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SLOTTED-HIDDEN-GAP (SHG) BRACE CONNECTIONS FOR SQUARE HOLLOW STRUCTURAL SECTIONS FOR SEISMIC APPLICATIONS

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Abstract

Hollow structural section (HSS) brace members may be connected to a steel braced frame using a slotted tube-to-gusset plate (conventional) connection or knife-plate connection. When only the HSS is slotted to accept the gusset plate a net section exists in the brace, which often requires reinforcement to satisfy the seismic capacity design requirements. If reinforcement is not provided, the conventional slotted HSS connection tends to concentrate inelastic behaviour in a small portion of the tube near the slot region. As a result, net-section fracture may occur before the tube has yielded along its length, i.e. the ductility associated with the choice of moderately ductile or limited ductility seismic force modification factors from the National Building Code of Canada (NBCC) and CSA S16 may not be achieved. The "Slotted-Hidden-Gap" (SHG) connection represents an attractive alternative to traditional connection reinforcement, whereby the brace is able to yield along its length during tension cycles without having to install cover plates or extending the welds to fill the gap left at the connection. During fabrication, slots are created in both the gusset plate and HSS, which allows for the termination of the connecting fillet welds at a position corresponding with the full gross cross-section of the brace. Researchers in Japan and Canada have demonstrated through laboratory testing the effectiveness of this connection detail for circular and square HSS braces. It is possible to design and fabricate this brace-connection detail if one matches the dimensions used in the various test programs. However, no encompassing seismic design method or detailing rules exist for this SHG connection for square HSS members that can be applied in a general sense. Thus, a numerical 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 various geometrical parameters on the overall performance of the connection. This article mainly focuses on examining the individual influence of three key factors; HSS brace geometrical parameters, weld related parameters and gusset plate related parameters. Results reveal that weld size and length as well as gusset plate thickness are critical in the design of SHG connection, and may hinder the connection performance if poorly designed or fabricated. Results also show the contribution of HSS size and thickness to the inelastic performance of the connection.

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

1. Introduction

Multiple framing options are available for seismic force resisting systems (SFRS) for low-to-medium-rise steel buildings. Steel concentrically braced frames (CBF) are among the most popular due to their high stiffness and efficiency in resisting lateral and earthquake loads [1]. A braced frame is essentially a planar vertically cantilevered truss that resists lateral loads through axial loads in braces, beams and columns forming the frame. The drift capacity in CBFs is provided through alternating cycles of buckling and yielding of the diagonal brace members. Therefore, to survive an earthquake, the braces must be able to sustain large inelastic displacement reversals without significant loss of strength and stiffness [2]. 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]. The HSS member is traditionally connected to the gusset plate through creating a slot in the tube, then inserting the gusset plate and applying fillet welds at the interfaces. This connection, herein referred to as a conventional connection, although highly favoured by fabricators and designers due to its simplicity, suffers major drawbacks: the reduced net section due to the slots, and the uneven tensile stress distribution due to the shear lag effects. Those downsides, along with the conservatism in shear lag factors [3-5], push engineers to specify connection reinforcement by means of cover plates or wrapped around welds to fulfill limits of the capacity design mandated by the CSA S16 Standard in Canada [6]. However, connection reinforcement schemes typically prove to be either uneconomic or unsuitable [3-5,7-10].

Therefore, to avoid having to reinforce the conventional end connections of an HSS brace, the Slotted-Hidden-Gap (SHG) connection was developed. The present form of the connection was adapted from the Architectural Institute of Japan (AIJ) recommendations for circular hollow sections (CHS) [11], which were based on the work by Mitsui et al. [12]. This seminal study in Japan was further advanced by Martinez-Saucedo [10] and Packer et al. [13]. The SHG connection is constructed by inserting the slotted end of the HSS brace onto a slotted gusset plate (Fig. 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 section area of the HSS, thus moving stress concentrations away from the reduced net section region caused by the slots.

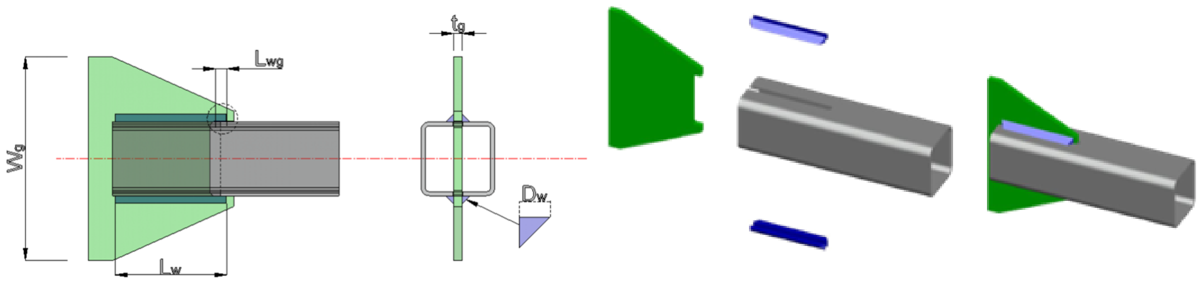

Fig. 1 - Details of SHG HSS brace connection and assembly of parts

Mitsui et al. [12] conducted the first investigation on the SHG connections by carrying out laboratory tests on five configurations of CHS braces of the same tube size under monotonic tension loading. Research programs were then carried out at the University of Toronto in Canada by Martinez-Saucedo et al. [14, 15], who executed laboratory tests and FE analyses of two CHS braces with SHG connections subjected to reversed-cyclic loading. This was followed by Packer et al. [13], who conducted reversed-cyclic testing of a further set of four CHS braces with SHG connections. These studies proved the advantages of the SHG connection over the conventional fabrication approach for which only the HSS is slotted; however, they were limited by the range of geometries and materials included in the laboratory test programs. Nor was a general design method / detailing approach for these connections provided at the time. Furthermore, the use of the SHG connection was not investigated for square or rectangular HSS braces.

