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An Experimental and Numerical Study of Square and Rectangular Slotted HSS Connections

by

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Research in partial fulfillment of the requirements for the
degree of

Master of Applied Science

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ABSTRACT

Experimental and numerical studies have been carried out on slotted connections for both rectangular (RHS) and square (SHS) structural hollow sections with no welding at the end of the slot opening. Slotted connections with different weld length ratio, slot orientation, gusset plate thickness and opening length were investigated.

Provisions to account for the shear lag effect on slotted RHS or SHS connections are found to be overly conservative in a number of design standards including CSA-S16.1-01 and AISC-LRFD-2000 Design Specification for Steel Hollow Structural Sections. Shear lag has been found to have no effect on the tensile strength of a hollow section for a weld length to distance between welds ratio as low as unity. The orientation of the slot opening, the slot opening length and the gusset plate thickness only have a minor effect on the strength of the slotted connections.

Based on the studies, guidelines on designing an economical full-strength slotted HSS connection for CSA-S16.1-01 without end welding are recommended. Proposed improvements to provisions in CSA-S16.1 and AISC design standards have also been put forward.

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LIST OF SYMBOLS

a	—	width of the tubular section on the slot side.
A	—	current cross-section area.
A_0	—	original cross-section area of a tension coupon.
A_a	—	actual cross-section area during the test.
A_{cn}	—	area of connected leg.
A_e	—	effective area.
A_f	—	final cross-section area at fracture.
A_g	—	gross area of the tubular section.
$A_{gCorner}$	—	gross area of the corner of HSS.
A_{gFlat}	—	gross area of the flat portion of HSS.
A_{max}	—	product of the corner dimensions at the necking region.
A_{min}	—	product of the mid-point dimensions at the necking region.
A_n	—	net section area.
A_{n1}	—	net area when elements are connected by transverse welds.
A_{n2}	—	net area when elements are connected by longitudinal welds along two parallel edges.
A_{n3}	—	net area when elements are connected by a single longitudinal weld.
$A_{nCorner}$	—	net section area of the corner segment of HSS.
A_{ne}	—	effective net area.
A_{nFlat}	—	net section area of the flat segment of HSS.

A_{uc}	—	area of unconnected (outstanding) leg.
a/b	—	aspect ratio of HSS.
b	—	width of the tubular section at the side without slot.
b_{avg}	—	average of the corner and mid-point widths.
b_c	—	width of the connected leg.
b_{cor}	—	width of corner.
b_{mid}	—	width of mid-point.
c	—	outside circumference of the HSS.
d	—	width of the outstanding leg.
E	—	elastic modulus of steel.
F	—	load.
F_u	—	ultimate strength.
$F_{uCorner}$	—	ultimate strength of the corner of HSS.
F_{uFlat}	—	ultimate strength of the flat portion of HSS.
F_u^*	—	adjusted ultimate tensile strength.
F_y	—	yield strength.
G	—	length of the slot opening.
GS	—	straight segment length of the slot opening.
GW	—	width of slot opening.
HSS	—	hollow structural section.
L	—	length of longitudinal welds.
L_a	—	actual length of specimen during the test.
L_o	—	original length of specimen.

L/w	—	weld length ratio.
P	—	actual load.
P_U, P_u	—	ultimate load capacity.
P_{u_anal}	—	peak load from the numerical analysis.
P_{u_calc}	—	calculated net section ultimate load without any reduction.
P_{uTest}	—	peak test load.
r	—	effective eccentricity.
RL	—	HSS 127 x 51, slot on the long side.
RS	—	HSS 127 x 51, slot on the short side.
SM	—	HSS 89 x 89.
t'	—	thickness of the tube wall.
t	—	thickness of the gusset plate.
t_{avg}	—	average of the corner and mid-point thicknesses.
t_c	—	idealized uniform thickness.
t_{cor}	—	thickness of corner.
t_{max}	—	maximum thickness at the corner.
t_{mid}	—	thickness of mid-point.
T_r	—	factored resistance of the tension member.
U	—	shear lag reduction coefficient.
U_F	—	gross section yield factor.
U_F^*	—	modified gross section yield factor.
U_g	—	gross section efficiency.
U_g^*	—	adjusted gross section efficiency.

U_n	—	net section efficiency.
U_n^*	—	adjusted net section efficiency.
U_{n_anal}	—	net section efficiency from numerical analysis.
U_{n_test}	—	measured net section efficiency.
U_{pw}	—	proposed efficiency factor based on the net section eccentricity.
U_{px}	—	proposed efficiency factor based on the weld length ratio.
U_{rect}	—	net section efficiency of the rectangular HSS.
U_{square}	—	net section efficiency of the square HSS.
v	—	poison's ratio.
w	—	weld distance.
w_a	—	actual weld distance.
w_c	—	straight centerline distance between welds.
w_n	—	nominal distance between welds.
WP	—	actual width of the gusset plate.
$\bar{x}$	—	perpendicular distance from the weld to the centroid of the cross sectional area that is tributary to the weld.
$\bar{x}^*$	—	modified perpendicular distance from the weld to the centroid of the cross sectional area that is tributary to the weld.
β	—	factor which takes into account the Munse shear lag factor as well as the effect of the relative width of the connected leg.

ϵ_e	—	engineering strain.
ϵ^e	—	elastic strain.
ϵ_{eq}^p	—	equivalent plastic strain.
ϵ_{eqf}^p	—	equivalent plastic strain at fracture.
ϵ_f^p	—	true plastic strain at fracture.
ϵ_{ij}^p	—	plastic strain tensor.
ϵ^p	—	plastic strain.
ϵ_t	—	true strain.
σ^e	—	engineering stress
σ^t	—	true stress.
σ_{von}	—	von Mises stress.
σ_{xx}	—	principal tensile stress in the loading direction.
σ_{yy}	—	principal tensile stress in the transverse direction.
ϕ	—	resistance factor.

CHAPTER 1 INTRODUCTION

Hollow structural sections (HSS) are commonly used in engineering structures, especially as welded tension and compression members in bracing and trusses. For a tubular tension member, there are two ways to make the end connection. An inexpensive and easy way is to slot the tube longitudinally and insert a gusset plate. The gusset plate is then welded to the tube by longitudinal fillet welds. This arrangement is shown in Figure 1.1. In this case, the net section may not be fully effective in carrying the load because of the non-uniform stress distribution at the connection due to shear lag. The effect of shear lag is predominantly influenced by the ratio of the weld length (L) to either the circumferential distance (w) between the longitudinal welds or the net section area eccentricity ($\bar{x}$). Figure 1.2 shows the graphical representation of the weld length, net section area eccentricity and the distance between welds (w). The effect of shear lag is also affected by several other factors, such as the thickness of gusset plate, the length of slot opening and the slot orientation. Another way to make the connection is to slot the gusset plate instead of the tube. However, the former is a more convenient arrangement preferred by fabricators. For ease of fabrication, welding is sometimes not provided at the end of the slot. As such, the net cross-section area for a slotted tubular member is thus smaller than its gross cross-section area.

Both Canadian Standard CSA-S16.1-01 (2001) and AISC (2000) Design Specification for Steel Hollow Structural Sections have provisions to account for the effect of shear lag and the reduction in the cross-section area due to the material removed to form the slot. The two limit states for a tension member in the design standards are gross

section yielding and net section fracture. Thus, in order to utilize the full strength of the tension member, it is necessary to have a right slotted connection detail so that the capacity of the tension member is governed by gross section yielding. In other words, the net section fracture strength has to be higher than the load required to cause gross section yielding.

A review of the literature indicates that only a few studies have been carried out on the slotted connection of a tubular tension member. Results from these limited studies have suggested that provisions for shear lag in both CSA-S16.1-01 and AISC (2000) are overly conservative for a slotted tubular connection. Thus, it is felt that a more thorough study of this subject will expand the existing knowledge on slotted connection and eventually lead to the adoption of a more efficient and economical design provisions for a slotted HSS connection.

1.1 Objective of the Thesis

The objective of this study is to investigate various slotted connection details for square and rectangular HSS shapes that achieve the full strength of the member allowed in the design without end welding. Achieving the full strength implies that the tension strength of the member is governed by the gross section yielding rather than the net section fracture. This study will investigate the connection strength and the effect of shear lag for different combinations of weld length, slot orientation and slot opening size. Experimental and finite element analyses results from this study will be used in developing guidelines for designing an economical full-strength slotted HSS connection without end welding, and to put forward recommendations to improve the shear lag provisions for

slotted HSS connections in design standards. However, no detailed parametric finite element analysis is conducted as it is outside the scope of this thesis.

1.2 Methodology Used in the Research

A total of twenty six slotted HSS tension specimens with thirteen different connection configurations were tested. These configurations consist of different combinations of weld length, gusset plate thickness, size of slot opening and slot orientation that enable the influence of these parameters on shear lag to be studied experimentally. Two different HSS shapes were used. One of the shapes is a square HSS (89 x 89 x 4.8) and the other is a rectangular HSS (127 x 51 x 4.8). As shown in Figure 1.3, there are two slotting options for a rectangular HSS. Thus, together with the square HSS specimen, three slot orientations and three net section area eccentricities were available for consideration in the combinations. Three different weld lengths, slot opening lengths and gusset plate thicknesses were also investigated in the test program.

Tension coupon tests were carried out to obtain material properties that are used in assessing the performance of the test specimen and to obtain a complete stress versus strain relationship of the material required in the finite element modeling. Net section fracture of the connection involves large localized deformation and strain. Thus, the material property input that can represent the behavior of steel up to fracture is essential in carrying out the finite element analysis.

The performance of each specimen is calculated using the actual material strength obtained from the coupon tests. The effect on shear lag due to different weld length, gusset plate thickness, size of slot opening and slot orientation was analyzed and studied

using the test results. Together with results from other researchers, test results were compared against net section efficiencies calculated from provisions for shear lag in design standards and recommendations were proposed to improve on these provisions. Based on the study, guidelines on designing a full-strength slotted square and rectangular HSS in tension were developed.

Finite element analyses of test specimens were carried out with ABAQUS using the material stress versus strain relationship obtained from the coupon tests. Results of the finite element analyses were used to help clarify findings from the experimental study and to provide greater insights into the behavior of the connection.

1.3 Organization of the Thesis

Chapter 2 presents a literature review on the effect of shear lag in tension connections, with a greater emphasis on welded connections. Provisions to account for shear lag in design standards for welded connection are presented.

In Chapter 3, the experimental program including the tension coupon test is presented. This chapter describes the testing procedure and steps involved in the data collection and calculations of the connection geometry.

Test results are presented in Chapter 4. Results from the test program are discussed and analyzed. Effect of weld length, gusset plate thickness, slot opening size and slot orientation on the net section efficiency are discussed. Comparisons of test results against provisions by design standards are made. Recommendations to improve these provisions and guidelines in order to achieve full strength of the member in design are presented.

In Chapter 5, finite element analyses of the test specimens are presented and discussed. The finite element model and material properties used in the analyses are described in this chapter. A further discussion on the findings of chapter 4 and on the behavior of the connection is performed using results of numerical analyses.

Chapter 6 consists of summary of the thesis along with conclusions and recommendations.

Additional test data are presented in the appendices.

(a) Slotted HSS member and gusset plate

(b) Assembly of HSS member and gusset plate

Figure 1.1 Slotted structural hollow section welded to a gusset plate.

Figure 1.2 Weld length, net section area eccentricity and distance between welds.

(a) Short side

(b) Long side

Figure 1.3 Slot orientation of rectangular HSS member.

CHAPTER 2 LITERATURE REVIEW

Welded tension members are used extensively in steel construction as bracings in trusses. In most situations, however, it is not practical to weld across the member entirely. For a tubular tension member, an inexpensive and easy way of making the end connection is to slot the tube longitudinally and insert it with a gusset plate. The gusset plate is then welded to the tube by longitudinal fillet weld. An alternate arrangement is to slot the gusset plate instead of the tube. However, slotting the hollow structural section (HSS) member is a more convenient arrangement preferred by fabricators. Also for ease of fabrication, sometimes there is no welding at the end of the slot. Therefore, the net cross-section area for a slotted tubular member is smaller than its gross cross-section area. Furthermore, the reduction in the net cross-section area is compounded by the loss in the net section efficiency due to shear lag.

2.1 Shear Lag

Shear lag has a significant effect on the behavior of many tension members. When only a portion of a tension member is welded or bolted to the connecting element, the net section area used in calculating the member strength must be reduced because of shear lag.

Shear lag is a phenomenon associated with the non-uniform stress distribution at the location adjacent to a connection when all elements of the cross-section of a tension member are not connected directly. Consequently, the full net cross-section area is not effective in carrying the tension load and the member strength is correspondingly reduced. In the design of a tension member, the shear lag effect is accounted for by using a shear lag

factor. This factor takes into account the eccentricity of the connected parts relative to the line of load transfer as well as the connection length.

One example of a situation where shear lag occurs is when only one leg of an angle is bolted to a gusset plate. The consequence of this partial connection is that the connected element becomes overloaded and the unconnected part is not fully stressed. However by lengthening the connection, there will be a more gradual load transfer and all elements will be more evenly loaded. It was suggested by Munse and Chesson (1963) that the effect of shear lag should be considered by using a reduced or effective net area. Since shear lag affects both bolted and welded connections, the effective net area concept is applied to both of these connections. Figure 2.1 shows an example of the effect of shear lag in a welded connection where the stress in the plate immediate after the end of the weld is not uniform. There is a higher stress concentration at the side of the plate close to the weld.

Munse and Chesson (1963) found that tension members did not always develop an average stress across the net section that was equal to the tensile strength. The reduction in strength can be expressed as the net section efficiency. Their work has demonstrated that the following factors affect the net section efficiency.

- 1) The ductility of the steel.

A higher ductility in steel allows for a greater stress redistribution, which reduces the stress concentration and the effect of shear lag.

- 2) The geometry of the cross section.

A convenient way to measure the effect of the cross-sectional area distribution is to use the distance from the centroid of the cross-section to the fastener

plane or a gusset plate. The net section efficiency reduces as this distance increases. Thus, the efficiency of a member can be increased by reducing the area of the unconnected components relative to the area of the whole member.

3) The length of the connection.

A longer connection reduces the stress concentration at the connected part, which allows for a greater utilization of other unconnected elements.

2.2 Provisions for Shear Lag in Welded Tension Members in Design Standards

For the slotted tubular tension member welded to a gusset plate, there are two limit states that need to be considered in the design.

- 1) The overall yielding of the member (gross section yielding).
- 2) The fracture of the member at the net section of the connection where the cross-section area is smaller than the gross section area (net section fracture).

The net section fracture strength is influenced by shear lag and the amount of material that has been removed.

Both Canadian Standard CSA-S16.1-01 (2001) and American Specification AISC-LRFD-1999 (1999) have provisions to account for the effect of shear lag. For a slotted tubular tension member, CSA-S16.1-01 (2001) allows the net section efficiency up to unity to be used. However, AISC-LRFD-1999 (1999) limits the efficiency to 0.9.

2.2.1 CSA-S16.1-01

In the Canadian Standard CAN/CSA-S16.1-01 (2001) on Limit State Design of Steel Structures, the factored resistance of the tension member (T_r) is taken as the least of

- 1) yielding in the gross cross-sectional area,

$$T_r = \phi \cdot A_g F_y, \quad (2.1)$$

- 2) fracture of the net area,

$$T_r = 0.85\phi \cdot A_n F_u, \quad (2.2)$$

- 3) fracture of the effective net area accounting for shear lag,

$$T_r = 0.85\phi \cdot F_u A_{ne} \quad (2.3)$$

where

F_y = the yield strength of the material,

F_u = the ultimate strength of the material,

A_g = the gross area of the member,

A_n = the net area,

A_{ne} = the effective net area reduced for shear lag, and

ϕ = the resistance factor taken as 0.90.

According to Clause 12.3.3.3 in CSA-S16.1-01, when the tension load is transmitted by welds, the effective net area is computed as

$$A_{ne} = A_{n1} + A_{n2} + A_{n3} \quad (2.4)$$

where A_{n1} , A_{n2} and A_{n3} are defined as follows:

- a) When elements are connected by transverse welds,

$$A_{n1} = wt, \quad (2.5)$$

where

w = the plate element width,

t = the thickness of the element.

- b) When elements are connected by longitudinal welds along two parallel edges,

i) for $L \geq 2w$, $A_{n2} = 1.00 wt$, (2.6)

ii) for $2w > L \geq w$, $A_{n2} = 0.50 wt + 0.25Lt$, (2.7)

iii) for $w > L$, $A_{n2} = 0.75 Lt$, (2.8)

where

L = the average length of welds on the two edges, and

w = the plate width (distance between welds).

- c) When elements are connected by a single longitudinal weld,

i) for $L \geq w$,

$$A_{n3} = \left(1 - \frac{\bar{x}}{L}\right) wt, \quad (2.9)$$

ii) for $w > L$,

$$A_{n3} = 0.50Lt, \quad (2.10)$$

where

L = the length of the weld in the direction of the loading, and

$\bar{x}$ = the eccentricity of the weld with respect to the centroid of the connected element.

2.2.2 AISC-LRFD-1999

In AISC-LRFD-1999 (1999) on Load and Resistance Factor Design Specification for Structural Steel Building, when a tension load is transmitted by welds through some but not all of the cross-sectional elements of the member, the effective net area (A_e) is computed depending on how the member is connected.

- a) When the tension load is transmitted only by longitudinal welds to other than a plate member or by longitudinal welds in combination with transverse welds,

$$A_e = A_g U, \quad (2.11)$$

where

A_g = the gross area of member.

U = the reduction coefficient calculated by

$$U = 1 - \frac{\bar{x}}{L} \leq 0.9, \quad (2.12)$$

where

$\bar{x}$ = the connection eccentricity, and

L = the length of the connection in the direction of the loading.

- b) When the tension is transmitted only by a transverse weld,

$$A_e = AU, \quad (2.13)$$

where

U = 1.0, and

A = the area of directly connected elements.

- c) When the tension is transmitted to a plate only by longitudinal welds along both edges at the end of the plate,

$$A_e = A_g U, \quad (2.14)$$

where

A_g = the gross cross-sectional area,

for $L \geq 2w$, $U = 1.00$,

for $2w > L \geq 1.5w$, $U = 0.87$,

for $1.5w > L \geq w$, $U = 0.75$,

where

L = the length of weld, and

w = the plate width (distance between welds).

2.2.3 AISC Design Specification for Steel Hollow Structural Sections

A more detailed AISC specification for hollow structural sections is given in AISC-LFRD Design Specification for Steel Hollow Structural Section (2000). In AISC (2000), the effective net area (A_e) of tension members is given by

$$A_e = AU \quad (2.15)$$

The parameters A and U vary with the type of connection.

- a) For a welded connection that is continuous around the perimeter,

$$A = A_g, \quad (2.16)$$

where

A_g = the gross area, and

$U = 1$.

- b) For connections with concentric gusset plates and slotted HSS,

$$A = A_n, \text{ and} \quad (2.17)$$

$$U = 1 - \frac{\bar{x}}{L} \leq 0.9 \quad (2.18)$$

where

A_n = the net area at the end of the gusset plate, which is the gross area minus the product of the thickness and total width of material that is removed to form the slots,

$\bar{x}$ = the perpendicular distance from the weld to the centroid of the cross-sectional area that is tributary to the weld, and

L = the length of the connection in the direction of the loading.

c) For connections with rectangular HSS and a pair of side gusset plates,

$$A = A_g,$$

where

A_g = the gross area, and U is as given by (2.18).

2.3 Research on Shear lag

There have been a number of studies carried out on shear lag in connections. Most of earlier studies were mainly on tension connections for angles, channels and plates.

2.3.1 Shear Lag on Bolted Connection

In a bolted connection, usually not all elements of the member are directly connected. For example, Figure 2.2 shows an angle that is connected only on one leg. Consequently, the outstanding leg is not fully utilized in the load transfer as a result of

shear lag. For this reason, the load carrying capacity of the member is correspondingly reduced.

Davis and Boomsliter (1934) conducted a series of tests on different configurations of L 76 x 76 x 7.9 (3 x 3 x 5/16) angles. Only one leg of the angle was connected to the gusset plate by rivets. The efficiency of the member was found to vary from 0.70 to 0.81, and the stress was very unevenly distributed over the cross-section of the angle. The efficiency was the lower for the specimens with the angle on only one side of the gusset plate.

