variables

Model Label	Size	W_g	t_g	L_w	D_w	L_{wg}	L_{wg}/L_w
SP1	HSS254x254x13	700 mm	32 mm	390 mm	29 mm	20 mm	5.1%
SP2						10 mm	2.5%
SP2A						0 mm	0%
CONV						0 mm	0%
SP3	HSS254x254x13	700 mm	32 mm	620 mm	19 mm	20 mm	3.2%
SP4						10 mm	1.6%

First-order reduced-integrated hexahedral 8-noded solid elements with hourglass control (C3D8R) were used to model the tube, welds and gusset plate, as were chosen by Moreau et al. [1]. A fine mesh was used near the weld region at the overlap length where large-strain gradients are expected. Three elements were used through the thickness of the gusset plate and tube to control hour-glassing. A non-linear isotropic von-Misses hardening module was used to model all materials.

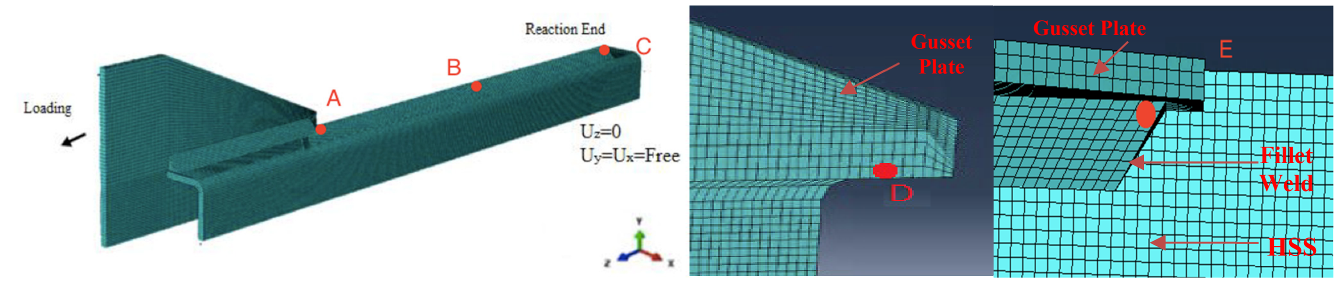


Figure 2. FE Model Showing mesh, boundary conditions, and locations of evaluation.

Fracture models were not implemented in this study; however, the equivalent plastic strains (PEEQ) were used as a relative indicator for fracture potential. Fracture PEEQ values between 0.8 – 1.0 have been reported by Zhao et al. [4]. The measured material properties from the HSS braces tested by Moreau et al. [1] were used for the weld metal since true stress-strain curves for welds are difficult to obtain.

PARAMETRIC STUDY RESULTS

Influence of Overlap length

The global load-displacement responses for different overlap lengths are shown in Figure 3. The SHG connection allows the entire tube to yield on the gross area for all overlap lengths. The conventional connection is unable to reach the same ultimate load as the SHG connections due to yielding and necking on the net area. The SHG model with no overlap length (L_{wg}=0 mm) was able to attain yielding on the gross area. However, connections with longer overlap lengths attained higher forces; as increasing overlap length means a stiffer and stronger connection capable of forcing the development of inelastic demands away from the connection region.

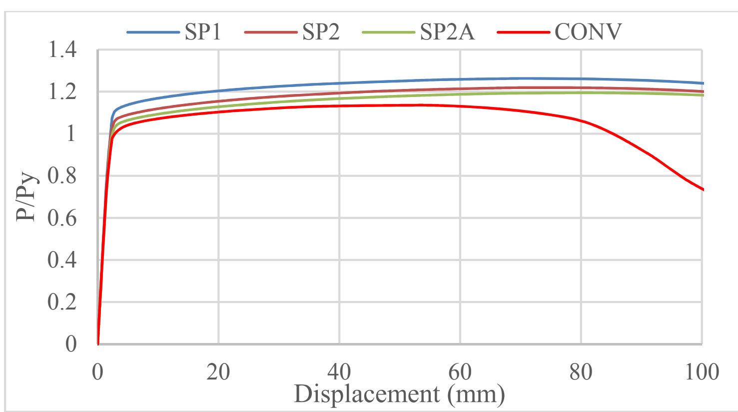


Figure 3. Global Load-Displacement for different overlap lengths.