A research project was initiated at McGill University and Polytechnique Montréal by Moreau et al. [1], who conducted laboratory tests and FE modeling of two square HSS brace sizes (HSS 152×152×9.5 and HSS 203×203×13) to determine the minimum overlap length required to develop the yield resistance of the braces over their full length. This study led to the recommendation that an overlap length of 5% of the weld length in the SHG connection could be sufficient to develop the yield tensile resistance of the HSS brace. Overall design and detailing rules were not developed from these past research projects. Thus, the aforementioned research program was continued, with the objective of developing general design and detailing rules for the SHG HSS brace connection through a combination of laboratory testing and advanced numerical analysis. Described herein, is the preliminary phase of the numerical analysis, comprising a parametric study carried out using 3D continuum finite element (FE) models of the Slotted-Hidden-Gap connection for square HSS braces to evaluate the influence of different geometrical parameters on the overall performance.

2. Finite Element Simulations

2.1 Overview and Methodology

To better understand the different geometric properties that influence the behaviour of a SHG connection, a numerical parametric study was conducted. Monotonic tensile loading of the connection was investigated for this study because it represents an extreme loading case, and also gives an opportunity to study the stress-strain distribution of the connection before proceeding into the reversed-cyclic loading routine.

Table 1 - Summary of finite element model variables

HSS Size	**HSS thickness (mm)**	**L_w (mm)**	**D_w (mm)**	**W_g (mm)**	**t_g (mm)**	**L_{wg} (mm)**
Part 1 - HSS Parameters						
HSS 305x305	19	460	32	840	32	19
	16		29		29	
HSS 254x254	16	390	29	700	29	16
	13		25		25	
HSS 203x203	16	280	29	530	29	13
	13		25		25	
	9.5		19		22	
HSS152x152	16	210	29	390	29	10
	13		25		25	
	9.5		19		22	
	8		16		19	
Part 2 - Weld Parameters						
HSS 254x254	13	260	32	700	25	16
		390	25			
		620	19			
Part 3 - Gusset Plate Parameters						
HSS 254x254	13	390	25	700	19	16
					22	
					25	
					29	
					32	

The brace configurations from [1] were used as the starting point for this study. In all FE models, HSS size and thickness, weld size D_w and length L_w and gusset plate width W_g and thickness t_g (Fig. 1) were varied; their effects on the connection response were investigated. Fracture models were not implemented in this study; however, the equivalent plastic strain (PEEQ) was used as a relative indicator for fracture potential. Fracture PEEQ values between 0.8 – 1.0 have been reported by Zhao et al. [5].

This study was divided into three main parts to evaluate the effects of varying the HSS, the gusset plate and the geometrical properties of the welds. In Part 1, four different square HSS sizes (HSS 305, 254, 203 and 152), commonly found in US/Canadian low-medium rise steel practice, were examined while keeping constant thicknesses. The HSS thickness was then investigated by modelling different thicknesses for each HSS size. The b/t limit for use in the seismic design of HSS braces, mandated by CSA S16, was respected while varying sizes and thicknesses. In Part 2 of the study, the weld details were examined through varying the weld length from 260 mm to 620 mm, and decreasing the weld size from 32 mm to 19 mm. In Part 3, the gusset plate thickness was investigated through modelling five different gusset thicknesses ranging from 19 mm to 32 mm, while keeping the gusset width constant. The overlap length, L_{wg}, is defined as the length of weld on the gross cross-sectional area of the tube (Fig. 1). It is believed to be one of the most important parameters influencing the response to loading of the SHG connection, and it was previously investigated as part of this project [16]. All HSS tubes were grade CSA G40.20-21 350W class C with nominal F_{ys} = 350 MPa and F_{us} = 450 MPa, and plates were ASTM A572-50 with nominal F_{ys} = 345 MPa and F_{us} = 448 MPa. Matching electrodes with an ultimate tensile strength, X_u, of 490 MPa was selected for the welds. The width of the slot created in the HSS is typically 3 mm greater than the thickness of the gusset plate. The slot also has a rounded end to match the common detailing practice. The material properties used in the modeling were those obtained through measurement in the test program by Moreau et al. [1] and are displayed through the true stress-strain curve in Fig. 2. A summary of the models and corresponding geometric aspects is found in Table 1.

