A Study on Slotted Square and Rectangular Hollow Structural Section Connections

by

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ABSTRACT

A numerical study has been carried out on slotted rectangular (RHS) and square (SHS) structural hollow section connections with and without welding at the end of the gusset plate. The effect of weld length ratio, slot orientation, gusset plate thickness, slot opening length and weld height on slotted RHS or SHS connections were investigated numerically. A total of four rectangular and square HSS specimens were also tested.

Results from the current study support findings from other research that show provisions to account for the effect of shear lag in slotted RHS or SHS connections are overly conservative in the design standard for both the Canadian CSA-S16.1-01 and the American ANSI/AISC-360-05. Shear lag has been found to have no effect on the tensile strength of a square or a rectangular hollow section when a weld length ratio is larger than 0.8 for a connection with end welding and when the ratio is larger than 0.9 for a connection without end welding. Parameters such as orientation of the slot opening, slot opening length, gusset plate thickness, weld height, welding at the end of the gusset plate and material properties of HSS corner have been found to have some effect on the strength of slotted HSS connections under some specific conditions.

Based on results of the study, guidelines for designing an economical full-strength slotted RHS or SHS connection with or without end welding are developed for CSA-S16.1-01. Improvements to provisions in CSA-S16.1-01 and AISC design standards were also proposed.

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List of Symbols

a	—	overall height of the HSS in the direction perpendicular to the plane of the gusset plate
A	—	current cross-section area.
A_0	—	original cross-section area of a tension coupon.
A_{cor}	—	cross-section area of a tension coupon measured at the corner
A_d	—	part of the cross-section area under direct tension
A_e	—	effective area
A_f	—	cross-section area of the coupon at fracture
A_{fcor}	—	cross-section area of the coupon at fracture measured at the corner
A_{fmid}	—	cross-section area of the coupon at fracture measured at the middle of the section
A_g	—	gross area of the member
A_{mid}	—	cross-section area of a tension coupon measured at the middle of the section
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_n/A_g	—	net to gross area ratio
A_{ne}	—	effective net area
a/b	—	aspect ratio of HSS
b	—	overall width of the HSS in the direction parallel to the plane of the gusset plate
c	—	outside circumference of the HSS
E	—	elastic modulus of steel
f_m	—	factor for the actual aspect ratio
f_s	—	factor for the reference aspect ratio
f_t	—	factor for the net thickness reduction
F	—	load on the tension specimen
F_u	—	ultimate strength
F_y	—	yield strength
G	—	total 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/w	—	weld length ratio

P_{u_assm}	—	peak load predicted by the finite element model with an assumed higher strength corner
P_{u_calc}	—	ultimate load of the finite element model
P_{u_ousts}	—	ultimate strength of the outstanding part of HSS
P_{u_pred}	—	peak load predicted by the numerical model
P_{uTest}	—	peak tested load
P_{u_unif}	—	peak load predicted by the finite element model with entirely flat part material
r	—	corner outside radius
R	—	radius of curvature of the neck surface in the longitudinal plan at the minimum section of a circular coupon
RL	—	HSS 127 x 51, slot on the long side
RS	—	HSS 127 x 51, slot on the short side
S	—	cross-section aspect ratio
SM	—	HSS 89 x 89
t'	—	thickness of the HSS walls
t	—	thickness of the gusset plate
t_c	—	averaged corner thickness
t_e	—	weld height of the end welding
t_{max}	—	maximum thickness at the corner

t_o	—	initial thickness of a tension coupon
t_w	—	weld height of the longitudinal weld
T_r	—	factored resistance of the tension member
U	—	shear lag reduction coefficient
U_{base}	—	predicted net section efficiency of the baseline model
U_n	—	net section efficiency
U_{n_assum}	—	predicted net section efficiency of a HSS connection model with a higher strength corner
U_{n_test}	—	measured net section efficiency
U_{norm}	—	normalized section efficiency
$U_{n-outsd}$	—	predicted net section efficiency for the outstanding part of HSS
U_{n_unif}	—	predicted net section efficiency of a HSS specimen model with entirely flat part material
U_{param}	—	predicted net section efficiency of the parametric study models
U_{pw}	—	proposed efficiency factor based on the weld length ratio
U_{px}	—	proposed efficiency factor based on the net section eccentricity
ν	—	the poison's ratio
w	—	distance between the welds
wh	—	weld height
WP	—	actual width of the gusset plate

W_t	—	width of the gusset plate in parametric study
$\bar{x}$	—	eccentricity of the weld with respect to the centroid of the connected element
$\bar{x}/L$	—	net section eccentricity ratio
$\bar{x}^*$	—	modified net section eccentricity
$\bar{x}^*/L$	—	modified net section eccentricity ratio
$\bar{x}_n$	—	distance from the centroid of one-half of the HSS net cross-section area to the face of the gusset plate
$\bar{x}_n/L$	—	net section eccentricity ratio of eccentricity calculated to the face of the gusset plate
$\bar{x}^*$	—	modified net section eccentricity
$\bar{x}^*/L$	—	modified net section eccentricity ratio
$\bar{x}_n^*$	—	modified net section eccentricity calculated to the face of the gusset plate
$\bar{x}_n^*/L$	—	modified net section eccentricity ratio calculated to the face of the gusset plate
β	—	the 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^p	—	true plastic strain
ϵ_c^p	—	critical equivalent plastic strain
ϵ_{eq}^p	—	equivalent plastic strain
ϵ_f^p	—	true plastic strain at the peak load
ϵ_o^p	—	true plastic strain at the start of strain hardening
ϵ_t	—	true strain
σ	—	engineering stress
σ_{avg}	—	average tensile stress
σ_f^t	—	true stress at the peak load
σ_o^t	—	true stress at the end of proportional limit when there is no yield plateau or at the start of strain hardening
σ_y^t	—	true stress at the start of yield plateau
σ^t	—	true stress
ϕ	—	resistance factor

CHAPTER 1 INTRODUCTION

Hollow structural sections (HSS) are widely used in many steel structures, especially as welded tension and compression members in bracing and trusses. There are two ways to make a slotted connection for a hollow structural section in tension. As shown in Figure 1.1, the most commonly employed method is to slot the tube longitudinally and insert a gusset plate into the slot. The gusset plate is then welded to the tube by longitudinal fillet welds. Welding may or may not be provided around the end of the gusset plate. However, it is easier not to weld around the end of the gusset plate in fabrication. In both cases, the stress is not distributed uniformly across the section because not all elements of the HSS are directly connected to the gusset plate. Thus, the net section may not be fully effective in carrying the load. The phenomenon associated with this non-uniform distribution of stress at the connection is termed shear lag. The effect of shear lag can be characterized by either the ratio of the weld length (L) to the circumferential distance (w) between the longitudinal welds or the ratio of the net section area eccentricity ($\bar{x}$) to the weld length (L). Figure 1.2 shows the graphical representation of the weld length, net section area eccentricity and the distance between welds (w) for a connection with end welding. Another way to make the connection is to slot the gusset plate instead of the tube. But it is not an arrangement as convenient as the former.

Both the Canadian Standard CSA-S16.1-01 (2001) Limit States Design of Steel Structures and American ANSI/AISC-360-05 (2005) Specification for Structural Steel Building have provisions to account for the effect of shear lag in calculating the capacity of a tension member. The net cross-section area is reduced in the strength calculation when

the effect of shear lag is significant. However, results of a few testing programs on slotted HSS connections suggest that provisions for shear lag in both CSA-S16.1-01 and ANSI/AISC-360-05 (2005) are overly conservative. Compared to AISC (2000) Design Specification for Steel Hollow Structural Sections, there is an improvement in ANSI/AISC-360-05 (2005) for slotted round HSS connection, but none for square or rectangular HSS connection.

In both CSA-S16.1-01 and ANSI/AISC-360-05 (2005), gross section yielding and the net section fracture are the two limit states which need to be considered in designing a tension member. Thus, in order to fully utilize a tension member, the connection should be designed so that gross section yielding is the governing state. In other words, the ultimate strength for net section fracture should be higher than that for gross section yielding when designing a tension member. The net section fracture strength of slotted HSS connection is affected by shear lag. Thus, through the detailed study of slotted square and rectangular HSS connections, a more efficient and economical design provision may be recommended.

1.1 Objective of the Thesis

The objective of this study is to investigate the strength and behavior of square and rectangular HSS for various slotted connection details. The study consists of a combination of testing and finite element analyses of slotted HSS connections with and without end welding for different geometrical parameters, such as weld length, weld height, gusset plate thickness, slot orientation and slot opening size. Finite element models are developed and validated using the test results. Models for slotted HSS connections with no end welding are validated using test results from another study. Thus, only slotted

HSS connection with end welding were tested in this study. A finite element analyses parametric study is conducted based on the validated finite element models. Results of the parametric study are used in developing guidelines for designing an economical full-strength slotted HSS connection, and formulating recommendations to improve the shear lag provisions for slotted square and rectangular HSS connections in design standards.

1.2 Methodology Used in the Research

The overall testing program consists of slotted square and rectangular HSS connections with and without end welding. Both slotted HSS 89 x 89 x 4.8 and HSS 127 x 51 x 4.8 connection specimens were tested. One part of the testing program consisting of twenty six slotted HSS specimens with no end welding and thirteen different connection configurations were tested by Huang (2005). Only four slotted HSS specimens with end welding and three connection configurations were tested in this study. Connection configurations consisting of different combinations of weld length, gusset plate thickness, size of slot opening and slot orientation were investigated in the overall testing program. It is expected that the effect of shear lag is more severe for connections with no end welding. Thus any guideline and provision developed for the connection with no end welding will be conservative when applied to that with end welding. For this reason, the overall testing program focuses more on specimens with no end welding and only four specimens with end welding were tested mainly to verify that shear lag is less severe when end welding is provided.

Tension coupon tests from the flat part of HSS and gusset plates were carried out to obtain material properties for assessing the test results of HSS specimens. The

performance of each HSS specimen, evaluated using the actual material strength obtained from coupon tests, is compared against net section efficiencies calculated according to the provisions in design standards. Material properties are also important in carrying out the numerical simulation because a complete stress versus strain relationship of the material is required in order to perform the finite element analysis to predict the performance of the connection. An iterative procedure is employed to calculate a precise stress versus true plastic strain of the material up to fracture through numerical simulation of the tension coupon test. Since the material properties vary across the HSS section due to cold-forming, the HSS is idealized to have two regions of distinct material properties in the numerical simulation. One region is the HSS corner and the other region is the flat part of HSS. Thus, the true stress versus true plastic strain relationship is assumed for the HSS corner in order to give a more accurate representation of the HSS cross-section in the modeling. The assumed corner HSS material properties are determined through trial and error by matching numerical simulation result to that of the test.

Finite element analyses of test specimens are carried out with ABAQUS (2003) using the stress versus strain relationship of the material obtained from coupon tests. The failure of a specimen in the simulation is assumed to have occurred when the critical equivalent plastic strain limit is reached in any part of the specimen. The critical equivalent plastic strain limit used in the simulation is also determined from the tension coupon tests. Finite element models of the connections are validated with results from the whole testing program as well as other existing test results. A finite element analysis parametric study based on the validated finite element models is conducted to study the effect of each geometric parameter. Based on results of the parametric study,

recommendations to improve on shear lag provisions for slotted square and rectangular HSS connections are formulated and guidelines on designing a full-strength slotted HSS connection are developed.

1.3 Organization of the Thesis

Chapter 2 presents a literature review on shear lag in tension connections with an emphasis on slotted HSS connections. Design provisions to account for shear lag in welded connection are presented. In addition, a few procedures to calculate the true stress versus true strain relationship of the material are discussed.

Chapter 3 presents the testing program on slotted square and rectangular HSS connections with end welding. The specimens and testing procedures are described. Test results of slotted HSS specimens and tension coupons are also presented.

In Chapter 4, methods to obtain the true stress versus true plastic strain relationship for the material are discussed. This includes discussions on the material failure limit and procedures to determine the assumed material properties for the HSS corner.

Chapter 5 consists of the finite element models development and validation using the test results. Finite element models are developed for both phase 1 and phase 2 test specimens. Material properties from tension coupon tests are used in the analysis.

A detailed parametric study based on the validated finite element models is presented in Chapter 6. Parameters affecting shear lag in slotted HSS connections are investigated and discussed. Using results of the parametric study, design guidelines are developed and recommendations to improve the shear lag provisions in design standards are proposed.

Chapter 7 consists of a summary of the thesis, and as well as conclusions and recommendations.

Additional test and numerical analyses data are presented in the appendices.

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

CHAPTER 2 LITERATURE REVIEW

The research on slotted HSS connections is similar to those conducted on connections of other steel shapes. One of the primary considerations when examining the ultimate strength of a member is the net section efficiency. Among all factors affecting the net section efficiency of a tension member, the effect of shear lag is of particular importance. Some of the previous studies have revealed that the ultimate strength of a HSS member slotted with a gusset plate is greatly influenced by the ratio of the longitudinal weld length to the circumferential distance between the welds, and to a lesser extent by the cross-section area eccentricity relative to the line of load transfer. The following literature review summarizes previous work conducted on shear lag, HSS connection strength in tension, and procedures to determine material properties for large strain. Provisions to account for shear lag in design standards are also discussed.

2.1 Shear lag

When the connection to a tension member is made only to a portion of its cross section, such as flanges of a I shape section in Figures 2.1 and 2.2, the stress is not uniformly distributed across the section at the vicinity of the connection. The parts of the cross-section that are not directly connected will lag behind the connected parts in their contribution to the load carrying. This phenomenon of non-uniform stress distribution is commonly known as shear lag. The effect of shear lag effect may reduce

the ultimate strength of the member. This can happen to any structural shape with unconnected cross-section elements. Previous studies have shown that shear lag is affected by the eccentricity of the connected parts relative to the line of load transfer, the circumferential distance between welds and the connection length. It was suggested by Munse and Chesson (1963) that the effect of shear lag be accounted for by using a reduced or effective net area. Since shear lag affects both bolted and welded connections, the effective net area concept has been applied to both of these connections.

2.2 Provisions in design standards for shear lag in welded tension members

Both American and Canadian structural steel design standards have provisions to account for the effect of shear lag in calculating the resistance of a tension member. These provisions were derived mainly from the work of Munse and Chesson (1963), and Easterling and Giroux (1993).

2.2.1 CSA-S16.1-01

The current Canadian Standard CAN/CSA-S16.1-01 (2001) on Limit States Design of Steel Structures has adopted a comprehensive approach to account for shear lag in welded tension members.

The factored tensile resistance, T_r , of a member subjected to an axial tensile force 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 = yield strength of the material,

F_u = ultimate strength of the material,

A_g = gross area of the member,

A_n = net area,

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

ϕ = resistance factor taken as 0.90.

The effective net area is taken as

$$A_{ne} = A_{n1} + A_{n2} + A_{n3},$$

where A_{n1} , A_{n2} and A_{n3} are net areas of the connected plate elements subjected to one of the following methods of load transfer.

- a) Elements connected by transverse welds,

$$A_{n1} = wt, \quad (2.4)$$

where

w = plate element width, and

t = thickness of the element.

b) Elements connected by longitudinal welds along two parallel edges,

$$\text{i) for } L \geq 2w, \quad A_{n2} = 1.00 \, wt, \quad (2.5)$$

$$\text{ii) for } 2w > L \geq w, \quad A_{n2} = 0.50 \, wt + 0.25Lt, \quad (2.6)$$

$$\text{iii) for } w > L, \quad A_{n2} = 0.75 \, Lt, \quad (2.7)$$

where

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

w = plate width (distance between welds)

c) Elements connected by a single longitudinal weld,

i) when $L \geq w$,

$$A_{n3} = \left(1 - \frac{\bar{x}}{L}\right) wt, \quad (2.8)$$

ii) when $w > L$,

$$A_{n3} = 0.50Lt, \quad (2.9)$$

where

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

w = width of the outstanding leg, and

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

Equations (2.5) to (2.7) are the effective net area definitions in CSA-S16.1-01 that are applicable to slotted HSS connections.

2.2.2 AISC–LRFD–1999

In AISC–LRFD–1999 (1999) on Load and Resistance Factor Design Specification for Structural Steel Building, the effective area of a tension member is dependent on the structural shape and how it 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, the effective area

$$A_e = A_g U, \text{ with} \quad (2.10)$$

$$U = 1 - \frac{\bar{x}}{L} \leq 0.9, \quad (2.11)$$

where

A_g = gross area of member,

U = net area efficiency factor,

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

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

- (b) When the tension load is transmitted only by a transverse weld, the effective area $\bar{x}$

$$A_e = AU, \quad (2.12)$$

where

U = 1.0, and

A = area of directly connected elements.

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

$$A_e = A_g U, \quad (2.13)$$

where

A_g = gross cross-sectional area,

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

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

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

L = length of weld, and

w = plate width (distance between welds).

2.2.3 AISC Design Specification for Steel Hollow Structural Sections

A more detailed treatment of slotted HSS connections is provided by AISC-LFRD Design Specification for Steel Hollow Structural Section (2000). The effective area (A_e) of tension members is taken as

$$A_e = AU \quad (2.14)$$

with A and U vary with the connection type.

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

$$A = A_g, \quad (2.15)$$

where

A_g = gross area, and

$$U = 1.$$

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

$$A = A_n, \text{ and} \quad (2.16)$$

$$U = 1 - \frac{\bar{x}}{L} \leq 0.9, \quad (2.17)$$

where

A_n = 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,

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

L = 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 = gross area, and U is as given by (2.17).

2.2.4 ANSI/AISC 360-05

The latest AISC Specification for Structural Steel Building, ANSI/AISC 360-05 (2005), also accounts for shear lag in using a reduced effective area of a tension member. The effective area (A_e) of a tension member is similar to the combination of (2.14) and (2.16). It is taken as $A_n U$, where A_n is the net area and U is

the shear lag factor that varies for different tension member connections. Unlike previous specifications, an upper limit of 0.9 on the shear lag factor for all connections has been removed in ANSI/AISC 360-05 (2005).

- (a) For all tension members, except plates and HSS, where the tension load is transmitted to some but not all of the cross-sectional elements by fasteners or longitudinal welds

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

where

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

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

- (b) For all tension members where the tension load is transmitted only by a transverse weld, U is equal to 1.0.

- (c) For plates where the tension load is transmitted by longitudinal welds only,

$$\text{for } L \geq 2w, \quad U = 1.00,$$

$$\text{for } 2w > L \geq 1.5w, \quad U = 0.87,$$

$$\text{for } 1.5w > L \geq w, \quad U = 0.75,$$

where

L = length of weld, and

w = plate width (distance between welds).