The local PEEQ-displacement response at location A (Figure 2) in front of the weld was first considered (Figure 4). As expected, the PEEQ is the highest for the conventional connection, while the plastic strains decrease with increasing L_{wg} lengths from 0-20 mm. The SHG connections demonstrate similar PEEQ response of a steady increase until reaching a plateau, since the plastic strains concentrate at the mid-span, unlike the conventional connection that keeps increasing until failure occurs at the connection area. For SHG connections, a large improvement is noticed while increasing the overlap length from 0 mm (SP2A) to 10 mm (SP2), and a slight improvement happens when further increasing overlap length to 20 mm (SP1).

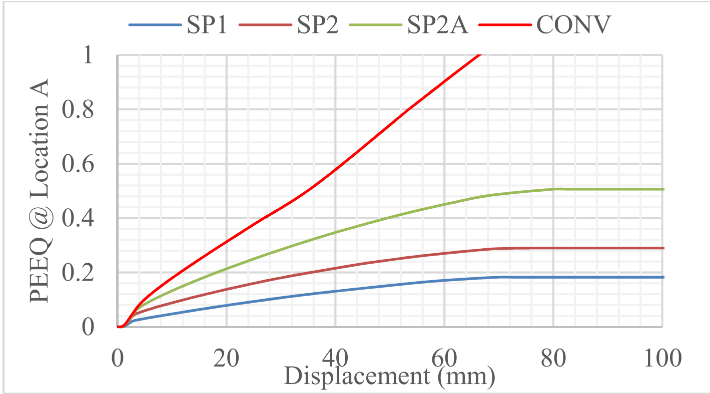


Figure 4. PEEQ at location A vs. Displacement for different overlap lengths.

The local PEEQ-displacement response at location B (Figure 2) along the tube is shown in Figure 5. Location C (Figure 2) at the tube reaction has similar PEEQ as location B for the same overlap lengths. There is an increase in the plastic strains along the tube with increasing overlap length. This behaviour is favourable since yielding occurs over the gross area away from the connection region. There are slight improvements in behaviour at this location between the overlap lengths from 0 mm to 20 mm. The conventional connection shows the least plastic strains at location B, since the plastic strains are concentrated in the connection region (location A) which may trigger early fracture.

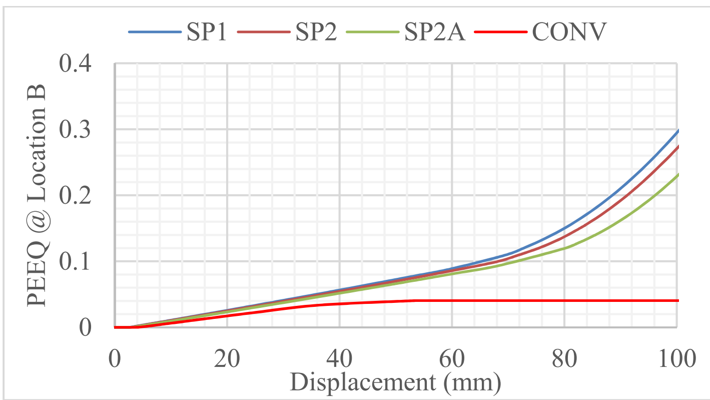
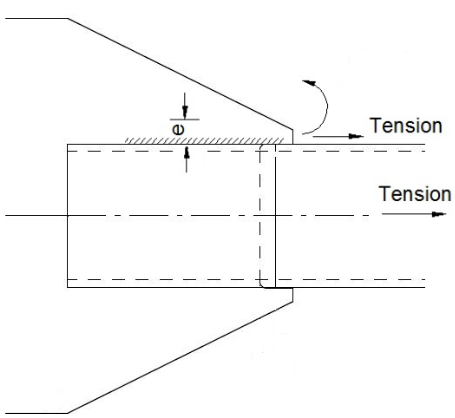


Figure 5. PEEQ at location B vs. Displacement for different overlap lengths.