Munse and Chesson (1963) examined the tensile behavior of various cross sections connected with bolts and rivets. The loss in the net section efficiency due to shear lag was found to be related to the ratio of the connection length (L) and eccentricity from the face of the gusset plate to the center of the gravity of the connected component ($\bar{x}$), as shown in Figure 2.3. The parameter, $\bar{x}/L$, was used to characterize the effectiveness of the cross-section area to transfer the force. Munse and Chesson found that a decrease in joint length increases the shear lag effect, and thus decreases the effectiveness of the fasteners. The configuration tested by Munse and Chesson is shown in Figure 2.4.

Munse and Chesson developed an empirical equation to calculate the net section efficiency of tension member by taking into account the joint length and the joint geometry.

The effective area,

$$A_e = A_n U \text{ and} \quad (2.19)$$

$$U = 1 - \frac{\bar{x}}{L}, \text{ the reduction coefficient,} \quad (2.20)$$

where

$$A_e = \text{the effective area,}$$

A_n = the net area,

$\bar{x}$ = the distance from the face of the fastener plates to the centroid of the area (connection eccentricity), and

L = the length of the connection in the direction of loading (distance from the first fastener to the last one).

Research on shear lag in bolted tension members were also carried out by Chakrabarti and Bjorhovde (1985), Hardash and Bjorhovde (1985), Madugula and Mohan (1988), Wu and Kulak (1993 and 1997), and Gupta et al. (2004).

2.3.2 Shear Lag on Welded Connection

The discussion about the research in shear lag on welded connections will be discussed separately for welded connections for an open section such as angle, channel and plate, and for welded connections for a closed section such as circular, square and rectangular tubes.

2.3.2.1 Shear Lag on Welded Connection for Open Sections

In addition to the bolted connection mentioned in Section 2.3.1, Davis and Boomsliiter (1934) also tested a number of welded connections for L 76 x 76 x 7.9 (3 x 3 x 5/16) angle. Similar to the riveted connection, the stress for the welded specimen was unevenly distributed over the cross-section of the angle and specimens with the angle on only one side of the gusset plate have the lowest efficiency.

Gibson and Wake (1942) conducted tests to investigate how the arrangement of welds affects the load carrying capacity of the angle. There were fifteen configurations considered in their test program. The size of angles in all cases was L 64 x 64 x 7.9 (2½ x 2½ x 5/16). The eccentricity normal to the plane of welds was found to be the major factor affecting the strength, and the stress in the angle was found to be unevenly distributed over its cross-section.

Easterling and Giroux (1993) conducted a series of tests to investigate the shear lag effect on the tension strength of weld connected channels, angles and plates. The maximum efficiency of the net section area was found to be greater than 0.9 for the plates and greater than 0.8 for the angles. For channels, the maximum efficiency was around 0.9. Based on the test results, the following modified Munse and Chesson equation with an upper limit on the reduction coefficient was proposed for most structural sections.

$$A_e = A_g U \quad \text{and} \quad (2.21)$$

$$U = 1 - \frac{\bar{x}}{L} \leq 0.9, \quad \text{the reduction coefficient,} \quad (2.22)$$

where

A_e = the effective area,

A_g = the gross area,

$\bar{x}$ = the connection eccentricity, and

L = the length of the longest weld.

Uzoegbo (1998) also conducted a series of tension tests on a single angle welded to the gusset plate at one leg. Fourteen specimens with different weld lengths at both sides of the connected leg were tested. At failure, the stress in the connected leg near the end of the weld was close to the ultimate tensile strength, but the stress in the outstanding leg was

predominantly below the yield stress. The location of failure varied depending on the length of the weld.

- 1) When both sides of the connected leg have the same weld length, the failure occurred at the heel of the connected leg.
- 2) When the weld length at each side of the connected leg differed, the failure occurred at the side with a shorter weld.

The ultimate capacity of an angle subject to tensile load was proposed to be given by

$$P_U = f_u A_{cn} + \beta f_y A_{uc}, \quad (2.23)$$

where

f_u = the ultimate strength,

f_y = the yield strength,

A_{cn} = the area of connected leg,

A_{uc} = the area of unconnected (outstanding) leg, and

β = a factor which takes into account the reduction proposed by Munse and Chesson for shear lag and the effect of the relative width of the connected leg.

The parameter β is given by

$$\beta = \left(1 - \frac{\bar{x}}{L}\right) \frac{b_c}{d}, \quad (2.24)$$

where

$$\frac{b_c}{d} \leq 1.1,$$

$\bar{x}$ = the connection eccentricity,

L = the length of the connection in the direction of loading,

b_c = the width of the connected leg, and

d = the width of the outstanding leg.

2.3.2.2 Shear Lag on Welded Connection for Close Sections

Tests on slotted tubular tension member welded with a gusset plate have been conducted by Korol (1996) on the square and rectangular HSS (HSS 127 x 51 x 6.4 and HSS 89 x 89 x 6.4) with no end welding, and by Cheng et al. (1998) mainly on round HSS (HSS 102 x 6.4, HSS 102 x 4.8, and HSS 219 x 8.0) with end welding. In the tests by Cheng et al., one of the specimens also has no end welding. Cheng et al. looked at specimens with the weld length (L) to the circumferential distance between the longitudinal welds (w) ratio around 1, and Korol mainly looked at specimens with the weld length ratio (L/w) less than or equal to 0.6. Other than the L/w ratio less than or equal to 0.6, one other ratio investigated by Korol was 1.0.

Korol (1996) found that expression (2.20) proposed by Munse and Chesson was not suitable for a slotted tubular tension member. The reduction factor obtained from Korol's tests for specimens was found to be slightly larger than that determined by (2.20). A modified Munse and Chesson reduction factor of

$$U = 1.0 - 0.4 \frac{\bar{x}}{L} \quad (2.25)$$

was found to give a better prediction of the connection efficiency. The tensile strength was found not to be significantly affected by shear lag when the L/w ratio was close to unity. Based on the study, a new net section efficiency expression was recommended.

$$\text{For } L/w > 1.2, \quad U = 1.0,$$

$$\begin{aligned}
 &\text{for } 1.0 < L/w \leq 1.2, & U = 0.9, \text{ and} \\
 &\text{for } 0.6 \leq L/w \leq 1.0, & U = 0.4 + 0.5 L/w.
 \end{aligned}
 \tag{2.26}$$

When the L/w ratio is less than 0.6, block shear tear-out was found to govern the failure.

For the rectangular HSS specimen with the slot located at the short side and the L/w ratio equal to 1.0, the net section efficiency was found to be 1.05. The capacity of the connection was found to be 5% higher than the product of the net cross-section area and tensile strength. But for some other configurations, the efficiency in a few cases was found to be below 1 at a weld length ratio of 1. Korol also found that the orientation of the slot (slot located on the long side or the short side, see Figure 1.3) only has a minor effect on the connection strength. The specimen with the slot in the short side has a slightly higher capacity than that at the long side.

Cheng et al. (1998) also found the same trend for a slotted round HSS tension member welded to gusset plates. When the L/w ratio was around 1.0, shear lag did not significantly affect the tensile strength of the tubular tension member. They recommended that no reduction in the net section strength due to shear lag is required as long as the weld length is at least 1.3 times the tube diameter.

Cheng et al. attributed the negligible effect from shear lag due to the biaxial stress at the connection because of the circumferential restraint provided by the gusset plate. This biaxial state of stress effectively counteracts the negative effect from shear lag. Their tests showed that fracture occurred at locations other than the slotted end when the ratio of L/w is around 1.0. On the other hand, the tension member may fracture at the slotted end if the weld is short or there is no end welding. When the failure occurred at the slotted end, the ductility of the connection was reduced considerably. For the specimen with no end

welding, the net section efficiency was greater than 1.

Studies by Korol and Cheng et al. have shown that the provisions for shear lag prescribed in CSA-S16.1-01 and AISC-LRFD-1999 appear to be overly conservative when applied to slotted tubular tension members. They found that slotted tubular tension member resistance was close to or exceeded the net section strength when a weld length is equal to the circumferential distance between the longitudinal welds ($L/w = 1.0$). However, both CSA-S16.1-01 and AISC-LRFD-1999 require the net section efficiency to be significantly reduced. In CSA-S16.1-01, the net section efficiency is limited to 75% when the L/w ratio is equal to 1.0.

Zhao and Hancock (1995) also conducted tests on square and rectangular hollow sections with and without end welding. Although the objective of their study is the weld and not the shear lag effect on the HSS sections, their results showed that end welding increases the load carrying capacity of the member by allowing greater plastic deformation at the connection before failure. On average, member capacities with end-return weld were about 9% to 12.5% higher than those without end-return weld.

More recently, Willibald et al. (2004) performed tests comprised of six welded connections of round hollow sections (HSS 168 x 4.8). Two of these specimens were fabricated by slotting gusset plate and four were fabricated by slotting the tube. Their study focused on the effect of end welding on slotted tube and the fabrication detail of either slotting the gusset plate or the tube. The L/w ratio varied from 0.66 to 0.88 in their tests. The connection length was found to have the largest effect on the connection capacity, and the fabrication detail has only little influence on the connection strength. In general, AISC-LRFD-1999 underestimated the strength by 20% and CSA-S16.1-01

underestimated by about 60%.

2.3.3 Finite Element Analyses on Slotted Tubular Tension Members

There have not been many numerical studies carried out for slotted tubular tension members. Among those that have been conducted were the finite element analyses performed by Girard et al. (1995), Cheng et al. (1998) and Willibald et al. (2004). So far, no thorough numerical study has been carried out on slotted square and rectangular HSS connections.

In the study by Girard et al. (1995), only square hollow sections were simulated and no experimental work was undertaken. However, finite element analyses by Girard et al. on square HSS were not able to capture the behavior of the HSS connection when compared to the tests by Korol (1996). The main reasons for the disagreement were due to an artificial displacement limit imposed by Girard et al. in their analyses and the material properties used were also overly simplified.

Cheng et al. (1998) carried out a numerical study on round HSS with the L/w ratio around 1.0. The numerical simulation using the critical equivalent strain as the failure limit was found to be able to predict the ultimate load and location of the fracture, but was unable to predict the deformation at fracture accurately. Nevertheless, the numerical analysis is able to provide a reasonable estimate of the connection ductility of the slotted tubular member. The study showed that the constraint provided by the gusset plate and the shape of the round HSS increases the effective stiffness of the tube at the slotted end, and thus increases the overall ductility and induces fracture away from the slotted end for some of the specimens.

Willibald et al. (2004) also conducted a numerical study on a round slotted HSS member welded to a gusset plate. The HSS member, gusset plate and weld of the connection were modeled using a solid element. Finite element analyses were carried out using ANSYS 5.7 (2000) with element kill option for two specimens with L/w ratios of 0.66 and 0.8 respectively. Their numerical analyses were able to give a good prediction of the peak load, which were within 2% of test results. However, converging problems were encountered close to the peak load because too many elements were killed in the analysis.

Figure 2.1 A plate connected with longitudinal welds.

Figure 2.2 An angle that is bolted only on one leg.

Figure 2.3 An example of the connection eccentricity for an angle section.

Figure 2.4 The configuration tested by Munse and Chesson (1963).

CHAPTER 3 TESTING PROGRAM

Korol (1996) found that there was little reduction in the net section efficiency on slotted connections of rectangular and square HSS members having a weld length to the weld distance (L/w_n) ratio of 1.0. However, most specimens tested by Korol have a weld length ratio less than 0.6.

In order to develop economical guidelines and recommendations to achieve the full strength of slotted HSS connections without end welding and to study the effect of shear lag, a series of tests were carried out on slotted connections of rectangular and square HSS member at L/w_n ratios around 1.0. The tests were conducted in the Civil Engineering Laboratory at Carleton University. Details of the specimens and testing program are described below. There are different weld distance measurements used in the discussion. The differences between various measurements used are described in the following sections.

Besides the L/w_n ratio, the effect of gusset plate thickness, width and length of the opening at the end of the gusset plate and slot orientation were investigated. All specimens were instrumented with strain gauges to measure the strain distribution and LVDTs linear variable differential transformer to record the deformation of the specimen.

3.1 Objective

The objective of the testing program is to investigate the shear lag effect on the net section efficiency of square and rectangular HSSs at L/w_n ratios around 0.75 to 1.25. Data

obtained from these tests will also be used in the parametric finite element analyses study that is outside the scope of this thesis. However, the influence of shear lag will be examined numerically through finite element analyses and presented in Chapter 5.

3.2 Test Matrix

A total of twenty six specimens consisting of six rectangular and twenty square specimens were fabricated. These specimens encompassed sixteen different connection configurations. The sixteen different connection configurations consisted of different combinations of weld length (in term of the L/w_n ratio), the gusset plate thickness, the width and length of the opening at the end of the gusset plate and the orientation of the slot.

In order to ensure that every specimen fails at the net section due to the shear lag, the following factors were considered in designing the test specimens.

- The width of the gusset plates was chosen to ensure that they would not fail.
- The gusset plates were connected to the HSS with a 8 mm E480xx fillet weld so that weld failure does not occur.

Different ways of presenting the distance between longitudinal welds are first described before continuing with the discussion of the test matrix. Three of the distances that can be used are listed below. These three weld distance measurements are shown in Figure 3.1.

- 1) The nominal distance w_n .

The nominal distance is the distance from the fillet weld face measured in a straight line along the center line of HSS wall,

$$w_n = (b + a - t' - GW). \quad (3.1)$$

- 2) The straight centerline distance w_c .

The straight centerline distance is the distance in a straight line along the centerline of the HSS wall from the edge of the slot,

$$w_c = (b + a - 2t' - GW). \quad (3.2)$$

- 3) The actual weld distance w_a .

The actual weld distance is the distance along the actual centerline of the HSS wall from the edge of the slot,

$$w_a = \frac{(c - \pi \cdot t')}{2} - GW. \quad (3.3)$$

Referring to Figures 3.2 and 3.3, b is the outside dimension of HSS on the slot side, a is the outside dimension of HSS on the non-slot side, t' is the wall thickness, GW is the slot width and c is the outside circumference of the HSS.

However, the corner of an actual HSS was found to be slightly thicker than the flat portion. In order to facilitate the calculation, the corner is idealized as having a uniform thickness as shown in Figure 3.4. The idealized uniform thickness (t_c) is given by

$$t_c = \frac{t_{\max} + t'}{2}, \quad (3.4)$$

where $t_{\max}$ is the maximum thickness at the corner. The weld distance (w) is thus taken as

$$w = \frac{c - \pi \cdot t_c}{2} - GW. \quad (3.5)$$

There is only a small difference between values calculated using (3.3) and (3.5).

The nominal distance (w_n) and the straight centerline distance (w_c) are about the same, with w_n being larger than w_c by the HSS wall thickness. The test matrix in this test program was designed using the ratio of L/w_n . However after the specimens have been

fabricated, it was decided that the weld distance (w) is a better measurement to characterize the weld distance, and it also provides a conservative assessment of the effect of weld length on shear lag. For this reason, the weld distance (w) is used in the discussion of test results. However, a practicing engineer will most likely use the straight centerline distance (w_c).

The hollow structural sections used in this test program consisted of ASTM-A500 Grade C HSS 89 x 89 x 4.8 and HSS 127 x 51 x 4.8, cold-formed non-stress relieved tubular sections. Even though the gusset plates were supposed to be CAN/CSA-G40.20/G40.21 grade 350W steel, the actual grade for some of the gusset plates may have been 300W. However, the exact grade of the gusset plate is not important. The study on the effect of L/w_n ratio, gusset plate thickness and opening at the end of the gusset plate was carried out using HSS 89 x 89, and the study on the effect of slot orientation was carried out using both HSS 127 x 51 and HSS 89 x 89.

Since extensive tests have been carried out by Korol (1996) to study the orientation of the slot, this test program will concentrate on the effect of other parameters. For this reason, there is a duplicate specimen for every configuration with HSS 89 x 89 and only one specimen for every configuration with HSS 127 x 51. The base configuration of the test specimen is 5 mm long straight segment of the opening (GS) and 16 mm thick gusset plate (t). Various terms used in describing the test specimen geometry are shown in Figures 3.2 and 3.3. The test matrix is listed in Table 3.1. Parameters that are being considered for the test program are described below.

- 1) L/w_n ratio.

For a slotted HSS member welded to a gusset plate, the most important parameter that influences shear lag is the weld length. Since tests by Korol (1996) were mainly on specimens with the L/w_n ratio below 0.6, three L/w_n ratios of 0.75, 1.0 and 1.25 were considered in the test. Both HSS 89 x 89 and HSS 127 x 51 were tested for these ratios.

2) Gusset plate thickness (t).

Gusset plates with the thicknesses of 12 mm, 16 mm and 20 mm were used. While specimens with 16 mm thick gusset plate were tested for all three L/w_n ratios, specimens with 12 mm and 20 mm gusset plate were tested for L/w_n ratios of only 0.75 and 1.25.

3) Opening straight segment length (GS).

Besides the straight segment length of 5 mm, two additional lengths of 25 mm and 50 mm were also considered. Specimens with 25 mm straight segment length were tested for the L/w_n ratio of 0.75, and specimens with 5 mm and 50 mm opening length were tested for L/w_n ratios of 0.75 and 1.25.

4) Orientation of the slot.

The ratio of the width of the long side over the width of the short side of HSS 127 x 51 is the largest among all available HSS. Therefore, results from HSS 127 x 51 were expected to show the greatest effect of the slot orientation compared to other sizes. For this reason, HSS 127 x 51 was selected over other rectangular HSS. Slots on both the long side and the short side of HSS 127 x 51 were considered in the test program.

3.3 Description of Test Specimens

Two hollow structural sections and three gusset plates were used in this experimental program. Each specimen consisted of a slotted HSS member welded to two gusset plates, as shown in Figure 3.5. The following notation is adopted to denote the test specimen:

$\alpha\alpha\rho G\beta\beta P\gamma\gamma R$

a) $\alpha\alpha$

The first two letters $\alpha\alpha$ denote the slot orientation and HSS. There are three designations.

RL = HSS 127 x 51, slot on the long side,

RS = HSS 127 x 51, slot on the short side, and

SM = HSS 89 x 89.

A graphical description of the slot orientation is shown in Figure 3.6.

b) ρ

This symbol represents the weld length to the nominal weld distance ratio, L/w_n .

Three ratios considered in the test are denoted with 3, 4 and 5.

3 is $L/w_n = 0.75$,

4 is $L/w_n = 1.0$, and

5 is $L/w_n = 1.25$.

c) $G\beta\beta$

This represents the length of the straight segment of the opening. $\beta\beta$ indicates the length of 5, 25 or 50 mm.

d) $P_{\gamma\gamma}$

This represents the thickness of gusset plates. $\gamma\gamma$ indicates the gusset plate thickness of 12, 16 or 20 mm.

e) The last letter R indicates the specimen is a duplicate specimen. The first test of the configuration has no trailing "R".

For example, SM3G05P12R denotes a duplicate test specimen with HSS 89 x 89, 0.75 weld length ratio (L/w_n), 5 mm long straight segment of the opening and 12 mm thick gusset plate.

3.4 Specimen Measurement

Tables 3.2 and 3.3 list the measured dimensions of the test specimens. Values shown in Tables 3.2 and 3.3 are the average of both ends of the specimen. The thickness of HSS in Table 3.2 is the average thickness of the flat portion of HSS. However, the corner of HSS was found to be thicker than the flat portion. The maximum measured corner thickness of HSS and average outside corner radius are shown in Table 3.4. The maximum thickness was found to vary from 4.84 mm to 4.90 mm for HSS 127 x 51 and 4.62 mm to 4.64 mm for HSS 89 x 89. Thus the average measured maximum thickness is used in (3.4) to calculate the idealized uniform corner thickness.

Based on the idealized uniform corner thickness geometry as shown in Figure 3.4, the gross cross-section area (A_g) of the test specimen can be calculated with

$$A_g = (c - 2\pi \cdot r) \cdot t' + 2\pi \left(r - \frac{t_c}{2} \right) \cdot t_c, \quad (3.6)$$

where c is the measured circumference, r is the corner outside radius, t' is the thickness of the flat portion and t_c is the idealized uniform corner thickness. The net section area (A_n) is given by

$$A_n = A_g - 2 \cdot GW \cdot t', \quad (3.7)$$

where GW is the width of the opening. The distance from the centroid for one half of the HSS net cross-section area to the face of the gusset plate ($\bar{x}$), as shown in Figure 3.7, is taken as

$$\begin{aligned} \bar{x} &= \frac{2(a-t')(b-t') + (a-t'-GW)(a-t'+GW)}{4(a+b-2t'-GW)} - \frac{t}{2} \\ &= \frac{2(a-t'-t)(b-t') + (a-t'-GW)(a-t'+GW+2t)}{4(a+b-2t'-GW)}. \end{aligned} \quad (3.8)$$

Variables used in (3.6) to (3.8) are depicted in Figures 3.2 to 3.4 and 3.7.