- (d) For a rectangular HSS with a single concentric gusset plate and

$$L \geq b, \quad U = 1 - \frac{\bar{x}}{L}, \quad (2.19)$$

where

$$\bar{x} = \frac{a^2 + 2ab}{4(a + b)}, \text{ connection eccentricity,} \quad (2.20)$$

a = overall height of the HSS in the direction perpendicular to the plane of the gusset plate, and

b = overall width of the HSS in the direction parallel to the plane of the gusset plate.

2.3 Research on Shear Lag

There have been a number of studies carried out on shear lag in connections. The presentation of the literature review on shear lag will be divided into welded connections and bolted connections. However, shear lag in bolted connections will only be briefly discussed.

2.3.1 Shear Lag on Bolted Connections

The interest on the shear lag effect was initially started from a more general research on the net section efficiency of the partially connected members. Munse and Chesson (1963) conducted a series of tests to evaluate the net section efficiency of bolted and riveted tension members. The net section efficiency is taken as the ratio of the maximum test load to the product of material tensile strength and net section area. Their

test results showed that several factors affected the test efficiency for a net section rupture failure. These factors include ductility of the connected material, geometry of the connected cross-section and length of the connection. Among all these factors, geometry of the connected cross-section and length of the connection have the greatest influence on the net section efficiency when not every cross-sectional element of the member is directly connected. The reduction in the net section efficiency is due mainly to shear lag, which is dependent on the geometry of the connected cross-section and the length of the connection.

The distance from the face of the gusset plate to the centroid of the tributary cross-section area ($\bar{x}$) and the length of the connection (L) are two parameters that are found to be pertinent in characterizing the effect of shear lag. An example of these two parameters are shown in Figure 2.3 on the configuration tested by Munse and Chesson. A simple ratio of centroidal distance and connection length ($\bar{x}/L$) was proposed by Munse and Chesson to account for the influence of both the cross-section geometry and the joint length. In order to characterize the effectiveness of the cross-section area to transfer the force, Munse and Chesson developed the following empirical effective net section area equation,

$$A_e = A_n U, \text{ with} \quad (2.21)$$

$$U = 1 - \frac{\bar{x}}{L}, \quad (2.22)$$

where

A_e = effective net section area,

A_n = net section area,

U = net section efficiency,

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

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

Equation (2.21) is the basis where some equations of net section area calculations in ANSI/AISC 360-05 (2005) and CAN/CSA-S16.1-01 (2001) originated.

Research on shear lag in bolted tension members were also carried out by Davis and Boomsliiter (1934), 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 in Welded Connection

The research on shear lag in welded connections will be discussed separately for opened sections such as angle, channel and plate, and for closed sections such as circular, square and rectangular HSS.

2.3.2.1 Shear Lag in Open Sections Connections

Gibson and Wake (1942) conducted tests to investigate the influence of the arrangement of weld on the load carrying capacity of the angle. The angles tested were

L 64 x 64 x 7.9 ($2\frac{1}{2}$ x $2\frac{1}{2}$ x $\frac{5}{16}$). Fifteen connection configurations for angles welded to gusset plates with both balanced and unbalanced weld were investigated. It was found that the eccentricity normal to the plane of the gusset plate is the major factor affecting the strength, and the stress in the angle was unevenly distributed over its cross-section.

Easterling and Giroux (1993) carried out a testing program on twenty seven welded tension members that comprised of plate, angle and channel specimens. Except for channel specimens whose predominant failure mode is rupture at the middle of the specimen, all other specimens failed at the net section close to the weld. For plate specimens, the net section efficiency ranged from 0.94 to 1.0 when the ratio of longitudinal weld length (L) to the distance between the welds (w) was between 1.5 and 2.0. This suggested that the longitudinal weld longer than 150% of the distance between the welds has little influence on the net section efficiency. Meanwhile, the net section efficiency computed using (2.22) gives values between 0.82 and 0.85 for plate specimens. For angle specimens, the net section efficiency for all but one specimen ranged between 0.8 and 0.82. The lower net section efficiency indicated that the whole section was not effective in taking the load since only one leg of the angle was connected to the gusset plate. The maximum net section efficiency was found to be greater than 0.9 for plates, 0.8 for angles and a maximum of 0.9 for channels. Based on the test results, an upper net section efficiency limit for (2.22) of 0.9 was recommended for most structural shapes.

Uzoegbo (1998) also conducted a series of tension tests on a single angle welded

to a gusset plate at one leg. Fourteen specimens with equal and unequal length fillet weld along the sides of the connected leg were tested. Even though the weld length was at least twice the length of the outstanding leg, most of the net section efficiency ranged between 0.7 and 0.8 for equal weld length specimens and between 0.66 and 0.77 for unequal weld length specimens. The full strength of the member was not achieved because of the non-uniform stress distribution across the cross-section due to shear lag.

2.3.2.2 Shear lag in HSS connections

Korol (1996) carried out a tension test program comprising six square HSS (HSS 89 x 89 x 6.4) and twelve rectangular HSS (HSS 127 x 51 x 6.4) specimens to investigate the effect of shear lag on a slotted HSS tension member connection. Specimens with different cross-section aspect ratios and weld length ratios were tested. The cross-section aspect ratio (a/b) being the ratio of the width of slotted side (a) over the unslotted side (b), as shown in Figure 2.4. Slots and welds were made to either the long or short side of the rectangular HSS members. There was no welding around the gusset plate at the end of the slot opening for all test specimens. The weld length ratio (L/w) of the specimens tested, taken as the ratio of the length of the fillet weld (L) over the circumferential distance between longitudinal fillet welds (w), varied from 0.4 to 1.0. Specimens with weld length ratios (L/w) around unity were found to have net section efficiencies close to 1.0, which were much higher than 0.75 allowed in CAN/CSA S16.1-01. Overall, test results showed that provisions for shear lag are

overly conservative in CAN/CSA-S16.1-01.

Based on results of the test, Korol proposed a net section efficiency coefficient

$$\begin{aligned}
 (U), \quad & \text{for} \quad \frac{L}{w} > 1.2, \quad U = 1.0, \\
 & \text{for} \quad 1.0 < \frac{L}{w} \leq 1.2, \quad U = 0.9, \text{ and} \\
 & \text{for} \quad 0.6 \leq \frac{L}{w} \leq 1.0, \quad U = 0.4 + 0.5 \frac{L}{w}.
 \end{aligned} \tag{2.23}$$

Below a weld length ratio (L/w) of 0.6, the failure mode was found to switch from net section fracture to block shear failure. Korol also proposed another net section efficiency equation based on the net section eccentricity as

$$U = 1 - 0.4 \frac{\bar{x}}{L} \tag{2.24}$$

Korol found that the orientation of the slot (slot located on the long side or the short side) only has a minor effect on the connection strength with the specimen having the slot on the short side has a slightly higher capacity than the one on the long side.

Cheng, et al. (1998) tested nine specimens of slotted circular HSS (HSS 102 × 6.4, HSS 102 × 4.8, and HSS 219 × 8.0) connections. In their test program, welding was provided across the gusset plate thickness at the end of the slot for all but one specimen. The ratio of weld length to the circumferential distance between the welds (L/w) was close to 1.0 for eight specimens and was 0.8 for one other specimen. Only two out of nine specimens tested fractured at the slotted end, while other specimens failed at the mid-length of the HSS after extensive deformation. For the two specimens that failed at the slotted end, one has a weld length ratio (L/w) of 0.8, and the other did not have any welding around the end of the gusset plate. Compared to a

specimen with a weld length ratio of 1, the specimen with a weld length ratio of 0.8 has a higher stress concentration at the slotted end of the HSS that resulted in crack initiation and fracture. When there is no end welding, failure occurred at the slotted end because the net section area at that section is the smallest.

Based on their test results, Cheng et al. concluded that the effect of shear lag is insignificant when the weld length ratio (L/w) is close to 1.0. Specimens that failed at the mid-length essentially have the net section efficiency of 1.0. For the two specimens that failed at the slotted end, their net section efficiencies were found to be close to 1.0. Again, tests results showed that provisions for shear lag in the CAN/CSA S16.1-01 were overly conservative.

A more recent study was carried out by Willibald et al. (2004) on six circular HSS (HSS 168 x 4.8) tension specimens with different slotting details. Two of these specimens were fabricated by slotting the gusset plate and four were fabricated by slotting the tube. Among specimens slotted at the tube, two have end welding around the gusset plate and two without. The weld length ratio (L/w) of the specimens varied from 0.5 to 0.88. All specimens failed in HSS. With a similar weld length ratio, a specimen with end welding and its tube slotted has almost the same tension capacity as one that has the gusset plate slotted. However, the specimen with the tube slotted but without end welding has a lower strength compared to that from the other two above configurations. Again, all specimens achieved higher net section efficiencies compared to values given by CAN/CSA S16.1-01 and ANSI/AISC 360-05 (2005).

Similar to tests by Korol, specimens without end welding and having weld length ratio (L/w) lower than 0.66 experienced block shear failure rather than net section failure.

2.3.2.3 Numerical simulation for slotted HSS connections

Finite element models (FEM) with different elements and boundary conditions have been employed to study the HSS connections. However, not all the numerical simulations were able to capture the behavior and predict the member strength of a slotted HSS connection accurately. The following are some of the numerical studies that have been carried out on slotted HSS connections.

Girard et al. (1994) developed a three dimensional finite element model for slotted rectangular and square HSS connections with six-node triangular elasto-plastic shell elements. A quarter of the HSS connection was modeled due to symmetry. Different weld length ratios (L/w), gusset plate thicknesses and widths were considered in their numerical study. However, only a simple idealized multi-linear stress versus strain curve with a yield plateau and a linear strain hardening was assumed. In addition, an artificial displacement limit was imposed in their simulation. For these reasons, the numerical analyses were not able to predict the behavior of the connection accurately.

Cheng et al. (1998) carried out numerical analyses of their circular HSS connections using ABAQUS. A four-node reduced integration finite strain membrane shell element (S4R) was used in the modeling. One-eighth of the test specimen was modeled due to symmetry. Connections were assumed to deform according to the

incremental flow theory of plasticity with isotropic hardening. Material properties used in the analyses were derived from results of tension coupon tests. The model was assumed to have failed when the equivalent plastic strain (ϵ_{eq}^p) reached a critical value.

The equivalent plastic strain (ϵ_{eq}^p) is given by

$$\epsilon_{eq}^p = \int d\epsilon_{eq}^p, \text{ with} \quad (2.25)$$

$$d\epsilon_{eq}^p = \left(\frac{2}{3} d\epsilon_{ij}^p d\epsilon_{ij}^p \right)^{\frac{1}{2}}, \quad (2.26)$$

where ϵ_{ij}^p is the plastic strain tensor. The critical value of the equivalent plastic strain (ϵ_{eq}^p) used was determined from tension coupon tests.

The overall prediction of the numerical simulations was good with respect to the ultimate strength and the load versus displacement relationship of the connection. While the numerical simulation could correctly predict the location of failure that occurs at either the mid-length or the slotted end of HSS, it could not predict the deformation at failure accurately. However, the predicted tensile ultimate strength of the HSS connection was within 2% of the test.

Willibald et al. (2004) also performed numerical simulations of their slotted circular HSS tension connection test. Numerical simulations were carried out using ANSYS. One-eighth of test specimen including the weld was modeled using eight-node large strain solid element with reduced integration. A multi-linear true stress versus true strain curve that was converted from an engineering stress versus engineering strain curve from a tension coupon test of the HSS was used to define the material plastic behavior.

Local failure was assumed to occur when a critical equivalent plastic strain limit was reached.

Numerical simulations on two test specimens showed good agreement with the experiment results. The predicted ultimate strength was all within 2% of the test and the simulated load versus displacement curve matched that of the test closely up to the peak load. However, the analysis encountered convergence problems after the peak load because of the severe stiffness reduction due to a large number of elements being killed when the critical plastic strain limit was reached. High stress and strain concentrations at the region around the slotted end were observed in the analysis similar to that of the test.

2.4 Determination of true stress versus true strain relationship

In order to carry out numerical simulations for HSS connections, an accurate material true stress versus true strain relationship up to the instant of fracture is required. There have been a number of studies carried out to determine the true stress versus true strain relationship after the peak load. A few of those will be discussed below.

The true stress versus true strain relationship of steel is normally calculated from a tension coupon test. It is common to convert the load and deformation measured from a tension coupon test to the true stress (σ^t) and true plastic strain (ϵ^p) through

$$\begin{aligned}\sigma^t &= \frac{F}{A} \\ &= \sigma(1 + \epsilon^e),\end{aligned}\tag{2.27}$$

$$\begin{aligned}\epsilon^p &= \ln(1 + \epsilon^e) - \frac{\sigma^t}{E} \\ &= \ln\left(\frac{A_o}{A}\right) - \frac{\sigma^t}{E},\end{aligned}\tag{2.28}$$

where

F = load on the tension specimen,

A = current cross-section area,

A_o = original undeformed cross-section area,

ϵ^e = engineering strain,

E = elastic modulus, and

σ = engineering stress.

However, (2.27) and (2.28) are only applicable for data up to the peak load before necking starts. A direct conversion of the tension coupon test data is not possible beyond the peak load of the test.

Hollomon (1945) proposed a true stress (σ^t) versus true strain (ϵ_t) curve in the plastic region after the initial yielding can be expressed by the following power-law equation,

$$\sigma^t = K(\epsilon_t)^m\tag{2.29}$$

where ϵ_t is the true strain, m is the slope of the natural logarithm of the true stress versus true strain curve and K is a constant related to the carbon content of the steel. This expression allows the true stress versus true strain relationship of the material after the peak load of a tension coupon test be approximated.

Bridgman (1943) proposed a correction factor to calculate the experimental average tension stress to the true tension stress when the geometric profile of the coupon is not straight. Once necking is initiated after the peak load, the geometric profile of the coupon is no longer straight. Therefore, the stress given by (2.27) will only be the average tensile stress, and not the true stress since the stress is no longer uniform across the cross-section. Based on the geometric profile of the necking region, Bridgman proposed that the true stress (σ^t) be calculated from the average tensile stress by

$$\frac{\sigma^t}{\sigma_{avg}} = \left[\left(1 + \frac{2R}{a} \right) \ln \left(1 + \frac{\sigma_{avg}}{2R} \right) \right]^{-1}, \quad (2.30)$$

where

σ_{avg} = average tensile stress obtained from a circular tension coupon test,

σ^t = adjusted true stress,

a = current radius of the neck, and

R = radius of curvature of the neck surface in the longitudinal plan at the minimum section.

It should be pointed out that (2.30) was derived based on results of circular coupons.

As necking starts in tension coupon test, the geometric profile of the coupon is no longer straight. Le Roy et al. (1981) proposed an empirical expression to relate the true strain to the geometric profile of the necking by

$$\frac{a}{R_c} = k(\epsilon_t - \epsilon_{tmax}), \quad (2.31)$$

where k is a constant, ϵ_t is the true strain and ϵ_{tmax} is the true strain at the peak load of a

coupon test.

Zhang et al. (1999) conducted experimental and numerical studies on rectangular coupons with cross-section width to thickness ratios of less than eight. The thickness reduction of the rectangular coupon was measured at the minimum section in the necking region. Since a rectangular specimen does not neck uniformly on all sides, a function was proposed to convert the measured thickness change to the change in the cross-section area of an equivalent circular coupon by

$$\frac{\Delta A}{A_o} = 2 \left(\frac{\Delta t}{t_o} \right) - \left(\frac{\Delta t}{t_o} \right)^2 - f_s(S) f_t \left(\frac{\Delta t}{t_o} - \left(\frac{\Delta t}{t_o} \right)_{P_{max}} \right) f_m \left(\left(\frac{\Delta t}{t_o} \right)_{P_{max}} \right) \quad (2.32)$$

where

Δ = denotes change in area or thickness,

A = current area of the cross section of an equivalent circular specimen,

A_o = initial area of the cross section,

t_o = initial thickness,

t = current thickness,

S = cross-section aspect ratio,

f_s = factor for the reference aspect ratio,

f_t = factor for the net thickness reduction, and

f_m = factor for the actual aspect ratio.

The true stress versus true strain relationship is then calculated using (2.30) to (2.31).

Instead of using just the minimum thickness of a rectangular coupon, Naqvi (2004)

showed that an equivalent area of a circular coupon can be approximated by using four dimensions at the minimum cross-section of a rectangular coupon. The area of an equivalent circular coupon in (2.32) can be approximated by

$$A = \frac{A_{\text{cor}} + A_{\text{mid}}}{2}, \text{ with} \quad (2.33)$$

$$A_{\text{cor}} = t_{\text{cor}} w_{\text{cor}}, \text{ and}$$

$$A_{\text{mid}} = t_{\text{mid}} w_{\text{mid}}.$$

As shown in Figure 2.5, w_{cor} and t_{cor} are the width and thickness at the corner, w_{mid} and t_{mid} are the width and thickness at the mid-point of the sides. Equation (2.33) was found to be applicable up to a width to thickness ratio of 6. In order to represent the yield plateau in the stress versus strain relationship of steel, Naqvi and Khoo (2004) proposed a variation of power-law equation to represent the true stress (σ^t) versus true plastic strain (ϵ^p) relationship. The proposed equation takes the form,

$$\text{when } \epsilon^p > \epsilon_o^p, \quad \epsilon^p = C \left[\left(\frac{\sigma^t}{\sigma_o^t} \right)^n - 1 \right] + \epsilon_o^p, \text{ and} \quad (2.34)$$

$$\text{when } \epsilon_o^p \geq \epsilon^p \geq 0, \quad \epsilon^p = \left(\frac{\sigma^t - \sigma_y^t}{\sigma_o^t - \sigma_y^t} \right) \epsilon_o^p, \quad (2.35)$$

where

σ_o^t = true stress at the end of proportional limit when there is no yield plateau
or at the start of strain hardening

σ_y^t = true stress at the start of yield plateau, and

ϵ_o^p = true plastic strain at the start of strain hardening.

C and n are two constants to be determined. It should be noted that (2.35) is only required when there is a yield plateau. Instead of using (2.35), the true stress may be assumed to be a constant value equal to the true stress at the start of strain hardening (σ_o^t) when the true plastic strain (ϵ^p) is below the true plastic strain at the start of strain hardening. The reason being that there is little change in the true stress at the yield plateau.

Unlike methods adopted by Naqvi and Khoo, Hollomon, and Zhang et al, Matic (1985) proposed a procedure that determines the true stress versus true plastic strain relationship iteratively instead of defining this relationship through a function. The multi-linear true stress versus true plastic strain points of the material are iteratively corrected until results of the numerical simulation of a circular tension coupon match that of the test.