Various Figure 6a shows the flexural demand created in the gusset plate due to the overlap length. This demand is developed due to the eccentricity between the force at the weld and the centroid of the part of the gusset plate that extends outside the tube width. This behaviour was noticed through prior numerical and experimental programs by Martinez-Saucedo [8], and Moreau et al. [1], hence were examined. Figure 6b shows the PEEQ at location D (Figure 2), at the end of the slot in the gusset plate. As the overlap length increases, the load transferred from the tube to the weld increases, leading to an increase in flexural demand, and hence increased plastic strains. This behaviour is not favourable since gusset bowing may occur which may reduce the brace ductility.

a)



b)

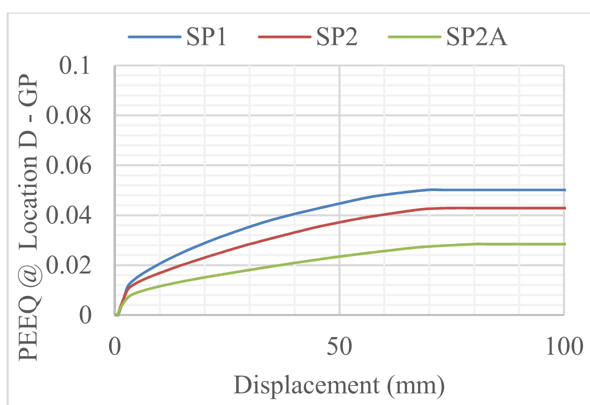


Figure 6. a) SHG connection detail showing flexural demand, b) PEEQ at location D vs. Displacement for different overlaps.

Figure 7 shows the local PEEQ-displacement response at location E (Figure 2), at the tip of the weld near or over the gross area of the tube. The conventional connection shows the lowest plastic strains, as all the deformation is concentrated in the net cross-section area of the tube. Model SP1 (L_{wg}=20 mm) shows the least values of plastic strain concentrations in the weld, slightly more than the observed in conventional connection. It is observed that plastic strains in the weld increased while decreasing the overlap length to 10 mm and 0 mm, respectively. The SHG connection with no overlap length (L_{wg}=0 mm) shows the largest concentrations of plastic strains, inelastic demand is concentrated in the weld region which may trigger early fracture.

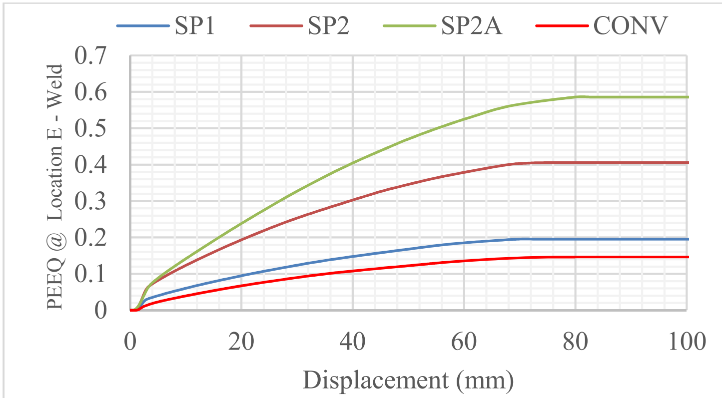


Figure 7- PEEQ at location E vs. Displacement for different overlap lengths.

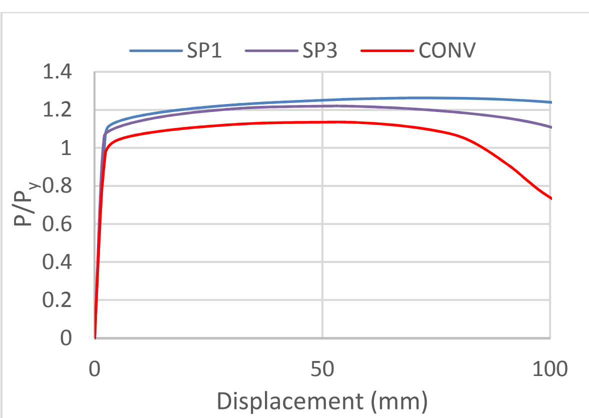
Influence of Weld Length and Size

The influence of weld size and length were investigated by increasing the weld length (L_w) and reducing the weld size (D_w) to a practical limit, while preventing any other tensile failures such as block shear failure in the tube and gusset plate, and weld fracture. Smaller weld size and longer welds are favourable in practice, as they require fewer weld passes, which consequently leads to reduced cost and less weld stepping; thus a longer effective length of weld ($L_{w\text{-}eff}$). In addition, a longer weld length means less shear lag effects. Martinez-Saucedo [8] and Packer et al. [12] developed a non-linear function describing the shear lag effects on conventional HSS slotted connections, which was later included in the CSA S16-14 Standard [17]. They showed that shear lag effects eventually vanish when providing sufficiently long welds.