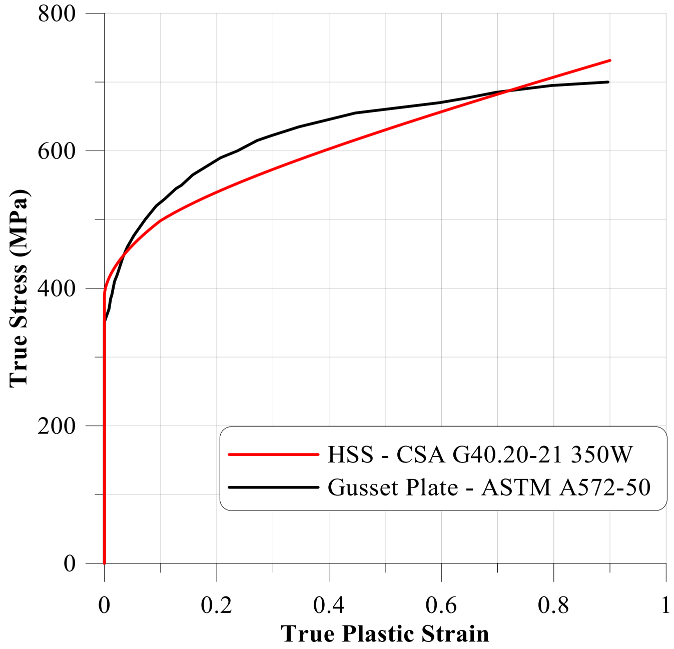

Fig. 2 – True Stress vs. True Plastic Strain for HSS and Gusset Plate used in FE Modelling.

2.2 FE Model Properties

The 3D continuum finite element (FE) models were developed in the commercial software ABAQUS 2017 [17] to obtain a better understanding of the behaviour of Slotted-Hidden-Gap connections. A 3D drawing of the as-built assembled brace connection was first created in AutoCAD 2017 [18], 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. The main features of the FE models were chosen to be representative of those seen in previous laboratory experiments. Calibration of the FE models against the results of the HSS SHG brace tests by Moreau et al. [1] was first completed. The inserted material properties were defined based on the true stress–strain curves (Fig. 2) obtained from tensile coupon tests, directly extracted from the various components of the tested components by Moreau at al. The measured material properties from the HSS braces tested were used for the weld metal since true stress-strain curves for welds are difficult to obtain. A displacement loading of 140 mm was applied at the gusset end, while the reaction forces were measured at the other end of the tube. The 140 mm displacement corresponds to the overall displacement level obtained from the SHG testing program (monotonic tension loading) described in [1]. 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 strains and stresses in the connection. The 140 mm axial displacement equates to a 13.5% storey drift ratio, Δ, calculated by assuming that the brace is part of a chevron frame and has an inclination angle of θ = 35° to the horizontal (Fig. 3). The axial deformations were assumed to occur uniformly over the length between brace hinge points, L_H, ($L_H = L_B + 2t_g$) and a 1.3 factor was used to transform the deformations of the brace from its centre-to-centre dimension $L_{o\text{-}c}$ to its L_H dimension (Fig. 3). This storey drift ratio is calculated based on a tension-only protocol; however, it should be noted that assuming the end connections would not precipitate failure, an actual brace undergoing reversed cyclic loading will likely fail due to low cycle fatigue fracture at the plastic hinge location along the length of the brace, away from the connection and long before achieving this large displacement level.

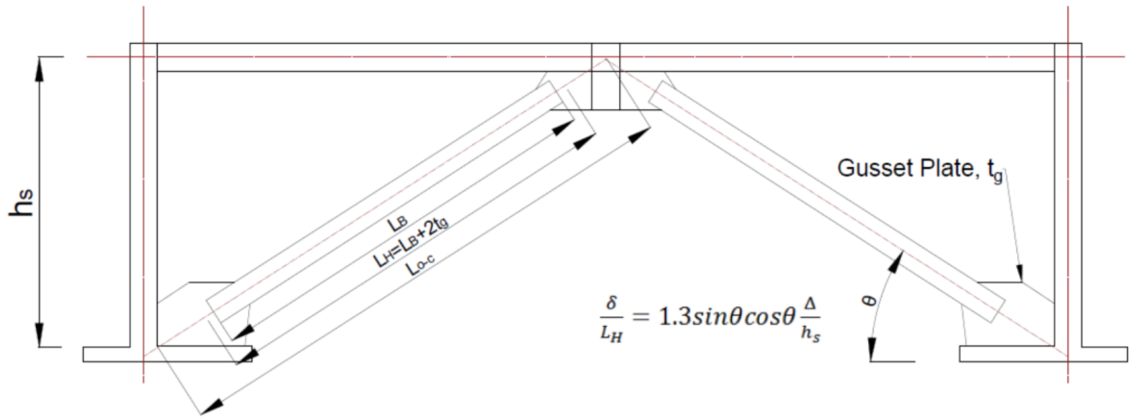

Fig. 3 - Schematic showing variables used to calculate storey drift based on brace axial deformations in a typical CBF.

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 in previous similar studies [1, 4, 10], due to their computational advantage over second-order elements, as well as their suitability in plasticity applications when there is a possibility of strain localisation [19]. The element sizes were determined based on a mesh sensitivity analysis. 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. To create time efficient FE analysis models, symmetry was utilized to model one-half of the geometry as shown in Fig. 4. This was considered acceptable since buckling is not expected under tension-only loading.