Figure 2.1 I shape section connected only to the flanges

Figure 2.2 Non-uniform stress distribution in the web of an I shape section

Figure 2.3 The configuration tested by Munse and Chesson (1963)

Figure 2.4 Slot orientation of the HSS connection

(a) Width to thickness ratio close to 1

(b) Width to thickness ratio greater than 3

Figure 2.5 Deformed cross-section shape of tension coupons

CHAPTER 3 TESTING PROGRAM

From the literature review, it was found that a more detailed study of slotted square and rectangular HSS tension members is required in order to improve on the provisions for shear lag in design standards. Therefore, a testing program was designed and carried out on slotted square and rectangular HSS connections in John Adjeleian Laboratory of Department of Civil and Environmental Engineering at Carleton University. The testing program was divided into two phases. The first phase of the testing program, consisting of twenty six HSS specimens with no end welding, were carried out by Huang (2005). Four slotted HSS specimens with end welding for the second phase of the testing program were conducted in this study.

Previous studies have shown that the effect of shear lag is more severe for slotted connections with no end welding. Thus any guideline and provision developed for the connections with no end welding will be conservative when applied to that with end welding. For this reason, the overall testing program focuses more on specimens with no end welding, and only four specimens with end welding were tested mainly to verify that the effect of shear lag is less severe when end welding is provided.

A brief description of test specimens, test setup and test results for phase 1 are provided in Appendix A as a reference. This chapter only deals with phase 2 of the testing program.

3.1 Objective

The objective of the test is to investigate the strength and behavior of square and rectangular HSS with end welding for various slotted connection details. Ultimate load, load versus deformation relationship and failure mode of the HSS connections with end welding are examined. Results of these tests are also used for validating the finite element models of the HSS connection that are to be used in the finite element analyses parametric study.

3.2 Specimen details

Four specimens consisting of one rectangular and three square specimens were fabricated. As shown in Figure 3.1, a continuous weld wrapping around the gusset plate was provided at the end of the slot of the HSS connection. The hollow structural sections consisted of ASTM-A500 Grade C cold-formed non-stress relieved HSS 89 x 89 x 4.8 and HSS 127 x 51 x 4.8. While the HSS 127 x 51 x 4.8 came from the same batch of HSS as that for phase 1, on the other hand the HSS 89 x 89 x 4.8 was from a different batch. Gusset plates were fabricated from 16 mm (0.625") thick ASTM-A572 Grade 55 plate. Longitudinal fillet welds of E48 xx grade were 8 mm in height and varied in length for different specimens. As shown in Figure 3.1, the weld length (L) is taken as the length of the straight segment of the longitudinal weld excluding the end weld, and the distance between the welds (w) is taken as half of the circumference along the centreline of the HSS section since the whole cross-section was connected. One duplicate square HSS specimen was fabricated for a weld length ratio (L/w) of 1.0. The specimen geometry is shown in Figure 3.2.

3.3 Specimen measurement and designation

Measured dimensions and designations of all four specimens are listed in Tables 3.1 and 3.2. The two numerical digit in the designations identify the weld length ratio (L/w), with 10 being a ratio of 1 and 07 a ratio of 0.7. Square HSS specimens are identified by the alphabet S and the rectangular HSS by R. Values shown in Tables 3.1 and 3.2 were the average for both ends of the specimen. It should be pointed out that the thickness of HSS in Table 3.1 is the average thickness of the flat part of HSS. The leg of the fillet weld was found to be uneven around the end of the gusset plate. At some of these locations, the measured effective height of the weld was only 7 mm instead of 11 mm. Additional data of the measurement are listed in Appendix B.

The corner of HSS was found to be thicker than its flat part as a result of cold-forming. Measured corner thickness and average outside corner radius of HSS were shown in Table 3.3. An idealized corner of HSS is shown in Figure 3.3. Referring to Figure 3.3, the gross cross-section area (A_g) and the net section area (A_n) of the test specimen can be calculated by

$$A_g = A_n = (c - 2\pi \cdot r) \cdot t' + 2\pi \left(r - \frac{t_c}{2} \right) \cdot t_c, \text{ with} \quad (3.1)$$

$$t_c = \frac{t_{\max} + t'}{2}, \quad (3.2)$$

where c is the measured outside circumference, r is the corner outside radius, t' is the thickness of the flat part, $t_{\max}$ is the maximum thickness at the corner and t_c is the average corner thickness. Since there was welding around the end of gusset plate, the gross cross-section area can be taken as equal to the net section area.

The distance from the centroid of one half of the HSS net section area to the centerline of the gusset plate, as shown in Figure 3.4, is taken as

$$\bar{x} = \frac{a^2 + 2ab}{4(a + b)}, \quad (3.3)$$

where b is the overall width of the HSS and a is the overall height of the HSS. Although this is not entirely correct, this definition is however adopted in order to be consistent with eccentricity calculation specified by ANSI/AISC-360-05 (2005). The distance between welds (w), as shown in Figure 3.5, is given by,

$$w = \frac{c - \pi t_e}{2} \quad (3.4)$$

The above geometric properties of the specimens are listed in Table 3.4.

3.4 Test setup and instrumentation

The test setup is shown in Figures 3.6 and 3.7. The loading was provided by 2000 MN (400 kips) capacity Tinius Olsen universal testing machine. All specimens were loaded axially through gusset plates that were connected to the top and bottom end fixtures mounted on the testing machine. The top fixture was designed to be able to swivel in a spherical support in order to align with the axis of the specimen during the test. There was no special provision to allow for swiveling with the bottom fixture. Figure 3.8 shows the end fixtures. All bolt holes are 24 mm in diameter to accommodate ASTM A325 M22 bolts.

Two LVDTs (linear variable differential transformer) were installed on both sides of the specimen to measure the axial deformation of the specimen. Their locations are shown in Figure 3.9. Five strain gauges were mounted at the slotted end on the surface of

HSS. They were orientated to measure the strain in the longitudinal (loading) direction. The strain gauge under the gusset plate is designated as G1 and the gauge furthest away designated as G5. Locations of strain gauge are shown in Figure 3.10.

3.5 Test procedure

During the test, readings of strain gauges, LVDT, stroke and load were recorded through a data acquisition system at an interval of 5 seconds. The real-time displays of load versus deformation curve and load versus strain curve were monitored by a personal computer that was connected to the data acquisition system. Stroke control was employed in all the tests.

The specimen was normally subjected to two stages of loading in a test. The initial stage of the loading is elastic, and was followed by an inelastic stage. Initially, a stroke rate of 1 mm per minute was used in the elastic stage of the test and no static reading was taken during this stage of loading. The First static reading was taken when the load versus deformation curve started to deviate from the straight line. After the first static reading, the loading rate was kept at 1 mm per minute for specimens with the weld length ratio (L/w) of 0.7. A higher rate of 2 mm per minute was used for specimens with the weld length ratio (L/w) of 1.0 since these tests were expected to fail in the mid-length after extensive deformation. Static readings were taken constantly at every 2 mm stroke interval during the inelastic stage of loading. The loading was put on hold for about 30 seconds before a static reading is taken. A test was terminated when fracture occurred in the specimen.

3.6 Material properties

Material properties of HSS and the gusset plates are required in evaluating the efficiency of the test specimen and for the numerical simulation of the test. Material tests were carried out to obtain material properties of HSS and the gusset plate. Tension coupons were fabricated in accordance to ASTM-E8-04 (2004) and CAN/CSA-G40.20-04 (2004). Coupons for HSS were cut longitudinally from the middle half of the flat part of HSS that was away from the seam weld and corners. Three non-standard triangular coupons were cut from the corner of HSS 89 x 89 in order to obtain a rough estimate of the strength increase due to cold-forming. These coupons were neither flat, uniform nor straight. Figure 3.11 shows the geometry of the corner coupon. After machining, the end of the coupon was subsequently flattened in order to fit into the grip of the test machine.

Tension coupon tests were carried out using a 100 kN capacity INSTRON testing machine as shown in Figure 3.12. An extensometer with a 57.2 mm gauge length was used to measure the longitudinal deformation during the test. Readings of load, stroke and extensometer 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. Static readings and transverse deformations were taken at every 0.5 to 0.8 mm stroke displacement after yielding. Corner and mid-point thicknesses and widths at the necking region were measured manually at every static reading once necking has started. Before necking, only corner thickness and width were measured.

Average mechanical properties of both HSS and gusset plate are listed in Table 3.5. The yield strength of HSS was calculated using the 0.2% offset method. Detailed results

of the tension coupon tests are listed in Appendix C. Engineering stress versus engineering strain curves for the test materials are shown in Figures 3.13 to 3.15. It should be noted that the sudden termination of the curve immediately after the peak stress is because the extensometer was removed after that point and not due to coupon fracture. The static representation of the engineering stress versus engineering strain relationship was created by fitting through the static reading points of test curves. Material properties were determined based on the static representation curve of the material. It can be seen that engineering stress versus engineering strain curves for flat part coupons of the HSS do not have a yield plateau, which is a typical phenomenon for a cold-formed steel.

Figure 3.16 shows the engineering stress versus engineering strain curves of the HSS corner coupons and one from the flat part. Since corner coupons were neither flat, uniform nor straight, their test results were not expected to show good consistency. Furthermore, coupons were cut from different corners of HSS that may have different level of cold-working. Nevertheless on average, corner coupons show that the ultimate strength at the corner of square HSS was stronger than the flat part by about 23%. Results of corner coupons are also listed in Tale 3.5.

3.7 Test results and discussions

The effect of shear lag on the test specimen is evaluated in term of the net section efficiency. In the discussion, the net section efficiency (U_n) is defined as

$$U_n = \frac{P_{uTest}}{A_n F_u}, \quad (3.5)$$

where

$$P_{uTest} = \text{peak static test load,}$$

A_n = net area of the cross-section, and

F_u = ultimate tensile strength of the flat part of HSS

The ultimate tensile strength of the material was determined by tension coupon tests.

3.7.1 Test results

All square HSS specimens fractured at the mid-length of the specimen after extensive necking. An example of the failure is shown in Figure 3.17. Unlike the square HSS specimens, the rectangular HSS specimen failed at the slotted end. Figure 3.18 shows cracks were initiated both at the end of the gusset plate and at the end of HSS. However, it was not able to tell at which location the crack has first started in the test. Subsequently, complete weld shear failure occurred as the crack ran a full length along the fillet weld on one side of HSS, as shown in Figure 3.19. The load versus average LVDT curves for all specimens are shown in Figures 3.20 and 3.21. All specimens exhibited significant deformation prior to fracture even for the rectangular HSS specimen. Figure 3.22 shows the measured strain distribution for square HSS specimens at two stages of loading where strains at strain gauge G1 are equal between specimens. It can be seen that there is higher stress concentration for the lower weld length ratio (L/w) specimen of 0.7 (S07) than that for 1.0 (S10-a). The higher stress concentration is characterized by the sharper increase in the strain from gauge G2 to G1.

Net section efficiencies (U_n) of the specimens are shown in Table 3.6. All specimens have efficiencies slightly greater than unity. The reason being that the corner of a HSS is stronger than its flat part. The effect of a stronger corner will be studied in more details through numerical simulations in Chapters 5 and 6. Test results shows that there is no significant net section efficiency difference between specimens with L/w of 0.7

and 1.0. The gross section area is used in calculating the net section efficiency with (3.1) because there is no opening at the end of the gusset plate. But it should be noted that ANSI/AISC-360-05 neglects the cross-section area removed to make the slot when calculating the net section area of the tension member. The net section reduction factors calculated by (2.5) to (2.7) for CSA-S16.1-01 and by (2.18) for ANSI/AISC-360-05 are also presented in Table 3.6. Compared to test results, it can be seen that provisions to account for shear lag in CSA-S16.1-01 and ANSI/AISC-360-05 greatly underestimate the efficiency by up to 20% to 40%. Specimens S07 and R07 with a weld length ratio of 0.7, have net section efficiencies that are comparable to specimens from phase 1 of the testing program that have the weld length ratio of around 0.8 (Appendix A). This shows that the effect of shear lag is more severe in a slotted HSS connection without end welding compared to the one with end welding. Thus, the efficiency equation developed for a slotted HSS connection with no end welding can be applied to one with end welding.

Table 3.1 Measured HSS gross section properties of test specimens

Specimen	HSS	Circumference, c (mm)	Width, a (mm)	Width, b (mm)	Thickness, t' (mm)
S10-a	89 x 89	342.5	88.66	89.32	4.42
S10-b	89 x 89	344.0	88.78	89.16	4.43
S07	89 x 89	343.0	88.81	89.16	4.44
R07	127 x 51	345.0	51.51	127.27	4.53

Table 3.2 Measured connection geometry of test specimens

Test specimen	Gusset plate		Weld length L (mm)	Weld height	
	Width, WP (mm)	Thickness, t (mm)		Longitudinal t _w (mm)	End t _e (mm)
S10-a	254.50	16.55	170.25	11.00	11.00
S10-b	254.20	16.61	172.38	10.50	11.50
S07	254.26	16.53	122.88	11.00	10.75
R07	254.35	16.46	125.63	11.00	10.50

Table 3.3 Measured thickness at the corner of HSS

HSS	Maximum thickness			Corner outside radius, r mm (inch)
	Low (mm)	High (mm)	Average (mm)	
89 x 89	4.64	4.73	4.69	11.11 (7/16)
127 x 51	4.92	4.82	4.87	11.11 (7/16)

Table 3.4 Calculated geometric properties of the specimen

Specimen	Weld distance w (mm)	Weld length ratio L/w	Net area A _n (mm ²)	Net area eccentricity and eccentricity ratio	
				$\bar{x}$ (mm)	$\bar{x}/L$
S10-a	165.0	0.97	1473	33.3	0.21
S10-b	165.2	0.98	1476	33.2	0.21
S07	165.0	0.68	1479	33.3	0.30
R07	165.4	0.69	1517	41.0	0.36

Table 3.5 Material properties of test specimens

Specimen	A_o/A_f	Elongation (%)	Yield strength F_y (MPa)	Ultimate strength F_u (MPa)
HSS 89 x 89 - flat	2.20	30.0	370.0	439.6
HSS 127 x 51	2.29	33.5	380.3	449.0
16mm plate	2.22	33.0	380.5	560.0
HSS 89 x 89 - corner			510.0	541.3

Table 3.6 Test results

Specimen	Capacity $A_n F_u$ (kN)	Peak static load, P_{uTest} (kN)	Efficiency		
			Test U_n	CSA U_{csa}	AISC-05 U_x
S10-a	647.6	668.4	1.03	0.76	0.81
S10-b	649.0	660.2	1.02	0.76	0.81
S07	650.2	667.3	1.03	0.56	0.73
R07	679.7	684.3	1.01	0.57	0.68

Figure 3.1 Slotted HSS connection with end welding

Figure 3.2 The specimen geometry

Figure 3.3 Corner of the HSS

Figure 3.4 Connection eccentricity

Figure 3.5 Definition of the distance between the welds (w)

Figure 3.6 Test setup

Figure 3.8 End fixture assemblies

Figure 3.9 Locations of LVDT.

Figure 3.10 Locations of strain gauges

Figure 3.11 Corner tension coupon

Figure 3.12 A tension coupon test in the testing machine

Figure 3.13 Engineering stress versus engineering strain for HSS 89 x 89 tension coupons

Figure 3.14 Engineering stress versus engineering strain for HSS 127 x 51 tension coupons

Figure 3.15 Engineering stress versus engineering strain for 16 mm gusset plate tension coupons

Figure 3.16 Engineering stress versus engineering strain for corner coupons

Failure of S-10a

Figure 3.17 A typical square HSS specimen failure at the mid-length

Figure 3.18 Cracks initiation of the rectangular HSS specimen R07

Figure 3.19 Failure of the rectangular HSS specimen R07

Figure 3.20 Load versus average LVDT displacement for HSS 89 x 89 specimens

Figure 3.21 Load versus average LVDT displacement for the HSS 127 x 51 specimen

Figure 3.22 Strain distribution for HSS 89 x 89 specimens at different stages of loading

CHAPTER 4 MATERIAL PROPERTIES

In a numerical 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 up to the instant of fracture is needed in order to carry out the finite element analysis to assess the performance of the connection. Procedures to determine the material true stress versus true strain plastic relationship of the gusset plate and HSS are discussed.

The following elastic modulus (E) and Poisson's ratio (ν) are used in all numerical analyses.

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

$$\nu = 0.3.$$

It should be noted that the extensometer used in the tension coupon test is not sensitive enough to measure the very small linear elastic deformation of the tension coupon accurately. But the extensometer has no problem measuring the remaining plastic deformation of the coupon when the deformation is large. This can be seen in the consistency of the engineering stress versus engineering strain curves after yielding as shown in Figures 3.14 and 3.15. It is well established that the elastic modulus of steel is around 200000 MPa. For this reason, the elastic modulus is simply taken as 200000 MPa in all analyses. The exact value of the elastic modulus is not important since the finite element analysis involved significant plastic deformation that greatly exceeds the strain at the elastic proportional limit.

4.1 True stress versus true strain curve

In a standard tension coupon test, measurements of the axial deformation versus load only allow the true stress versus true plastic strain relationship to be calculated up to the peak load. In this study, an interactive procedure is adopted to determine the true stress versus true plastic strain relationship of the material beyond the peak load. This procedure uses the function proposed by Naqvi and Khoo (2004) to define the true stress versus true plastic strain curve beyond the peak load. Similar to Metic (1985), the function is corrected iteratively until results of the numerical simulation of the tension coupon matches that of the test. The adopted procedure is discussed in the following sections.

4.1.1 True stress versus true strain curve up to the peak load

Up to the peak load, the true stress versus true strain relationship can be converted directly from the engineering stress versus engineering strain data of a standard tension coupon test. The engineering stress (σ^e) and engineering strain (ϵ^e) over a gauge length are defined as

$$\sigma^e = \frac{F}{A_o}, \text{ and} \quad (4.1)$$

$$\epsilon^e = \frac{L}{L_o} - 1 \quad (4.2)$$

where

F = load,

A_o = original cross-section area,

L = current length of the gauge, and

L_o = original gauge length.

Since the cross-section is in an uniaxial state of stress and by assuming that there is no volume change in plastic deformation, the true stress (σ^t) and true plastic strain (ϵ^p) can be written in terms of engineering stress and strain as

$$\sigma^t = \sigma^e (1 + \epsilon^e), \text{ and} \quad (4.3)$$

$$\epsilon^p = \epsilon^t - \frac{\sigma^t}{E}, \text{ with} \quad (4.4)$$

$$\epsilon^t = \ln(1 + \epsilon^e), \quad (4.5)$$

where

ϵ^t = true strain, and

E = elastic modulus

4.1.2 True stress versus true strain curve after the peak load

Khoo et al. (2000) has shown that the relationship of load versus axial deformation is sensitive to any slight geometric variation after the peak load is reached. On the other hand, the load versus transverse deformation relationship was found to be insensitive to a small geometric variation. Therefore, load versus transverse deformation data are more reliable in representing the material response in large strain.