Figure 8 shows the global load-displacement response curves for models with adjusted weld parameters compared to configurations with the default weld length and size for two overlap lengths L_{wg}=20 mm (Figure 8a) and L_{wg}=10 mm (Figure 8b). Figures 9a & 9b show the corresponding PEEQ at location A (Figure 2) in front of the weld. The curves are similar for both weld properties, with only a slight advantage of models with larger welds (SP1 & SP2) over smaller-sized ones (SP3 & SP4).

Figure 10 shows the PEEQ-Displacement curve for models with different weld parameters and overlap lengths at the tip of the weld start. It is noticed that the plastic strains increase more quickly for the smaller welds compared to the larger size welds. The behaviour is worsened with the decreased overlap lengths, because the model having the smaller weld size and least overlap length (SP4) has the greatest concentration of strain at the weld; this is undesirable and may cause weld failure.

a)



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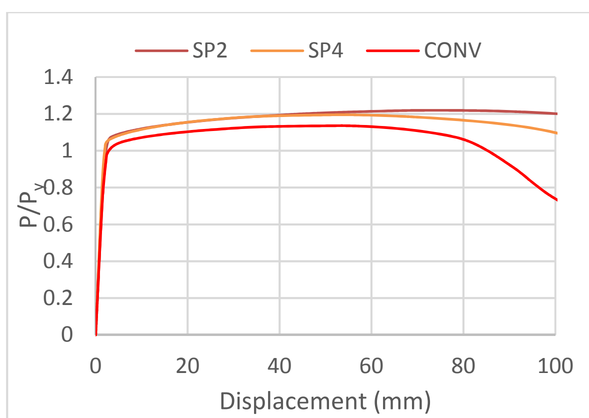

Figure 8. Global load-Displacement for a) Lwg=20mm and b) Lwg=10mm

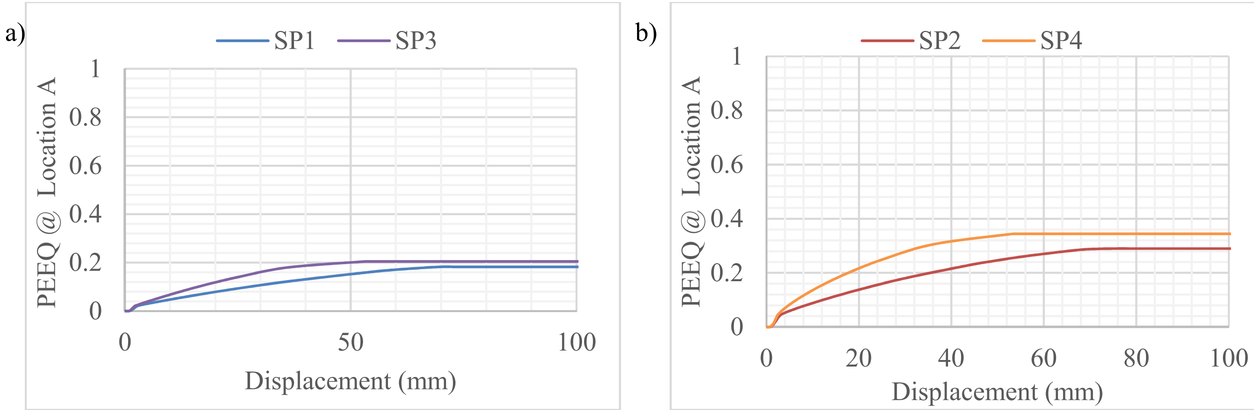

Figure 9. PEEQ at location A vs. Displacement at location A for a) Lwg=20mm and b) Lwg=10mm.