Other calculated values of the connection geometry are shown in Table 3.5. Distances between welds using three different definitions in Section 3.2 are shown in Table 3.6. The actual weld distance (w) is the lowest among the three and thus results in the highest weld length ratio (L/w). Additional measurement data of test specimens are shown in Appendix A.

3.5 Test Setup and Instrumentation

Tests were conducted in the 2000 MN (400 kips) capacity Tinius Olsen universal testing machine. LVDT (linear variable differential transformers) and strain gauges were used to measure the deformation of the specimen. The machine stroke, load, LVDT and

strain gauge readings were recorded continuously through the data acquisition system during the test.

3.5.1 Test Setup

The test setup is shown in Figures 3.8 and 3.9. In the test setup, the bottom fixture was fixed against rotation and the top fixture was allowed to swivel to align with the load by using a spherical end plate assembly. The bottom fixture is not really fixed, but rather no special provision was made to allow it to rotate freely. Figures 3.10 and 3.11 show the end fixture and the spherical end plate assembly. Both gusset plates were connected to the testing machine through the end fixtures. All bolt holes in the end fixtures were drilled to a diameter of 24 mm for ASTM A325 M22 bolts. In a small number of tests, ASTM A325 M20 bolts were used because some of the bolt holes were slightly misaligned.

3.5.2 Instrumentation

The test specimens were instrumented with LVDT and strain gauges. Four strain gauges and two LVDT were used for each specimen.

3.5.2.1 Strain Gauge

Strain gauges were used on all the specimens to record the strain distribution during the test. Since the critical section is across the slot at the end of the gusset plate, it is

desirable to measure the strain distribution at this region in order to study the effect of shear lag.

Therefore, four strain gauges were installed along this critical section for each specimen. All the strain gauges were oriented to measure the strain in the longitudinal (loading) direction. Locations of strain gauges are shown in Figure 3.12. The strain gauge is numbered sequentially with the gauge closest to the gusset plate numbered as G1 and the one furthest away as G4. Figure 3.13 shows examples of specimens with strain gauges.

3.5.2.2 LVDT

Two LVDT (linear variable differential transformers) were used for each specimen in the test to measure the deformation of the specimen. There is one LVDT placed on each side of the HSS so that any eccentricity in the loading can be captured by the LVDT. Locations of LVDT are shown in Figure 3.14 and the test setup showing the LVDT can also be seen in Figure 3.15.

3.6 Test Procedure

Both top and bottom end fixtures were first set into the platform of the testing machine. The specimen was then aligned and bolted to the end fixtures. This was followed by installing the LVDT and connecting the strain gauges to the data acquisition system.

The data acquisition system was zeroed before the application of the tension load. During the test, the loading head was held stationary for around 20 seconds at regular interval to record the static reading. Stroke control was employed in all tests and the data were automatically recorded every 5 seconds. The overall test setup including the testing machine and data acquisition system is shown in Figure 3.15.

There were a few stroke increment rates used in the test. For the first test on specimen SM4G05P16R, the following loading and recording rates were used.

- a) Before yielding (in the elastic range), a stroke rate of 1 mm per minute was maintained. No static reading was taken during this stage of testing.
- b) After yielding (in the plastic range), the displacement rate was maintained at 4.0 mm per minute and a static reading was taken at about every 1.0 mm stroke interval.

After the first test, the loading and data recording rates were modified in order to optimizing the test process. Two schemes were used depending on the weld length of the specimen.

- 1) For specimens with $L/w_n = 0.75$, the test was carried out at stroke rate of 1.0 mm per minute.
 - a) Before yielding (in the elastic range), no static reading was taken.
 - b) After yielding but before the load versus deformation curve flattens, the static reading was taken at about every 0.5 mm stroke interval.
 - c) After the load versus deformation curve has flattened, a static reading was taken at approximately every 1.0 mm stroke interval.
- 2) For specimens with $L/w_n \geq 1.0$, two stroke rates were employed.

- a) Before yielding, the stroke rate was set as 1.0 mm per minute. No static reading was taken for this stage.
- b) After yielding but before the load versus deformation curve flatten, the stroke rate was maintained at 1.0 mm per minute and a static reading was taken at about every 0.5 mm stroke interval.
- c) After the load versus deformation curve has flattened, the stroke rate was increased to 2.0 mm per minute and a static reading was recorded at about every 2.0 mm stroke interval.

3.7 Material Properties

The material properties of HSS and gusset plates are required in evaluating the efficiency of the test specimen and carrying out numerical simulations of the tests. These properties were obtained from tension coupons of gusset plates and HSS. Coupons for HSS were cut from the flat portion of the section that is located away from the seam weld and corners, and prepared in accordance to ASTM-E8-04 (2004) and CAN/CSA-G40.20-04 (2004).

Tensile coupon tests were carried out using 100 kN capacity INSTRON material testing machine as shown in Figure 3.16. An extensometer with a 50 mm gauge length was used to measure the longitudinal strain during the tests. But the actual gauge length was 57.2 mm. The load, stroke and extensometer readings were recorded through a data acquisition system. Displacement control was employed in all tests. The test was carried out at a stroke rate of 0.5 mm (0.02 inch) per minute.

There were regular stoppages during the test in order to take static readings. Studies by Khoo et al. (2002) showed that the longitudinal deformation versus load relationship after the peak load does not give consistent results, while the transverse deformation versus load relationship was found not to vary with the test. For this reason, the transverse deformation of the specimen was also measured with a caliper and a micrometer. Up until the peak load, the cross-section of the coupon has a uniform width and thickness. But once the peak load is reached, the coupon will start to neck and the cross-section will no longer be uniform. Thus in post-peak stage of testing, the maximum and minimum thicknesses and widths of the necking region were measured. The extensometer was removed from the coupon after the peak load has been attained so that the minimum thickness and width of the necking region can be measured. Furthermore at this testing stage, the deformation has localized and the extensometer is unable to capture the localized deformation of the coupon. Thus the removal of the extensometer after the peak load does not result in any loss of useful data.

Table 3.1 Test matrix.

Specimen	HSS	Slot location	Longitudinal weld length, L (mm)	Opening straight segment length, GS (mm)	Gusset plate thickness, t (mm)	Width of gusset plate, WP (mm)
RL5G05P16	127 x 51 x 4.8	Short side	$1.25w_n$	5	16	190
RS5G05P16	127 x 51 x 4.8	Long side	$1.25w_n$	5	16	190
SM5G05P16	89 x 89 x 4.8	-	$1.25w_n$	5	16	190
RL4G05P16	127 x 51 x 4.8	Short side	w_n	5	16	190
RS4G05P16	127 x 51 x 4.8	Long side	w_n	5	16	190
SM4G05P16	89 x 89 x 4.8	-	w_n	5	16	190
RL3G05P16	127 x 51 x 4.8	Short side	$0.75w_n$	5	16	190
RS3G05P16	127 x 51 x 4.8	Long side	$0.75w_n$	5	16	190
SM3G05P16	89 x 89 x 4.8	-	$0.75w_n$	5	16	190
SM3G05P12	89 x 89 x 4.8	-	$0.75w_n$	5	12	240
SM5G05P12	89 x 89 x 4.8	-	$1.25w_n$	5	12	240
SM3G05P20	89 x 89 x 4.8	-	$0.75w_n$	5	20	160
SM5G05P20	89 x 89 x 4.8	-	$1.25w_n$	5	20	160
SM3G25P16	89 x 89 x 4.8	-	$0.75w_n$	25	16	190
SM3G50P16	89 x 89 x 4.8	-	$0.75w_n$	50	16	190
SM5G50P16	89 x 89 x 4.8	-	$1.25w_n$	50	16	190

Table 3.2 Measured HSS gross section properties.

Test specimen	HSS			
	Circumference, c (mm)	Width, a (mm)	Width, b (mm)	Thickness, t' (mm)
RL5G05P16	343.00	127.04	51.63	4.52
RS5G05P16	343.00	51.39	127.30	4.50
SM5G05P16	343.00	89.61	89.77	4.42
SM5G05P16R	343.00	89.50	89.54	4.41
RL4G05P16	343.00	127.15	51.59	4.50
RS4G05P16	343.50	51.45	127.41	4.50
SM4G05P16	343.00	89.36	89.56	4.39
SM4G05P16R	343.00	89.61	89.51	4.40
RL3G05P16	343.00	127.08	51.46	4.47
RS3G05P16	343.00	51.32	127.21	4.50
SM3G05P16	343.00	89.93	89.67	4.40
SM3G05P16R	342.50	89.42	89.51	4.42
SM3G05P12	342.50	89.38	89.56	4.42
SM3G05P12R	343.00	89.56	89.50	4.42
SM5G05P12	343.00	89.52	89.53	4.41
SM5G05P12R	343.50	89.90	89.57	4.41
SM3G05P20	342.00	88.82	88.95	4.46
SM3G05P20R	344.00	89.39	90.10	4.45
SM5G05P20	343.00	89.56	89.59	4.42
SM5G05P20R	342.00	89.23	89.55	4.43
SM3G25P16	342.50	89.43	89.55	4.40
SM3G25P16R	343.50	89.37	89.70	4.42
SM3G50P16	342.00	89.18	89.63	4.41
SM3G50P16R	343.00	89.37	89.70	4.42
SM5G50P16	343.00	89.21	89.64	4.41
SM5G50P16R	343.00	89.40	89.69	4.41

Table 3.3 Measured connection geometry.

Test specimen	Gusset plate		Welds Length, L (mm)	Opening	
	Width, WP(mm)	Thickness, t (mm)		Length, G (mm)	Width, GW (mm)
RL5G05P16	187.25	15.72	195.06	14.68	17.19
RS5G05P16	187.38	15.71	194.75	15.83	18.51
SM5G05P16	187.00	15.70	194.31	14.47	17.98
SM5G05P16R	187.00	15.82	196.13	14.99	17.38
RL4G05P16	186.67	15.74	155.75	13.76	16.55
RS4G05P16	186.42	15.73	155.88	15.19	17.70
SM4G05P16	186.75	15.73	156.50	14.16	17.35
SM4G05P16R	186.67	15.75	156.63	14.24	18.40
RL3G05P16	186.50	15.72	116.13	15.28	17.10
RS3G05P16	187.08	15.81	116.63	15.45	18.46
SM3G05P16	186.67	15.65	116.50	14.64	17.46
SM3G05P16R	186.25	15.74	116.56	13.94	17.13
SM3G05P12	239.00	12.65	118.00	13.51	13.77
SM3G05P12R	238.17	12.69	118.44	12.70	13.49
SM5G05P12	237.33	12.69	201.75	9.90	13.59
SM5G05P12R	236.83	12.69	201.06	12.20	13.97
SM3G05P20	157.67	19.16	113.50	17.02	20.56
SM3G05P20R	157.88	19.07	113.94	16.55	20.70
SM5G05P20	156.84	19.15	190.63	16.23	20.56
SM5G05P20R	156.67	19.26	190.00	17.74	20.36
SM3G25P16	186.42	15.76	117.50	33.50	17.02
SM3G25P16R	187.08	15.70	116.63	34.24	17.46
SM3G50P16	188.72	15.69	116.69	59.14	15.61
SM3G50P16R	186.33	15.72	116.00	60.07	16.73
SM5G50P16	187.58	15.73	196.13	58.83	17.04
SM5G50P16R	187.17	15.64	195.50	59.32	16.96

Table 3.4 Measured maximum thickness at the corner of HSS.

HSS	Maximum thickness			Corner outside radius, r mm (inch)
	Low (mm)	High (mm)	Average (mm)	
HSS 127 x 51 x 4.8	4.84	4.90	4.87	11.11 (7/16)
HSS 89 x 89 x 4.8	4.62	4.66	4.64	11.11 (7/16)

Table 3.5 Calculated geometric properties of the specimen.

Test specimen	Weld distance, w (mm)	Weld length ratio, L/w	Net area, A_n (mm ²)	Gross area, A_g (mm ²)	Net area eccentricity and eccentricity ratio	
					$\bar{x}$ (mm)	$\bar{x}/L$
RL5G05P16	147.21	1.33	1338	1494	46.07	0.24
RS5G05P16	145.92	1.33	1321	1409	17.21	0.09
SM5G05P16	146.58	1.33	1300	1377	34.26	0.18
SM5G05P16R	147.20	1.33	1302	1386	34.15	0.17
RL4G05P16	147.88	1.05	1339	1424	45.98	0.30
RS4G05P16	146.98	1.06	1330	1429	17.23	0.11
SM4G05P16	147.25	1.06	1299	1385	34.10	0.22
SM4G05P16R	146.19	1.07	1291	1375	34.31	0.22
RL3G05P16	147.38	0.79	1325	1410	46.07	0.40
RS3G05P16	145.97	0.80	1321	1404	17.14	0.15
SM3G05P16	147.12	0.79	1301	1395	34.33	0.29
SM3G05P16R	147.18	0.79	1305	1389	34.09	0.29
SM3G05P12	150.54	0.78	1334	1418	33.81	0.29
SM3G05P12R	151.06	0.78	1341	1425	33.84	0.29
SM5G05P12	150.98	1.34	1338	1426	33.84	0.17
SM5G05P12R	150.86	1.33	1335	1421	34.03	0.17
SM3G05P20	143.43	0.79	1285	1369	33.98	0.30
SM3G05P20R	144.32	0.79	1288	1377	34.23	0.30
SM5G05P20	144.00	1.32	1277	1361	34.29	0.18
SM5G05P20R	143.69	1.32	1277	1355	34.13	0.18
SM3G25P16	147.32	0.80	1302	1386	34.08	0.29
SM3G25P16R	147.35	0.79	1307	1391	34.11	0.29
SM3G50P16	148.46	0.79	1315	1405	33.82	0.29
SM3G50P16R	147.83	0.78	1312	1396	34.02	0.29
SM5G50P16	147.53	1.33	1307	1391	34.00	0.17
SM5G50P16R	147.61	1.32	1307	1369	34.07	0.17

Table 3.6 Distances between welds of the specimen.

Test specimen	Weld length, L (mm)	Weld distance and weld length ratio					
		w_n (mm)	L/w_n	w_c (mm)	L/w_c	w (mm)	L/w
RL5G05P16	195.06	156.96	1.24	152.44	1.28	147.21	1.33
RS5G05P16	194.75	155.68	1.25	151.18	1.29	145.92	1.33
SM5G05P16	194.31	156.98	1.24	152.57	1.27	146.58	1.33
SM5G05P16R	196.13	157.25	1.25	152.85	1.28	147.20	1.33
RL4G05P16	155.75	157.69	0.99	153.19	1.02	147.88	1.05
RS4G05P16	155.88	156.66	0.99	152.16	1.02	146.98	1.06
SM4G05P16	156.50	157.18	1.00	152.79	1.02	147.25	1.06
SM4G05P16R	156.63	156.32	1.00	151.93	1.03	146.19	1.07
RL3G05P16	116.13	156.97	0.74	152.51	0.76	147.38	0.79
RS3G05P16	116.63	155.57	0.75	151.07	0.77	145.97	0.80
SM3G05P16	116.50	157.74	0.74	153.33	0.76	147.12	0.79
SM3G05P16R	116.56	157.39	0.74	152.97	0.76	147.18	0.79
SM3G05P12	118.00	160.76	0.73	156.34	0.75	150.54	0.78
SM3G05P12R	118.44	161.15	0.73	156.73	0.76	151.06	0.78
SM5G05P12	201.75	161.05	1.25	156.63	1.29	150.98	1.34
SM5G05P12R	201.06	161.09	1.25	156.68	1.28	150.86	1.33
SM3G05P20	113.50	152.75	0.74	148.28	0.77	143.43	0.79
SM3G05P20R	113.94	154.34	0.74	149.90	0.76	144.32	0.79
SM5G05P20	190.63	154.17	1.24	149.76	1.27	144.00	1.32
SM5G05P20R	190.00	154.00	1.23	149.57	1.27	143.69	1.32
SM3G25P16	117.50	157.56	0.75	153.16	0.77	147.32	0.80
SM3G25P16R	116.63	157.19	0.74	152.77	0.76	147.35	0.79
SM3G50P16	116.69	158.79	0.73	154.38	0.76	148.46	0.79
SM3G50P16R	116.00	157.92	0.73	153.50	0.76	147.83	0.78
SM5G50P16	196.13	157.40	1.25	152.99	1.28	147.53	1.33
SM5G50P16R	195.50	157.72	1.24	153.31	1.28	147.61	1.32

(a) The nominal distance w_n

(b) The straight centerline distance w_c

(c) The actual weld distance w_a

Figure 3.1 Distances between welds.

Figure 3.2 The test specimen geometry.

Figure 3.3 Opening at the end of gusset plate.

Figure 3.4 The corner segment of HSS.

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(a) Slot location for HSS 89 x 89

(b) Long side

(c) Short side

Figure 3.6 Slot orientation.

Figure 3.7 Connection eccentricity.

Figure 3.8 Test setup.

Figure 3.10 End fixture.

Figure 3.11 End fixture assemblies.

Figure 3.12 The location of strain gauges.

Figure 3.13 Example of specimens with strain gauges.

Figure 3.14 The location of LVDT.

Figure 3.15 Overall test setup.

Figure 3.16 A tension coupon test in the INSTRON testing machine.

CHAPTER 4 TEST RESULTS

The tests were successfully completed without any major problem. The effect on the net section efficiency of a slotted connection due to weld length, gusset plate thickness, opening at the end of the gusset plate and orientation of the slot are discussed in this Chapter. Based on the test data, guidelines are developed for designing a full-strength slotted square or rectangular HSS tension member without end welding and improvements to provisions for shear lag in CSA-S16.1 and AISC design standards are proposed.

4.1 Material Properties

Tension coupon test results of the HSS and gusset plates are summarized in Table 4.1. Coupons were obtained from the flat region of the HSS. The yield strength for the HSS is calculated using 0.2% offset method. Detailed tension coupon test results are shown in Appendix B. In addition to coupons from the spare HSS, tension coupons were also extracted from a number of failed test specimens with the L/w ratio close to 1.3. These additional coupons were cut from the centre of the non-slot side of HSS at the end of the specimen. Even though the stress at the location of the coupon may have exceeded the proportional limit during the test of the connection specimen, it is not expected to be sufficiently high to affect the ultimate strength that was measured in the subsequent tension coupon test since this is the least loaded region of the specimen. For the rectangular HSS, both coupons from the spare HSS and the failed specimen were found to have about the same ultimate strength with only 2.3% difference. However, coupons from the failed

square HSS specimen were found to have an ultimate strength that was about 12% higher than that from the spare HSS. Therefore, it is possible that the spare square HSS may not have come from the same batch of HSS used in the connection specimen. For this reason, material properties measured from the failed square HSS are used instead when discussing the test results. Material properties of the rectangular HSS were still obtained from the spare HSS. Since the proportional limit may have been exceeded during the connection test, the yield strength measured for the square HSS may be higher than the actual untested HSS.

Table 4.1 also shows the ratio of the undeformed cross-section area over the cross-section area at failure (A_o/A_f), with A_o being the undeformed cross-section area and A_f being the cross-section area (A) at failure. The cross-section area (A) is the product of the average width and thickness of the cross-section at the necking region. Appendix B gives a more detailed description of the cross-section area calculation.

4.2 Analyses of Test Results

All tests were carried out according to plan except for specimen SM3G05P16. During the test for specimen SM3G05P16, the load fluctuated considerably when attempting to take the static reading. For this reason, the maximum static load for SM3G05P16 was calculated assuming that amount of the load drop is the same as that for SM3G05P16R when taking the static reading. A loading rate of 0.001 mm per minute was used instead of holding the crosshead displacement stationary when taking the static reading for SM3G05P16.

As expected, all specimens fractured at the slot where the cross-section area is minimum. The failure occurred either close to the end of the gusset plate or at the end of the semi-circle of the opening. The failure for SM3G05P16 in Figure 4.1 shows an example of the failure that occurred close to the end of the gusset plate and the failure for RS3G05P16 in Figure 4.2 shows an example of the failure that occurred at the end of the semi-circle of the opening. The load versus deformation curve and the location of failure for every specimen are also shown in Appendix C.

In general, the location of the failure depends on the weld length. The gusset plate provides restraint against transverse contraction of HSS, and thus stiffens the section at the end of the gusset plate. This may have partially offset the negative effect of stress concentration and caused the failure to occur away from the end of the gusset plate. For this reason, most of the long weld length specimens failed at the end of the semi-circle of the opening. But for the short weld length specimens, failure occurred mostly close to the end of the gusset plate because of the higher stress concentration.

The overall test results are shown in Tables 4.2 and 4.3. Figure 4.3 depicts a typical LVDT displacement versus load curve for the test together with the definition on the average LVDT displacements at peak load and at failure, and the peak static load. As the curve is quite flat close to the peak load, the average LVDT displacement at peak load given in Table 4.2 is not precise.