After the peak load, an iterative numerical method is used in obtaining the true stress versus true strain relationship. The trial true stress versus true strain relationship is adjusted iteratively until the numerical simulation agrees with the engineering stress versus cross sectional deformation data of the tension coupon test. The version of power-law stress versus strain function proposed by Naqvi and Khoo (2004) is adopted in generating

the true stress versus true plastic strain relationship of the material. The start of strain hardening can be expressed by the function as

$$\varepsilon^p = C \left[\left(\frac{\sigma^t}{\sigma_o^t} \right)^n - 1 \right] + \varepsilon_o^p, \quad (4.6)$$

where ε_o^p and σ_o^t are the true plastic strain and true stress at the start of strain hardening respectively, C and n are parameters to be determined. As suggested by Naqvi and Khoo (2004), by forcing the function to pass through the point at peak load, the relationship between parameters C and n can be established as

$$\varepsilon_f^p = C \left[\left(\frac{\sigma_f^t}{\sigma_o^t} \right)^n - 1 \right] + \varepsilon_o^p, \text{ with} \quad (4.7)$$

$$C = \frac{\varepsilon_f^p - \varepsilon_o^p}{\left(\frac{\sigma_f^t}{\sigma_o^t} \right)^n - 1}, \quad (4.8)$$

where ε_f^p and σ_f^t are respectively the true plastic strain and true stress at the peak load. Thus, different true stress versus true plastic strain relationship can be generated by just varying n .

The true stress versus true plastic strain relationship after the peak load was generated by varying n until the stress versus transverse deformation curve from the numerical simulation closely matches that of the coupon test. One measure of the transverse deformation is the ratio of the average cross-section area over the original area. As proposed by Naqvi (2004), the average cross-section area is taken as

$$A = \frac{A_{cor} + A_{mid}}{2}, \text{ with} \quad (4.9)$$

$$A_{\text{cor}} = t_{\text{cor}} w_{\text{cor}}, \text{ and}$$

$$A_{\text{mid}} = t_{\text{mid}} w_{\text{mid}},$$

where w_{cor} and t_{cor} are the width and thickness at the corners, w_{mid} and t_{mid} are the width and thickness at the mid-point of the sides, as shown in Figure 2.5. Up to peak load, A_{cor} and A_{mid} are equal. Naqvi (2004) has shown that using the average area defined by (4.9), the load versus transverse deformation curve of a rectangular tension coupon up to a width to thickness ratio of 6 was almost identical to that of a circular coupon. For this reason, a finite element model of a circular tension coupon is used for the numerical simulation instead of a rectangular coupon. Because of symmetry, only one-half of the coupon has to be modeled. The axisymmetric finite element model of the coupon used in the simulation is shown in Figure 4.1. A bi-quadratic reduced integration axisymmetric element (CAX8R) is used in the modeling. In the simulation, the elastic modulus and Poisson's ratio were taken as 200000 MPa and 0.3 respectively. The detailed iterative procedure used in refining the true stress versus true plastic strain relationship of the material is illustrated in Appendix D. The simulated engineering stress versus transverse deformation curves based on the selected true stress versus true plastic strain relationship, as well as the test results, are shown in Figures 4.2 to 4.7. The selected true stress versus true plastic strain curves for all test materials are shown in Figures 4.8 to 4.9.

4.2 Determining failure limit of the material

In a tension coupon test, the large localized strain in the necking region caused crack initiation and fracture. Thus, it seems appropriate to use the plastic strain at fracture as the failure limit of the material. Khoo et al. (1997) and Willibald et al. (2004) showed that the

equivalent plastic strain at fracture can be used successfully as the failure limit of the material to predict the performance of slotted circular HSS connections. As defined by (2.25), the equivalent plastic strain is a measure of the state of the plastic deformation of the material. But it should be noted that equivalent plastic strain at fracture is not a material constant. Bridgman (1947) has shown that plastic strain at fracture is dependent of the level of hydrostatic stress.

The tension coupon test specimen of the HSS has a width to thickness ratio of close to three. Thus during necking, the deformation of the coupon in terms of its ratio relative to its original dimension is mainly in the direction of thickness and not the width. This is similar to the observed failure in the slotted HSS connection specimen where the localized deformation prior to fracture is in the direction of the wall thickness and not in the circumferential direction. Therefore, the level of hydrostatic stress that affect the failure strain limit of the connection can be assumed to be similar to that for the tension coupon HSS. For this reason, the measured equivalent plastic strain at fracture from a coupon test of HSS is used as the critical equivalent plastic strain limit (ϵ_c^p) that signifies the onset of local failure in the connection.

In this testing program, the cross-section dimensions of the coupon were measured regularly during the tension coupon test. If the state of stress is uniaxial, the equivalent plastic strain can be calculated as

$$\epsilon_{eq}^p = \ln\left(\frac{A_o}{A}\right), \quad (4.10)$$

where A_o is the original cross-section area and A is the current average cross-section area. Although the state of stress is not uniaxial at the region of necking, (4.10) or a variation of

it can still be used to estimate of the equivalent plastic strain. Table 4.1 lists averages of the cross-section area ratios based on last measurement before the coupon fractured. Three ratios of A_o/A_f , A_o/A_{fcor} , A_o/A_{fmid} and their natural logarithmic values are shown in Table 4.1. A_f , A_{fcor} and A_{fmid} are respectively the average area, the corner area and the mid-point area calculated according to (4.9) based on the last cross-section measurement. In a tension coupon test, the last manual measurement of the cross-section dimension was not at the instance of fracture. Since the actual cross-section area continues to decrease after the last measurement until fracture occurred, values reported in Table 4.1 are always lower and more conservative compared to the actual values at fracture. After necking, the cross-section deformation of the coupon mainly occurred by the thickness reduction at the mid half of the long side of the coupon, which was also the location of fracture initiation. Thus, the deformation that can better characterize strain at fracture was given by the mid-point cross-section area ratio of A_o/A_{fmid} rather than A_o/A_f or A_o/A_{fcor} . It follows that the critical equivalent plastic strain limit be taken as

$$\epsilon_c^p = \ln\left(\frac{A_o}{A_{fmid}}\right), \quad (4.11)$$

Table 4.1 gives the measured critical equivalent plastic strain value (ϵ_c^p) that varies between 0.8 and 1.0 for all HSS and gusset plates. Taking the medium of this range, a critical equivalent plastic strain limit (ϵ_c^p) of 0.9 was selected to represent all materials in the numerical simulation. The only exception being the corner of HSS, which was assumed to have a different limit. This is discussed in the next section. The effect of varying the limit between 0.8 to 1.0 in the numerical simulating is discussed in Chapter 5.

4.3 Material properties of HSS corner

It is well established that cold-forming affect material properties of the steel. Karren and Winter (1967) found that the corner of a cold-formed steel shape can have a yield strength that was 100% higher than that of the virgin material. The maximum increase in the ultimate strength at the corner was found to be 47% above the virgin material. On the other hand, the ductility was found to decrease after the cold-forming. The study by Abdel-Rahman et al. (1997) on cold-formed channel sections also showed that yield strength, ultimate tensile strength and ductility were all significantly changed at the corner of the section. At the corner, the yield strength was reported to be up to 47% higher and the ultimate tensile strength was up to 30% higher compared to that of the virgin material. Meanwhile, compared to the virgin material, the ductility of the corner reduced by as much as 90%.

Although a detailed study of the material property variation over the cross-section is outside the scope of this thesis, three non-standard corner coupons of phase 2 HSS 89x89 were tested to get a rough idea of the material strength at the corner. As can be seen in Figure 3.16 and Table 3.5, the ultimate strength of the corner is about 23% stronger than the flat part of HSS. The increase in the ultimate strength is accompanied by a severe decrease in elongation at both the peak load and at fracture. The average equivalent plastic strain at fracture of these coupons calculated with (4.11) based on the cross-section dimensions after fracture is shown in Table 4.1. The average equivalent plastic strain is only about half of that measured for the flat part of HSS. Thus, the critical equivalent plastic strain limit for a higher strength HSS corner was assumed to be 0.4 in the numerical simulation.

Since no proper tension coupon test nor study has been carried out for the HSS corner, the assumed true stress versus true plastic strain relationship for the HSS corner to be used in numerical simulations of the connections are generated using the power-law equation according to (4.6). The n value used in generating the assumed true stress versus true plastic strain data for the corner is normally much larger than that used for flat part of HSS because the strength of the corner increase faster before the peak load and drops faster after. The assumed material properties of the HSS corner are determined by trial and error until results of the numerical simulation of the HSS connection roughly match that of the test specimen with the largest weld length ratio. More details on the assumed material properties for the HSS corner are provided in Chapter 5.

Based on results of corner coupon tests, together with studies from Karren and Winter (1967), and Abdel-Rahman et al. (1997), the following guidelines were used in developing the assumed true stress versus true plastic strain relationship for the HSS corner.

- a) The true plastic strain at the start of strain hardening (ϵ_o^p) is taken as zero.
- b) The true plastic strain at the peak load point (ϵ_f^p) is around 0.015 to 0.02.
- c) The true stress at the start of strain hardening (σ_o^t) for the HSS corner is about 35% higher than that for the flat part of HSS.
- d) The true stress at the peak load (σ_f^t) for the HSS corner is at least 20% higher than that for the flat part of HSS.

Table 4.1 Cross-section area ratios of test materials

Material	Cross section area ratio			Natural logarithmic values		
	A_o/A_f	A_o/A_{fcor}	A_o/A_{fmid}	$\ln(A_o/A_f)$	$\ln(A_o/A_{fmid})$	$\ln(A_o/A_{fcor})$
HSS 89 x 89 (phase 1)	2.11	1.94	2.31	0.75	0.66	0.84
HSS 89 x 89 (phase 2)	2.20	1.95	2.53	0.79	0.68	0.93
HSS 127 x 51	2.29	2.04	2.62	0.83	0.71	0.96
12 mm plate (phase 1)	2.14	2.06	2.24	0.76	0.72	0.81
16 mm plate (phase 1)	2.41	2.22	2.62	0.88	0.80	0.96
16 mm plate (phase 2)	2.25	2.08	2.47	0.81	0.73	0.90
20 mm plate (phase 1)	2.14	1.98	2.34	0.76	0.68	0.85

Figure 4.1 Axisymmetric model of the circular coupon

Figure 4.2 Engineering stress versus change in cross-section area for HSS 89 x 89 (phase 1) tension coupons

Figure 4.3 Engineering stress versus change in cross-section area for HSS 127 x 51 tensions coupons

Figure 4.4 Engineering stress versus change in cross-section area for HSS 89 x 89 (phase 2) tension coupons

Figure 4.5 Engineering stress versus change in cross-section area for 12 mm gusset plate tension coupons

Figure 4.6 Engineering stress versus change in cross-section area for phase 1 16 mm gusset plate tension coupons

Figure 4.7 Engineering stress versus change in cross-section area for 20 mm gusset plate tension coupons

Figure 4.8 Engineering stress versus change in cross-section area for phase 2 16 mm gusset plate tension coupons

Figure 4.9 True stress versus true plastic strain curves for HSS

Figure 4.10 True stress versus true plastic strain curves for gusset plates

CHAPTER 5 FINITE ELEMENT MODELING AND VERIFICATION

Finite element models are developed based on geometries of test specimens to carry out numerical simulations of the slotted square and rectangular connections. The developed finite element models are validated against test results of HSS connections. Studies on the element type, equivalent plastic strain limit and mesh size are carried out before validating the finite element models. The purpose of these studies is to develop reliable finite element models that can simulate the strength and behavior of square and rectangular HSS connections. In Chapter 6, a parametric study for HSS connections is conducted using the validated finite element models

5.1 Finite Element Model

The numerical study is carried out with the finite element program ABAQUS (2003). A geometrical and material non-linear analysis is performed in this study. The model for the HSS connection is constructed with both the four-node, bi-linear shell element (S4) and the eight-node tri-linear solid element (C3D8). Only one eighth of the specimen is modeled due to symmetry. The fillet weld between the hollow section wall and the gusset plate is not explicitly modeled. Instead, the weld is modeled by constraining displacements and rotations of the node on the HSS wall to the corresponding node on the gusset plate. In the finite element analysis, it is assumed that no failure occurred in the fillet weld. This implies that the weld capacity will not govern the strength of the connection. With this assumption, the shear deformation of the fillet weld in the longitudinal direction will be quite small compared to the overall deformation.

Therefore, the fillet weld can be treated as a rigid connection between the HSS wall and the gusset plate. As shown in Figure 5.1, a rigid beam element is used to connect a node in the HSS to one in the gusset plate. The width of the fillet weld on the gusset plate is modeled by constraining two strips of nodes to the weld line strip. These three strips of nodes are equally spaced at 2 mm from each other to represent the width of the fillet weld. On the HSS wall, shell elements within the weld region are divided into several longitudinal zones of equal thickness. The shell elements in each of these zones are thickened to model the thickness of HSS wall and additional thickness from the fillet weld. An example of the idealization of the weld in the modeling is shown in Figure 5.1 for three weld zones. The width of HSS that is equal to the weld height (wh) is divided into 3 or 5 zones of approximately equal width, with the maximum zone width of less than 2.5 mm. At each of these zones, the shell element is assigned a thickness equal to the average thickness of the weld plus the HSS wall thickness. The modeling of end weld for a connection with end welding is discussed in Section 5.1.5, although the scheme is adopted in other subsections in Section 5.1.

Figures 5.2 and 5.3 show the typical mesh for the square HSS connection with and without end welding. Figures 5.4 and 5.5 are the enlarged views of the region at the end of the gusset plate. As shown in Figures 5.2 to 5.5, the part of the HSS wall at the end of the gusset plate is modeled with a two-layer solid element patch while the rest of the HSS section and the gusset plate are modeled with shell elements, as shown in Figure 5.4. For connections with no end welding, the solid element patch starts from the end of the gusset plate and extended longitudinally beyond the slot opening by a weld height (wh) that is at least 6 mm. For connections with end welding, the solid element patch starts at the toe of

the end weld and extended to about one-sixteenth of the gross section length (L_e), as shown in Figure 5.5. In the transverse direction, the solid element patch spans from the centerline of gusset plate thickness to the edge of HSS corner except when the slot is on the short side of a rectangular HSS. For this case, the solid element patch extends all the way around to the edge of the corner on the other side of HSS cross-section. The solid element patch is coupled to shell elements at their contact edges. The coupling constrained the deformation of solid element surface at a contact edge to the nodal displacements and rotations of the shell element. Since both high stress concentration and failure can occur at the slotted end, the solid element patch is employed only in this area to capture these localized effects. The difference of using a shell element and a solid element will be discussed in the following section.

All analyses are carried out using a material user-subroutine with ABAQUS. The finite element model is loaded by applying uniform displacement at the end of the gusset plate. Failure of the connection is assumed to have occurred and the analysis terminated when the equivalent plastic strain in any part of the model has reached the critical limit. The critical equivalent plastic strain limit is taken as 0.9 except for the HSS corner. For a few selected analyses where cracks in a HSS connection are modeled to propagate, the elastic modulus at the integration point of the element whose equivalent plastic strain value exceeded the critical limit is reduced by a factor of 0.001 to simulate the loss of stiffness due to material failure. The stresses at this integration point are also zeroed at the start of every time increment thereafter. Once a crack has started, significantly more iteration are required to achieve convergence for each time increment because there is a greater load redistribution needed due to the zeroing of the stresses and

the reduction in the stiffness at the failed integration point. Thus in a crack propagation simulation, the analysis is not terminated when the equivalent plastic strain has exceeded the critical limit. But it should be noted that only the numerical simulation that is terminated when any part of the model has reached the critical equivalent plastic strain limit is used in determining of the capacity of the connection.

In the studies to develop the finite element model in this section, material properties used in the simulation are the actual values from the test specimen on which the finite element model is based upon. These properties are provided in Section 4.2. Although the increase in the HSS corner thickness is considered in the finite element models in this section, no increase in corner strength is included. Detailed studies of element type, critical equivalent plastic strain limit and finite element mesh in developing the finite element model are presented in the following subsections.

5.1.1 Shell element versus solid element

The major difference between an S4 shell element and a C3D8 solid element is the ability to capture the out of plane stress in the cross-section after necking has started. This can best be illustrated by simulating a rectangular tension coupons test using the shell and solid elements. The coupon has a width to thickness ratios (a/b) of 3.0. Finite element meshes of both shell and solid element models are shown in Figure 5.6.

Figure 5.7 shows the predicted engineering stress versus engineering strain relationships of a rectangular tension coupon modeled with shell elements and solid elements. Numerical simulations are carried out using material properties of HSS 89 x 89 from phase 1 of the testing program. It can be seen that all curves are identical up to the peak stress. After the peak stress, analyses with shell elements predicted a sharper drop in

the load than that with solid elements. The sharper drop of load carrying capacity with respect to axial deformation is due to the inability of the shell element to capture the out of plane stress associated with necking.

After the peak load, the state of stress in the cross-section of a coupon at the region of necking transforms from uniaxial to multiaxial. Consequently, an out of plane tensile stress is generated due to the necking geometry. This out of plane tensile stress stiffens the cross-section. As a result, the cross-section thickness reduction is slowed down with respect to the axial deformation. However, a shell element with no out of plane stress cannot model this stiffening effect. Therefore, a shell element is not suitable to be used in a region where significantly localized through thickness necking is expected, but can be used in other regions of the connection.

5.1.2 Element type comparison on the slotted HSS connection model

Comparison of the ultimate strength of the analyses with models based on the geometry of square HSS specimens with no end welding, SM5G05P20 and SM3G05P20, using the solid element patch and entirely shell element are shown in Table 5.1. It should be noted that in these simulations, no critical equivalent plastic strain limit is used. SM5G05P20 and SM3G05P20 have weld length ratios of 1.33 and 0.79 respectively. The mesh used in the analysis is based on the mesh configuration selected in Section 5.1.3. The load versus displacement curves from both the solid element patch and the full shell element models are shown in Figure 5.8. The mesh designs are identical for both model types in terms of the element size.

It can be seen in Figure 5.8 and Table 5.1 that the solid element patch and the full shell element models predicted the same maximum load when the weld length ratio (L/w)

is around 1.33. But at a weld length ratio of 0.79, the solid element patch model predicts a 2% higher ultimate load than the full shell element model. The reason is that the solid element patch model is able to slow down the progression of through thickness necking and allow a greater utilization of the cross-section area. At a higher weld length ratio of 1.33, there is a lower stress concentration. For this reason, the cross section area is close to be fully utilized before through thickness necking becomes critical. Thus, there is no difference in the predicted maximum load from both model types when the L/w ratio is high.

5.1.3 Mesh study

A mesh study is carried out to investigate the influence of mesh density before the finite element models are validated with test results. The study is carried out for the mesh of HSS in the region at the end of gusset plate and on the number of solid element layers to model the thickness of HSS.