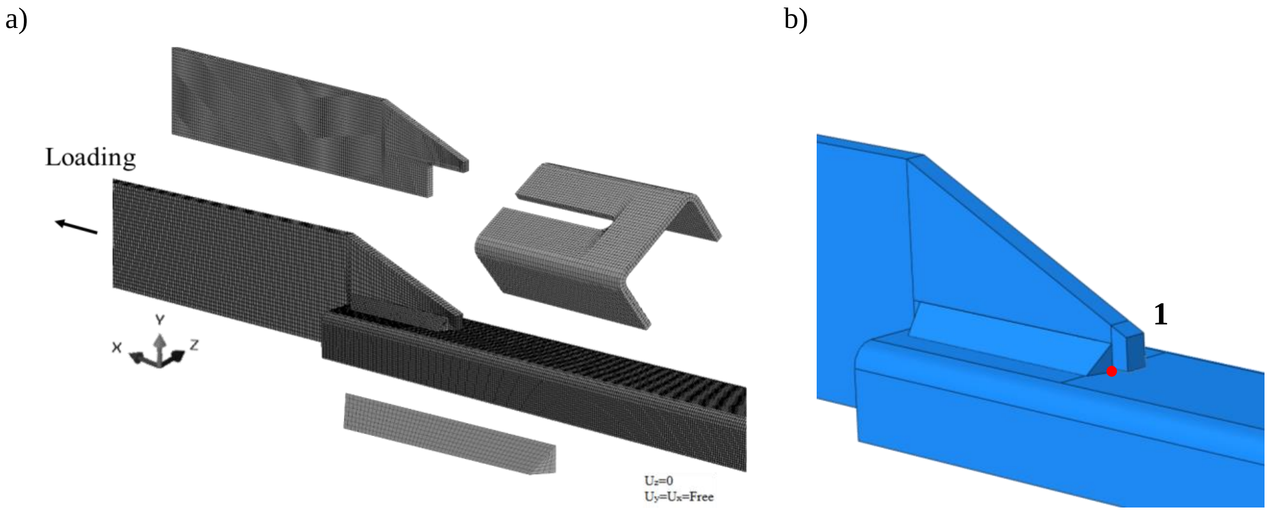

Fig. 4 – a) FE model showing model elements, mesh, boundary conditions and b) location 1 on the tube where axial strains were evaluated

3. Parametric Study Results

This section is divided into three main subsections to show the individual influence of the HSS parameters, the weld properties and the gusset plate dimensions on the performance of SHG connections under monotonic tension loading. A snapshot of prior FE analyses showing the difference in stress concentration between the conventional and SHG connection is displayed in Fig. 5. As shown, the SHG connection allows inelastic demands to develop along the tube and away from the connection region, compared to the conventional connection that concentrates inelastic demand in the net section region of the HSS brace.

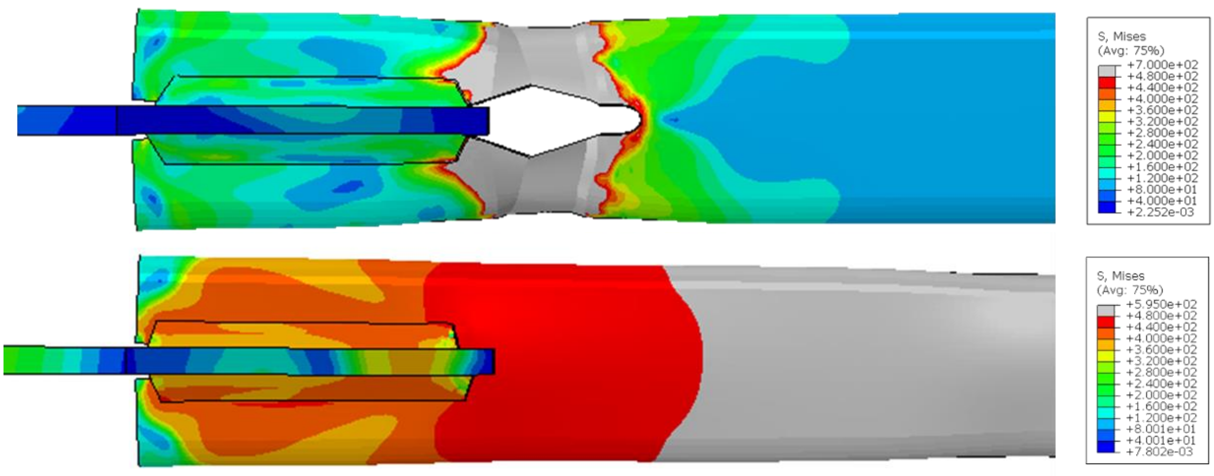

Fig. 5 – Snapshot of the connection region from the FE analysis of: Conventional connection (Top) and SHG connection (Bottom).

3.1 Influence of HSS Parameters (Part 1)

SHG connection demonstrates a PEEQ response of a steady increase until reaching a plateau, since the plastic strains concentrate at the brace mid-length, away from the connection, unlike the conventional connection where strains keep increasing until failure occurs in the connection region.