To facilitate the discussion, the specimens are divided into three groups according to the weld length ratio (L/w). Table 4.4 shows the grouping according to the L/w ratio of the specimen. The group GLW79 denotes specimen with the L/w ratio from 0.78 to 0.80,

GLW106 for the ratio from 1.05 to 1.08, and GLW133 for the ratio from 1.32 to 1.34. In addition, the net section efficiency (U_n) is defined as

$$U_n = \frac{P_{uTest}}{A_n F_u}, \quad (4.1)$$

and the gross section efficiency (U_g) as

$$U_g = \frac{P_{uTest}}{A_g F_u}, \text{ with} \quad (4.2)$$

$$A_n F_u = A_{nFlat} F_{uFlat} + A_{nCorner} F_{uCorner} \quad (4.3)$$

$$\text{and } A_g F_u = A_{gFlat} F_{uFlat} + A_{gCorner} F_{uCorner}, \quad (4.4)$$

where

P_{uTest} = the peak static test load,

A_{nFlat} = the net area of the flat portion,

$A_{nCorner}$ = the net area of the corner,

A_{gFlat} = the gross area of the flat portion,

$A_{gCorner}$ = the gross area of the corner,

F_{uFlat} = the ultimate strength of the flat portion, and

$F_{uCorner}$ = the ultimate strength of the corner.

In the following sections, effects of various parameters on the net section efficiency are discussed. Efficiencies of the connection in the discussion are defined according to (4.1) and (4.2), and modified accordingly by Sections 4.2.2.

4.2.1 Section Efficiency

The section efficiencies of all specimens are tabulated in Table 4.3. In the calculation of the efficiencies U_n and U_g , the tensile strength of the corner region of HSS is assumed to be the same as the flat region ($F_{uCorner} = F_{uFlat}$). Tensile strengths of the flat region obtained from the tension coupon test are listed in Table 4.1.

Net section efficiencies (U_n) of all specimens are found to be above unity. An interesting observation is that the gross section efficiency (U_g) of the rectangular HSS specimen is above unity for L/w greater than 1.00. One of the reasons for this is that the tensile strength at the corner for the rectangular HSS may be much higher than that at the flat region. However, this effect is not accounted for in the calculation of U_n and U_g .

4.2.2 Adjustment of Rectangular HSS Specimen Strength for Comparison

Both the square and rectangular HSS used in the test are cold-formed sections. Consequently, the ultimate strength of the HSS corner can be much higher than the flat region due to cold-forming. However, the strength of the HSS is determined by the material in the flat region as specified by CSA-G40.20-04 (2004). According to the findings by Abdel-Rahman et al. (1997) and Yu (1991), cold-forming can increase the yield strength by up to 75% and the ultimate strength by up to 47%. Figure 4.4 shows the stress versus strain curve of a coupon taken from the region close to the corner (R6) compared to that from the flat region. As mentioned in Section 3.7, the extensometer was removed from the coupon after the peak load has been attained. Thus, the sudden termination of the graphs immediate after reaching the peak stress is not due to the failure of the coupon.

There was consideration deformation in the coupon after the removal of the extensometer. This can be seen in Table 4.1 on the elongation of the 50 mm gauge lens of the coupon at fracture. Even though R6 is not exactly at the corner, it still shows an increase in the ultimate strength that is 5% higher than the flat region coupon. But the net section efficiency in Table 4.3 is calculated using the tensile strength of the flat region. Thus in order to compare the net section efficiencies of rectangular and square HSS specimens, it is necessary to reconcile the difference in the relative strength of the corner to the flat region between the rectangular and square HSS.

It is expected that the shear lag effect is negligible for long weld length specimens. Thus if the actual corner strength is considered, the net section efficiency should be about equal for both rectangular and square specimens with L/w close to 1.30. The ultimate load of the specimen can be expressed as

$$P_u = U_n (A_{nFlat} F_{uFlat} + A_{nCorner} F_{uCorner}),$$

where U_n , A_{nFlat} , $A_{nCorner}$, F_{uFlat} and $F_{uCorner}$ are parameters that have been defined previously in Section 4.2. In order to combine results of square and rectangular HSS specimens in the discussion, the corner strength of the rectangular HSS ($F_{uCorner}$) is adjusted so that the net section efficiencies for specimens with the square HSS (U_{square}) and rectangular HSS (U_{rect}) are equal when the weld length ratio (L/w) is high. Results of specimens RL5G05P16, RS5G05P16, SM5G05P16 and SM5G05P16R were used in the adjustment calculation. For the square HSS, the corner tensile strength ($F_{uCorner}$) is taken as equal to that of the flat region (F_{uFlat}). Thus, the adjusted corner strength of the rectangular HSS is calculated by setting

$$U_{square} = U_{rect} \quad \text{with} \quad (4.6)$$

$$U_{\text{square}} = \left(\frac{P_{\text{utest}}}{A_{\text{nFlat}} F_{\text{uFlat}} + A_{\text{nCorner}} F_{\text{uFlat}}} \right)_{\text{square}} \quad \text{and} \quad (4.7)$$

$$U_{\text{rect}} = \left(\frac{P_{\text{utest}}}{A_{\text{nFlat}} F_{\text{uFlat}} + A_{\text{nCorner}} F_{\text{uCorner}}} \right)_{\text{rect}} . \quad (4.8)$$

Using (4.6) to (4.8), the corner tensile strength for the rectangular HSS is calculated to be 605 MPa. Table 4.5 shows the efficiency of the rectangular HSS specimen based on the adjusted tensile strength. The adjusted values for these specimens are denoted with an asterisk. There is no adjustment carried out for the square HSS specimens. Thus, the adjusted values for square HSS specimens are the same as the non-adjusted values.

It should be noted that this adjustment only compensates for the difference in the relative strength of the corner to the flat region between the rectangular and square HSS. It does not account for the actual strength difference between the corner and the flat region. The finite element analysis discussed in Chapter 5 excludes the higher corner strength in its determination of net section efficiency.

4.2.3 Weld Length Ratio

Both the net section efficiency and adjusted net section efficiency are plotted in Figure 4.5 and 4.6. It can be seen that there is little improvement in the net section efficiency for weld length ratio (L/w) greater than 1.0. For a rectangular HSS specimen, the net section efficiency can go as high as 1.15 if the higher corner strength is not adjusted in the calculation. For all cases, the net section efficiency is greater than unity for L/w as low as 0.8 and above 1.05 for L/w greater than 1.0. Even when adjusted for a higher corner strength, only one rectangular HSS specimen (RL3G05P16) has an adjusted net section efficiency that is slightly less than unity at a L/w of 0.79. Thus, the actual

efficiency of the specimens is much higher than the net section efficiency of 0.75 specified by CSA-S16.1-01 at L/w of 1.0 and 0.6 at L/w of 0.8.

There are three possible factors that enable the HSS specimens to achieve the adjusted net section efficiency that is greater than unity. One factor is that the actual corner tensile strength of the square HSS is higher than the flat region. The tensile strength used in calculating the efficiency is determined by the material at the flat part of HSS. Another factor is that the gusset plate restrains the transverse contraction of HSS and thus induces additional transverse stress at the section. This effectively stiffens the section at the end of the gusset plate. The last factor is the stress flow around the opening, as shown in Figure 4.7, also creates transverse stress that stiffens the section. The stiffening effect can be viewed in term of von Mises stress. For a two-dimensioned stress state with one principal stress in the direction of loading, the von Mises stress (σ_{von}) can be written as

$$\sigma_{von} = \sqrt{\sigma_{xx}^2 + \sigma_{yy}^2 - \sigma_{xx}\sigma_{yy}}, \quad (4.9)$$

where σ_{xx} is the principal tensile stress in the loading direction and σ_{yy} is the principal tensile stress in the transverse direction. When σ_{xx} is greater than σ_{yy} , any transverse tensile stress essentially makes σ_{von} less than σ_{xx} . This has the same effect as stiffening the section at the end of the gusset plate.

Figure 4.8 shows the adjusted gross section efficiency for different weld length ratios. When L/w is greater than 1.0, the adjusted gross section efficiency (U_g^*) is equal or greater than 0.93. Even for an L/w ratio around 0.8, the adjusted gross section efficiency is at least 0.87. Thus, the full strength of the hollow section may be achieved with a weld

length ratio (L/w) as low as 1.0. A more detailed discussion on the guidelines for designing a full-strength slotted tension HSS is carried out in a separate section.

The strain distribution for three specimens with different weld length is plotted in Figure 4.9 at the average net section stress of 389 MPa. In Figure 4.9, the strain gauge G1 is the gauge closest to the gusset plate. It can be seen that the strain in HSS close to the gusset plate is the highest for a short weld length specimen (SM3G05P16) and lowest for a long weld specimen (SM5G05P16). The long weld specimen (SM5G05P16) also has a more uniform strain distribution and a lower stress concentration as compared to the short weld length specimen (SM3G05P16).

4.2.4 Gusset Plate Thickness

Table 4.6 shows test results of square HSS specimens with different gusset plate thicknesses for two weld length ratios of around 0.8 (GLW79) and 1.3 (GLW133). All specimens have a straight segment length of about 5 mm at the opening. The net section efficiencies are shown in Figures 4.10 to 4.12 with respect to the gusset plate thickness, cross-section area ratio (A_g/A_n) and the aspect ratio of the opening (GW/G). In Figures 4.10 to 4.12, the trend of the efficiency is shown with a line. Trend lines are constructed for a number of Figures throughout this thesis to facilitate the discussion. The increase in the gusset plate thickness essentially increases the cross-section area ratio and the aspect ratio of the opening.

From the Figures 4.10 to 4.12, it can be seen that the net section efficiency increases with the gusset plate thickness, A_g/A_n and GW/W ratios for the long weld length specimens. However, the reverse occurs when the weld length is short. For a specimen with a 20 mm gusset plate, the stress flow around the opening generates a higher transverse stress as a

result of a higher GW/G and A_g/A_n ratios. Even though the increase in the transverse stress increases the overall section strength at the opening, it may not be able to compensate for the combined effect of the increase in stress concentration with a thicker gusset plate and a shorter weld length. As a result, the specimen with a 20 mm gusset plate and high weld length can utilize the increase in strength due to the increase in the transverse stress, but not the short weld length specimen. Figures 4.13 and 4.14 show the strain distribution in HSS at the end of the gusset plate for different plate thicknesses at a net average stress around 400 MPa. In Figure 4.13 for a weld length ratio (L/w) around 0.8, the specimen with a 20 mm gusset plate (SM3G05P20R) has the highest strain at strain gauge G1, the gauge closest to the gusset plate; however, SM3G05P20R also has the lowest overall strain. This can also be seen in Figure 4.14 for specimens with weld length ratio (L/w) around 1.33 where SM5G05P20R has an overall lower strain than SM5G05P12R.

However, it should be noted that the increase in the gusset plate thickness reduces the gross section efficiency, for short weld specimens as shown in Figure 4.15. The reduction in the gross section efficiency is less when the weld length is long. Even though the increase or decrease in the net section efficiency is only around 2 to 3% in either direction with the increase in the gusset plate thickness for all weld lengths, there is a drop close to 6% in the gross section efficiency for the short weld length specimen. This effect is important when designing the connection to ensure that gross section yielding governs.

4.2.5 Opening Length

The study on the effect of the opening length is carried out using square HSS specimens with 16 mm gusset plate. Test results of these specimens are shown in Table 4.7. The same data are also plotted in Figure 4.16.

For a weld length ratio (L/w) around 0.8, the net section efficiency is the highest at the opening length around 33 mm. The efficiency reduces with any other opening length. A shorter opening length increases the stress concentration, while a longer length reduces the transverse stress generated by the stress flow around the opening and the constraint of the gusset plate. However, the average difference in the efficiency is only about 2%. For a high weld length configuration (GLW133), the testing program did not include any specimen with the intermediate opening length. Between the tested long weld length specimens (GLW133), the average difference in the efficiency is only 1%, and with the short opening specimen having a better efficiency. In the test, the shortest straight segment length (GS) of the opening is 5 mm. However from test results of short weld length specimens, there is a possibility that the efficiency may reduce further if the straight segment length is reduced to zero. Thus, this effect should be looked at in the parametric study.

In most practical situations, the straight portion of the opening at the end of gusset plate is shorter than the longest straight segment tested. Thus any drop in the efficiency with a long opening in practice is at most limited to 2%.

4.2.6 Slot Orientation

Table 4.8 shows the adjusted test results for specimens with a 5 mm long straight segment of the opening (GS) with respect to the ratio of the slot to non-slot HSS side dimension. The slot orientation can be characterized by the HSS aspect ratio (a/b) or the net section eccentricity ($\bar{x}$). The net section eccentricity is given by (3.8) in Section 3.3. A higher aspect ratio corresponds to a higher net section eccentricity.

Figure 4.17 shows the effect of the slot orientation on the net section efficiency due to different aspect ratio (a/b) for specimens with 16 mm gusset plate. The aspect ratio has little effect on the net section efficiency when the weld length is long (GLW133). Even for the weld length close to unity (GLW106), there is little change in the net section efficiency when the aspect ratio is greater than 1. But there is a drop in the net section efficiency at the aspect ratio of 0.4.

According to the findings by Korol (1996), the efficiency reduces with an increase in the aspect ratio. Similar to results of Korol (1996), the efficiency of short weld length specimens (GLW79) also reduces with an increase in the aspect ratio. The reduction is about 4% from RS3G05P16 to RL3G05P16. When the weld length ratio is close to unity (GLW106), the rectangular HSS specimen with the slot on the long side (RL4G05P16) has a 3% higher efficiency than that on the short side (RS4G05P16). However, this contradicts the results from Korol, which showed that at the weld length ratio close to unity, the average efficiency of the long side slotted specimens is slightly lower than the short side slotted specimens. But even then, one of the long side slotted specimens in Korol's test has about the same efficiency as the short side slotted specimens. The variability in test results for duplicate specimens from Korol was as high as 6%. In this test program,

the largest variability of the efficiency is 2% between duplicate specimens. Test results also show that there is little change in the efficiency when the weld length ratio reduces from about 1.33 to 1.06 except for the short side slotted specimens RS5G05P16 and RS4G05P16. Thus the lower efficiency of RS4G05P16 compared to RL4G05P16 can be attributed to the variability in testing since the difference is only 3%. Based on this, the aspect ratio can be assumed to have little effect on the net section efficiency for the weld length ratio as low as unity.

Figure 4.18 shows the adjusted net section efficiency versus the net section area eccentricity to the weld length ratio ($\bar{x}/L$). While most test results appear to follow a trend with respect to the $\bar{x}/L$ ratio, results of short side slotted specimens appear to be out of place. When the HSS aspect ratio is lower, the eccentricity of the net area in the direction parallel to the plane of the gusset plate becomes larger than its eccentricity normal to the plane. But the net section eccentricity ($\bar{x}$) calculated using (3.8) is for the eccentricity normal to the plane of the gusset plate, as defined by Munse and Chesson (1963) and AISC (2000) Design Specification for Hollow Structural Sections. Thus, a modified eccentricity ($\bar{x}^*$) may have to be used when the aspect ratio (a/b) is low. Figure 4.19 shows the relationship between the effective eccentricity (r) measured from the weld length and the aspect ratio (a/b). The effective eccentricity is the distance from the centroid of a quarter of HSS to the weld. For an aspect ratio of unity, the effective eccentricity is only slightly larger than $\bar{x}$. When the aspect ratio is greater than 1.0, the effective eccentricity (r) is almost equal to $\bar{x}$. For the aspect ratio from 0.2 to 1.0, there is only a slight difference between r and $\bar{x}$, and thus the effective eccentricity can be assumed to be equal to $\bar{x}$. For this reason, the net section eccentricity of an equivalent

square HSS with equal circumferential length is used as the lower limit of the modified eccentricity ($\bar{x}^*$) at this range of aspect ratio. Figure 4.20 shows the efficiency versus the modified eccentricity ratio for the same data set shown in Figure 4.19. In Figure 4.20, the efficiency shows a more consistent trend with respect to the modified eccentricity ratio than the unmodified eccentricity ratio. Except for out layer in RS4G05P16, there is little change in the efficiency when the modified eccentricity ratio ($\bar{x}^*/L$) is below 0.25.

4.2.7 Specimen Ductility

The measured LVDT displacement at failure for each specimen is listed in Table 4.2. Load versus average LVDT displacement curves for all specimens are also shown in Appendix C. All tested specimens manage to achieve considerable deformation before failure occurred. The deformation at failure in all but one specimen is greater than 12 mm, which is 3% of the specimen length of 400 mm. For a number of specimens, the deformation at failure was as high as 5% (20 mm) of the specimen length.

Figure 4.21 shows the deformation at failure versus the weld length ratio (L/w) for specimens with 16 mm gusset plate thickness and 5 mm straight segment length of the opening. Both the square and rectangular specimens generally show a reduction in ductility with the increase in the weld length ratio. However, this reduction is only about 4 mm. Even though a lower weld length ratio implies that there is a greater stress concentration, specimens with a weld length ratio around 0.80 manage to achieve a greater ductility than those with a higher weld length ratio. One of the reasons can be attributed to the localized deformation of the HSS in the region of the opening at the end of the gusset plate. As this region starts to neck and unload, other regions of the HSS have to pick up

the extra load. For the specimen with a high weld length ratio, the cross-section is more uniformly loaded. Thus when the region close to the opening starts to unload, a high weld length ratio specimen has less reserved capacity available in other regions to pick up the load than a low weld length ratio specimen. Thus for a low weld length ratio specimen, it can undergo more deformation after the region at the opening starts to neck and unload. This increases the measured displacements at the peak load and at failure for the specimen with L/w of 0.8 as compared to 1.3. Figure 4.22 shows the strain distribution in HSS at the end of the gusset plate with three weld length ratios at the LVDT displacement around 4 mm. The minimum strain in the high weld length ratio specimen is higher than the low weld length ratio specimen. On average, SM5G05P16R has higher strain across the section than SM3G05P16. This indicates that there is less reserved capacity for a long weld length specimen when the deformation at the region close to the gusset plate starts to localize. However, when the weld length is very short, the gross area deformation for the rest of the HSS may be significantly reduced because the peak load is lower. So the increase in the localized deformation may not offset the reduction in the HSS gross area deformation when the weld length is very short. Therefore, a shorter weld length will eventually reduce the ductility of the specimen. When the reduction occurs is dependent on the specimen length. Thus test results showing an increase in the ductility with the reduction in the weld length ratio can be misleading.

The relationship of the deformation at failure versus gusset plate thickness is shown in Figure 4.23. A thicker gusset plate reduces the net section area available to redistribute the stress. Thus, the connection with a thicker gusset plate has lesser capacity to deform

before failure occurs. This is especially true for short weld length specimens where there is a higher stress concentration.

It is expected that the ductility increases with the length of the opening since a longer segment of net cross-section area is subjected to a higher stress, and thus increases the specimen deformation. Figure 4.24 shows the deformation at failure versus the length of the opening. Overall, the ductility increases with the length of the opening.

4.3 Comparison of Test Results with Provisions in Design Standards

Test results are compared against provisions to account for shear lag in design standards and proposed reduction factors by Korol (1996). The net section reduction factor is given by (2.6) to (2.8) for CSA-S16.1-01 and by (2.18) for AISC (2000). The reduction factors proposed by Korol are given by (2.25) and (2.26). Test results from Korol (1996) on HSS 127 x 51 x 6.4 and HSS 89 x 89 x 6.4 are also included in the discussion. The reduction factors according to CSA-S16.1-01 and (2.26) are dependent on the weld length ratio (L/w), while the reduction factors for AISC (2000) and (2.25) are dependent on the net section eccentricity ratio ($\bar{x}/L$). The proposed equation (2.26) by Korol is limited to the weld length ratio above 0.6. Tables 4.9 to 4.12 show the test efficiencies and calculated efficiencies using different equations. Calculated efficiencies according for AISC (2000) and (2.26) using the modified eccentricity ($\bar{x}^*$) for rectangular HSS slotted on the short side are also presented.

Figure 4.25 shows the net section efficiency versus the weld length ratio (L/w) from the current test program and Korol (1996). It can be seen that the provisions in

CSA-S16.1-01 greatly underestimates the efficiency with the underestimation of up to 80% for the specimen from the current test program and close to 100% for the specimen from Korol (1996). On the other hand, the proposed equation (2.26) by Korol provides a better prediction. But it still clearly does not reflect the actual connection efficiency. An improvement to the equation in calculating the net section efficiency factor using the weld length ratio (L/w) is thus proposed. The proposed equation for the efficiency factor can be expressed as

$$U_{pw} = 0.05 + 1.1 \left(\frac{L}{w} \right) \leq 1, \quad (4.10)$$

with an upper limit of 1. The new calculated efficiency is also compared to the test efficiency in Tables 4.13 and 4.14 and in Figure 4.25. In almost all cases, (4.10) gives a conservative estimate of the efficiency except for a number of tests from Korol (1996) at a weld length ratio around 1 that have the efficiency below 1. In general, the proposed equation underestimates the efficiency by less than 20%.