5.1.3.1 HSS mesh densities at the end of gusset plate

In Figures 5.2 and 5.3, typical mesh designs for modeling the HSS connection are shown. Mesh is refined in the region at the end of the gusset plate. The intent of using a finer mesh is to capture the detailed stress and strain distribution in a region of high stress concentration in order to obtain more accurate analytical results. Three different meshes of the solid element patch studied are shown in Figures 5.9 and 5.10 for square HSS connection models with and without end welding respectively. Mesh 1 has the coarsest mesh, with the transverse to longitudinal for the smallest element of 0.5 mm x 0.6 mm for models with end welding, and 0.8 mm x 0.8 mm for models without end welding. The

sizes of element in Mesh 2 are about half that of Mesh 1 and Mesh 3 are about half that of Mesh 2. Finite element models with no end welding are based on the geometry of the test specimen SM5G05P20, while the models with end welding are based on the test specimen S10-a.

Results of analyses for different mesh densities with various weld length ratios are shown in Tables 5.2 and 5.3 and in Figures 5.11 to 5.13. While the predicted maximum load is almost identical for all three meshes, the analysis predicts a lower deformation at failure with the densest mesh, Mesh 3. All three meshes also predict almost the same load versus deformation curve. It should be noted that the main objective of the numerical simulation is to predict the maximum load carrying capacity of the connection. Thus, based on the small difference in the predicted maximum load for all three meshes and a small difference in the predicted deformation at failure for Mesh 2 and Mesh 3, Mesh 2 is adopted for all numerical simulations in the thesis. Mesh 2 requires less computing effort than Mesh 3 and gives a better predicted deformation at failure than Mesh 1.

5.1.3.2 Layers of solid element in the patch

Numerical simulations are carried out for models with two-layer and four-layer solid element patches that are based on the geometry of the square HSS specimen with no end welding, SM5G05P16, but at L/w ratios of 0.4 and 1.33. The load versus displacement curves are shown in Figure 5.14 for models with different weld length ratios.

Figure 5.13 shows that there is very little difference in the predicted peak load by models with two-layer and four-layer solid element patches. The deformation at failure predicted by the four-layer solid element patch model is found to be slight larger. The reason for the slight difference is that a four-layer solid element patch can more accurately

model the through thickness variation of the out of plane stress, and thus is better able to represent the stiffening effect provided by the out of plane stress. Since there is only a slight difference between the predicted peak load by both two-layer and four-layer models, the two-layer model, with a less required computing effort, is adopted in all numerical simulations.

5.1.4 Critical equivalent plastic strain limit

In the numerical simulation of a HSS connection, the material in any part of the model is assumed to have failed when its equivalent plastic strain has reached the critical limit. The critical equivalent plastic strain limit is taken as 0.9 except for the corner of HSS. A different critical equivalent plastic strain limit is used for the HSS corner, when higher strength corner material properties are used in the analysis. In Section 4.2, the measured equivalent plastic strain at fracture from tension coupon tests varies between 0.8 and 1.0. Thus, numerical simulations are carried out with critical equivalent plastic strain limit of 0.8, 0.9 and 1.0 to study the sensitivity of the results to the limit used.

Simulations of slotted square HSS connections with and without end welding are carried out for different critical equivalent plastic strain limits. Finite element models with no end welding are based on the geometry of test specimen SM5G05P20, while the models with end welding are based on test specimen S10-a. Three weld length ratios (L/w) of 0.4, 0.79 and 1.33 are modeled for connections without end welding, and 0.4, 0.7 and 1.0 are modeled for connection with end welding. Results of the simulations in Tables 5.4 and 5.5, and Figures 5.15 to 5.17 show that there is little difference in the predicted maximum load with critical equivalent plastic strain limits of 0.8, 0.9 and 1.0. The symbols on the graph identify the deformation when each of the limit has been reached.

Most specimens attain their maximum loads before the large local strain at the end of gusset plate reaches the critical equivalent plastic strain limit. Since anyone of these limits can be used without significantly affecting the predicted maximum load, the average measured limit of 0.9 is thus used for all numerical simulations.

5.1.5 Modeling end weld

For a slotted HSS connection with end welding, the weld height reduces gradually away from the end of the gusset plate. Figure 5.18 shows two schemes of modeling for the end weld. The thinner line represents the change in weld thickness in the modeling for different weld zones as described in Section 5.1. Scheme B is a more accurate representation of the end weld compared to Scheme A. In Scheme A, the longitudinal weld is modeled to extend all the way to the end. Numerical simulation of the slotted square HSS connections based on the geometry of the test specimen S10-a for L/w ratio of 0.4 and 1.0 are carried out for both schemes. Figure 5.19 shows that there is hardly any difference between results for both schemes. Thus for ease of modeling, Scheme A is adopted for all numerical simulations in this study.

5.2 Validation of the models

In order to validate the developed finite element models, numerical simulations are carried out on the actual test specimens. Specimens from both Korol (1996) and the current testing program are modeled. Two sets of numerical simulations are carried out. One set using material properties of the flat part of HSS applied entirely over the whole HSS cross-section and another set assuming the corner of HSS has a higher strength. The simulation is terminated and the connection is assumed to have failed when the critical

equivalent plastic strain limit has been reached in any part of the model. Results of numerical simulations are compared to that from actual tests. Crack propagation simulations are also carried out for some finite element models.

To facilitate the discussion, the following terms are used. The ultimate load of the finite element model of a specimen is defined as

$$P_{u_calc} = F_u A_n, \quad (5.1)$$

where F_u is the ultimate strength at the flat part of HSS and A_n is the net cross-section area. The predicted net section efficiency of a HSS specimen modeled with the entirely flat part material properties is defined as

$$U_{n_unif} = \frac{P_{u_unif}}{P_{u_calc}}, \quad (5.2)$$

where P_{u_unif} is the peak load predicted by the finite element analysis with entirely flat part material properties. The predicted net section efficiency of a HSS connection modeled with a higher strength HSS corner is defined as

$$U_{n_assm} = \frac{P_{u_assm}}{P_{u_calc}}, \quad (5.3)$$

where P_{u_assm} is the peak load predicted by the finite element model with an assumed higher strength corner. The test specimen net section efficiency calculated according to (3.5) is denoted as U_{n_test} in the discussion. The peak loads P_{u_unif} and P_{u_assm} are determined through numerical simulations that are terminated when any part of the model has reached the critical equivalent plastic strain limit and not from the crack propagation simulation.

5.2.1 Material properties for HSS corner

Material properties are not uniform over the entire cross-section of square and rectangular HSS. But in the finite element modeling, it is idealized that only the HSS corner can have different material properties from that of its flat part. Thus, any strength increase of the flat part at the region close to the corner is assumed to be concentrated at the corner.

Assumed material properties for the HSS corner are determined by trial and error until the numerical simulation of the connection roughly matches that of the test with the largest weld length ratio, as outlined in Section 4.3. But there is no systematic way employed in the determination of the assumed material properties for the HSS corner. However, some rough guidelines are provided in Section 4.3 on how to determine the properties. Thus, no detailed explanation is provided on the trial and error process. The assumed material properties are shown in Tables 5.6 and 5.7 and Figures 5.20 to 5.23. The ultimate strength of the assumed corner material is 28% higher than that of the flat part of square HSS and is 75% higher than the flat part for rectangular HSS. The critical equivalent plastic strain limit is taken as 0.4. It should be noted that the assumed strength increase for the corner of rectangular HSS is unusually high. This is mainly due to the idealization that all the strength increase is concentrated at the HSS corner. In a real rectangular HSS, the region close to the corner may have a higher ultimate strength than the mid-region of its flat part. As can be seen in Figure 5.24, coupon R6 of HSS 127 x 51 from a region close to the corner gives a stress versus strain curve that is higher and flatter in shape compared to that for R4, which is a coupon from the middle half of the flat part of HSS.

5.2.2 Crack propagation analyses

A limited number of numerical simulations that consider crack propagation are carried out to predict the descending branch of the load versus deformation curve. In crack propagation analyses, material failure is assumed to have occurred when the critical equivalent plastic strain limit has been reached at an integration point. But instead of terminating the simulation, the elastic modulus is artificially reduced by a factor of 0.001 to simulate crack and material failure at that integration point. This analysis is carried out using a material user-subroutine with ABAQUS.

Due to the symmetry in the finite element modeling, the deformation in the simulation is half of that of the actual specimen. However, strain localization, and crack initiation and propagation normally occur at only one end. Thus when comparing to the experimental load versus deformation curves, the predicted LVDT displacement is doubled up to the point of peak load, but no doubling thereafter since the deformation occurs only at one end of the specimen.

5.2.3 HSS connections with no end welding - phase 1 testing program

Finite element models of slotted square and rectangular HSS connections with no end welding are validated with phase 1 test results. Comparisons are made in terms of the net section efficiency and load versus deformation curve. The load versus deformation curve is obtained only from the simulation that incorporates material properties of an assumed higher strength HSS corner.

On the rectangular HSS specimens slotted on the short side, the fillet weld on the test specimen was found to have extended into the corner of HSS. In a HSS, cold-forming

increases its ultimate strength at the corner. But this increase in strength will be lost if the steel is reheated. Welding involves fusion of metal at high temperature. Thus, welding into the corner of HSS has a similar effect as reheating and normalizing the steel. For this reason, when the higher corner strength is incorporated in the simulation, the region of HSS corner where the fillet weld has extended into is modeled with material properties of the flat part of HSS rather than the higher strength material properties of the corner.

5.2.3.1 Net section efficiency

Numerical simulations are carried out with both the HSS having an entirely flat part material properties and the HSS corner having the assumed higher strength material properties, as described in Section 5.2.1. Comparisons of test and simulated results are shown in Table 5.8 for simulations with the entirely flat part material properties and Table 5.9 for simulations with the higher strength HSS corner.

As shown in Table 5.8, the simulation with the entirely flat part material properties predicts a lower net section efficiency than the test. The lower predicted efficiency is the result of neglecting the higher corner material strength in the finite element model. For the square HSS specimens, denoted with prefix SM, the discrepancy between the test and predicted efficiency is 5% to 6% for specimens with weld length ratios (L/w) larger than 1.0, and 2% to 3% for weld length ratios (L/w) around 0.79. For rectangular specimens, denoted with prefix RS and RL, the discrepancy between the test and predicted efficiency is more than 10% for specimens with weld length ratios (L/w) larger than 1.0, and 5% to 9% for the specimens with L/w ratios around 0.79. The larger discrepancy noticed for the rectangular specimen implies that the increase in the ultimate strength of the HSS corner over its flat part is much higher for the rectangular HSS than the square HSS.

Simulation results for HSS connections with an assumed higher strength corner material are compared to test efficiencies in Table 5.9. For most cases, the difference between the test and predicted net section efficiency is within 2%. Only for SM3G50P16R, does the difference exceed 2%. It should be pointed out that specimen RS4G05P16 is modeled with a weld height of 11 mm according to the actual measurement. For other rectangular HSS specimens slotted on the short side, the weld heights were found to be around 9 mm. Since the overall simulation results are in good agreement with the test, the assumed material properties for the HSS corner and the idealization that the strength increase is concentrated only at the corner, can be considered as a reasonable representation of the HSS in the numerical simulation.

5.2.3.2 Load versus displacement curve

The test and predicted load versus LVDT displacement curves for some specimens are shown in Figures 5.25 to 5.28. On the same figure, the point where the critical equivalent plastic strain limit has first been reached is also identified. The load versus LVDT displacement curve is obtained through the numerical simulation that considers crack propagation.

For all specimens, the initial predicted load versus LVDT displacement curve has a steeper slope than that from the test. The reason for this discrepancy is mainly due to the residual stress in the HSS from the manufacturing process. The residual stress manifests itself in the shape of every metal strip that is cut from the HSS to form the tension coupon. Each strip cut from the HSS curled in both directions along the width and length of the strip. However, the residual stress is neglected in the finite element model. Due to the residual stress, yielding of the cross-section occurred earlier in the test. For

this reason, the measured load versus displacement curve of the test deviates from the straight line at a lower displacement than in a simulation.

Other than at the initial displacement, there is a good agreement between the test and predicted load versus displacement curves up to the peak load. In general, the numerical simulation is able to give a reasonably close prediction of the displacement at peak load. The crack propagation analysis can also capture the general shape of the descending branch of the load versus displacement curve except for a rectangular specimen slotted at the short side, as shown in Figure 5.28.

In the test, the load dropped smoothly with the displacement. But in the simulation, the load drops in steps. This is due to the procedure adopted in modeling crack propagation. Failure of the material is checked and the contribution of that integration point is eliminated only at the beginning of each time increment. Thus during a time increment, many elements may have failed but these elements are only eliminated at the next time increment. This causes a large load drop in the next time increment that shows up as steps in the load versus displacement curve.

Figure 5.28 for rectangular HSS slotted at the short side shows that predicted load drop is much steeper than that for the test. One reason is that the corner of HSS is very close to the slot opening and the area of stress concentration. Once crack has been initiated at the slot opening, it propagates immediately into the corner. In the modeling, all the strength increase is assumed to be concentrated at the HSS corner. As a result, the assumed material for the HSS corner is stronger than what it actually is. Thus, when a crack propagates into the corner, the strength drop of the specimen is also steeper. This may partly explain why the simulation predicts a steeper load drop when compared to the

experimental load versus deformation curve. Nevertheless, this does not affect the validity of using the finite element model to assess the capacity of a slotted HSS connection since there is a good agreement between the measured and predicted peak load.

Crack propagation simulation shows that there is hardly any load increase once a crack has been initiated. Thus when predicting the maximum load carrying capacity of a HSS connection, the numerical simulation can be terminated once the critical equivalent plastic strain limit is reached without any loss of the accuracy.

5.2.4 HSS connections with end welding – phase 2 testing program

All numerical simulations of HSS connection with end welding are terminated once the critical equivalent plastic strain limit has been reached in any part of the model. Both models that assumed the HSS having the entirely flat part material properties and having a stronger corner are considered.

As shown in Table 5.10, for square HSS specimens, net section efficiencies predicted by the numerical model with the entirely flat part material are 3% lower than that for the test. However, finite element numerical models with an assumed stronger corner predict net section efficiencies that are in good agreement with the test. For square HSS specimens, the assumed corner material properties are determined by matching the simulation result to that of the test. Thus, it is no surprise that there is a good agreement in the predicted efficiency for the square HSS specimens. However, it should be pointed out that the stress versus strain curve of the assumed HSS corner is within the range of the measured values of corner coupons, as shown in Figure 5.23.

Figure 5.29 shows that the predicted load versus displacement curve for the square HSS connection with an assumed corner material is in good agreement with that from the

test. Since the failure is due to gross section fracture at the mid-length of the specimen, the deformation at the start of gross section necking is greatly influenced by imperfection. Thus, the numerical simulation is not expected to predict the start of load reduction accurately for S10 and S07. However, the numerical simulation correctly predicts the failure location, which is at the mid-length of the square HSS. The predicted deformed shape at fracture for S10 is shown in Figure 5.30. It can be clearly seen that there is considerable necking at the mid-length of the HSS.

Simulations of two finite element models of rectangular HSS connection are carried out. Model R07 has a weld length ratio similar to the test specimen R07, while model R075 has a slightly higher weld length ratio at 0.75. The predicted peak load for R07 is shown in Table 5.10. With the entirely flat part material properties, the numerical simulation of R07 under predicts the capacity by 1%. But with the assumed corner material, the numerical simulation over predicts the capacity by 6%. This over prediction maybe due to the fact that the ultimate strength of the assumed corner material may have been too high. Another possible reason is the premature failure at the fillet weld. But since only one rectangular HSS specimen with end welding was tested, it is difficult to be certain about the exact cause of the over prediction. However, no further adjustment is made on the assumed corner material properties for the rectangular HSS in order to improve on the peak load.

Predicted and test load versus displacement curves for the rectangular specimen are shown in Figure 5.31. The numerical simulation of R07 predicts the failure at the slotted end, similar to that observed in the test. However, if the weld length ratio is increased by 0.05, the failure shifts from the slotted end to the mid-length of the HSS. This is

represented by model R075. Thus, the transition from a mid-length fracture to a slotted end fracture is around a weld length ratio of 0.7 for the rectangular HSS specimen with end welding and slotted on its long side.

Even though the numerical simulation gives a reasonably accurate prediction of the displacement at fracture, there is considerable difference in the shape of the predicted and test load versus displacement curves. As can be seen in Figure 5.31, the test curve flattens out after only 10 mm LVDT displacement, while the load in the simulation curve still increases after 30 mm LVDT displacement. The difference in the shape is partially due to the idealization of the material properties variation over the HSS cross-section and the shape of the stress versus strain relationship of the HSS. As can be seen in Figure 5.24, coupon R6 of HSS 127 x 51 from a region close to the corner gives a stress versus strain curve that is higher and flatter in shape compared to that for R4, which is a coupon from the middle half of the flat part of HSS. Therefore, if a greater percentage of the cross-section is modeled with a flatter stress versus strain material curve, the predicted load versus displacement curve will also be flatter. Overall, there is a reasonable agreement between the test and predicted peak load and failure location. However, more test data are required in order to perform a more thorough validation of the model.

Numerical simulation that considers crack propagation is also carried out for R07. Contour plot of the equivalent plastic strain of the simulation after considerable specimen deformation is shown in Figure 5.32. It can be seen that locations with high level of equivalent plastic strain correspond to locations of cracks noticed in the test, as shown in Figure 3.18. The contour plot shows that the region at the end of the gusset plate has a

higher equivalent plastic strain than the end of HSS. This implies that the material failure occurs first at the end of the gusset plate.

5.2.5 HSS specimens tested by Korol (1996)

Numerical simulations are also carried out on HSS specimens tested by Korol (1996). Since material properties reported for Korol's test specimens are incomplete, material properties in this testing program for phase 1 HSS 89 x 89 and HSS 127 x 51 are used in the simulations for square and rectangular HSS specimens respectively. Material properties of 16 mm gusset plate for phase 1 are used in modeling the gusset plate of Korol's test specimens. It has been found that using different material properties affect the peak load and the load versus displacement curve of the numerical simulation, but have little effect on the net section efficiency. Therefore, the comparison between the simulation and test is carried out using the net section efficiency.

Figures 5.33 to 5.35 show the test and predicted net section efficiency versus weld length ratio (L/w) plot for Korol's test. Results from simulations with an entirely flat part material is denoted as Flat and results with a higher strength corner material as Corner. Intermediate weld length ratios are also modeled in order to obtain a smoother predicted curve. In Korol's test program, the static reading is not mentioned specifically as being used in calculating the efficiency. But according to Mirza (1994), it may be deduced that the HSS specimen was loaded slowly with a stoppage at every load increment. Thus, the load recorded in the HSS specimen test may be considered to be the static load. However, the ultimate strength of the material is obtained from the tension coupon tested according to ASTM-E8-04 (2004), which does not require any static reading to be taken. Thus, the reported material ultimate strength may be around 5

to 10% higher than the static ultimate strength. For this reason, the efficiency reported for Korol's test may have been underestimated by around 5 to 10%. Test results from Korol's test program are shown in Appendix E. This can be seen in Figure 5.33, where the measured net section efficiencies for the square HSS at the weld length ratio (L/w) of around 1.0 are 0.95 and 1.00, while the net section efficiency of a square HSS specimen with the same weld length ratio in the current testing program is around 1.07.