Values of the parameters varied are given in Table 1. The effect of varying the HSS size while keeping the same HSS wall thickness was first investigated. The local PEEQ-displacement response at location 1 on the HSS brace (Fig. 4b) in front of the weld was considered and is presented in Fig. 6. Although larger HSS sizes have longer welds lengths L_w, and overlap lengths L_{wg}, they exhibit larger concentration of plastic strains at the connections. At 16 mm of wall thickness, the PEEQ value at maximum displacement for the HSS 305 is more than 25% of the plastic strains exhibited by the smallest section of HSS 152. The cross sections with a thickness of 13 mm have shown similar behaviour. This behaviour is interpreted to have occurred as a result of keeping the gusset plate thickness t_g and weld size D_w constant, which attracted plastic strains to the stiffer HSS that has a larger gross sectional area A_g.

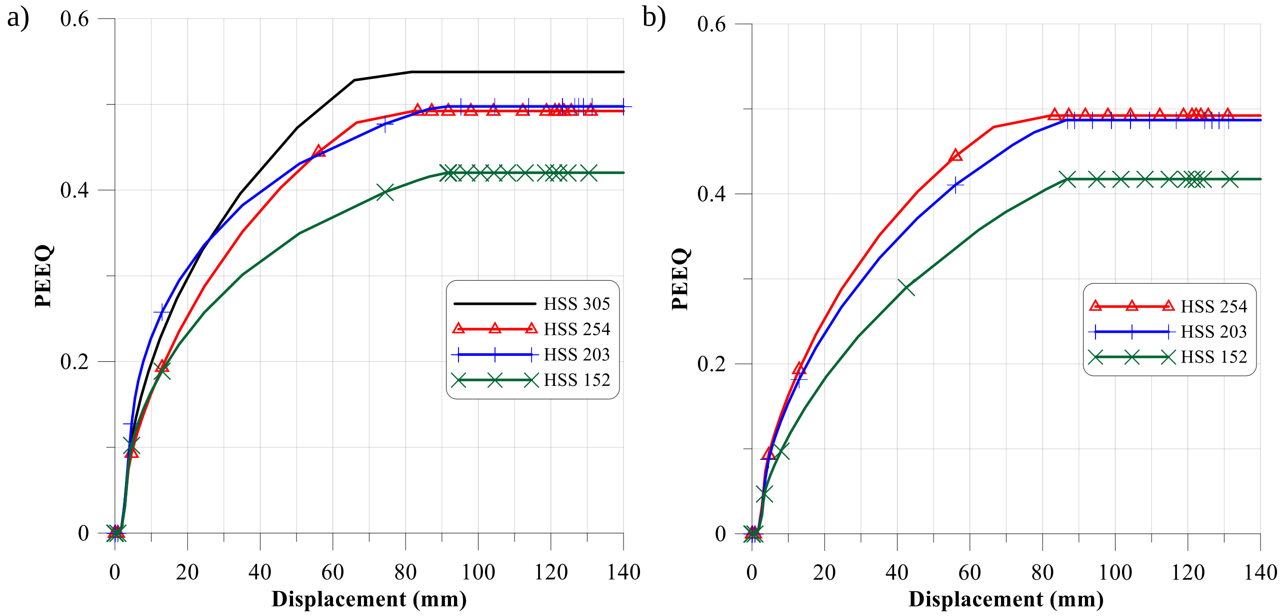

Fig. 6 – PEEQ vs. Displacement for models with different HSS Sizes for a) t = 16mm, and b) t = 13mm.