Every specimen with the weld length ratio (L/w) around 1 in the current test program has an efficiency greater than unity. For the current test program, the efficiency is calculated using the static peak load of the specimen and the tension coupon. However in Korol's test program, the static reading was not specifically mentioned as being used in calculating the efficiency. Thus, the efficiency reported for Korol's test may actually be higher or lower depending on the rate of loading and procedures used in testing the specimen and the tension coupon. Based on results of the finite element analyses in Chapter 5, the reported efficiency for Korol's specimens should be higher than 1 for a weld length ratio close to 1. For this reason, the proposed net section efficiency factor equation

developed is expected to predict an efficiency that is higher than a number of Korol's tests. A more detailed discussion of the finite element analyses will be carried in Chapter 5.

Figure 4.26 and 4.27 show the net section efficiency versus the unmodified and modified eccentricity ratio respectively. It can be seen that there is a significant scatter in the results with respect to the unmodified eccentricity ratio in Figure 4.26. However, a clear trend can be observed when results are plotted against the modified eccentricity ratio in Figure 4.27.

Similar to provisions from CSA-S16.1, provisions for shear lag from AISC (2000) clearly significantly underestimate the net section efficiency. On the other hand, the proposed equation (2.25) by Korol is also not suitable as it cannot capture the efficiency of the connection. Therefore, another equation for calculating the net section efficiency factor that based on the net section eccentricity ratio ($\bar{x}/L$) is also being proposed. The proposed net section efficiency factor takes the form of

$$U_{px} = 1.25 - 1.25 \left(\frac{\bar{x}}{L} \right) \leq 1, \quad (4.11)$$

with an upper limit of 1. The new calculated efficiency based on (4.11) is also being compared to the test efficiency in Tables 4.13 and 4.14, and in Figure 4.27. Again, the calculated net section efficiency factor based on (4.11) is expected to be higher than the efficiency of a number of Korol's tests as has been explained previously. Compared to (4.10), there is a larger underestimation of the efficiency with (4.11). This indicates that the weld length ratio (L/w) is a better parameter to characterize the net section efficiency.

Overall, both proposed equations (4.10) and (4.11) for the efficiency factors are able to better capture the actual efficiency of a slotted square or rectangular HSS tension member with no end welding. Refinements to the proposed equations for the efficiency

factor will be carried out through an analytical parametric study with finite element analyses that is outside the scope of this thesis.

4.4 Guidelines to Design Full-Strength Slotted HSS Members

One of the objectives of this research project is to develop guidelines for designing an economical full-strength slotted square and rectangular HSS tension member with no end welding. However, only preliminary guidelines are proposed in this thesis. More detailed guidelines will be developed through an analytical parametric study with finite element analyses that is outside the scope of this thesis.

In order to develop the full strength of the member according to CSA-S16.1-01, the limiting strength should be governed by the gross section yielding rather than the net section fracture. Thus, the connection should be designed with the net section fracture strength being greater than the gross section yielding strength. This can be achieved by ensuring that

$$0.85A_{ne}F_u \geq A_gF_y, \quad (4.12)$$

where F_y is the yield strength, A_{ne} is the effective net cross-section area, F_u is the ultimate strength and A_g is the gross cross-section area. The effective net cross-section area (A_{ne}) is given by

$$A_{ne} = U_n A_n, \quad (4.13)$$

the product of the net section efficiency (U_n) and net section area (A_n). Thus (4.12) can be rearranged into

$$\frac{A_{ne}}{A_g} = \frac{U_n A_n}{A_g} \geq \frac{F_y}{0.85F_u} = 0.915, \quad (4.14)$$

by taking F_y equal to 350 MPa and F_u equal to 450 MPa, the respective minimum nominal yield and ultimate strengths for grade 350W steel. Normal strengths of grade 350W steel are substituted into (4.14) because it is the most commonly used grade of steel for HSS in a structure. Equation (4.14) can be rewritten in a more convenient form by requiring the gross section yield factor to be greater than unity,

$$U_F = \frac{A_{ne}}{0.915A_g} \geq 1.0. \quad (4.15)$$

When U_F is greater than unity, the gross section yielding will govern the strength of a member with a grade 350W steel.

Table 4.13 lists the gross section yield factor calculated for the square HSS specimens. Results that are lower than unity are enclosed with parentheses. There is only one configuration that gives the yield factor (U_F) that is lower than unity. This configuration corresponds to specimens with 20 mm gusset plates and a weld length ratio of 0.80 (SM3G05P20s). The low weld length ratio reduces the net section efficiency and the reduction in the efficiency is compounded by a lower net cross-section area as a result of using a 20 mm gusset plate.

The adjusted and unadjusted gross section yield factor for rectangular HSS specimens are listed in Table 4.16. The adjusted factor is calculated using the adjusted net section efficiency that assumes the corner of HSS has a higher strength than its flat portion. All rectangular HSS specimens have an unadjusted yield factors (U_F) greater than unity. However, specimens with a weld length ratio of 0.80 have the adjusted yield factor (U_F^*) less than unity. But it should be noted that the adjusted yield factor is dependent on the

correction carried out on the net section efficiency in Section 4.2.2, which has been without any rigorous study. Thus for now, the proposed preliminary guidelines should be developed based on results of square HSS specimens alone.

Based on results in Table 4.15, the HSS connection should have a minimum weld length ratio (L/w) of 0.8 and a net area to gross area ratio (A_n/A_g) of 0.9 in order to be able to fully utilize the HSS strength in the design based on CSA-S16.1-01 for grade 350W steel. Conservatively, a minimum weld length ratio of 0.9 may be used instead. If either one of the ratios falls below the limits, the other ratio has to be adjusted by using either one of the proposed efficiency factor equations of (4.10) or (4.11). For other grades of steel and design standards, a more economical design of a full-strength slotted HSS tension member with no end welding can also be achieved by using the proposed net section efficiency factor equations. In addition, it is best to keep the thickness of the gusset plate low so that the net to gross area ratio and the gross section yield factor are high.

Table 4.1 Material properties.

Coupon	A_o/A_f	Elongation (%)	Yield strength, F_y (MPa)	Ultimate strength, F_u (MPa)
HSS 89 x 89	2.29	33.5	380.3	485.0
HSS 127 x 51	2.15	29.1	404.0	448.0
Plate t=12mm	2.14	35.1	319.3	494.8
Plate t=16mm	2.41	39.0	337.7	466.0
Plate t=20mm	2.14	39.6	288.7	457.3

Table 4.2 Measured test load and displacement at peak load and failure.

Specimen No.	Average LVDT displacement (mm)		Peak static load, P_{uTest} (kN)
	At peak load	At failure	
RL5G05P16	7.99	13.85	674.6
RS5G05P16	6.44	14.40	674.4
SM5G05P16	9.06	13.96	679.9
SM5G05P16R	5.97	12.33	673.3
RL4G05P16	7.74	14.80	676.8
RS4G05P16	7.59	13.27	652.6
SM4G05P16	7.90	13.32	677.5
SM4G05P16R	8.85	14.47	674.3
RL3G05P16	8.69	18.34	615.6
RS3G05P16	6.83	16.81	641.5
SM3G05P16	9.26	16.92	650.6
SM3G05P16R	10.14	16.55	652.6
SM3G05P12	10.52	18.24	676.4
SM3G05P12R	9.18	16.27	668.8
SM5G05P12	9.46	15.47	695.6
SM5G05P12R	10.14	16.58	690.9
SM3G05P20	9.42	13.68	621.2
SM3G05P20R	6.87	11.11	634.9
SM5G05P20	7.88	13.63	666.9
SM5G05P20R	9.51	13.32	673.8
SM3G25P16	13.27	18.66	664.0
SM3G25P16R	15.06	20.27	667.7
SM3G50P16	12.59	19.84	665.5
SM3G50P16R	9.00	14.92	650.3
SM5G50P16	11.66	19.50	670.2
SM5G50P16R	14.58	20.24	670.4

Table 4.3 Test results calculated based on the geometry at the failure end.

Specimen No.	Net area, A_n (mm ²)	Gross area, A_g (mm ²)	Weld length ratio and Net area eccentricity ratio		Capacity		Efficiency	
			L/w	$\bar{x}/L$	Net area, $A_n F_u$ (kN)	Gross area, $A_g F_u$ (kN)	Net area, U_n	Gross area, U_g
RL5G05P16	1325	1479	1.33	0.24	593.6	662.4		
RS5G05P16	1310	1476	1.34	0.09	586.7	661.5	1.15	1.02
SM5G05P16	1304	1462	1.33	0.18	632.5	709.0	1.07	0.96
SM5G05P16R	1304	1458	1.34	0.17	632.2	707.3	1.06	0.95
RL4G05P16	1330	1480	1.05	0.30	595.9	662.9	1.14	1.02
RS4G05P16	1327	1486	1.06	0.11	594.4	665.7	1.10	0.98
SM4G05P16	1300	1450	1.06	0.22	630.3	703.4	1.07	0.96
SM4G05P16R	1290	1456	1.08	0.22	625.8	705.9	1.08	0.96
RL3G05P16	1323	1475	0.79	0.40	592.7	661.0	1.04	0.93
RS3G05P16	1326	1489	0.80	0.15	594.2	667.0	1.08	0.96
SM3G05P16	1302	1456	0.79	0.30	631.5	706.2	1.03	0.92
SM3G05P16R	1305	1456	0.79	0.29	632.9	706.3	1.03	0.92
SM3G05P12	1335	1457	0.79	0.28	647.3	706.5	1.04	0.96
SM3G05P12R	1338	1459	0.78	0.29	649.1	707.7	1.03	0.95
SM5G05P12	1334	1463	1.34	0.17	647.2	709.4	1.07	0.98
SM5G05P12R	1336	1460	1.34	0.17	647.9	707.9	1.07	0.98
SM3G05P20	1272	1454	0.80	0.30	616.8	705.3	1.01	0.88
SM3G05P20R	1288	1472	0.79	0.30	624.8	714.1	1.02	0.89
SM5G05P20	1273	1459	1.33	0.18	617.4	707.6	1.08	0.94
SM5G05P20R	1275	1459	1.33	0.18	618.3	707.5	1.09	0.95
SM3G25P16	1303	1457	0.80	0.29	631.9	706.7	1.05	0.94
SM3G25P16R	1309	1461	0.79	0.29	635.0	708.7	1.05	0.94
SM3G50P16	1316	1456	0.79	0.29	638.0	706.2	1.04	0.94
SM3G50P16R	1315	1462	0.78	0.29	637.8	708.9	1.02	0.92
SM5G50P16	1302	1458	1.34	0.17	631.6	706.9	1.06	0.95
SM5G50P16R	1304	1453	1.32	0.17	632.4	704.8	1.06	0.95

Table 4.4 Test specimens grouping.

Group	Specimen No.	Weld length ratio, L/w	Slot orientation	Gusset plate thickness, t (mm)	Opening length, G (mm)
GLW133	RL5G05P16	1.33	Long side	15.72	14.33
	RS5G05P16	1.34	Short side	15.71	15.74
	SM5G05P16	1.33	-	15.70	14.62
	SM5G05P16R	1.34	-	15.82	15.95
	SM5G05P12	1.34	-	12.69	11.20
	SM5G05P12R	1.34	-	12.69	12.83
	SM5G05P20	1.33	-	19.15	16.59
	SM5G05P20R	1.33	-	19.26	17.18
	SM5G50P16	1.34	-	15.73	58.30
	SM5G50P16R	1.32	-	15.64	59.61
GLW106	RL4G05P16	1.05	Long side	15.74	13.46
	RS4G05P16	1.06	Short side	15.73	15.12
	SM4G05P16	1.06	-	15.73	14.36
	SM4G05P16R	1.08	-	15.75	13.89
GLW79	RL3G05P16	0.79	Long side	15.72	15.06
	RS3G05P16	0.80	Short side	15.81	14.98
	SM3G05P16	0.79	-	15.65	16.15
	SM3G05P16R	0.79	-	15.74	14.35
	SM3G05P12	0.79	-	12.65	13.75
	SM3G05P12R	0.78	-	12.69	13.35
	SM3G05P20	0.80	-	19.16	16.06
	SM3G05P20R	0.79	-	19.07	17.26
	SM3G25P16	0.80	-	15.76	33.30
	SM3G25P16R	0.79	-	15.70	34.66
	SM3G50P16	0.79	-	15.69	59.41
	SM3G50P16R	0.78	-	15.72	60.21

Table 4.5 Adjusted efficiency for rectangular HSS specimens with $F_{u\text{Corner}} = 605 \text{ MPa}$.

Specimen No.	Peak test load, $P_{u\text{Test}}$ (kN)	Capacity		Efficiency	
		Net area, $A_n F_u^*$ (kN)	Gross area, $A_g F_u^*$ (kN)	Net area, U_n^*	Gross area, U_g^*
RL5G05P16	674.560	634.04	708.94	1.06	0.95
RS5G05P16	674.366	627.08	698.26	1.08	0.97
RL4G05P16	676.750	636.31	707.40	1.06	0.96
RS4G05P16	652.623	634.91	703.98	1.03	0.93
RL3G05P16	615.608	633.07	705.18	0.97	0.87
RS3G05P16	641.506	634.72	705.24	1.01	0.91

Table 4.6 Test results on the effect of gusset plate thickness.

Specimen No.	Weld length ratio, L/w	Gusset plate thickness, t (mm)	Gross to net area ratio, A_g/A_n	Opening aspect ratio, GW/G	Capacity	
					Net area, U_n	Gross area, U_g
SM3G05P12	0.79	12.65	1.09	1.01	1.04	0.96
SM3G05P12R	0.78	12.69	1.09	1.02	1.03	0.95
SM3G05P16	0.79	15.65	1.12	1.08	1.03	0.92
SM3G05P16R	0.79	15.74	1.12	1.19	1.03	0.92
SM3G05P20	0.80	19.16	1.14	1.29	1.01	0.88
SM3G05P20R	0.79	19.07	1.14	1.20	1.02	0.89
SM5G05P12	1.34	12.69	1.10	1.29	1.07	0.98
SM5G05P12R	1.34	12.69	1.09	1.09	1.07	0.98
SM5G05P16	1.33	15.70	1.12	1.22	1.07	0.96
SM5G05P16R	1.34	15.82	1.12	1.10	1.06	0.95
SM5G05P20	1.33	19.15	1.15	1.27	1.08	0.94
SM5G05P20R	1.33	19.26	1.14	1.21	1.09	0.95

Table 4.7 Test results on the effect of opening length.

Specimen No.	Weld length ratio, L/w	Opening length, G (mm)	Efficiency	
			Net area, U_n	Gross area, U_g
SM3G05P16	0.79	16.15	1.03	0.92
SM3G05P16R	0.79	14.35	1.03	0.92
SM3G25P16	0.80	33.30	1.05	0.94
SM3G25P16R	0.79	34.66	1.05	0.94
SM3G50P16	0.79	59.41	1.04	0.94
SM3G50P16R	0.78	60.21	1.02	0.92
SM5G05P16	1.33	14.62	1.07	0.96
SM5G05P16R	1.34	15.95	1.06	0.95
SM5G50P16	1.34	58.30	1.06	0.95
SM5G50P16R	1.32	59.61	1.06	0.95

Table 4.8 Adjusted efficiencies due to the effect of the slot orientation.

Specimen No.	Slot orientation	Side aspect ratio, net area eccentricity and weld length ratio				Efficiency	
		a/b	$\bar{x}/L$	$\bar{x}^*/L$	L/w	Net area, U_n^*	Gross area, U_g^*
RL5G05P16	Long side	2.46	0.24	0.24	1.33		
SM5G05P16	-	1.00	0.18	0.18	1.33	1.07	0.96
SM5G05P16R	-	1.00	0.17	0.17	1.34	1.06	0.95
RS5G05P16	Short side	0.40	0.09	0.18	1.34	1.08	0.97
RL4G05P16	Long side	2.46	0.30	0.30	1.05	1.06	0.96
SM4G05P16	-	1.00	0.22	0.22	1.06	1.07	0.96
SM4G05P16R	-	1.00	0.22	0.22	1.08	1.08	0.96
RS4G05P16	Short side	0.40	0.11	0.22	1.06	1.03	0.93
RL3G05P16	Long side	2.47	0.40	0.40	0.79	0.97	0.87
SM3G05P16	-	1.00	0.30	0.30	0.79	1.03	0.92
SM3G05P16R	-	1.00	0.29	0.29	0.79	1.03	0.92
RS3G05P16	Short side	0.40	0.15	0.29	0.80	1.01	0.91
SM3G05P12	-	1.00	0.28	0.28	0.79	1.04	0.96
SM3G05P12R	-	1.00	0.29	0.29	0.78	1.03	0.95
SM5G05P12	-	1.00	0.17	0.17	1.34	1.07	0.98
SM5G05P12R	-	1.00	0.17	0.17	1.34	1.07	0.98
SM3G05P20	-	1.00	0.30	0.30	0.80	1.01	0.88
SM3G05P20R	-	0.99	0.30	0.30	0.79	1.02	0.89
SM5G05P20	-	1.00	0.18	0.18	1.33	1.08	0.94
SM5G05P20R	-	1.00	0.18	0.18	1.33	1.09	0.95

Table 4.9 Test and calculated efficiencies.

Specimen No.	Test	CSA	AISC ($\bar{x}$)	AISC ($\bar{x}^*$)	Korol (2.25)	Korol ($2.26\bar{x}$)	Korol ($2.26\bar{x}^*$)
	U_n^*	U_{nc}	$U_{\bar{x}}$	$U_{\bar{x}}^*$	$U_{2.25}$	$U_{2.26\bar{x}}$	$U_{2.26\bar{x}}^*$
RL5G05P16	1.06	0.83	0.76	0.76	1.00	0.91	0.91
RS5G05P16	1.08	0.83	0.90	0.82	1.00	0.96	0.93
SM5G05P16	1.07	0.83	0.82	0.82	1.00	0.93	0.93
SM5G05P16R	1.06	0.83	0.83	0.83	1.00	0.93	0.93
RL4G05P16	1.06	0.76	0.70	0.70	0.90	0.88	0.88
RS4G05P16	1.03	0.76	0.90	0.78	0.90	0.96	0.91
SM4G05P16	1.07	0.76	0.78	0.78	0.90	0.91	0.91
SM4G05P16R	1.08	0.77	0.78	0.78	0.90	0.91	0.91
RL3G05P16	0.97	0.58	0.60	0.60	0.79	0.84	0.84
RS3G05P16	1.08	0.60	0.85	0.71	0.80	0.94	0.88
SM3G05P16	1.03	0.59	0.70	0.70	0.79	0.88	0.88
SM3G05P16R	1.03	0.59	0.71	0.71	0.79	0.88	0.88
SM3G05P12	1.04	0.59	0.72	0.72	0.80	0.89	0.89
SM3G05P12R	1.03	0.58	0.71	0.71	0.79	0.89	0.89
SM5G05P12	1.07	0.83	0.83	0.83	1.00	0.93	0.93
SM5G05P12R	1.07	0.83	0.83	0.83	1.00	0.93	0.93
SM3G05P20	1.01	0.60	0.70	0.70	0.80	0.88	0.88
SM3G05P20R	1.02	0.59	0.70	0.70	0.79	0.88	0.88
SM5G05P20	1.08	0.83	0.82	0.82	1.00	0.93	0.93
SM5G05P20R	1.09	0.83	0.82	0.82	1.00	0.93	0.93
SM3G25P16	1.05	0.60	0.71	0.71	0.80	0.88	0.88
SM3G25P16R	1.05	0.59	0.71	0.71	0.80	0.88	0.88
SM3G50P16	1.04	0.59	0.71	0.71	0.79	0.88	0.88
SM3G50P16R	1.02	0.58	0.71	0.71	0.79	0.88	0.88
SM5G50P16	1.06	0.83	0.83	0.83	1.00	0.93	0.93
SM5G50P16R	1.06	0.83	0.83	0.83	1.00	0.93	0.93

Table 4.10 Ratios of test efficiency against calculated efficiency.