Figures 5.33 to 5.35 show that assuming a stronger HSS corner only affects the capacity at high L/w ratios for square HSS and rectangular HSS slotted on its long side. Due to the high stress concentration at low L/w ratios, HSS corner is not being fully utilized because the deformation is concentrated at the opening. For a rectangular HSS slotted on the short side, the contribution of a stronger corner is still significant at a low ratio because of its proximity to the slot. The predicted net section efficiency plot also shows that the net section efficiency is proportional to the weld length ratio (L/w) up to around 0.9 before plateauing out thereafter. The net section efficiencies predicted by numerical models with the entirely flat part material properties are consistently lower than that with an assumed stronger corner. It should be noted that there is considerable scatter in the test results by Korol compared to the current testing program. In Korol's test, the specimen with the same geometry can have an efficiency difference of 6%. Nevertheless, there is a good agreement between the test and predicted shape of the efficiency versus weld length ratio curve except at the low L/w ratio for a rectangular HSS slotted on the long side. As expected, the model with an entirely flat part material properties predicts the efficiency that is closer to the test, since it is assumed that the efficiency in Korol's test

may have been under reported by 5 to 10% due to the non-static ultimate strength of the material being used in calculating the efficiency.

In Figure 5.35, for rectangular HSS connections slotted on the long side, the simulation predicts an efficiency that is about 5% higher than the test at the L/w of 0.5. However, it should be viewed in the context that this error is within the range of scatter in the test result, and as well as the possible under reporting of the test efficiency by Korol. Thus, overall, it can be concluded that numerical simulations with the developed finite element models can be used to predict the efficiency of the slotted HSS connection.

Table 5.1 Net section efficiency comparison between a complete shell model and a solid-shell coupled model

L/w	Maximum load (kN)		
	Solid Patch	Full Shell	Solid Patch/ Full Shell
0.79	618.6	607.3	1.02
1.33	638.2	638.6	1.00

Table 5.2 Ultimate load comparison for different mesh densities of models without end welding

L/w	Mesh 1	Mesh 2	Mesh 3
	Smallest element size 0.5 mm x 0.6 mm	Smallest element size 0.25 mm x 0.3 mm	Smallest element size 0.125 mm x 0.15 mm
	P_{u_simul} (kN)	P_{u_simul} (kN)	P_{u_simul} (kN)
0.40	383.0	381.5	380.5
0.60	528.0	528.0	527.0
1.33	638.0	637.0	634.0

Table 5.3 Ultimate load comparison for different mesh densities of models with end welding

L/w	Mesh 1	Mesh 2	Mesh 3
	Smallest element size 0.8 mm x 0.8 mm	Smallest element size 0.4 mm x 0.4 mm	Smallest element size 0.2 mm x 0.2 mm
	P_{u_simul} (kN)	P_{u_simul} (kN)	P_{u_simul} (kN)
0.40	489.0	486.0	485.0
0.50	573.0	569.0	568.0
1.00	640.2	640.2	640.2

Table 5.4 Maximum load of square HSS with no end welding for different critical equivalent plastic strain limit

ϵ_c^p	L/w=0.4	L/w=0.79	L/w=1.33
	Peak load (kN)	Peak load (kN)	Peak load (kN)
0.8	381.5	618.0	637.5
0.9	382.3	618.2	637.6
1.0	382.7	620.5	637.6

Table 5.5 Maximum load of square HSS with end welding for different critical equivalent plastic strain limit

ϵ_c^p	L/w=0.4	L/w=0.7	L/w=1.0
	Peak load (kN)	Peak load (kN)	Peak load (kN)
0.8	486.0	640.2	640.2
0.9	486.0	640.2	640.2
1.0	486.0	640.2	640.2

Table 5.6 True stress and true plastic strain parameters for the assumed HSS corner

HSS	ϵ_o^p	ϵ_f^p	σ_o^t (Mpa)	σ_f^t (Mpa)	n	C
89 x 89 phase1	0.000	0.049	520	645	50	5.72E-6
89 x 89 phase2	0.000	0.068	480	595	40	3.25E-6
127 x 51	0.000	0.080	670	812	80	4.59E-6

Table 5.7 Material properties of the flat part of HSS and its assumed corner

HSS	F_u - flat (Mpa)	F_u -corner (Mpa)	F_u - corner/ F_u - flat
89 x 89 phase1	485.0	620.3	1.28
89 x 89 phase2	439.6	565.5	1.28
127 x 51	449.0	789.1	1.75

Table 5.8 Results of numerical analyses for phase 1 test specimens with entirely flat part material properties

Specimen	L/w	Ultimate load (kN)		Efficiencies		
		Calculated, P_{u_calc}	Analysis, P_{u_unif}	Analysis, U_{n_unif}	Test, U_{n_test}	Ratio, U_{n_unif}/U_{n_test}
RL5G05P16	1.33	599.6	587.8	0.98	1.14	0.86
RS5G05P16	1.33	595.6	603.0	1.01	1.15	0.88
SM5G05P12	1.33	651.9	668.1	1.02	1.07	0.95
SM5G05P12R	1.33	651.9	668.1	1.02	1.07	0.95
SM5G05P16	1.05	634.8	650.7	1.03	1.07	0.96
SM5G05P16R	1.06	634.8	650.7	1.03	1.06	0.97
SM5G50P16	1.06	634.8	655.4	1.03	1.06	0.97
SM5G50P16R	1.07	634.8	655.4	1.03	1.06	0.97
SM5G05P20	0.79	621.9	638.7	1.03	1.08	0.95
SM5G05P20R	0.80	621.9	638.7	1.03	1.09	0.94
RL4G05P16	0.79	599.6	591.2	0.99	1.14	0.87
RS4G05P16	0.79	595.6	603.2	1.01	1.10	0.92
SM4G05P16	0.78	634.8	642.0	1.01	1.07	0.94
SM4G05P16R	0.78	634.8	642.0	1.01	1.08	0.94
RL3G05P16	1.34	599.6	586.0	0.98	1.04	0.94
RS3G05P16	1.33	595.6	584.8	0.98	1.08	0.91
SM3G05P12	0.79	651.9	645.5	0.99	1.04	0.95
SM3G05P12R	0.79	651.9	645.5	0.99	1.03	0.96
SM3G05P16	1.32	634.8	628.0	0.99	1.03	0.96
SM3G05P16R	1.32	634.8	628.0	0.99	1.03	0.96
SM3G25P16	0.80	634.8	637.5	1.00	1.05	0.95
SM3G25P16R	0.79	634.8	637.5	1.00	1.05	0.95
SM3G50P16	0.79	634.8	639.4	1.01	1.04	0.97
SM3G50P16R	0.78	634.8	639.4	1.01	1.02	0.99
SM3G05P20	1.33	621.9	618.4	0.99	1.01	0.98
SM3G05P20R	1.32	621.9	618.4	0.99	1.02	0.97

Table 5.9 Results of numerical analyses for phase 1 test specimens with an assumed stronger HSS corner

Specimen	L/w	Ultimate load (kN)		Efficiencies		
		Calculated, P_{u_calc}	Analysis, P_{u_assm}	Analysis, U_{n_assm}	Test, U_{n_test}	Ratio, U_{n_assm}/U_{n_test}
RL5G05P16	1.33	599.6	683.7	1.14	1.14	1.00
RS5G05P16	1.33	595.6	676.4	1.14	1.15	0.99
SM5G05P12	1.33	651.9	697.3	1.07	1.07	1.00
SM5G05P12R	1.33	651.9	697.3	1.07	1.07	1.00
SM5G05P16	1.05	634.8	681.5	1.07	1.07	1.00
SM5G05P16R	1.06	634.8	681.5	1.07	1.06	1.01
SM5G50P16	1.06	634.8	682.2	1.07	1.06	1.01
SM5G50P16R	1.07	634.8	682.2	1.07	1.06	1.01
SM5G05P20	0.79	621.9	672.8	1.08	1.08	1.00
SM5G05P20R	0.80	621.9	672.8	1.08	1.09	0.99
RL4G05P16	0.79	599.6	679.9	1.13	1.14	0.99
RS4G05P16	0.79	595.6	670.4	1.11	1.10	1.01
SM4G05P16	0.78	634.8	678.0	1.07	1.07	1.00
SM4G05P16R	0.78	634.8	678.0	1.07	1.08	0.99
RL3G05P16	1.34	599.6	611.6	1.02	1.04	0.98
RS3G05P16	1.33	595.6	652.4	1.10	1.08	1.02
SM3G05P12	0.79	651.9	672.1	1.03	1.04	0.99
SM3G05P12R	0.79	651.9	672.1	1.03	1.03	1.00
SM3G05P16	1.32	634.8	655.6	1.03	1.03	1.00
SM3G05P16R	1.32	634.8	655.6	1.03	1.03	1.00
SM3G25P16	0.80	634.8	665.4	1.05	1.05	1.00
SM3G25P16R	0.79	634.8	665.4	1.05	1.05	1.00
SM3G50P16	0.79	634.8	668.4	1.05	1.04	1.01
SM3G50P16R	0.78	634.8	668.4	1.05	1.02	1.03
SM3G05P20	1.33	621.9	642.6	1.03	1.01	1.02
SM3G05P20R	1.32	621.9	642.6	1.03	1.02	1.01

Table 5.10 Results of numerical analyses for phase 2 test specimens

Model No.	Ultimate load (kN)			Efficiencies		
	Calculated, P_{u_calc}	Analysis, P_{u_unif}	Analysis, P_{u_assm}	Analysis, U_{n_unif}	Analysis, U_{n_assm}	Test, U_{n_test}
S10-a	641.2	640.2	657.6	1.00	1.03	1.03
S10-b	641.2	640.2	657.6	1.00	1.03	1.02
S07	641.2	640.2	657.8	1.00	1.03	1.03
R07	670.0	671.7	716.2	1.00	1.07	1.01

Figure 5.1 Modeling of the fillet weld with three weld zones

Figure 5.2 Typical mesh for the HSS connection model with end welding

Figure 5.3 Typical mesh for the HSS connection model with end welding

Figure 5.4 Enlarged view of the mesh at slot opening area for the HSS connection model without end welding

Figure 5.5 Enlarged view of the mesh at the slot opening area for the HSS connection model with end welding

Figure 5.6 Tension coupon model with solid or shell elements

Figure 5.7 Engineering stress versus engineering strain of tension coupon modeled with shell and solid elements

Figure 5.8 Load versus displacement curve for solid patch and full shell models for square HSS connections

Figure 5.9 Different mesh densities of the solid element patch for a HSS connection model with no end welding

Mesh 1
Smallest element
0.8 x 0.8 mm

Mesh 2
Smallest element
0.4 x 0.4 mm

Mesh 3
Smallest element
0.2 x 0.2 mm

Figure 5.10 Different mesh densities of the solid element patch for a HSS connection model with end welding

Figure 5.11 Load versus LVDT displacement curves of HSS 89 x 89 models without end welding for different mesh densities

Figure 5.12 Load versus LVDT displacement curves of HSS 89 x 89 models with end welding for different mesh densities at L/w = 0.4 and 0.5

Figure 5.13 Load versus LVDT displacement curves of HSS 89 x 89 models with end welding for different mesh densities at $L/w = 1.0$

Figure 5.14 Load versus LVDT displacement curves of HSS 89 x 89 models without end welding for two and four layers of solid element patches

Figure 5.15 Load versus LVDT displacement curves of HSS 89x89 models without end welding for different equivalent plastic strain limit

Figure 5.16 Load versus LVDT displacement curves of HSS 89x89 models with end welding for different equivalent plastic strain limit at L/w = 0.4

Figure 5.17 Load versus LVDT displacement curves of HSS 89x89 models with end welding for different equivalent plastic strain limit at $L/w = 1.0$

Figure 5.18 Weld modeling at the end of the gusset plate for HSS connections with end welding

Figure 5.19 Load versus LVDT displacement curves of HSS 89x89 models with end welding for different end welding schemes

Figure 5.20 Engineering stress versus change in cross-section area curves for HSS 89 x 89 together with assumed corner

Figure 5.21 Engineering stress versus change in cross-section area curves for HSS 127 x 51 together with assumed corner

Figure 5.22 Engineering stress versus engineering strain curves for HSS 89 x 89 (phase 1) and HSS 127 x 51 together with assumed corner

Figure 5.23 Engineering stress versus engineering strain curves for HSS 89 x 89 (phase 2) together with assumed corner

Figure 5.24 Engineering stress versus engineering strain curve of HSS 127 x 51 coupons from the middle of the flat part and close to the corner

Figure 5.25 Test and simulation load versus LVDT displacement curves for SM3G05P20 and SM3G05P20R at $L/w = 0.79$

Figure 5.26 Test and simulation load versus LVDT displacement curves for SM5G05P20 and SM5G05P20R at $L/w = 1.33$

Figure 5.27 Test and simulation load versus LVDT displacement curves for rectangular HSS slotted at the long side, RL5G05P16 and RL3G05P16

Figure 5.28 Test and simulation load versus LVDT displacement curves for rectangular HSS slotted at the short side, RS5G05P16 and RS3G05P16

Figure 5.29 Test and simulation load versus LVDT displacement curves for S10-a, S10-b and S07

Figure 5.30 Predicted deformed shape at fracture for S10

Figure 5.31 Test and simulation load versus LVDT displacement curves for rectangular HSS specimen with end welding

Figure 5.32 Contour plot of the equivalent plastic strain for model R07

Figure 5.33 Test and simulation net section efficiency versus L/w ratio for Korol's square HSS connections

Figure 5.34 Test and simulation net section efficiency versus L/w ratio for Korol's rectangular HSS connections with the short side slotted

Figure 5.35 Test and simulation net section efficiency versus L/w ratio for Korol's rectangular HSS connections with the long side slotted

CHAPTER 6 PARAMETRIC STUDY

In chapter 5, finite element models for slotted tension square and rectangular HSS were developed and validated. The good agreement between test and predicted peak load shows that finite element analyses can be used to predict the strength of a slotted HSS connection. Based on these models, a finite element analyses parametric study is carried out to investigate effects of various parameters on the strength of HSS connections. Both HSS connections with and without end welding are examined in the study. Results of this parametric study are used in developing guidelines for designing an economical full-strength HSS connection, and to provide recommendations on improving the provisions for shear lag on slotted HSS connections in design standards.

6.1 Parameters considered in the parametric study

Previous studies have shown that geometrical parameters such as weld length (in terms of weld length ratio, L/w), gusset plate thickness, size of slot opening and slot orientation (in terms of aspect ratio, a/b) could affect the strength of HSS connections. Thus, in addition to these parameters, weld height, size factor and HSS wall thickness are investigated in this study. The parametric study is carried out on one parameter at a time, while other parameters are held constant. The baseline model for the parametric study is HSS 89 x 89 x 4.8 with 12 mm thick gusset plate and 6 mm fillet weld. For models without end welding, the baseline model has a straight segment length (GS) of 5 mm at the slot opening. Figure 6.1 shows the straight segment of the opening (GS) with respect to the overall opening. Since the weld length ratio (L/w) has been identified as the most

important parameter affecting shear lag in a HSS connection, numerical models with varied L/w ratios are designed and investigated with each parameter.

Parameters investigated in the parametric study are described below.

- HSS wall thickness

The HSS wall thickness of the baseline model is 4.8 mm. The effect of HSS wall thickness is being investigated with models having 1.5 to 2 times the HSS wall thickness of the baseline model.

- Size factor

The effect of size is being investigated by analyzing models with twice the size of the baseline model.

- Gusset plate thickness (t)

12 mm and 16 mm are two of the gusset plates thicknesses likely to be used with a 4.8 mm or a 6.4 mm thick HSS to design for a full-strength HSS tension member. Thus, slotted HSS connection strength with gusset plate thickness of 12, 16 and 20 mm gusset plate are investigated.

- Straight segment length of the slot opening (GS)

The length of slot opening may vary in a construction. But for HSS 89 x 89, it is unlikely that the straight segment length of the slot opening be greater than 50 mm. Thus, the parametric study with the straight segment length from 0 to 50 mm is carried out.

- Weld height (wh)

In an actual construction, many different weld sizes may be used. For this reason, the effect due to weld height of 2, 5, 8, 10 and 12 mm are being investigated.

- Aspect ratio (a/b)

The effect of HSS shape can be studied by varying the aspect ratio (a/b), which characterizes the relative cross-section area eccentricity to the line of load for HSS with equal circumference. Aspect ratios from 0.4 to 2.5 are investigated in this study.

For HSS connections with no end welding, all parameters described above are examined. But for HSS connections with end welding, only gusset plate thickness, aspect ratio and L/w ratio are examined.

6.2 Numerical models for the parametric study

Numerical models in the parametric study are derived from the validated finite element models developed in Chapter 5. Nominal cross-section dimensions of the HSS are used in the modeling. The HSS connection with no end welding is modeled with an opening between the end of gusset plate and the HSS. On the other hand, the gap between the end of gusset plate and the HSS is filled over with the fillet weld for a HSS connection with end welding. The HSS is being modeled with a uniform wall thickness even though the actual corner is thicker.

Since the amount of strength increase at the corner varies with the HSS, it is prudent and conservative to ignore the corner strength increase in evaluating the capacity of a slotted HSS connection. Furthermore, the overall strength increase due to the stronger

corner for square HSS specimens is only about 4% in this study. Material properties from specimens in the testing program are used in the parametric study. All square HSS connections are modeled with phase 1 HSS 89 x 89 material properties and all rectangular HSS specimens are modeled with HSS 127 x 51 material properties. The exception is in the study on the effect of the aspect ratio (a/b). In the study on the aspect ratio, all HSS specimens without end welding are modeled with HSS 127 x 51 material properties and all HSS specimens with end welding are modeled with phase 1 HSS 89 x 89 material properties. As noted in Section 5.2.5, material properties have little effect on the net section efficiency. Thus, using two separate materials for with and without end welding models will not affect results of the aspect ratio study. A simulation is terminated when the equivalent plastic strain limit of 0.9 is reached in any part of the model.

Finite element models for the investigation of each parameter are collected in one group. The model configurations for each group of numerical models and results of the simulations are listed in Tables 6.1 to 6.7 for HSS connections with no end welding and in Tables 6.8 to 6.10 for HSS connections with end welding.