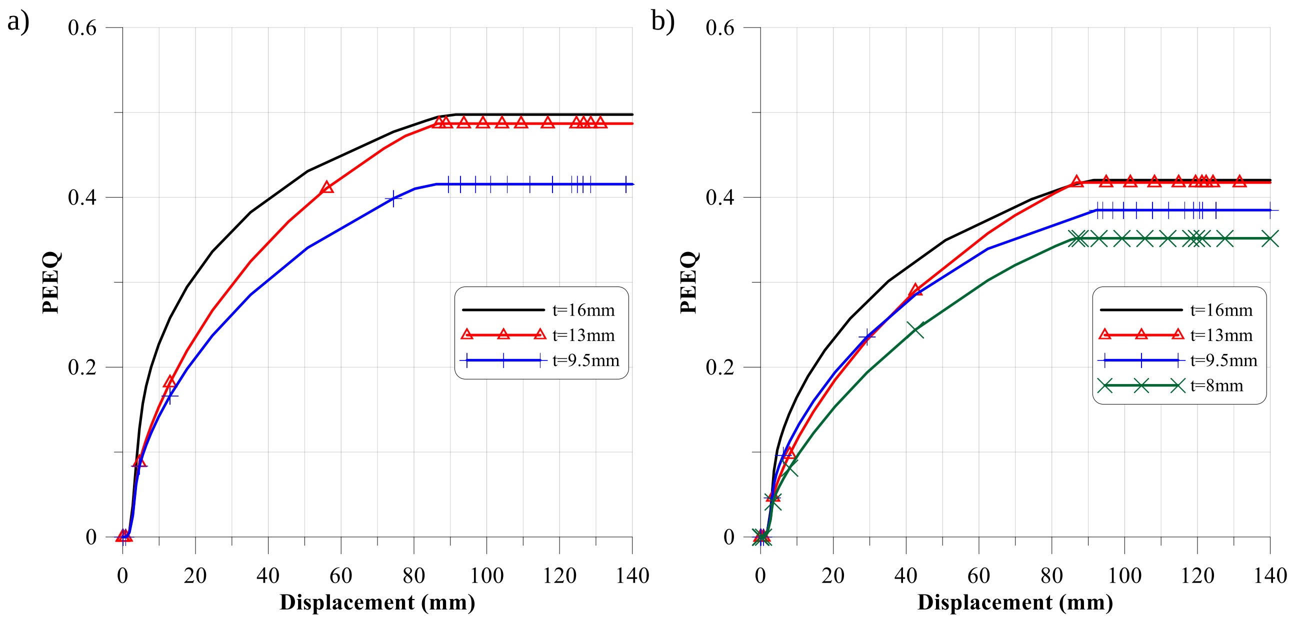

Fig. 7 – PEEQ vs. Displacement for models with different HSS thicknesses of a) HSS 203, and b) HSS 152.

The effect of varying the wall thickness of the same HSS size can be observed in Fig. 7. While keeping same weld length L_w, gusset plate width W_g, and weld overlap length L_{wg} for each examined HSS size, decreasing wall thickness of the HSS has shown improvement in the behaviour of the SHG connection as a result of the lower PEEQ concentration at the connection region. Inelastic demands at the connection (Fig. 4b) were increased by almost 20% while increasing the thickness from 9.5 mm to 16 mm for HSS 203 and from 8mm to 16mm for HSS 152. In all cases, the PEEQ values for the examined cases were kept well below 60% plastic strain, meaning that no yielding or fracture is expected to take place in the connection region at the tested displacement of 140 mm (13.5% storey drift ratio). The findings of this investigation suggest that more inelastic demands concentrate at the connection region of the SHG connections with larger size or thicker HSS, and hence, connection stiffness shall be improved in the form of increased weld overlap length (L_{wg}).

3.2 Influence of Weld Parameters (Part 2)

In Part 2 of the parametric study the influence of weld size and length were investigated by varying the weld length (L_w) and the weld size (D_w) within practical limits, while preventing any other tensile failures such as block shear failure in the tube and gusset plate, and weld fracture. To independently investigate the effect of the weld properties on SHG performance, three models of HSS 254x254x13 were examined while keeping the gusset plate dimensions, and the weld overlap length fixed.

Fig. 8 shows the PEEQ-Displacement curve for models with different weld parameters and overlap lengths at location 1 in front of the weld termination point (Fig. 4b). Increasing the weld length L_w from 390 mm to 620 mm, while decreasing the weld size D_w from 25 mm to 19 mm, has shown a slight reduction of the PEEQ concentration at the connection region. This indicates that a smaller weld size and longer welds should be favoured in practice, as they require fewer passes, consequently leading 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. A non-linear function describing the shear lag effects on conventional HSS slotted connections has been developed in previous studies [10, 13] and was subsequently included in the CSA S16 Standard. These studies showed that the shear lag effects in HSS connections eventually vanish when providing sufficiently long welds.

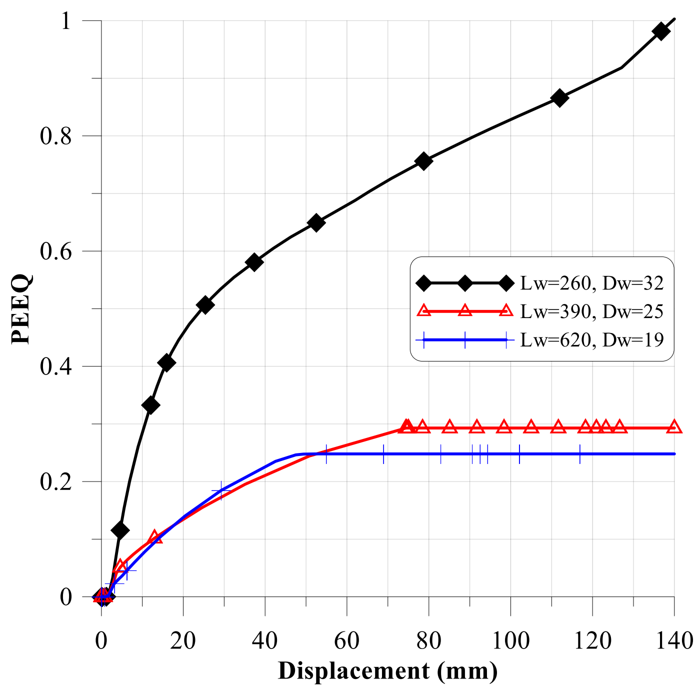

Fig. 8 – PEEQ vs. Displacement for models with different weld parameters.

Contrarily, utilizing shorter welds of larger size (D_w) has revealed detrimental effects on the performance of SHG connections. It can be observed from Fig. 8 that the model with the short and large size weld (L_w = 260 mm, D_w = 32 mm) develops significantly higher inelastic demands at the connection region. Where the other models reach a PEEQ plateau at almost 60 mm of displacement (storey drift ratio = 6%), the model with the short weld length kept increasing, surpassing the PEEQ fracture limit of 0.8 [5] at only 90 mm of axial displacement (storey drift ratio = 9%).