Specimen No.	CSA	AISC ($\bar{x}$)	AISC ($\bar{x}^*$)	Korol (2.25)	Korol ($2.26\bar{x}$)	Korol ($2.26\bar{x}^*$)
	U_n^*/U_{nc}	$U_n^*/U_{\bar{x}}$	$U_n^*/U_{\bar{x}^*}$	$U_n^*/U_{2.25}$	$U_n^*/U_{2.26\bar{x}}$	$U_n^*/U_{2.26\bar{x}^*}$
RL5G05P16	1.29	1.39	1.39	1.06	1.42	1.54
RS5G05P16	1.30	1.19	1.30	1.08	1.35	1.29
SM5G05P16	1.30	1.30	1.30	1.07	1.40	1.40
SM5G05P16R	1.28	1.29	1.29	1.06	1.38	1.38
RL4G05P16	1.40	1.51	1.51	1.18	1.59	1.71
RS4G05P16	1.35	1.14	1.32	1.14	1.42	1.25
SM4G05P16	1.41	1.38	1.38	1.19	1.55	1.51
SM4G05P16R	1.41	1.38	1.38	1.20	1.54	1.51
RL3G05P16	1.67	1.62	1.62	1.23	1.98	1.92
RS3G05P16	1.80	1.26	1.52	1.35	1.92	1.43
SM3G05P16	1.76	1.47	1.47	1.30	2.00	1.66
SM3G05P16R	1.75	1.46	1.46	1.30	1.99	1.66
SM3G05P12	1.76	1.46	1.46	1.31	1.99	1.65
SM3G05P12R	1.77	1.45	1.45	1.30	2.00	1.63
SM5G05P12	1.29	1.29	1.29	1.07	1.39	1.39
SM5G05P12R	1.28	1.28	1.28	1.07	1.38	1.38
SM3G05P20	1.69	1.43	1.43	1.26	1.92	1.63
SM3G05P20R	1.72	1.45	1.45	1.28	1.96	1.65
SM5G05P20	1.30	1.32	1.32	1.08	1.41	1.42
SM5G05P20R	1.32	1.33	1.33	1.09	1.42	1.43
SM3G25P16	1.76	1.48	1.48	1.31	1.99	1.68
SM3G25P16R	1.78	1.48	1.48	1.32	2.01	1.68
SM3G50P16	1.78	1.47	1.47	1.31	2.01	1.66
SM3G50P16R	1.74	1.44	1.44	1.29	1.98	1.63
SM5G50P16	1.28	1.28	1.28	1.06	1.37	1.38
SM5G50P16R	1.28	1.28	1.28	1.06	1.38	1.38

Table 4.11 Test results modified from Korol (1996).

Specimen No.	HSS	Slot orientation	Weld length, L (mm)	Weld length ratio and eccentricity ratio			Net area efficiency U_n
				L/w	$\bar{x}/L$	$\bar{x}^*/L$	
1A	127x51x6.4	Long side	160	1.17	0.28	0.28	0.98
1B	127x51x6.4	Long side	157	1.14	0.28	0.28	1.04
2A	89x89x6.4	-	157	1.13	0.21	0.21	0.95
2B	89x89x6.4	-	162	1.17	0.20	0.20	1.00
3A	127x51x6.4	Short side	156	1.12	0.10	0.21	1.05
3B	127x51x6.4	Short side	161	1.16	0.10	0.20	1.05
4A	127x51x6.4	Long side	90	0.64	0.50	0.50	0.77
4B	127x51x6.4	Long side	89	0.63	0.50	0.50	0.82
5A	89x89x6.4	-	98	0.69	0.34	0.34	0.89
5B	89x89x6.4	-	85	0.60	0.39	0.39	0.80
6A	127x51x6.4	Short side	91	0.66	0.18	0.37	0.81
6B	127x51x6.4	Short side	88	0.64	0.18	0.38	0.86
7A	127x51x6.4	Long side	70	0.50	0.64	0.64	0.63
7B	127x51x6.4	Long side	66	0.47	0.68	0.68	0.59
8A	89x89x6.4	-	64	0.46	0.51	0.51	0.62
8B	89x89x6.4	-	69	0.50	0.48	0.48	0.70
9A	127x51x6.4	Short side	66	0.48	0.25	0.50	0.73
9B	127x51x6.4	Short side	65	0.47	0.25	0.51	0.66

Table 4.12 Ratios of Korol's test efficiency against calculated efficiency.

Specimen No.	CSA	AISC ($\bar{x}$)	AISC ($\bar{x}^*$)	Korol (2.25)	Korol ($2.26\bar{x}$)	Korol ($2.26\bar{x}^*$)
	U_n/U_{nc}	$U_n/U_{\bar{x}}$	$U_n/U_{\bar{x}^*}$	$U_n/U_{2.25}$	$U_n/U_{2.26\bar{x}}$	$U_n/U_{2.26\bar{x}^*}$
1A	1.24	1.35	1.35	0.99	1.40	1.52
1B	1.33	1.45	1.45	1.07	1.50	1.63
2A	1.21	1.20	1.20	0.98	1.32	1.31
2B	1.26	1.25	1.25	1.01	1.37	1.36
3A	1.35	1.18	1.34	1.10	1.41	1.23
3B	1.33	1.17	1.32	1.07	1.38	1.21
4A	1.59	1.53	1.53	1.07	1.99	1.91
4B	1.71	1.64	1.64	1.14	2.14	2.06
5A	1.69	1.35	1.35	1.19	1.96	1.56
5B	1.75	1.31	1.31	1.14	2.08	1.56
6A	1.64	0.98	1.27	1.10	1.76	1.05
6B	1.81	1.06	1.39	1.20	1.96	1.14
7A	1.67	1.74	1.74	0.97	2.24	2.34
7B	1.67	1.84	1.84	0.93	2.29	2.53
8A	1.80	1.28	1.28	0.98	2.26	1.61
8B	1.89	1.34	1.34	1.08	2.33	1.66
9A	2.04	0.97	1.45	1.14	2.26	1.07
9B	1.87	0.87	1.33	1.03	2.07	0.97

Table 4.13 Test and calculated efficiency from proposed reduction factor equations.

Specimen No.	Test	Equation (4.10)		Equation (4.11)	
	U_n^*	U_{PW}	U_n^*/U_{PW}	U_{PX}	U_n^*/U_{PX}
RL5G05P16	1.064	1.000	1.064	0.955	1.114
RS5G05P16	1.075	1.000	1.075	1.000	1.075
SM5G05P16	1.075	1.000	1.075	1.000	1.075
SM5G05P16R	1.065	1.000	1.065	1.000	1.065
RL4G05P16	1.064	1.000	1.064	0.880	1.209
RS4G05P16	1.028	1.000	1.028	0.975	1.054
SM4G05P16	1.075	1.000	1.075	0.977	1.100
SM4G05P16R	1.078	1.000	1.078	0.977	1.103
RL3G05P16	0.972	0.914	1.064	0.752	1.294
RS3G05P16	1.080	0.935	1.155	0.886	1.218
SM3G05P16	1.030	0.914	1.127	0.879	1.172
SM3G05P16R	1.031	0.916	1.125	0.882	1.170
SM3G05P12	1.045	0.923	1.132	0.895	1.167
SM3G05P12R	1.030	0.909	1.133	0.891	1.157
SM5G05P12	1.075	1.000	1.075	1.000	1.075
SM5G05P12R	1.066	1.000	1.066	1.000	1.066
SM3G05P20	1.007	0.928	1.086	0.878	1.147
SM3G05P20R	1.016	0.918	1.107	0.874	1.163
SM5G05P20	1.080	1.000	1.080	1.000	1.080
SM5G05P20R	1.090	1.000	1.090	1.000	1.090
SM3G25P16	1.051	0.929	1.131	0.886	1.185
SM3G25P16R	1.051	0.921	1.141	0.885	1.187
SM3G50P16	1.043	0.916	1.139	0.887	1.176
SM3G50P16R	1.020	0.911	1.119	0.884	1.154
SM5G50P16	1.061	1.000	1.061	1.000	1.061
SM5G50P16R	1.060	1.000	1.060	1.000	1.060

Table 4.14 Korol's test and calculated efficiency from proposed reduction factor equations.

Specimen No.	Test	Equation (4.10)		Equation (4.11)	
	U_n	U_{PW}	U_n/U_{PW}	U_{PX}	U_n/U_{PX}
1A	0.975	1.000	0.975	0.904	1.079
1B	1.038	1.000	1.038	0.897	1.158
2A	0.949	1.000	0.949	0.988	0.961
2B	0.996	1.000	0.996	0.997	1.000
3A	1.054	1.000	1.054	0.986	1.068
3B	1.048	1.000	1.048	0.995	1.054
4A	0.769	0.755	1.019	0.628	1.224
4B	0.816	0.748	1.091	0.621	1.313
5A	0.890	0.813	1.095	0.824	1.081
5B	0.799	0.714	1.119	0.760	1.052
6A	0.806	0.778	1.035	0.792	1.018
6B	0.863	0.753	1.145	0.776	1.112
7A	0.627	0.596	1.051	0.449	1.395
7B	0.592	0.566	1.046	0.401	1.476
8A	0.622	0.561	1.108	0.609	1.021
8B	0.703	0.599	1.175	0.654	1.075
9A	0.729	0.574	1.270	0.628	1.161
9B	0.656	0.570	1.150	0.618	1.061

Table 4.15 Gross section yielding factor for square HSS specimen.

Specimen No.	Weld length ratio, L/w	Net to gross area ratio		Gross section yield factor, U_F
		A_n/A_g	A_{ne}/A_g	
SM5G05P20	1.33	0.873	0.943	1.030
SM5G05P20R	1.33	0.874	0.952	1.041
SM5G05P16	1.33	0.892	0.959	1.048
SM5G05P16R	1.34	0.894	0.952	1.040
SM5G50P16	1.34	0.893	0.948	1.036
SM5G50P16R	1.32	0.897	0.951	1.040
SM5G05P12	1.34	0.912	0.981	1.072
SM5G05P12R	1.34	0.915	0.976	1.067
SM4G05P16	1.06	0.896	0.963	1.053
SM4G05P16R	1.08	0.886	0.955	1.044
SM3G05P20	0.80	0.874	(0.881)	(0.963)
SM3G05P20R	0.79	0.875	(0.889)	(0.972)
SM3G05P16	0.79	0.894	0.921	1.007
SM3G05P16R	0.79	0.896	0.924	1.010
SM3G25P16	0.80	0.894	0.940	1.027
SM3G25P16R	0.79	0.896	0.942	1.030
SM3G50P16	0.79	0.903	0.942	1.030
SM3G50P16R	0.78	0.900	0.917	1.003
SM3G05P12	0.79	0.916	0.957	1.046
SM3G05P12R	0.78	0.917	0.945	1.033

Table 4.16 Adjusted and unadjusted gross section yielding factor for rectangular HSS specimen.

Specimen No.	Weld length ratio, L/w	Net to gross area ratio			Gross section yield factor	
		A_n/A_g	$(A_{ne}/A_g)^*$	A_{ne}/A_g	U_F^*	U_F
RL5G05P16	1.33	0.896	0.953	1.018	1.042	1.113
RS5G05P16	1.34	0.887	0.954	1.007	1.042	1.101
RL4G05P16	1.05	0.899	0.956	0.934	1.045	1.020
RS4G05P16	1.06	0.893	0.918	1.026	1.003	1.122
RL3G05P16	0.79	0.897	(0.872)	0.984	(0.953)	1.076
RS3G05P16	0.80	0.891	(0.900)	0.962	(0.984)	1.051

Note: * indicates that the values are calculated using the adjusted net section efficiency U_n^* .

Figure 4.1 Failure of SM3G05P16, a typical failure near the end of the gusset plate.

Figure 4.2 Failure of RS3G05P16, a typical failure at the end of the semi-circle of the opening.

Figure 4.3 A typical LVDT displacement versus load curve for the test.

Figure 4.4 Stress versus strain for HSS 127 x 51 tension coupons from flat and close to corner regions.

Figure 4.5 Unadjusted net section efficiency versus weld length ratio, L/w .

Figure 4.6 Adjusted net section efficiency versus weld length ratio, L/w .

Figure 4.7 Stress flow around the opening at the end of the gusset plate.

Figure 4.8 Adjusted gross section efficiency versus weld length ratio, L/w .

Figure 4.9 Strain distributions for different weld length at an average net section stress of 389MPa.

Figure 4.10 Net section efficiency versus gusset plate thickness.

Figure 4.11 Net section efficiency versus cross-section area ratio, A_g/A_n .

Figure 4.12 Net section efficiency versus the aspect ratio of the opening, GW/G .

Figure 4.13 Strain distributions with different gusset plate thicknesses for low weld length specimens at an average net section stress of 420MPa.

Figure 4.14 Strain distributions with different gusset plate thicknesses for high weld length specimens at an average net section stress of 400MPa.

Figure 4.15 Gross section efficiency versus gusset plate thickness.

Figure 4.16 Net section efficiency versus opening length.

Figure 4.17 Adjusted net section efficiency versus aspect ratio (a/b) for G05P16 specimen group.

Figure 4.18 Adjusted net section efficiency versus eccentricity ratio, $\bar{x}/L$, for G05 specimen group.

Figure 4.19 Distance from weld to centroid versus aspect ratio, a/b .

Figure 4.20 Adjusted net section efficiency versus modified eccentricity ratio, $\bar{x}^*/L$, for G05 specimen group.

Figure 4.21 Deformation at failure versus the weld length ratio, L/w .

Figure 4.22 Strain distribution for square HSS with different weld lengths at an average LVDT displacement of 4 mm.

Figure 4.23 Deformation at failure versus gusset plate thickness.

Figure 4.24 Deformation at failure versus opening length.

Figure 4.25 Net section efficiency versus weld length ratio, L/w .

Figure 4.26 Net section efficiency versus eccentricity ratio, $\bar{x}/L$.

Figure 4.27 Net section efficiency versus modified eccentricity ratio, $\bar{x}^*/L$.

CHAPTER 5 NUMERICAL ANALYSIS

Finite element analyses of the tests were carried out to help clarify the findings in Chapter 4 and to provide insights into the behavior of the connection. Since the objective of the finite element analyses is to acquire a better understanding of the connection, only a finite element model with a reasonable accuracy is required. For this reason, no detailed mesh sensitivity study was carried out nor any significant attempt was made to duplicate test results exactly in the simulation. Finite element analyses of the tests were carried out with ABAQUS (2002).

5.1 Material Properties

In the finite element simulation, gusset plates and HSS members are assumed to deform according to the incremental flow plasticity theory with isotropic hardening. Thus, the true stress versus true plastic strain relationship data of the material are required to be provided in the input file in order to carry out the numerical analyses with ABAQUS.

The true stress versus true plastic strain data of the material were approximated according to Khoo et al. (2002) using the combination of the pre-peak load versus axial deformation relationship and the post-peak load versus transverse deformation relationship from a tension material test. Up to the peak load, the true stress versus true plastic strain relationship is obtained directly from the load versus axial extensometer strain data. The engineering stress (σ^e) and engineering strain (ϵ^e) in the longitudinal direction are given by

$$\sigma^e = \frac{F}{A_o} \text{ and} \quad (5.1)$$

$$\varepsilon^e = \frac{L}{L_o} - 1 \quad (5.2)$$

respectively, where

F = the load,

A_o = the original cross-section area,

L = the current length of the gauge, and

L_o = the original gauge length.

The true stress (σ^t) and true plastic strain (ε^p) are respectively given by

$$\sigma^t = \sigma^e (1 + \varepsilon^e) \text{ and} \quad (5.3)$$

$$\varepsilon^t = \varepsilon^p + \frac{\sigma^t}{E} \quad (5.4)$$

where E is the elastic modulus. After the peak load, the true stress (σ^t) and true plastic strain (ε^p) are estimated by

$$\sigma^t = \frac{F}{A} \text{ and} \quad (5.5)$$

$$\varepsilon^p = \ln\left(\frac{A_o}{A}\right) - \frac{\sigma^t}{E}, \quad (5.6)$$

where A is the current cross-section area. Equations (5.5) and (5.6) are formulated based on the assumption that the state of stress across the tension coupon is still uniaxial. Thus as necking progresses, this assumption becomes less valid and so are the values given by (5.5) and (5.6). Naqvi (2004) showed that the cross-section area (A) should be taken as

the product of the average cross-section dimension of a rectangular coupon when using (5.5). The cross-section area in (5.5) and (5.6) is taken as

$$A = b_{avg} \cdot t_{avg} , \quad (5.7)$$

where b_{avg} is the average of the corner and mid-point widths, and t_{avg} is the average of the corner and mid-point thicknesses. A more detailed description of the cross-section area calculation is provided in Appendix B. The true stress versus true plastic strain relationship is assumed to be equal to the 50% slope of the linear least square fitting line on the projected true stress versus true plastic strain data after the peak load that are calculated using (5.5) and (5.6). The procedure to approximate the true stress versus true plastic strain for HSS 89 x 89 is shown in Figure 5.1. The true plastic strain at fracture (ϵ_f^p) can be approximated by

$$\epsilon_f^p = \ln \left(\frac{A_o}{A_f} \right) , \quad (5.8)$$

which is about 0.8 using tension coupon test data in Table 4.1. A_f is the final cross-section area at fracture of tension coupon. The following elastic modulus (E), Poisson's ratio (ν), and true plastic strain at fracture (ϵ_f^p) or equivalent plastic strain at fracture (ϵ_{eqf}^p) are used in the finite element analyses of the tests.

$$E = 200000 \text{ MPa},$$

$$\nu = 0.3 \text{ and}$$

$$\epsilon_{eqf}^p = \epsilon_f^p = 0.8 .$$

For uniaxial loading, ϵ_f^p is the true plastic strain at fracture. For multiaxial loading, this value can be taken as equal to the equivalent plastic strain at fracture. The equivalent plastic strain (ϵ_{eq}^p) is given by

$$\epsilon_{eq}^p = \int d\epsilon_{eq}^p \quad \text{with} \quad (5.9)$$

$$d\epsilon_{eq}^p = \left(\frac{2}{3} d\epsilon_{ij}^p d\epsilon_{ij}^p \right)^{\frac{1}{2}}, \quad (5.10)$$

where ϵ_{ij}^p is the plastic strain tensor. The extensometer used in the test is not sensitive enough to measure the very small linear elastic deformation of the tension coupon accurately. But there is no problem using the extensometer to measure the remaining plastic deformation of the coupon when the deformation is large. This can be seen in the consistency of the stress versus extensometer strain graphs after yielding as shown in Appendix B. Since it is well established that the elastic modulus of steel is about 200 000 MPa. Thus the elastic modulus is simply taken as 200000 MPa in the analysis. The exact value of the elastic modulus is not important since the finite element analysis involved significant plastic deformation in the HSS that greatly exceeds the proportional limit. The true stress versus true plastic strain curves used in analyses for HSS and gusset plates are shown in Figures 5.2 and 5.3, and their numerical values are listed in Tables 5.1 and 5.2.

5.2 Finite Element Model

The test specimen is modeled with a S4 four-node bi-linear finite membrane strain shell element that allows the element thickness to change with strain. Making use of

symmetries, only one-eighth of the specimen is modeled in the finite element analysis. However, the weld was not explicitly modeled in the analysis. Instead, it was indirectly modeled by constraining the HSS and the gusset plate to have the same displacement and rotation at nodal points that are supposedly connected by the weld. In the model, this was achieved by tying one node in the HSS to three nodes in the gusset plate. The width of the gusset plate that is directly connected to the weld is almost equal to the width of three nodes. Multiple node sets along the weld line were constrained in the modeling. An example of the mesh used in the finite element analyses is shown in Figure 5.4. The cross-section of the HSS is assumed to have a constant thickness in the modeling.

The Finite element analyses were carried out using the non-linear geometric analysis option in ABAQUS. This option is able to account for large deformation and finite strain. The material is assumed to deform according to the incremental flow theory of plasticity with isotropic hardening. Material properties used in the analyses have been described in Section 5.1. Both the corner and the flat portion of HSS are assumed to have the same material properties. Any strength improvement of the corner due to cold-working is neglected in the modeling. All analyses were carried out using displacement control in order to capture the descending branch of the load versus displacement relationship of the test by applying a uniform axial displacement along the width at the end of the gusset plate.

5.3 Results of Finite Element Analyses

Finite Element Analyses were carried out for specimens in the current test program and a few specimens from Korol (1996). Only specimens with the weld length ratio (L/w)

close to 1 from Korol (1996) were simulated. Numerical simulation of Korol's tests were carried out using material properties of HSS 89 x 89, HSS 127 x 51 and 16 mm gusset plate from this test program.