6.3 Discussion of the parametric study results

Results of the parametric study are discussed separately for HSS connections with end welding and without end welding. The discussion will be based on the net section efficiency of the connection. To facilitate the discussion, the following terms are used. The ultimate load capacity of the numerical model is defined as

$$P_{u_calc} = F_u A_n, \quad (6.1)$$

where F_u is the ultimate tensile strength of the flat part of HSS. For HSS connections with no end welding, A_n is the net cross-section area (excluding the area of slot opening), and for HSS connections with end welding, A_n is the gross cross-section area. The predicted net section efficiency by the numerical model is defined as

$$U_n = \frac{P_{u_pred}}{P_{u_calc}}, \quad (6.2)$$

where P_{u_pred} is the peak load predicted by the finite element model. In order to remove the influence of the weld length ratio when discussing the effect of each parameter, the predicted net section efficiency is sometimes normalized with respect to that of the baseline model. The normalized efficiency is defined as

$$U_{norm} = \frac{U_{param}}{U_{base}}, \quad (6.3)$$

where U_{base} is the predicted net section efficiency of the baseline model and U_{param} is the predicted net section efficiency of the other model.

6.3.1 Parametric study for HSS connections with no end welding

The discussion of the results of the parametric study is grouped into HSS wall thickness, size factor, gusset plate thickness, straight segment length of the slot opening, weld height, aspect ratio and weld length ratio.

6.3.1.1 HSS wall thickness

Numerical models with different HSS wall thicknesses are studied. HSS wall thickness of the baseline model is increased by 1.5 and 2.0 times in the parametric study. The model configurations and results of the simulations are shown in Table 6.1. Figure

6.2 shows the normalized efficiency versus L/w ratio for different HSS wall thicknesses. It can be seen that the normalized efficiencies are close to 1, which suggests that the HSS wall thickness has little effect on the net section efficiency. Therefore, the net section efficiency for the baseline model can be applied to other HSS wall thicknesses.

6.3.1.2 Size factor

Numerical models with twice the size of the baseline model are used in studying the effect of scaling. Every dimension of the baseline model is doubled in the scaled-up model. Table 6.2 shows the relative dimension of both models and results of the simulations. Again, the net section efficiency of the scaled-up model is normalized with respect to that of the baseline model. Figure 6.3 shows L/w ratio versus normalized efficiency, which is close to 1. This shows that scaling the dimension of HSS connection proportionally has little effect on the net section efficiency of the HSS connection. Thus, the predicted net section efficiency by the baseline model can be extended to other HSS connections with a similar geometric proportion.

6.3.1.3 Gusset plate thickness (t)

Other than 12 mm gusset plate in the baseline model, models with two other gusset plate thicknesses of 16 and 20 mm are also investigated. Finite element models and results of the simulations for different gusset plate thickness are shown in Table 6.3. The predicted net section efficiency for each of the model with 16 or 20 mm gusset plate is normalized with respect to that of the baseline model. The normalized efficiency versus L/w ratio is shown in Figure 6.4. In Figure 6.4, the normalized efficiency with a gusset

plate thicker than 12 mm are found to be slightly greater than 1. The difference is within 1% for the 16 mm gusset plate and within 1.5% for the 20 mm gusset plate when the weld length ratio is less than 0.75.

As the gusset plate thickness increases, the ratio of the eccentricity from the face of the gusset plate over the distance between the welds (w) of the outstanding HSS cross-section area reduces. Thus in general, for the same weld length ratio (L/w), a model with a thicker gusset plate have a slightly better efficiency than that with a thinner gusset plate. However, this difference is small for the range of gusset plate thickness that is to be used with the size of HSS in this study. Therefore for practical purposes, the effect of the gusset plate thickness on the net section efficiency can be ignored.

6.3.1.4 Straight segment length of the slot-opening (GS)

In the baseline model, the straight segment length of the slot opening is 5 mm. In the parametric study, straight segment lengths from 0 to 50 mm are being considered. This is the practical range of the slot opening size that is likely to be used in practice with the size of HSS in the study. The model configurations and results of the simulations are listed in Table 6.4. Figure 6.5 shows the net section efficiency versus the straight segment length plot for different L/w ratios. The numerical value of the group number is the weld length ratio in percentage. It can be seen that for every L/w ratio, the 0 and 2 mm straight segment length models have net section efficiencies consistently lower than those with longer straight segment lengths by about 2% to 3%. It should be noted that even with a large weld length ratio (L/w) of 1.25 and 1.5, the net section efficiency of a 0 or 2 mm

straight segment length model still does not improve to the level for models with longer opening length.

The failure of the connection with no end welding occurs at the slot opening region due to stress concentration (strain localization). Thus, the ability of a connection to utilize the outstanding cross-section area of the HSS is dependant on the deformation limit of the HSS at the slot opening. It requires a larger deformation to induce the same strain if a point is further away. In this study, 0 and 2 mm straight segment lengths are not sufficiently long to provide the deformation required to allow the net section area to be fully utilized before failure occurs.

For a short straight segment length specimen, one possible way to improve the net section efficiency is to extend the fillet weld by 5 mm beyond the end of the gusset plate. For the case with 0 mm straight segment length, the additional 5 mm weld extends the weld into a section that has a bigger net section area, thus improving the load carrying capacity of the connection. Results of the analyses with an extended 5 mm weld length for 0 mm straight segment length models are also plotted in Figure 6.5. There is an improvement in the efficiency of about 3% with the weld extension. But mainly, this extension allows the connection with 0 mm straight segment length to achieve the same maximum efficiency as those with longer straight segment lengths. For this reason, the ratio of straight segment length to the distance between welds (GS/w) should be maintained at 1/40 based on results of 5 mm straight segment length of the slot opening in the parametric study or the weld length should be extended by 5 mm beyond the end of the gusset plate for a slotted HSS connection with no end welding. For HSS of different sizes, this requirement can be scaled proportionally.

6.3.1.5 Weld height (wh)

The weld height of the baseline model is 6 mm. Since other weld heights may be used in the connection, weld heights of 2, 5, 8, 10 and 12 mm are also investigated. Results of simulations and models for studying the effect of weld height are listed in Table 6.5.

Figure 6.6 shows the weld height versus net section efficiency plot for different L/w ratios. The numerical number in the legend denotes the weld length ratio in percentage. It can be seen that at low L/w ratios, the net section efficiency increases with the weld height. But when the L/w ratio is greater than 1, there is little change in the net section efficiency with the weld height larger than 2 mm. A larger weld height is able to even out the stress concentration at the slot opening over a wider area, and effectively reduces its effect. At a low L/w ratio, the stress concentration is high. Thus, a larger weld height reduces the stress concentration and delays the failure so that a higher overall cross-section strength can be attained. However, the stress concentration is low when the L/w ratio is high. Thus a small weld height together with a high L/w ratio can still achieved the full net section area utilization before the failure occurs. Figure 6.6 shows that the maximum strength of the HSS connection can still be achieved at a L/w ratio of 1.0 with the weld height greater than 5 mm. This suggests that the net section efficiency is not affected by the weld height when the L/w ratio is greater than 1 as long as the required minimum fillet weld height is provided. Although the efficiency reduces with the weld height, a 6 mm fillet weld is selected for the baseline model rather than a smaller weld in order to represent a weld height that is likely to be used with HSS 89 x 89 x 4.8. A 6 mm fillet weld has the effective throat width that is close to the HSS wall thickness. The net

section efficiency difference between 5 mm and 6 mm fillet weld models is only about 0.02 when the weld length ratio is less than 0.75.

6.3.1.6 Aspect ratio (a/b)

The definition of parameters a and b are shown in Figure 3.2. Parameter a is the dimension of the side to which the gusset plate is connected to or the side HSS is slotted, and parameter b is the other side of the HSS. The aspect ratio (a/b) characterizes the relative cross-section area eccentricity with respect to the line of load for HSS with equal circumference. For example, a low aspect ratio (a/b) suggests that the tributary net section area of the HSS is closer to the gusset plate than that with a high aspect ratio. In other words, an aspect ratio (a/b) less than 1 corresponds to the configuration with the gusset plate connected to the short side of the rectangular HSS and the aspect ratio (a/b) greater than 1 corresponds to the configuration with the gusset plate connected to its long side. In this study, three shapes of HSS 89 x 89 x 4.8, HSS 125 x 51 x 4.8 and HSS 102 x 76 x 4.8 are modeled. Aspect ratios (a/b) of 0.4, 0.75, 1.0, 1.34 and 2.5 are investigated by connecting the gusset plate to either the long or short side of the rectangular HSS.

Figure 6.7 shows the aspect ratio (a/b) versus net section efficiency plot for different L/w ratios. The numerical number in the legend denotes the weld length ratio in percentage. Results of the simulations and model configuration are listed in Table 6.6. To facilitate the discussion, the simulation results are sorted into three groups in accordance to the L/w ratio. The first group is for L/w ratios of 1.0 and above, the second group is for L/w ratios of 0.6, 0.75 and 0.85 and the third group is for a L/w ratio of 0.4. It can be seen that for models in each group, the net section efficiency decreases as the a/b ratio increases,

but the descending rate of the net section efficiency is not uniform. The rate of the net section efficiency reduction is higher between the ratios of 0.4 to 1.34 than when ratio is greater than 1.34. This suggests that a higher net section efficiency can be obtained with a lower cross-section area eccentricity of the HSS connection.

It can be explained by looking at the effectiveness of the constraint provided by gusset plate against the transverse contraction of the HSS section for different aspect ratios. When the HSS is loaded in tension, the cross-section contracts due to Poisson's effect. But as can be seen in Figure 6.8, the contraction of the unconnected sides of HSS is restrained by the gusset plate through bending of the connected side. This constraining effect generates transverse tension stress that increases the effective stiffness and strength of the unconnected side, and the overall connection strength. Since the bending stiffness increases as the connected side decreases in length, a connection with a lower aspect ratio has a higher bending stiffness with its shorter connected side than the one with a higher aspect ratio. For this reason, the reduction in the aspect ratio increases the bending stiffness and the net section efficiency. Consequently, the net section efficiency increases when the aspect ratio decreases below 1.34. When the gusset plate is connected to the long side of the HSS, for a/b ratios such as 1.34 and 2.5, the unconnected side is further away from the gusset plate. Therefore, the net section efficiency for models with a/b ratios of 1.34 and 2.5 are lower. Furthermore, a connection with a higher aspect ratio also has a higher net section eccentricity. This generates a higher stress concentration at the slotted end and reduces the strength of the connection.

As can be seen in Figure 6.7, the rate of efficiency reduction is lower when the weld length ratio is above 1.0 or at 0.4. For these weld length ratio ranges, there is little

change in the net section efficiency going from an aspect ratio of 1.34 to 2.5. There is no clear explanation for this response. A more detailed study to look into this phenomenon is outside the scope of the thesis.

6.3.1.7 Weld length ratio (L/w)

As stated in Section 6.1, the weld length ratio (L/w) is the most important parameter affecting the effect of shear lag in HSS connections. Therefore, this parameter is studied thoroughly from 0.4 to 1.25. The study is carried out using the baseline model. The weld length ratio (L/w) versus net section efficiency is plotted in Figure 6.9. Results of simulations and model configurations are shown in Table 6.7.

Figure 6.9 clearly shows that the net section efficiency increases close to linearly with L/w ratio up to around 0.9, and maintains an efficiency of 1.03 thereafter. This suggests that the HSS connection reaches its maximum capacity at a L/w ratio around 0.9. The linear variation of the efficiency with respect to L/w ratio is due to the stress concentration as a result of shear lag.

6.3.1.8 Proposed equations for net section efficiency

From the parametric study, the net section efficiency is found to vary with the weld length ratio and aspect ratio. In developing the net section efficiency equations, the effect of weld height is ignored. Only results of models with the weld height of 6 mm are used. A 6 mm weld is a weld size that is likely to be used with a 4.8 mm thick HSS. Furthermore, 6 mm weld is only 1 mm larger than the allowable minimum fillet weld height of 5 mm when connected to a 6 to 12 mm thick gusset plate. It is also assumed that

the straight segment length of the opening does not limit the net section efficiency. This is not an unreasonable assumption since the fillet weld normally extends beyond the end of the gusset plate in a real connection.

The L/w ratio versus net section efficiency data from the aspect ratio study for all a/b ratios are plotted in Figure 6.10. A bi-linear equation along close to the lower bound of the L/w ratio versus net section efficiency data in Figure 6.10 is developed to predict the net section efficiency. The proposed net section efficiency equation is given by

$$U_{pw} = 0.15 + 0.9 \left(\frac{L}{w} \right) \leq 1, \quad (6.4)$$

with an upper limit of 0.95. Except for a/b ratios of 1.34 and 2.5 at L/w ratios larger than 0.8, (6.4) gives lower net section efficiencies than results of parametric study models for all a/b ratios. The net section efficiency given by (6.4) is only less than 2% higher than that from parametric study data for large a/b ratios of 1.34 and 2.5 with L/w ratio larger than 0.95.

Equations (2.5) to (2.7) for CSA-S16.1-01 and (2.23) by Korol are also plotted in Figure 6.10. It is clear that the provisions for shear lag in CSA-S16.1-01 is overly conservative. Improvements can also be made to proposed efficiency equation by Korol. It should be reiterated that the simulation efficiencies are based on models neglecting the contribution from the possible strength increase at the HSS corner due to cold-forming. In order to assess the margin of the safety afforded by the equation in the context of the strength increase at the HSS corner due to cold-forming, two sets of simulations are conducted respectively using material properties of the flat part of phase 1 HSS 89 x 89 and HSS 127 x 51 with their assumed corner material properties developed in Section 5.2.1. The ultimate strength of the corner of HSS 89 x 89 is 28% stronger and HSS 127 x 51 is

75% stronger than their corresponding flat parts. Results of these simulations are in Appendix F and are also plotted in Figures 6.11 and 6.12. It can be seen (6.4) is conservative even for a connection with only 28% strength increase in the HSS corner compared to its flat part.

Previous studies have shown that the shear lag effect can also be characterized by the net section eccentricity ratio ($\bar{x}/L$). The net section eccentricity ($\bar{x}$) is calculated according to (2.18) as specified by ANSI/AISC 360-05. It should be pointed out that when a/b ratio is less than 1, the net section eccentricity ($\bar{x}$) calculated by (2.18) cannot realistically characterize the cross-section area eccentricity tributary to the line of weld. Huang (2005) proposed that the eccentricity of a square HSS with an equal circumferential length be used as the lower limit. This limit is adopted when calculating the net section eccentricity. The aspect ratio is less than 1 when HSS 127 x 51 is slotted on its short side. For this situation, the net section eccentricity ($\bar{x}$) of HSS 89 x 89 is used instead. The net section eccentricity for each of the HSS in the study is listed in the Appendix G.

The net section efficiency versus net section eccentricity ratio ($\bar{x}/L$) data for all a/b ratios are plotted in Figure 6.13. It can be seen that the net section efficiency decreases with an increase in $\bar{x}/L$. A bi-linear equation is developed to define the net section efficiency with respect to the net section eccentricity ratio. The proposed equation is given by

$$U_{PX} = 1.35 - 1.65 \left(\frac{\bar{x}}{L} \right) \leq 1 \quad (6.5)$$

with an upper limit of 1. Figure 6.13 shows the proposed equation is conservative for all models studied except for large a/b ratios of 1.34 and 2.5 at a $\bar{x}/L$ ratio less than 0.2. Similar to (6.4), the net section efficiency given by (6.5) is also only less than 2% higher

than the parametric study data. This overestimation is accepted since it is small and the beneficial effect of a stronger HSS corner has not been included when developing the equation. Since the strength increase at the HSS corner has not been included, there will be additional margin of safety if (6.5) is used in designing a real slotted HSS connection. Results of two sets of simulations with 28% and 75% stronger HSS corner are plotted against (6.5) in Figures 6.14 and 6.15 to assess the beneficial effect of a stronger HSS corner. Again, (6.5) is conservative for all connections with only 28% strength increase at the corner.

Equations (2.18) for ANSI/AISC 360-05 and (2.24) by Korol are also plotted in Figure 6.13. Again provisions for shear lag in ANSI/AISC-360-05 are overly conservative, while the equation by Korol is definitely not applicable.

6.3.2 Parametric study for HSS connection with end welding

The discussion of the results of the parametric study is grouped into gusset plate thickness, aspect ratio and weld length ratio.

6.3.2.1 Gusset plate thickness (t)

Gusset plate thicknesses of 12 and 20 mm are investigated in the study. The predicted net section efficiency of the 20 mm gusset plate is normalized with respect to that of the baseline model. Results of simulations and model configurations are listed in Table 6.8. The normalized efficiency versus L/w ratio relationship is shown in Figure 6.16 for HSS connection models with 12 mm and 20 mm gusset plates. As can be seen in Figure 6.16, the normalized efficiency is 1.0 when the L/w ratio is greater than 0.7. Since all models failed at the mid-length of the HSS and the full strength of HSS is

achieved. But unlike the connection with no end welding, the gusset plate thickness significantly affects the strength of the connection with end welding. When the L/w ratio is lower than 0.7, the normalized efficiency with 20 mm gusset plate is found to be higher than 1.0. The difference is around 9% at a L/w ratio of 0.4. The difference in the efficiency at a L/w ratio lower than 0.7 can be explained by looking at the way the HSS is connected to the gusset plate. Compared to a 12 mm gusset plate connection, a 20 mm gusset plate connection has a larger area of HSS in a direct tension to the gusset plate because of end welding. Thus, the cross-section area that relies on shearing to transfer the load to the gusset plate is correspondingly reduced. This means that the stress concentration in the region at the end of the gusset plate or the effect of shear lag is less with a thicker gusset plate. For this reason, a thicker gusset plate connection has a better net section efficiency.

6.3.2.2 Aspect ratio (a/b)

The definitions of parameters a and b is the same as that for HSS connections with no end welding. In this study, three shapes of HSS 89 x 89 x 4.8, HSS 125 x 51 x 4.8 and HSS 102 x 76 x 4.8 are considered. Aspect ratios (a/b) of 0.4, 1.0, 1.34 and 2.5 are investigated using the above HSS shapes with the gusset plate connected to either the long side or short side of the HSS. Results of simulations and model configurations are listed in Table 6.9.

Figure 6.17 shows the net section efficiency versus aspect ratio (a/b) plot for different L/w ratios. The numerical number in the legend denotes the weld length ratio in percentage. It can be seen that for a L/w ratio greater than 0.8, the net section efficiency

of 1.0 is achieved for all a/b ratios because failure occurs at the mid-length of HSS. This suggests that a HSS connection with end welding achieves its full strength for all a/b ratios when the L/w ratio is larger than 0.8. Similar to the connection with no end welding, a higher a/b ratio signifies a higher net section eccentricity, which implies that a greater stress concentration is induced in the region at the end of gusset plate. Thus, the net section efficiency reduces with the increase in the aspect ratio.