Fig. 9 shows the variation of inelastic demands along the length of the HSS member for models with different weld parameters. The extreme cases of a long and small size weld, 620 mm length and 19 mm size, versus a short weld, 260 mm length and 32 mm size, were examined. The cross-section positions (A – I) along the HSS member, as denoted in Fig. 8, were chosen for evaluation for both cases. The bar and whisker graph shows the maximum, minimum, and average PEEQ values, as well as how far the values are dispersed from the mean at these cross-section locations. It is worth noting that the model with a short and large size weld Fig. 9a) has reached the highest PEEQ value of 1.0 at the connection region (Point D), whereas the long and small size weld model (Fig. 9b) has achieved the same PEEQ value at the mid-length of the HSS brace (Point I). The variability within each cross-section is displayed through the box length. The short weld model has displayed high variability of PEEQ values, especially at the connection region, mainly due to the presence of shear lag effects. For example, point D experienced a maximum PEEQ of 1.0, minimum of 0.66 and mean of 0.85. The model with a longer weld has displayed a smoother PEEQ trend through the HSS length, and the least variability within each cross-section, which illustrates the diminished shear lag effects and the smoother load transfer mechanism between elements of SHG HSS connection.

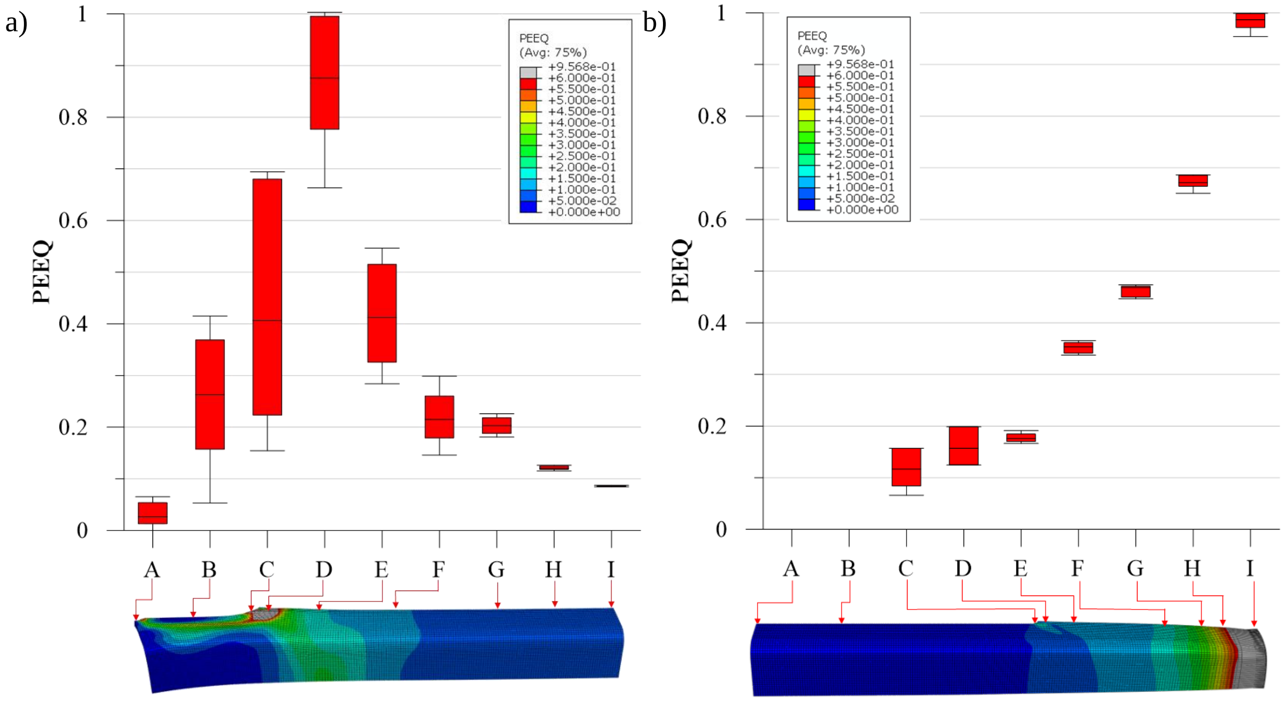

Fig. 9 – Variation of inelastic demands along HSS length for models with:
a) L_w = 260 mm - D_w = 32 mm, and b) L_w = 620 mm - D_w = 19 mm.

3.3 Influence of Gusset Plate Parameters (Part 3)

In this third part of the study the effect of the gusset plate thickness on the performance of the SHG connection was examined through modelling five different thicknesses of the gusset plate, from 19 mm to 32 mm, matching the common plate thicknesses found in North American practice. To independently investigate the effect of the gusset plate thickness on the SHG performance, five models of HSS 254x254x13 were examined while keeping the weld parameters, the gusset plate width and the weld overlap length unchanged.