5.3.1 Overall Results

Figure 5.5 and 5.6 show the test and predicted net stress versus deformation curves for SM3G05P16 and SM5G05P16. Overall, the shape of the predicted curve up to the peak load is close to that from the test. The predicted curve shows a sharp change in the slope at the initial stage of the inelastic deformation, but the experimental data show a more gradual change. This is due to the fact that tension coupons for the square HSS were cut from failed specimens that may have experienced some additional yielding during the test. Another reason is that HSS has residual stress and strain. However, a coupon cut from the HSS does not retain the residual stress because it can deform freely. For this reason, the stress versus strain curve from a coupon test will exhibit a higher proportional limit and a sharper elastic-plastic transition than a HSS test specimen.

The predicted peak stress is also lower than the measured peak stress because the corner of HSS is assumed to have the same strength as its flat portion. However, the actual corner strength is higher due to cold-working. In the analysis, the specimen is considered to have failed and the analysis terminated when any point within the specimen reaches the equivalent plastic strain fracture limit. A slow progressive failure of the specimen is not considered in the analysis. For this reason, the predicted curve for SM3G05P16 in Figure 5.5 terminates before reaching zero slope because of the high stress concentration. Furthermore, the equivalent plastic strain fracture limit used in the

analysis may also have been too conservative. But for SM5G05P16 in Figure 5.6, the predicted curve manages to reach a plateau. However, the predicted curve does not start to drop sooner, because the mesh size used may have been too coarse. The coarser the mesh, the longer it takes to initiate strain localization. The contour plot of the von Mises stress for SM5G05P16 is shown in Figure 5.7. It clearly illustrates the typical stress concentration in HSS at the end of the gusset plate.

Results of the analyses are shown in Table 5.3. In order to facilitate the discussion, the following terms are used. The ultimate load is defined as

$$P_{u_calc} = F_u A_n, \quad (5.11)$$

where F_u is the ultimate strength at the flat part of HSS and A_n is the net cross-section area. The predicted efficiency is defined as

$$U_{n_anal} = \frac{P_{u_anal}}{P_{u_calc}}, \quad (5.12)$$

where P_{u_anal} is the peak load predicted by the finite element analysis. In Table 5.3, U_{n_test} is the measured net section efficiency from Chapter 4.

The analyses show that there is no change in the efficiency when the weld length ratio is greater than 1, and the minimum efficiency is around 1.0. This is consistent with results from the test that show there is little change in the net section efficiency when the weld length ratio is greater than 1. In all cases, the numerical simulation underestimates the net section efficiency of the specimen. The underestimation is around 5% for the square specimen and around 12% for the rectangular specimen. One of the reasons for the underestimation is that the corner of HSS is expected to have a higher strength than its flat part. However, only material properties from the flat portion of the HSS were used in the

numerical analyses. Thus the numerical simulation gives the lower bound of the specimen efficiency.

Comparisons to the Korol's tests are shown in Table 5.4. In general, the numerical simulation overestimates the measured net section efficiency of the test. As mentioned in Chapter 4, the efficiency reported for Korol's test may actually be higher or lower depending on the rate of loading and procedures used in testing the specimen and the tension coupon. Based on results of the analyses and the measured efficiency of a test specimen with a comparable connection detail, the reported efficiency for Korol's test may have been underestimated by 5 to 10%.

The proposed equations for calculating the efficiency factors in Section 4.3 are developed using test results of cold-formed HSS. Compared to a cold-formed HSS, a hot-formed HSS will have a lower net section efficiency since the corner will not be significantly stronger than its flat region. Thus the efficiency for hot-formed HSS will most likely be similar to results of the numerical simulation in Table 5.3. From the preliminary assessment by looking at the test data against the proposed efficiency factor equations in Figures 4.25 and 4.27, there is a good possibility that the proposed equation may be applicable to hot-formed HSS. However, a more detailed study is required to assess the applicability of these equations to a hot-formed HSS.

5.3.2 Ductility

From the test observation, the ductility of the specimen was found to decrease with an increase in the weld length. One of the reasons can be attributed to the localized deformation of the HSS in the region of the opening at the end of the gusset plate. As this

region starts to neck and unload, other regions of the HSS have to pick up the extra load. For the specimen with a high weld length ratio, there is less stress concentration and the cross-section is more uniformly loaded. Thus when the region close to the opening starts to unload, there is less reserved capacity available in other regions to pick up the load for a high weld length ratio specimen than for a low weld length ratio specimen. Thus for a low weld length ratio specimen, it can undergo more deformation after the region at the opening starts to neck and unload. Figures 5.8 and 5.9 show the strain distribution in HSS at the end of the gusset plate from numerical analyses of square G05P16 specimen group with three weld length ratios at the LVDT displacement of 4 mm. Results of the numerical simulation confirm findings in the test that show that the high weld length specimen (SM5G05P16) has a higher and more uniform strain distribution than SM3G05P16. But the low weld length specimen (SM3G05P16) has a much higher strain close to the gusset plate.

5.3.3 Slot Orientation

Results of the predicted net section efficiency for the connection configuration of G05P16 specimen group with different HSS side aspect ratio (a/b) and weld length ratio are shown in Figure 5.10. The analyses show that slotting the rectangular HSS on the short side has a 5% higher efficiency than slotting the rectangular HSS on the long side. However, tests show that the aspect ratio has little effect on the efficiency when the weld length is long. Thus, more detailed study is required to characterize the combined effect of weld length, side aspect ratio and different material strength for the corner and the flat region.

In the test, RS4G05P16 was found to have a net section efficiency that is 5% lower than RS5G05P16. It was reasoned that the discrepancy is due to the variability in testing. Thus in fact, the efficiency of RS4G05P16 should be the same as RS5G05P16. This conclusion is supported by results of the numerical analyses, which show that the efficiency of RS4G05P16 is equal to that of RS5G05P16.

5.3.4 Opening Size

The stress flow around the opening at the end of the gusset plate induces transverse stress that stiffens the cross-section. Figure 5.11 shows the vector plot of the typical maximum principal stress distribution around the opening. It can be seen that the maximum principal stress vector is not parallel to the longitudinal axis of the specimen as a result of having to flow around the opening. Thus it induces transverse stress in HSS.

Figure 5.12 shows the transverse stress distribution in HSS for the square HSS specimens at the end of the gusset plate at a net stress of 420 MPa. The specimens have a weld length ratio (L/w) around 0.8 and three different gusset plate thicknesses. As stated in Section 4.2.5, a wider opening or a larger opening aspect ratio (GW/W) induces a larger transverse stress. This is supported by results of the numerical analyses where SM3G05P12 has a lower overall transverse stress than SM3G05P20. While a wider opening improves the stiffening effect due to the transverse stress, but it also increases the stress concentration. This can be seen in Figure 5.13 for the same group of specimens where SM3G05P20 has the highest strain at the location of strain gauge G1.

Figure 5.14 shows the von Mises stress distribution in HSS for the square HSS specimens at the end of the gusset plate. It shows that the specimen with a wider opening

or a thicker gusset plate (SM3G05P20) has a lower overall von Mises stress across the section. This translates into a greater potential for taking additional load compared to SM3G05P12. If the stress concentration is not high, there is a good possibility that the potential strength increase associated with a thicker gusset plate can be realized. For this reason, SM5G05P20 has a higher net section efficiency than SM5G05P12 and SM3G05P20 has a lower efficiency than SM3G05P12. The SM3 test specimen group has a shorter weld length than the SM5 specimen group and as a result, a higher stress concentration.

The net section efficiency versus opening length at the end of the slot is shown in Figure 5.15. The numerical analyses agree with the trend found in the test on the effect of opening length for a high weld length specimen (GLW133), which is shown in Figure 4.16. The specimen with a 13 mm long opening has a 1% better efficiency than the one with a 58 mm long opening when the weld length is long (GLW133). But when the weld length is short (GLW79), the analyses instead show a drop of 5% in the efficiency when the opening length reduces from 58 mm to 13 mm. In the test, the efficiency difference was only about 2%. The reason is due to the increase in the stress concentration with a shorter opening and an equivalent plastic strain fracture limit used that may have been too conservative. In addition, the contribution of the fillet weld in helping to reduce the stress concentration was not considered in the modeling. This contribution can be added by thickening parts of the HSS to include the fillet weld.

Table 5.1 True stress versus true plastic strain data for HSS.

127 x 51 x 4.8		89 x 89 x 4.8	
True plastic strain (mm/mm)	True stress (MPa)	True plastic strain (mm/mm)	True stress (MPa)
0.00000	356.4	0.00000	360.0
0.00612	387.0	0.00075	385.0
0.00688	392.0	0.00115	400.0
0.01692	416.0	0.00200	420.0
0.03109	432.2	0.00440	445.1
0.04527	445.4	0.00800	455.0
0.06074	459.0	0.02000	477.4
0.07430	471.3	0.02400	483.8
0.09235	484.3	0.04000	498.7
0.11006	496.2	0.06100	507.5
0.12333	504.7	0.08300	520.6
0.13743	515.1	0.09600	531.3
0.15101	518.0	0.11000	541.4
0.16969	522.1	0.13800	550.4
0.19202	526.9	0.16300	567.1
0.21030	530.9	0.20000	575.2
0.22891	534.9	0.26200	589.0
0.23535	536.3	0.33000	603.8
0.47827	589.0	0.46100	632.4
0.64523	625.3	0.53800	649.3
0.83574	666.6	0.58500	659.5
0.90000	680.6	0.77800	701.8
1.00000	702.3	0.80000	706.7
1.40000	789.1	0.90000	728.6
		1.00000	750.5
		1.40000	838.1

Table 5.2 True stress versus true plastic strain data for gusset plate.

20 mm gusset plate		16 mm gusset plate		12 mm gusset plate	
True plastic strain (mm/mm)	True stress (MPa)	True plastic strain (mm/mm)	True stress (MPa)	True plastic strain (mm/mm)	True stress (MPa)
0.00000	300.8	0.00000	343.7	0.00000	320.0
0.00829	297.5	0.01018	344.0	0.00801	320.0
0.01800	300.0	0.03408	403.8	0.02609	375.6
0.03393	357.5	0.04709	426.2	0.04305	416.2
0.04729	386.2	0.06493	454.4	0.06736	467.5
0.06021	412.0	0.08685	485.0	0.09356	513.6
0.07282	435.2	0.11075	513.3	0.11514	544.4
0.09221	467.1	0.13115	533.3	0.13879	570.8
0.10721	488.8	0.15476	551.7	0.16323	590.0
0.12438	510.2	0.17569	563.6	0.17680	597.1
0.14092	527.6	0.23111	589.7	0.21470	621.4
0.15670	541.0	0.27225	598.5	0.26544	632.5
0.17384	552.3	0.37780	621.3	0.37612	656.9
0.20584	563.9	0.56046	660.6	0.60179	706.4
0.23489	579.1	0.72595	696.3	0.79475	748.8
0.27750	588.2	0.89873	733.5	0.90000	772.0
0.34515	602.7	1.00000	755.4	1.00000	793.9
0.41000	616.5	1.40000	841.5	1.40000	881.8
0.54190	644.7				
0.69740	677.9				
1.00000	742.5				
1.40000	827.9				

Table 5.3 Results of finite element analyses.

Specimen No.	Ultimate load (kN)		Efficiency and efficiency ratio		
	Calculated, P_{u_calc}	Analysis, P_{u_anal}	Analysis, U_{n_anal}	Test, U_{n_test}	U_{n_test}/U_{n_anal}
RL5G05P16	620.0	616.8	0.99	1.14	1.14
RS5G05P16	620.0	642.3	1.04	1.15	1.11
SM5G05P16	671.2	687.4	1.02	1.07	1.04
SM5G05P16R	671.2	687.4	1.02	1.06	1.03
SM5G50P16	671.2	679.9	1.01	1.06	1.05
SM5G50P16R	671.2	679.9	1.01	1.06	1.05
SM5G05P12	689.8	704.0	1.02	1.07	1.05
SM5G05P12R	689.8	704.0	1.02	1.07	1.05
SM5G05P20	652.6	670.8	1.03	1.08	1.05
SM5G05P20R	652.6	670.8	1.03	1.09	1.06
RL4G05P16	620.0	613.9	0.99	1.14	1.15
RS4G05P16	620.0	640.4	1.03	1.10	1.06
SM4G05P16	671.2	687.2	1.02	1.07	1.05
SM4G05P16R	671.2	687.2	1.02	1.08	1.05
RL3G05P16	620.0	569.4	0.92	1.04	1.13
RS3G05P16	620.0	590.4	0.95	1.08	1.13
SM3G05P16	671.2	640.2	0.95	1.03	1.08
SM3G05P16R	671.2	640.2	0.95	1.03	1.08
SM3G25P16	671.2	667.4	0.99	1.05	1.06
SM3G25P16R	671.2	667.4	0.99	1.05	1.06
SM3G50P16	671.2	670.6	1.00	1.04	1.04
SM3G50P16R	671.2	670.6	1.00	1.02	1.02
SM3G05P12	689.8	662.6	0.96	1.04	1.08
SM3G05P12R	689.8	662.6	0.96	1.03	1.07
SM3G05P20	652.6	626.6	0.96	1.01	1.05
SM3G05P20R	652.6	626.6	0.96	1.02	1.06

Table 5.4 Results of finite element analyses for Korol's tests.

Specimen No.	Ultimate load (kN)		Efficiency and efficiency ratio		
	Calculated, P_{u_calc}	Analysis, P_{u_anal}	Analysis, U_{n_anal}	Test, U_{n_test}	U_{n_test}/U_{n_anal}
1A - HSS 127x51 long	792.6	800.2	1.01	0.98	0.97
1B - HSS 127x51 long	792.6	800.2	1.01	1.04	1.03
2A - HSS 89x89	858.0	884.0	1.03	0.95	0.92
2B - HSS 89x89	858.0	884.0	1.03	1.00	0.97
3A - HSS 127x51 short	792.6	844.0	1.06	1.05	0.99
3B - HSS 127x51 short	792.6	844.0	1.06	1.05	0.98

Figure 5.1 The procedure to approximate true stress versus true plastic strain for HSS 89 x 89.

Figure 5.2 True stress versus true plastic strain curves for HSS.

Figure 5.3 True stress versus true plastic strain curve for gusset plates.

Figure 5.4 The typical finite element mesh for the specimen.

Figure 5.5 Test and predicted net stress versus deformation curves for SM3G05P16.

Figure 5.6 Test and predicted net stress versus deformation curves for SM5G05P16.

Figure 5.7 Contour plot of the von Mises stress for SM5G05P16 at an average net stress of 497 MPa.

Figure 5.8 Test and predicted strain distribution for square G05P16 specimen group with different weld length at an average LVDT displacement of 4 mm.

Figure 5.9 Predicted strain distribution across HSS for square G05P16 specimen group with different weld length at the LVDT displacement of 4 mm.

Figure 5.10 The predicted net section efficiency for the connection configuration of G05P16 specimen group with different HSS side aspect ratio (a/b) and weld length ratio.

Figure 5.11 Vector plot of the maximum principal stress for SM3G05P16 at peak load around the opening.

Figure 5.12 Predicted transverse stress distribution across HSS for different gusset plate thickness with a low weld length at an average net section stress of 420 MPa.

Figure 5.13 Test and predicted strain distribution for different gusset plate thickness with a low weld length at an average net section stress of 420 MPa.

Figure 5.14 Predicted von Mises stress distribution at an average net section stress of 420 MPa across HSS for different gusset plate thickness with a low weld length.

Figure 5.15 Net section efficiency versus the opening length.

CHAPTER 6 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

A literature review on the effect of shear lag on the tension member connection was carried out in Chapter 2. Various factors affecting shear lag were discussed. Only a few studies have been carried out to investigate the effect of shear lag on a slotted square or rectangular HSS. From results of the limited studies, it was found that provisions to account for shear lag in the design standards are overly conservative when applied to a slotted tubular tension member.

Thus, this study was undertaken to expand the knowledge of the shear lag effect on a slotted square or a rectangular HSS, particularly at the weld length ratio (L/w) around 1. Two HSS shapes of HSS 89 x 89 x 4.8 and HSS 127 x 51 x 4.8 were used in this study. A total of twenty-six specimens were tested. These specimens consisted of thirteen different configurations that have different weld length ratio, gusset plate thickness, length of slot opening and slot orientation.

Tension coupons fabricated from gusset plates and HSS were tested to obtain material properties and the stress versus strain relationship needed to analyze the test results and carry out finite element analyses. For the square HSS, tension coupons were extracted from the failed test specimens rather than the spare piece that has been set aside. All specimens and tension coupons were tested until fracture under displacement control with regular stoppages to record the static reading.

Test results were analyzed and studied. Effects of weld length ratio, gusset plate thickness, length of slot opening and slot orientation on the net section efficiency were

discussed. In order to combine results of both square and rectangular HSS specimens in the discussion, the calculated experimental net section efficiency of the rectangular HSS specimen was adjusted by using different tensile strengths for its corner and its flat region.

Based on the test results, preliminary guidelines were proposed for designing an economical full-strength slotted rectangular and square tension member without end welding. Together with results from Korol (1994), experimental data were compared to provisions to account for shear lag in CSA-S16.1-01 and AISC Design Specification for Steel Hollow Structural Sections. Recommended modifications to provisions in these design standards were proposed to better reflect the actual strength of a slotted tubular tension member.

Finite element analyses of the test specimens were carried out and discussed in order to help clarify findings from the test results and to provide greater insights into the behavior of a slotted tubular tension member. Material properties from coupon tests were used in the analyses. The true stress versus true plastic strain relationship beyond the point corresponding to the peak load in the coupon test was approximated by a simple linear projection. The finite element analysis is terminated when the equivalent plastic strain of 0.8 has been reached in any point of the test specimen.

6.2 Conclusions

The following conclusions can be drawn based on results of the experiment and finite element analyses.

- 1) Provisions for shear lag prescribed in CSA S16.1-01 and AISC (2000) are overly conservative when applied to slotted square and rectangular HSS tension member

without end welding. Two equations for calculating the net section efficiency factor were proposed. One equation is a function of weld length ratio and the other is a function of net section eccentricity ratio. The weld length ratio is found to be a better parameter to characterize the net section efficiency than the net section eccentricity ratio.

- 2) The weld length is the main factor that affects shear lag. For a weld length ratio (L/w) greater than 1, a 100% net section efficiency can be used in calculating the net section fracture strength of the member. There is little to no change in the net section efficiency when the weld length ratio is greater than 1.
- 3) The thickness of gusset plate, slot opening length and orientation of the slot have only minor effect on shear lag.
- 4) Both the restraint by the gusset plate against the transverse contraction of HSS and the stress flow around the opening induce transverse stress that effectively stiffens the HSS section at the end of gusset plate. For this reason, the connection is able to achieve a net section efficiency greater than 1 when the weld length ratio is high.
- 5) A thicker gusset plate increases the net section efficiency when the weld length ratio is high, but reduces the net section efficiency when the weld length ratio is low. Thus, the gross section efficiency is not significantly affected by the gusset plate thickness when the weld length ratio is high because the increase in the net section efficiency offsets the reduction in the net area.
- 6) If the net section eccentricity ($\bar{x}$) is used in calculating the net section efficiency, it should not be lower than that given by an equivalent square HSS with the same

circumference. Without this lower bound limit, the calculated net section efficiency may be overestimated for some of the rectangular HSS.

- 7) Similar to findings by Korol (1996), making the connection by slotting the long side of a rectangular HSS produces a lower net section efficiency compared to that by slotting the short side. However, the difference in the efficiency is small and there is no difference when the weld length ratio is high.
- 8) In the study, the slot opening length did not significantly change the net section efficiency. For most situations, the slot opening length can be ignored when calculating the net section efficiency.
- 9) The HSS connection should have a minimum weld length ratio (L/w) of 0.9 and a net area to gross area ratio (A_n/A_g) of 0.9 in order to fully utilize the HSS strength in the design based on CSA-S16.1-01 for grade 350W steel. For other grades of steel and design standards, a more economical design of a full-strength slotted HSS tension member with no end welding can also be achieved by using the proposed net section efficiency factor equations. However, it is best to keep the gusset plate thickness low so that both the net to gross area ratio and the gross section yield factor are high.

6.3 Recommendations

- 1) The finite element model in this study has not been thoroughly examined and refined. Thus, developing an improved finite element model that has been properly validated using the test data will enhance the confidence in the results of the finite element analyses. A detailed parametric finite element analyses study carried out using the improved model will be able to better quantify the effect of different factors, such as

weld length, higher tensile strength at the corner of HSS and slot orientation, on the net section efficiency.