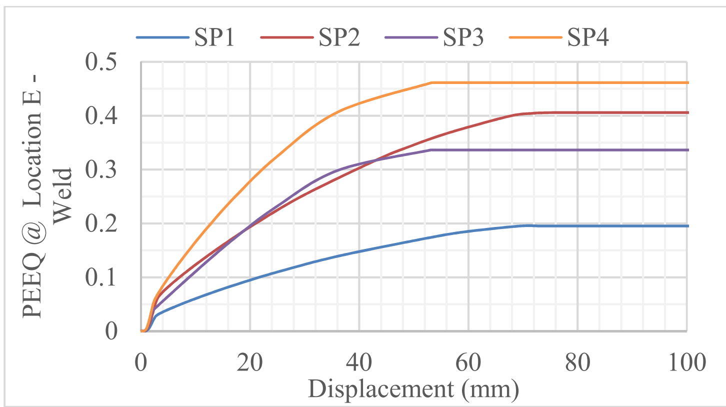

Figure 10. PEEQ at location E vs. Displacement at weld tip for different overlap lengths.

SHG HSS Brace Constructability

Figure 11 shows the two paddle-gusset plate scenarios that were investigated. The 4-Angle configuration (Figure 11a) comprises a paddle plate which is bolted to the gusset plate using four back-to-back angles. The 2-Plate connection (Figure 11b) connects the gusset plate to the paddle plate using two bolted side plates. The SHG HSS brace connection for both paddle-gusset plate connection configurations was of model SP1, having L_w=390 mm, D_w=29 mm and L_{wg}=20 mm. ABAQUS parameters were the same, with the addition of contact properties for the bolts used to connect different parts of the assemblies.

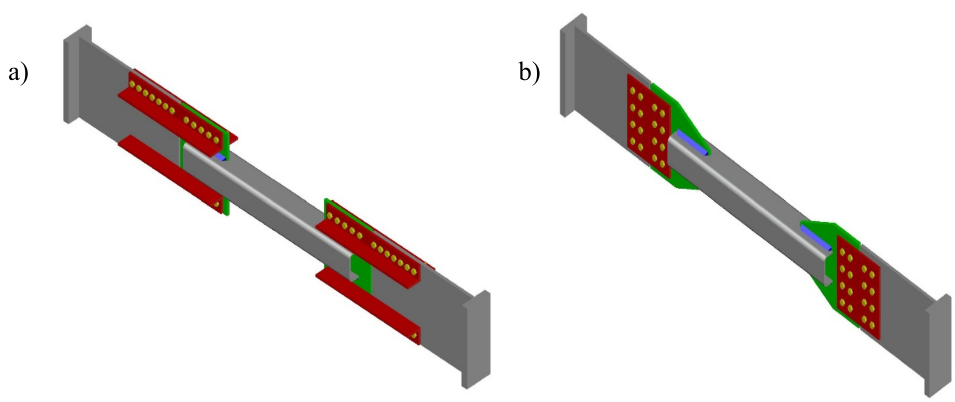

Figure 11. Paddle-gusset plate connection scenarios; a) 4-Angle, and b) 2-Plate.

Figure 12 shows the global load-displacement response for the two connection scenarios; both attained similar response with a slight edge for the 2-Plate over the 4-Angle configuration. Also, both connections have almost the same plastic strain values over the connection region as seen in the PEEQ-displacement relations (Figure 13a). This behaviour is of benefit as none of the proposed scenarios induces higher demand in the SHG connection region despite having different load transfer mechanisms.

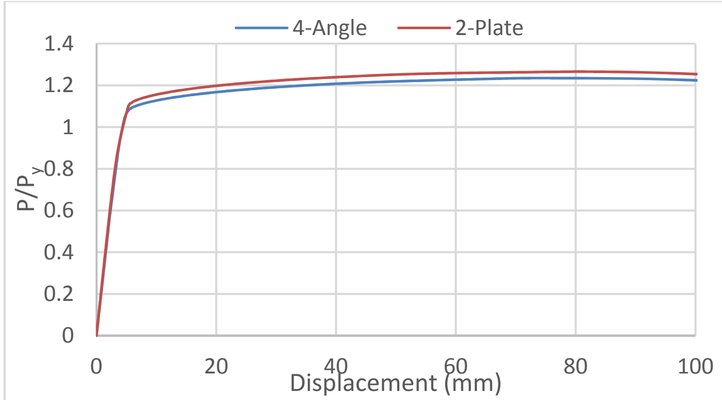

Figure 12. Global load-displacement for different paddle-gusset connection scenarios.