The concentration of inelastic strains in the HSS in front of the weld tip (Fig. 4b) for various gusset plate thicknesses is presented in Fig. 10. It can be observed that the PEEQ value at the connection region has increased by 42% with increasing plate thickness from 19 mm to 32 mm. Also, two plate thicknesses (29 mm & 32 mm) have pushed the HSS to surpass the 0.6 PEEQ value at 70 mm of displacement (storey drift ratio = 7%), signaling possible yielding at the connection location. The thicker gusset plates being stiffer and hence attracting more inelastic demands away from the connection region, create wider slots in the HSS tube. This causes two major drawbacks: 1) less net area of HSS creating a greater possibility of net-section rupture, and 2) a wider slot means that a larger tension force needs to be transmitted to the gusset plate through the welds directly in front of the slot (Fig. 10b). Thus, a longer weld overlap length L_{wg} would be required to transfer that force smoothly to the gusset plate through the welds, while preventing longitudinal shear or tensile failure in the HSS. Hence, the ratio of the length of weld overlap to the thickness of the gusset (L_{wg}/t_g) is likely a key parameter controlling the response of SHG connections.

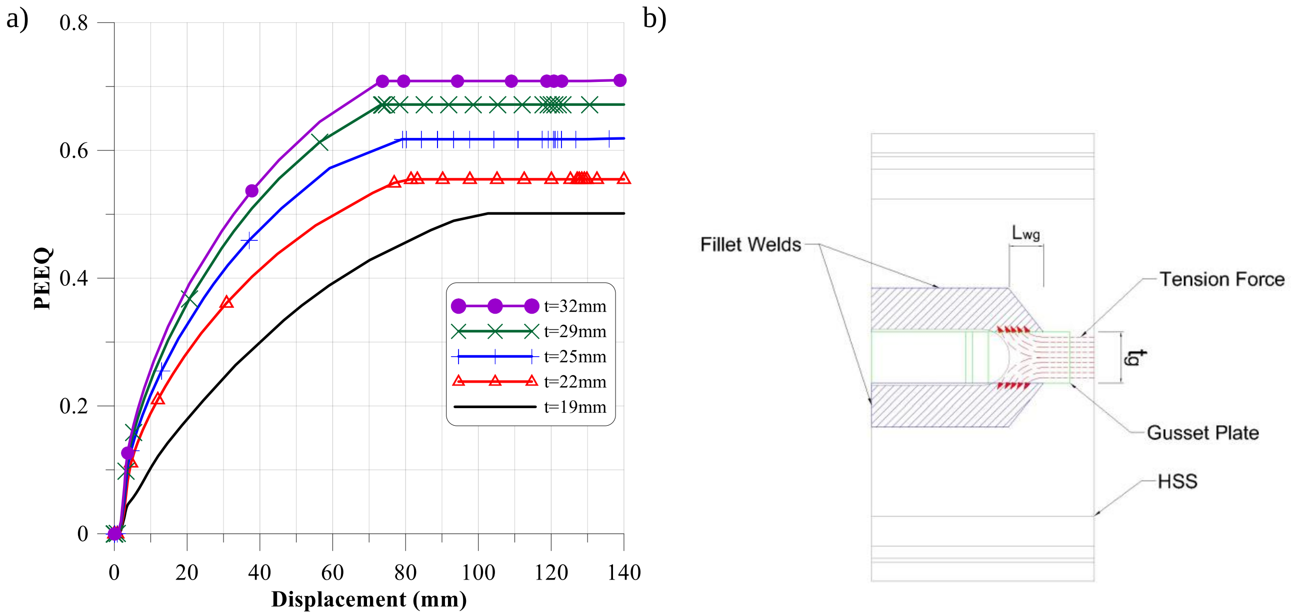

Fig. 10 – a) PEEQ vs. Displacement for models with different gusset plate thicknesses, and b) Idealised sketch of the force distribution that occurs from the HSS material in front of the tube slot to the fillet welds.

4. Conclusions

This parametric study has provided useful insight into the parameters affecting the response of Slotted-Hidden-Gap (SHG) HSS brace connections. The results of the numerical modelling have shown that the HSS size and thickness, the weld size and length and the gusset plate thickness contribute significantly to the performance of the SHG connection. Enhancing connection stiffness by increasing weld overlap length (L_{wg}) should be considered while designing SHG connections with larger HSS sizes and thicknesses because the larger brace sections attract more inelastic demands to the connection region. Smaller size longer welds showed promising results and can be utilized in a SHG connection due to the lower shear lag effects, as well as the maximized effective length of weld. Also, shorter and larger size welds can hinder the performance of SHG connections and cause premature fracture in the connection region. Whenever design allows, thinner gusset plates are favoured because they create narrower slot in the HSS and thus transfer loads more uniformly from the gusset plate to the HSS through the fillet welds. Alternatively, weld overlap length should be increased with the specification of thicker gusset plates.

5. Future Work

This numerical parametric study was limited to a few geometric aspects of SHG connections; more parameters are to be investigated in the future, including different material grades and various geometries of the connection and its components. A laboratory testing program is also planned, which will include additional SHG HSS configurations that have not previously been tested. The results of the laboratory study will be used in further calibration of the FE models. Design recommendations will ultimately be developed and verified through the evaluation of reversed-cyclic force / deformation loading on SHG HSS connections.

6. Acknowledgements

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