- 2) The proposed guidelines for designing a full-strength slotted tubular tension member and improvements to shear lag provisions in the design codes were mainly developed based on test results. Further improvements can be made on the proposed guidelines and proposed net section efficiency factor equations by utilizing results of the detail parametric finite element analyses study.
- 3) The current study only looked at slotted rectangular and square HSS connections without end welding. A further research on slotted rectangular and square HSS connections with end welding is required to complete the study on the effect of shear lag on slotted rectangular and square HSS connections.
- 4) In both Korol's (1996) and current studies, HSS members tested are relatively small. Even though the size effect can probably be neglected, its effect on the net section efficiency still needs to be investigated further with either additional tests or through numerical simulations.
- 5) Only one size of weld has been used in this test program. A larger weld size can reduce the stress concentration due to shear lag because it is able to transfer the load directly over a larger cross-section area. The reverse is true when the weld size is small. Additional studies are required to study the effect of weld size on the net section efficiency.
- 6) The proposed equations for calculating the net section efficiency were developed based on test results of cold-formed HSS that has higher corner strength. Additional

research is required to study the validity of these proposed equations when applied to hot-formed HSS.

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APPENDIX A: SPECIMEN MEASUREMENT

Every specimen was measured on all sides of both ends, and all data shown in Tables 3.2 to 3.5 were the average value for each end. Detailed dimensions at the failed end and opposite to the failed end for each specimen were presented separately.

Tables A.1 to A.4 present the measured data for HSS and connection at the failed end. Tables A.5 and A.6 present the measured data for HSS and connection opposite to the failed end.

Table A.1 Measured HSS gross section properties at the failed end.

Test specimen	Circumference, c (mm)	Width, a (mm)	Width, b (mm)	Thickness, t' (mm)
RL5G05P16	343.00	127.04	51.63	4.52
RS5G05P16	343.00	51.39	127.30	4.50
SM5G05P16	343.00	89.61	89.77	4.42
SM5G05P16R	343.00	89.50	89.54	4.41
RL4G05P16	343.00	127.15	51.59	4.50
RS4G05P16	343.50	51.45	127.41	4.50
SM4G05P16	343.00	89.36	89.56	4.39
SM4G05P16R	343.00	89.61	89.51	4.40
RL3G05P16	343.00	127.08	51.46	4.47
RS3G05P16	343.00	51.32	127.21	4.50
SM3G05P16	343.00	89.93	89.67	4.40
SM3G05P16R	342.50	89.42	89.51	4.42
SM3G05P12	342.50	89.38	89.56	4.42
SM3G05P12R	343.00	89.56	89.50	4.42
SM5G05P12	343.00	89.52	89.53	4.41
SM5G05P12R	343.50	89.90	89.57	4.41
SM3G05P20	342.00	88.82	88.95	4.46
SM3G05P20R	344.00	89.39	90.10	4.45
SM5G05P20	343.00	89.56	89.59	4.42
SM5G05P20R	342.00	89.23	89.55	4.43
SM3G25P16	342.50	89.43	89.55	4.40
SM3G25P16R	343.50	89.37	89.70	4.42
SM3G50P16	342.00	89.18	89.63	4.41
SM3G50P16R	343.00	89.37	89.70	4.42
SM5G50P16	343.00	89.21	89.64	4.41
SM5G50P16R	343.00	89.40	89.69	4.41

Table A.2 Measured connection geometry at the failed end.

Test specimen	Gusset plate		Weld length, L (mm)	Opening	
	Width, WP (mm)	Thickness, t (mm)		Width, GW (mm)	Length, G (mm)
RL5G05P16	187.00	15.71	195.25	17.18	14.33
RS5G05P16	187.38	15.76	195.00	18.70	15.74
SM5G05P16	187.17	15.72	194.88	17.80	14.62
SM5G05P16R	186.67	15.75	196.88	17.53	15.95
RL4G05P16	186.67	15.74	155.50	16.72	13.46
RS4G05P16	186.83	15.77	155.63	17.74	15.12
SM4G05P16	187.00	15.77	156.13	17.18	14.36
SM4G05P16R	187.00	15.78	157.13	18.76	13.89
RL3G05P16	186.67	15.70	115.50	17.10	15.06
RS3G05P16	187.33	15.91	117.50	18.05	14.98
SM3G05P16	187.00	15.59	115.38	17.47	16.15
SM3G05P16R	186.17	15.73	115.75	17.13	14.35
SM3G05P12	238.33	12.66	119.25	13.82	13.75
SM3G05P12R	238.00	12.69	117.75	13.67	13.35
SM5G05P12	236.83	12.72	201.38	14.47	11.20
SM5G05P12R	237.50	12.67	201.50	14.02	12.83
SM3G05P20	157.67	19.14	114.25	20.66	16.06
SM3G05P20R	158.75	19.10	113.75	20.69	17.26
SM5G05P20	157.50	19.18	190.63	21.04	16.59
SM5G05P20R	157.00	19.14	190.13	20.74	17.18
SM3G25P16	186.00	15.76	117.25	17.44	33.30
SM3G25P16R	188.00	15.72	116.75	17.20	34.66
SM3G50P16	188.43	15.70	116.50	15.89	59.41
SM3G50P16R	186.00	15.68	115.75	16.57	60.21
SM5G50P16	186.67	15.73	196.00	17.60	58.30
SM5G50P16R	187.50	15.69	195.25	16.96	59.61

Table A.3 Calculated geometric properties of the specimen at the failed end.

Test specimen	Weld distance, w (mm)	Weld length ratio, L/w	Net area, A_n (mm ²)	Gross area, A_g (mm ²)	Net area eccentricity and eccentricity ratio	
					$\bar{x}$ (mm)	$\bar{x} / L$
RL5G05P16	146.98	1.33	1325	1479	46.10	0.24
RS5G05P16	145.47	1.34	1310	1476	17.22	0.09
SM5G05P16	146.56	1.33	1304	1462	34.25	0.18
SM5G05P16R	146.84	1.34	1304	1458	34.14	0.17
RL4G05P16	147.44	1.05	1330	1480	46.07	0.30
RS4G05P16	146.66	1.06	1327	1486	17.26	0.11
SM4G05P16	147.22	1.06	1300	1450	34.10	0.22
SM4G05P16R	145.62	1.08	1290	1456	34.34	0.22
RL3G05P16	147.07	0.79	1323	1475	46.04	0.40
RS3G05P16	146.09	0.80	1326	1489	17.13	0.15
SM3G05P16	146.91	0.79	1302	1456	34.25	0.30
SM3G05P16R	146.99	0.79	1305	1456	34.12	0.29
SM3G05P12	150.30	0.79	1335	1457	33.82	0.28
SM3G05P12R	150.71	0.78	1338	1459	33.83	0.29
SM5G05P12	149.89	1.34	1334	1463	33.97	0.17
SM5G05P12R	150.61	1.34	1336	1460	34.02	0.17
SM3G05P20	143.21	0.80	1272	1454	34.01	0.30
SM3G05P20R	144.16	0.79	1288	1472	34.22	0.30
SM5G05P20	143.33	1.33	1273	1459	34.36	0.18
SM5G05P20R	143.12	1.33	1275	1459	34.21	0.18
SM3G25P16	146.68	0.80	1303	1457	34.11	0.29
SM3G25P16R	147.42	0.79	1309	1461	34.05	0.29
SM3G50P16	147.98	0.79	1316	1456	33.85	0.29
SM3G50P16R	147.80	0.78	1315	1462	33.91	0.29
SM5G50P16	146.77	1.34	1302	1458	34.10	0.17
SM5G50P16R	147.43	1.32	1304	1453	34.02	0.17

Table A.4 Distances between welds of the specimen at the failed end.

Test specimen	Weld length, L (mm)	Weld distance and weld length ratio					
		w (mm)	L/w	w _n (mm)	L/w _n	w _c (mm)	L/w _c
RL5G05P16	195.25	146.98	1.33	157.03	1.24	152.56	1.28
RS5G05P16	195.00	145.47	1.34	155.61	1.25	151.14	1.29
SM5G05P16	194.88	146.56	1.33	157.19	1.24	152.76	1.28
SM5G05P16R	196.88	146.84	1.34	157.08	1.25	152.67	1.29
RL4G05P16	155.50	147.44	1.05	157.71	0.99	153.23	1.01
RS4G05P16	155.63	146.66	1.06	156.56	0.99	152.07	1.02
SM4G05P16	156.13	147.22	1.06	157.59	0.99	153.20	1.02
SM4G05P16R	157.13	145.62	1.08	155.89	1.01	151.48	1.04
RL3G05P16	115.50	147.07	0.79	156.82	0.74	152.36	0.76
RS3G05P16	117.50	146.09	0.80	156.03	0.75	151.52	0.78
SM3G05P16	115.38	146.91	0.79	157.53	0.73	153.12	0.75
SM3G05P16R	115.75	146.99	0.79	157.44	0.74	153.02	0.76
SM3G05P12	119.25	150.30	0.79	160.66	0.74	156.24	0.76
SM3G05P12R	117.75	150.71	0.78	160.93	0.73	156.52	0.75
SM5G05P12	201.38	149.89	1.34	160.17	1.26	155.74	1.29
SM5G05P12R	201.50	150.61	1.34	160.99	1.25	156.57	1.29
SM3G05P20	114.25	143.21	0.80	152.69	0.75	148.27	0.77
SM3G05P20R	113.75	144.16	0.79	154.35	0.74	149.90	0.76
SM5G05P20	190.63	143.33	1.33	153.84	1.24	149.42	1.28
SM5G05P20R	190.13	143.12	1.33	153.75	1.24	149.32	1.27
SM3G25P16	117.25	146.68	0.80	157.13	0.75	152.72	0.77
SM3G25P16R	116.75	147.42	0.79	157.52	0.74	153.10	0.76
SM3G50P16	116.50	147.98	0.79	158.52	0.73	154.10	0.76
SM3G50P16R	115.75	147.80	0.78	157.74	0.73	153.31	0.76
SM5G50P16	196.00	146.77	1.34	156.98	1.25	152.57	1.28
SM5G50P16R	195.25	147.43	1.32	157.64	1.24	153.24	1.27

Table A.5 Measured HSS gross section properties opposite to the failed end.

Test specimen	Circumference, c (mm)	Width, a (mm)	Width, b (mm)	Thickness, t' (mm)
RL5G05P16	343.00	126.95	51.71	4.57
RS5G05P16	343.00	51.37	127.24	4.54
SM5G05P16	343.00	89.58	89.76	4.40
SM5G05P16R	343.00	89.56	89.49	4.40
RL4G05P16	343.00	127.02	51.56	4.53
RS4G05P16	343.50	51.37	127.57	4.51
SM4G05P16	343.00	89.31	89.37	4.40
SM4G05P16R	343.00	89.63	89.56	4.39
RL3G05P16	343.00	127.18	51.53	4.47
RS3G05P16	343.00	51.27	127.20	4.50
SM3G05P16	343.00	90.15	89.65	4.40
SM3G05P16R	342.50	89.34	89.53	4.41
SM3G05P12	342.50	89.37	89.61	4.41
SM3G05P12R	343.00	89.63	89.47	4.43
SM5G05P12	343.00	89.45	89.57	4.40
SM5G05P12R	343.50	89.95	89.57	4.40
SM3G05P20	342.00	88.82	88.96	4.51
SM3G05P20R	344.00	89.40	90.09	4.44
SM5G05P20	343.00	89.50	89.50	4.41
SM5G05P20R	342.00	89.12	89.51	4.42
SM3G25P16	342.50	89.48	89.48	4.39
SM3G25P16R	343.50	89.44	89.57	4.42
SM3G50P16	342.00	89.18	89.60	4.40
SM3G50P16R	343.00	89.60	89.81	4.42
SM5G50P16	343.00	89.12	89.58	4.41
SM5G50P16R	343.00	89.52	89.67	4.42

Table A.6 Measured connection geometry opposite to the failed end.

Test specimen	Gusset plate		Weld length, L (mm)	Opening	
	Width, WP (mm)	Thickness, t (mm)		Width, GW (mm)	Length, G (mm)
RL5G05P16	187.50	15.74	194.88	17.20	15.04
RS5G05P16	187.39	15.66	194.50	18.32	15.92
SM5G05P16	186.83	15.69	193.75	18.16	14.32
SM5G05P16R	187.33	15.90	195.38	17.23	14.03
RL4G05P16	186.67	15.75	156.00	16.38	14.06
RS4G05P16	186.01	15.70	156.13	17.66	15.26
SM4G05P16	186.50	15.70	156.88	17.52	13.96
SM4G05P16R	186.34	15.72	156.13	18.04	14.60
RL3G05P16	186.33	15.74	116.75	17.10	15.50
RS3G05P16	186.83	15.72	115.75	18.87	15.93
SM3G05P16	186.34	15.71	117.63	17.45	13.13
SM3G05P16R	186.33	15.75	117.38	17.13	13.53
SM3G05P12	239.67	12.64	116.75	13.72	13.27
SM3G05P12R	238.34	12.69	119.13	13.32	12.06
SM5G05P12	237.83	12.67	202.13	12.71	8.60
SM5G05P12R	236.16	12.71	200.63	13.92	11.57
SM3G05P20	157.67	19.18	112.75	20.46	17.99
SM3G05P20R	157.01	19.04	114.13	20.71	15.84
SM5G05P20	156.18	19.12	190.63	20.08	15.88
SM5G05P20R	156.34	19.38	189.88	19.98	18.30
SM3G25P16	186.84	15.76	117.75	16.60	33.71
SM3G25P16R	186.16	15.68	116.50	17.72	33.82
SM3G50P16	189.01	15.68	116.88	15.33	58.87
SM3G50P16R	186.66	15.76	116.25	16.90	59.94
SM5G50P16	188.49	15.73	196.25	16.48	59.36
SM5G50P16R	186.84	15.59	195.75	16.96	59.04

APPENDIX B:TENSION COUPON TEST

Tension coupon tests were carried out to obtain material properties of the test specimen. The yield strength of the HSS is calculated using the 0.2% offset method since there is no yield plateau for HSS coupons. The definitions of yield strength (F_y) and ultimate strength (F_u) for HSS coupons are shown in Figure B.1.

Two material ductility values are also reported. One is the % elongation over a 50mm gauge length of the coupon at fracture. The other is the ratio of the original cross-section area over the cross-section area at fracture, A_o/A_f . A_o is the original cross-section area and A_f is the cross-section area (A) of the coupon at fracture. Three cross-section areas at fracture (A_f , A_{fMax} and A_{fMin}) are presented. Figure B.2 shows a typical cross-section of a rectangular coupon at the necking region with an undeformed width to the undeformed thickness ratio of less than 2.0. The cross-section area A is defined as

$$A = b_{avg} \cdot t_{avg} \quad (B.1)$$

where b_{avg} is the average of the corner (b_{cor}) and mid-point (b_{mid}) widths, and t_{avg} is the average of the corner (t_{cor}) and mid-point (t_{mid}) thicknesses. A_{fmax} is the value of A_{max} at fracture with

$$A_{max} = t_{cor} \cdot b_{cor} \quad (B.2)$$

A_{fmin} is the value of A_{min} at fracture with

$$A_{min} = t_{mid} \cdot b_{mid} \quad (B.3)$$

The stress versus extensometer strain and stress versus change in cross-section area ($1 - A_o/A$) curves for all coupons are shown in Figures B.3 to B.12. All data are from the

static readings except for the curve with dash line. The dash line represents all recorded data of stress versus extensometer strain of a coupon test. The sudden termination of the stress versus extensometer strain curve immediately after the peak stress is because the extensometer was removed after that point and not due to the fracture of the coupon.

Table B.1 Summary of tension coupon test.

Coupon	Elongation (%)	Cross section area ratio			Yield strength, F_y (MPa)	Ultimate strength, F_u (MPa)
		A_o/A_f	A_o/A_{fmax}	A_o/A_{fmin}		
HSS 89 x 89						
SM5G05P12	28.9	2.18	2.04	2.35	403.0	482.9
SM5G50P16	30.3	2.15	1.95	2.38	408.0	485.0
SM5G05P20	24.8	2.01	1.84	2.21	396.0	488.0
SM5G05P16R	32.4	2.27	2.00	2.62	409.0	484.1
Average	29.1	2.15	1.96	2.39	404.0	485.0
HSS 127 x 51						
R1	33.2	2.31	2.03	2.67	376.0	445.9
R2	34.1	2.35	2.05	2.74	383.0	450.8
R4	33.2	2.19	2.01	2.41	387.0	446.6
R5	33.7	2.32	2.04	2.67	375.0	448.9
Average	33.5	2.29	2.04	2.62	380.3	448.0
12 mm plate						
P121	36.1	2.15	2.05	2.25	312.9	493.9
P122	35.5	2.22	2.17	2.28	318.2	495.7
P123	33.5	2.06	1.95	2.17	326.9	494.9
Average	35.1	2.14	2.06	2.24	319.3	494.8
16 mm plate						
P161	40.4	2.47	2.26	2.71	340.7	465.7
P162	38.4	2.34	2.19	2.51	329.7	465.1
P163	38.2	2.41	2.21	2.65	342.7	467.1
Average	39.0	2.41	2.22	2.62	337.7	466.0
20 mm plate						
P201	38.6	2.01	1.90	2.14	284.0	457.7
P202	39.4	2.24	2.03	2.48	279.7	455.0
P203	40.0	2.27	2.07	2.51	295.5	458.5
P204	40.2	2.05	1.90	2.22	295.5	457.9
Average	39.6	2.14	1.98	2.34	288.7	457.3

Figure B.1 Definitions of yield strength (F_y) and ultimate strength (F_u) for HSS.

Figure B.2 Cross-section of rectangular coupon at the necking region.

Figure B.3 Engineering stress versus engineering strain for HSS 89 x 89 tension coupons.

Figure B.4 Engineering stress versus engineering strain for HSS 127 x 51 tension coupons.

Figure B.5 Engineering stress versus engineering strain for 12 mm gusset plate tension coupons.

Figure B.6 Engineering stress versus engineering strain for 16 mm gusset plate tension coupons.

Figure B.7 Engineering stress versus engineering strain for 20 mm gusset plate tension coupons.

Figure B.8 Stress versus change in cross-section area for HSS 89 x 89 tension coupons.

Figure B.9 Stress versus change in cross-section area for HSS 127 x 51 tensions coupons.

Figure B.10 Stress versus change in cross-section area for 12 mm gusset plate tension coupons.

Figure B.11 Stress versus change in cross-section area for 16 mm gusset plate tension coupons.

Figure B.12 Stress versus change in cross-section area for 20 mm gusset plate tension coupons.

APPENDIX C: TEST RESULTS

The load versus average LVDT displacement curves for all test specimens were grouped and presented in Figures C.1 to C.6 in this section. The data of the LVDT shown in Figures C.1 to C.6 are the average from LVDT1 and LVDT2 that are installed on both sides of the specimen as shown in chapter 3. Figures C.7 to C.19 show pictures of failure for all specimens.

Figure C.1 Load versus average LVDT displacement for rectangular HSS specimens with the slot at the long side.

Figure C.2 Load versus average LVDT displacement for rectangular HSS specimens with the slot at the short side.

Figure C.3 Load versus average LVDT displacement for square HSS specimens with 16 mm gusset plate and GS = 5 mm.

Figure C.4 Load versus average LVDT displacement for square HSS specimens with 16 mm gusset plate and GS greater than 5 mm.

Figure C.5 Load versus average LVDT displacement for square HSS specimens with 20 mm gusset plate and GS = 5 mm.

Figure C.6 Load versus average LVDT displacement for square HSS specimens with 12 mm gusset plate and GS = 5 mm.

Figure C.7 Failures of RL3G05P16 and RL4G05P16.

Figure C.8 Failures of RL5G05P16 and RS3G05P16.

Figure C.9 Failures of RS4G05P16 and RS5G05P16.

Figure C.10 Failures of SM3G05P12 and SM3G05P12R.

SM3G05P16

SM3G05P16R

Figure C.11 Failures of SM3G05P16 and SM3G05P16R.

SM3G05P20

SM3G05P20R

Figure C.12 Failures of SM3G05P20 and SM3G05P20R.

SM3G25P16

SM3G25P16R

Figure C.13 Failures of SM3G25P16 and SM3G25P16R.

SM3G50P16

SM3G50P16R

Figure C.14 Failures of SM3G50P16 and SM3G50P16R.

SM4G05P16

SM4G05P16R

Figure C.15 Failures of SM4G05P16 and SM4G05P16R.

SM5G05P12

SM5G05P12R

Figure C.16 Failures of SM5G05P12 and SM5G05P12R.

SM5G05P16

SM5G05P16R

Figure C.17 Failures of SM5G05P16 and SM5G05P16R.

SM5G05P20

SM5G05P20R

Figure C.18 Failures of SM5G05P20 and SM5G05P20R.

SM5G50P16

SM5G50P16R

Figure C.19 Failures of SM5G50P16 and SM5G50P16R.