An important observation is the PEEQ value concentrated at the weld tip. In Figure 7, model SP1 had a maximum of 0.2 at the maximum displacement applied, however when the same model was used to examine constructability, the PEEQ values almost doubled for corresponding displacements as seen in Figure 13b. This is because the load is transferred through a smaller gusset plate width; through the width of plates or the angles. The elevated inelastic demands at the weld tip means more emphasis in future study shall be put on weld dimensions and overlap length.

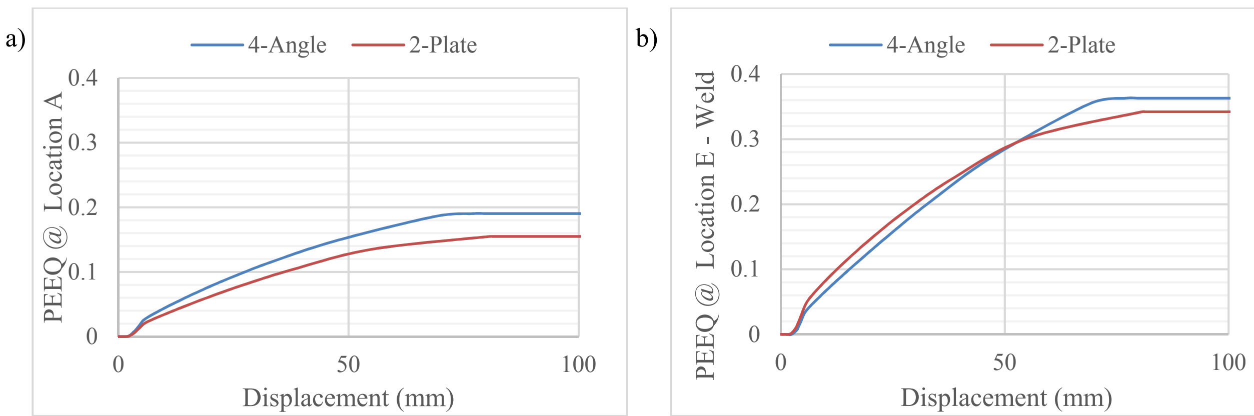

Figure 13. PEEQ vs. Displacement for different paddle-gusset connections at a) location A and b) location E.

The largest difference between the two connection scenarios is in the concentration of plastic strains in the gusset plate slot. There is less concentration of inelastic demand in the 4-Angle connection, mainly due to the increased width of the gusset plate, which provides space for the angles to be placed parallel to the weld. The bowing effect in the gusset plate, discussed earlier, needs to be carefully considered if the 2-Plate connection configuration is to be utilized. This is illustrated in Figure 14.

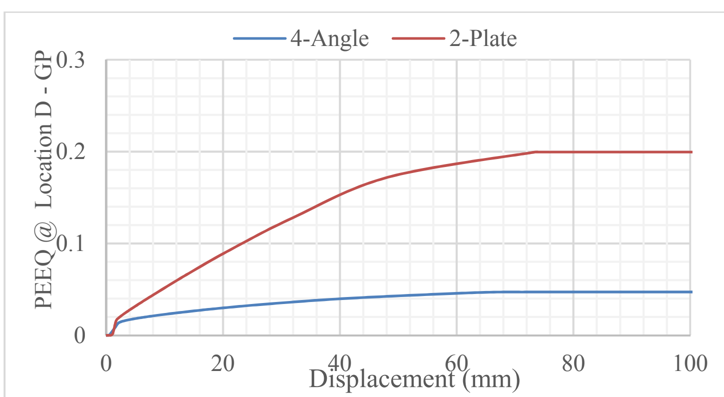

Figure 14. PEEQ at location D vs. Displacement for different paddle-gusset connections at slot of gusset plate.

CONCLUSION

This parametric study has provided insight into the parameters affecting the SHG HSS brace connection. Results have shown that the overlap length, weld length and weld size contribute significantly to the performance of the SHG connection. In general, the welding of the gusset plate to the gross area of the tube allows the tube to attain its full yield strength on the gross area. Furthermore, the stiffness of the connection allows inelastic demand to develop along the tube and away from the connection region, compared to the conventional connection that concentrates inelastic demand in the weld region. Higher overlap lengths induce higher flexural demands, and accordingly increase the plastic strains on the gusset plate slot. Smaller size longer welds can be utilized in a SHG connection due to the lower shear lag effects, as well as the maximized effective length of weld. The overall behaviour of the SHG connection was not overly affected by the different paddle-gusset plate connections despite the different load transfer mechanisms.

FUTURE WORK

This parametric study was limited to a few geometric aspects of SHG connections; more aspects are to be investigated to include different HSS sizes, material grades and various geometric parameters, e.g. gap length, gusset plate widths, tube size, etc. Significance of flexural demand created in the gusset plates as a result of increasing overlap lengths will also be examined. An experimental testing program is also planned, which will include the configurations described in this paper. The results of the laboratory study will be used in further calibration of the FE models. Design recommendations will be developed and verified through reversed-cyclic tests for SHG Connection.

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REFERENCES

[1] Moreau, R., Tremblay, R., Rogers, C.A. 2014. Evaluation of the "Modified-Hidden-Gap" Connection for Square HSS Brace Members. Research Report, Dept. of Civil Eng., McGill University.

[2] Cheng, J. J. R., Kulak, G. L., and Khoo, H. A. 1998. Strength of slotted tubular tension members. Canadian Journal of Civil Engineering 25: 982-991.

[3] Willibald, S., Packer, J. A., and Martinez-Saucedo, G. 2006. Behaviour of gusset plate connections to ends of round and elliptical hollow structural section members. Canadian Journal of Civil Engineering 33: 373-383.

[4] Zhao, R. G., Huang, R. F., Khoo, H. A., and Cheng, J. J. R. 2008. Experimental study on slotted rectangular and square hollow structural section (HSS) tension connections. Canadian Journal of Civil Engineering 35: 1318-1330.

[5] Yang, F., and Mahin, S. A. 2005. Limiting Net Section Fracture in Slotted Tube Braces. Steel Tips Series. Structural Steel Education Council: Moraga, CA.

[6] Fell, B. V., Kanvinde, A. M., Deierlein, G. G., Myers, A. T., and Fu, X. 2006. Buckling and Fracture of Concentric Braces Under Inelastic Cyclic Loading. Steel Tips. Structural Steel Education Council: Moraga, CA.

[7] Haddad, M., and Tremblay, R. 2006. Influence of Connection Design on the Inelastic Seismic Response of HSS Steel Bracing Members. Proc. of the 11th Int. Symp. and IIW Int. Conf. on Tubular Structures, ed. by J. Packer and S. Willibad, Taylor & Francis, Leiden, The Netherlands. pp 639-646.

[8] Martinez-Saucedo, G. 2007. Slotted End Connections to Hollow Sections. Department of Civil Engineering, University of Toronto, Toronto, Canada

[9] AIJ. 2002. Recommendations for the design and fabrication of tubular truss structures in steel. Architectural Institute of Japan, Tokyo, Japan.

[10] Mitsui, Y., Kurobane, Y., and Endoh, K. 1985. Experimental study on ultimate strength and deformation capacity of welded tube-to-through gusset plate joints. Journal of Structural Engineering JSCE 31 (B): 145-156.

[11] Kurobane, Y. 1989. Design of Plate-to-Tube Joints. 8th International Conference on Offshore Mechanics and Arctic Engineering (OMAE). Materials Technology Symposium, March 19-23, The Hague, Netherlands.

[12] Packer, J. A., Chiew, S. P., Tremblay, R., and Martinez-Saucedo, G. 2010. Effect of material properties on hollow section performance. Proceedings of the Institution of Civil Engineers Structures and Buildings 163 (SB6): 375-390.

[13] Martinez-Saucedo, G., Packer, J. A., and Christopoulos, C. 2008. Gusset Plate Connections to Circular Hollow Section Braces under Inelastic Cyclic Loading. Journal of Structural Engineering 134 (7): 1252-1258.

[14] Martinez-Saucedo, G., Packer, J. A., and Tremblay, R. 2008. Seismic response of circular hollow section braces with slotted end connections. Tubular Structures XII, Shanghai, China. Taylor and Francis: 227-233.

[15] Abaqus. 2017. Dassault Systemes Simulia Corp. Providence, RI, USA.

[16] AutoCAD. 2019. AutoCAD 2019. Autodesk, Inc.

[17] CSA. 2014. CSA S16-14 Design of Steel Structures. Canadian Standards Association: Mississauga, ON, Canada.