6.3.2.3 Weld length ratio (L/w)

Weld length ratios (L/w) of 0.4, 0.55, 0.65, 0.7, 0.75, 1.0 and 1.1 are investigated for the baseline model using HSS 89 x 89 x 4.8 with end welding. The net section efficiency versus weld length ratio (L/w) is plotted in Figure 6.18. Results of simulations and model configurations are listed in Table 6.10. Similar to the connection with no end welding, the net section efficiency can be represented by a bi-linear equation. The net section efficiency increases close to linearly up to around 0.7, and reaches a constant efficiency of 1 thereafter. This suggests that the connection achieves its full strength at a L/w ratio of 0.7.

In general, the connection with end welding achieves a better net section efficiency compared to that without end welding for an equal weld length ratio. The reason being that with end welding, the stress concentration is evened out over a wider area, thus the intensity of stress concentration is reduced. In addition, there is the beneficial effect of having a part of HSS is connected to the gusset plate in tension. As a result, the connection with end welding has a better efficiency. The maximum efficiency is achieved at a L/w ratio of 0.7 for the connection with end welding and 0.9 for the one without. It

should be noted that although the maximum net section efficiency of a connection with no end welding can be greater than 1.0, its actual capacity is always less than that with end welding for the same weld length ratio.

6.3.2.4 Comparison to the proposed net section efficiency equation

Results of the connections with end welding from the aspect ratio study are plotted in Figure 6.19 against (6.4), the proposed net section efficiency equation in Section 6.3.1.8. Simulations with an assumed 28% stronger corner for phase 1 HSS 89 x 89 material properties developed in Section 5.2.1 are also conducted. Results of these simulations are listed in Appendix F and plotted in Figure 6.20 against the proposed net section efficiency. It can be seen that in both figures, the proposed net section efficiency is valid for a slotted HSS connection with end welding, although it is rather conservative.

6.4 Net section efficiency based on outstanding area

In a connection with end welding, the part of HSS that is immediately behind the gusset plate and the fillet weld in the longitudinal direction is under direct tension, while the other outstanding part of HSS relies on shearing to transfer the load. However the ultimate strength (P_{u_calc}) of the finite element model, as defined by (6.1), is calculated based on overall net section area A_n . Thus, (6.1) does not correctly reflect the load transfer mechanism on different parts of the HSS for a slotted connection with end welding. Since the part of HSS immediately behind the gusset plate and the fillet weld is in direct tension, this part of HSS can be ignored in calculating the net section efficiency due to shear lag. Thus, the ultimate strength of the outstanding part of HSS for the model can be

defined as

$$P_{u_outsd} = F_u A_n - F_u A_d, \text{ and} \quad (6.6)$$

$$A_d = 2(W_t + 2wh)t', \text{ with end welding or} \quad (6.7)$$

$$A_d = 4(wh)t', \text{ with no end welding,} \quad (6.8)$$

where F_u is the ultimate tensile strength of the flat part of HSS, A_n is the net section area, A_d is part of the cross-section area under direct tension, W_t is the width of the gusset plate, wh is the height of the weld and t' is the wall thickness of HSS. The predicted net section efficiency for the outstanding part can be defined as

$$U_{n_outsd} = \frac{P_{u_pred} - F_u A_d}{P_{u_outsd}}, \quad (6.9)$$

where P_{u_pred} is the peak load predicted by the numerical model. It is assumed that the ultimate strength of the material is developed for the part in direct tension. The distance between the welds (w) is taken as the circumferential distance from the toe of the weld along the centreline of the outstanding part.

The net section efficiency versus weld length ratio relationships from parametric study for 12 mm and 20 mm gusset plates in sections 6.3.1.3 and 6.3.2.1 are plotted in Figure 6.21. The net section efficiency of outstanding HSS versus outstanding part L/w ratio is plotted in Figure 6.22. All the results are based on HSS 89 x 89 x 4.8 models consist entirely of the material properties of the flat part of HSS. It can be seen that there is a better correlation between net section efficiency and the weld length ratio in Figure 6.22 compared to Figure 6.21. There is slight improvement for connections with no end welding, but a significant improvement can be observed for connections with end welding. Overall, there is an improvement in characterizing the net section efficiency with L/w ratio

using (6.9). For example, at a L/w ratio of 0.6, the difference in the net section efficiency between 12 and 20 mm gusset plate connections with end welding reduces from 0.096 to almost zero by considering just the outstanding HSS section area. Similarly at the L/w ratio of 0.6, the difference in the net section efficiency for 12 mm gusset plate connections with and without end welding reduces from 13% to 9%. Figures 6.23 and 6.24 also show results of the net section efficiency calculated using both (6.2) and (6.9) for different weld heights from Section 6.3.1.5 of the parametric study for a connection with no end welding. Again, it can be seen that there is a better correlation when the efficiency calculation is based on the outstanding HSS section area alone.

Even though the shear lag effect on the net section efficiency can be better characterized by the weld length ratio when applied to the outstanding part of the HSS alone, using the distance between welds from the face of the gusset plate or the centerline of the gusset plate thickness is still preferred for the ease of its application when designing. However, (6.6) to (6.9) may be used in conjunction with (6.4) to estimate a more precise net section efficiency. It should be noted that the baseline model used in developing the proposed efficiency equation has a 12 mm gusset plate and a 6 mm weld height.

6.5 Guidelines to Design Full-Strength Slotted HSS Members

One of the objectives of this thesis is to develop guidelines for designing an economical full-strength square or rectangular HSS connection. Results of the parametric study are used in developing the following guidelines.

In order to develop the full strength of the member according to CSA-S16.1-01, the limit state should be governed by the gross section yielding rather than the net section fracture. In other words, the connection should be designed with the net section fracture

strength being greater than its gross section yielding strength. This can be achieved by ensuring that

$$0.85A_{ne}F_u \geq A_gF_y, \quad (6.10)$$

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 section area (A_{ne}) is given by

$$A_{ne} = U_n A_n, \quad (6.11)$$

the product of the net section efficiency (U_n) and net section area (A_n). Thus (6.10) can be rearranged into

$$\frac{A_{ne}}{A_g} = \frac{U_n A_n}{A_g} \geq \frac{F_y}{0.85F_u} = 0.915, \quad (6.12)$$

by substituting F_y with 350 MPa and F_u with 450 MPa, the minimum nominal yield and ultimate strength for grade 350W steel respectively. The strengths of grade 350W steel are substituted into (6.10) because it is the most common grade of steel for HSS used in the construction. Replacing U_n in (6.12) with the proposed efficiency U_{pw} in (6.4), (6.12) can be rearranged into

$$\frac{L}{w} \geq 1.017 \left(\frac{A_n}{A_g} \right)^{-1} - 0.167, \quad (6.13)$$

with the limit of maximum A_n/A_g being 1, and the maximum net section efficiency is achieved when L/w is 0.95. Figure 6.25 give a feasible combinations of the weld length ratio (L/w) and the net to gross area ratio A_n/A_g for a full strength slotted HSS connection. The feasible combination is above and to the right of the equation. In essence, the minimum A_n/A_g ratio is limited to 0.915 or the maximum gusset plate thickness is roughly

limited to 4.25% of the circumference along the centerline of HSS. However, this limit may be increased to 6.5 % if a strength increase at the HSS corner is considered. The net section efficiency is 1.05 at L/w of 1.0 when a 28% strength increase at the corner is included, as indicated in Appendix F. Another option of achieving the full strength of HSS is by providing end welding and a ratio of L/w greater than 0.8. In parametric study, all models with end welding and a weld length ratio greater than 0.8 fail at the mid-length of the HSS.

The parametric study also shows that other factors such as straight segment length of the slot opening, weld height and aspect ratio could affect the net section efficiency of the HSS connection. The following guidelines are recommended when designing a full-strength HSS connection with no end welding.

- a) The straight segment length of the slot opening should be at least half of the gusset plate thickness or the width of the slot opening. If the specified straight segment length cannot be guaranteed, an extended fillet weld beyond the gusset plate equals to the weld height should be provided. This is to ensure that there is sufficient ductility at the region around the opening to fully utilize the cross-section.
- b) The weld height should be at least 1.3 times of the HSS wall thickness and 1.7% of the HSS circumference along the centreline. This is based on the weld height and the size of HSS used in developing the proposed net section efficiency equation. But this requirement can be waived if a weld length ratio (L/w) greater than 1.0 can be provided. When the L/w ratio is greater

than 1.0, the strength of the HSS connection no longer varies with the weld height.

- c) If possible, the rectangular HSS should always be slotted on its short side. A rectangular HSS connected to its short side can have an efficiency up to 5% higher than the one connected to its long side.

Table 6.1 Parametric study models for HSS wall thickness with no end welding

Group	Model	HSS	Weld length ratio, L/w	HSS wall thickness, t (mm)	Net section efficiency, U _n
1.0t'	W40t48	89 x 89 x 4.8	0.40	4.8	0.55
	W75t48	89 x 89 x 4.8	0.75	4.8	0.93
	W100t48	89 x 89 x 4.8	1.00	4.8	1.01
	W125t48	89 x 89 x 4.8	1.25	4.8	1.02
1.5t'	W40t72	89 x 89 x 7.2	0.40	7.2	0.55
	W75t72	89 x 89 x 7.2	0.75	7.2	0.93
	W100t72	89 x 89 x 7.2	1.00	7.2	1.02
	W125t72	89 x 89 x 7.2	1.25	7.2	1.02
2.0t'	W40t96	89 x 89 x 9.6	0.40	9.6	0.55
	W75t96	89 x 89 x 9.6	0.75	9.6	0.92
	W100t96	89 x 89 x 9.6	1.00	9.6	1.02
	W125t96	89 x 89 x 9.6	1.25	9.6	1.02

Table 6.2 Parametric study models for size factor with no end welding

Group	Model	HSS	Weld length ratio, L/w	Gusset plate thickness, t (mm)	Opening length, GS (mm)	Net section efficiency, U _n
Doubled	D40	178 x 178 x 9.6	0.40	24	10	0.55
	D75	178 x 178 x 9.6	0.75	24	10	0.92
	D100	178 x 178 x 9.6	1.00	24	10	1.01
	B125	178 x 178 x 9.6	1.25	24	10	1.02
Baseline	B40	89 x 89 x 4.8	0.40	12	5	0.55
	B75	89 x 89 x 4.8	0.75	12	5	0.93
	B100	89 x 89 x 4.8	1.00	12	5	1.01
	B125	89 x 89 x 4.8	1.25	12	5	1.02

Table 6.3 Parametric study models for gusset plate thickness with no end welding

Group	Model	HSS	Weld length ratio, L/w	Gusset plate thickness, t (mm)	Net section efficiency, U_n
P12	P12w40	89 x 89 x 4.8	0.40	12	0.55
	P12w60	89 x 89 x 4.8	0.60	12	0.77
	P12w75	89 x 89 x 4.8	0.75	12	0.93
	P12w80	89 x 89 x 4.8	0.80	12	0.96
	P12w125	89 x 89 x 4.8	1.25	12	1.02
P16	P16w40	89 x 89 x 4.8	0.40	16	0.56
	P16w60	89 x 89 x 4.8	0.60	16	0.77
	P16w75	89 x 89 x 4.8	0.75	16	0.93
	P16w80	89 x 89 x 4.8	0.80	16	0.97
	P16w125	89 x 89 x 4.8	1.25	16	1.02
P20	P20w40	89 x 89 x 4.8	0.40	20	0.56
	P20w60	89 x 89 x 4.8	0.60	20	0.78
	P20w75	89 x 89 x 4.8	0.75	20	0.94
	P20w80	89 x 89 x 4.8	0.80	20	0.97
	P20w125	89 x 89 x 4.8	1.25	20	1.02

Table 6.4 Parametric study models for straight segment length of slot opening with no end welding

Group	Model	HSS	Weld length ratio, L/w	Opening length, GS (mm)	Net section efficiency, U_n
W40	W40s0	89 x 89 x 4.8	0.40	0	0.53
	W40s2	89 x 89 x 4.8	0.40	2	0.54
	W40s5	89 x 89 x 4.8	0.40	5	0.55
	W40s10	89 x 89 x 4.8	0.40	10	0.56
	W40s25	89 x 89 x 4.8	0.40	25	0.56
	W40s50	89 x 89 x 4.8	0.40	50	0.56
W75	W75s0	89 x 89 x 4.8	0.75	0	0.87
	W75s2	89 x 89 x 4.8	0.75	2	0.90
	W75s5	89 x 89 x 4.8	0.75	5	0.92
	W75s10	89 x 89 x 4.8	0.75	10	0.93
	W75s25	89 x 89 x 4.8	0.75	25	0.94
	W75s50	89 x 89 x 4.8	0.75	50	0.94
W125	W125s0	89 x 89 x 4.8	1.25	0	0.98
	W125s2	89 x 89 x 4.8	1.25	2	1.01
	W125s5	89 x 89 x 4.8	1.25	5	1.02
	W125s10	89 x 89 x 4.8	1.25	10	1.02
	W125s25	89 x 89 x 4.8	1.25	25	1.02
	W125s50	89 x 89 x 4.8	1.25	50	1.02
W150	W150s0	89 x 89 x 4.8	1.50	0	0.98
	W150s2	89 x 89 x 4.8	1.50	2	1.01
	W150s5	89 x 89 x 4.8	1.50	5	1.02
	W150s10	89 x 89 x 4.8	1.50	10	1.02
	W150s25	89 x 89 x 4.8	1.50	25	1.02
	W150s50	89 x 89 x 4.8	1.50	50	1.02

Table 6.5 Parametric study models for weld height with no end welding

Group	Model	HSS	Weld length ratio, L/w	Weld height, wh (mm)	Net section efficiency, U_n
W40	W40h2	89 x 89 x 4.8	0.40	2	0.52
	W40h5	89 x 89 x 4.8	0.40	5	0.53
	W40h8	89 x 89 x 4.8	0.40	8	0.59
	W40h10	89 x 89 x 4.8	0.40	10	0.62
	W40h12	89 x 89 x 4.8	0.40	12	0.64
W75	W75h2	89 x 89 x 4.8	0.75	2	0.88
	W75h5	89 x 89 x 4.8	0.75	5	0.91
	W75h8	89 x 89 x 4.8	0.75	8	0.96
	W75h10	89 x 89 x 4.8	0.75	10	0.99
	W75h12	89 x 89 x 4.8	0.75	12	1.00
W100	W100h2	89 x 89 x 4.8	1.00	2	1.00
	W100h5	89 x 89 x 4.8	1.00	5	1.01
	W100h8	89 x 89 x 4.8	1.00	8	1.02
	W100h10	89 x 89 x 4.8	1.00	10	1.02
	W100h12	89 x 89 x 4.8	1.00	12	1.02
W125	W125h2	89 x 89 x 4.8	1.25	2	1.01
	W125h5	89 x 89 x 4.8	1.25	5	1.02
	W125h8	89 x 89 x 4.8	1.25	8	1.02
	W125h10	89 x 89 x 4.8	1.25	10	1.02
	W125h12	89 x 89 x 4.8	1.25	12	1.02

Table 6.6 Parametric study models for aspect ratio with no end welding

Group	Model	HSS	Weld length ratio, L/w	Aspect ratio, a/b	Connected section side	Net section efficiency, U_n
W40	W40r40	127 x 51 x 4.8	0.38	0.40	Short side	0.54
	W40r75	102 x 76 x 4.8	0.38	0.75	Short side	0.53
	W40sh	89 x 89 x 4.8	0.38	1.00	–	0.53
	W40h14	102 x 76 x 4.8	0.38	1.34	Long side	0.53
	W40h25	127 x 51 x 4.8	0.38	2.50	Long side	0.54
W60	W60r40	127 x 51 x 4.8	0.58	0.40	Short side	0.78
	W60r75	102 x 76 x 4.8	0.58	0.75	Short side	0.74
	W60sh	89 x 89 x 4.8	0.58	1.00	–	0.73
	W60h14	102 x 76 x 4.8	0.58	1.34	Long side	0.72
	W60h25	127 x 51 x 4.8	0.58	2.50	Long side	0.72
W75	W75r40	127 x 51 x 4.8	0.73	0.40	Short side	0.93
	W75r75	102 x 76 x 4.8	0.73	0.75	Short side	0.89
	W75sh	89 x 89 x 4.8	0.73	1.00	–	0.88
	W75h14	102 x 76 x 4.8	0.73	1.34	Long side	0.87
	W75h25	127 x 51 x 4.8	0.73	2.50	Long side	0.85
W85	W85r40	127 x 51 x 4.8	0.83	0.40	Short side	1.00
	W85r75	102 x 76 x 4.8	0.83	0.75	Short side	0.96
	W85sh	89 x 89 x 4.8	0.83	1.00	–	0.95
	W85h14	102 x 76 x 4.8	0.83	1.34	Long side	0.93
	W85h25	127 x 51 x 4.8	0.83	2.50	Long side	0.91
W90	W100r40	127 x 51 x 4.8	0.90	0.40	Short side	1.01
	W100sh	89 x 89 x 4.8	0.90	1.00	–	1.00
	W100h25	127 x 51 x 4.8	0.90	2.50	Long side	0.99
W95	W100r40	127 x 51 x 4.8	1.00	0.40	Short side	1.03
	W100sh	89 x 89 x 4.8	1.00	1.00	–	1.01
	W100h25	127 x 51 x 4.8	1.00	2.50	Long side	0.98
W100	W100r40	127 x 51 x 4.8	1.00	0.40	Short side	1.03
	W100r75	102 x 76 x 4.8	1.00	0.75	Short side	1.01
	W100sh	89 x 89 x 4.8	1.00	1.00	–	1.00
	W100h14	102 x 76 x 4.8	1.00	1.34	Long side	0.99
	W100h25	127 x 51 x 4.8	1.00	2.50	Long side	0.99

Table 6.6 Continue

Group	Model	HSS	Weld length ratio, L/w	Aspect ratio, a/b	Connected section side	Net section efficiency, U_n
W125	W125r40	127 x 51 x 4.8	1.25	0.40	Short side	1.04
	W125r75	102 x 76 x 4.8	1.25	0.75	Short side	1.01
	W125sh	89 x 89 x 4.8	1.25	1.00	-	1.00
	W125h14	102 x 76 x 4.8	1.25	1.34	Long side	1.00
	W125h25	127 x 51 x 4.8	1.25	2.50	Long side	0.99
W150	W150r40	127 x 51 x 4.8	1.50	0.40	Short side	1.04
	W150r75	102 x 76 x 4.8	1.50	0.75	Short side	1.01
	W150sh	89 x 89 x 4.8	1.50	1.00	-	1.00
	W150h14	102 x 76 x 4.8	1.50	1.34	Long side	1.00
	W150h25	127 x 51 x 4.8	1.50	2.50	Long side	0.99

Table 6.7 Parametric study models for L/w ratio with no end welding

Model	HSS	Weld length ratio, L/w	Gusset plate thickness, t (mm)	Distance between welds, w (mm)	Opening length, GS (mm)	Net section efficiency, U_n
P12w40	89 x 89 x 4.8	0.40	12	150	5	0.56
P12w50	89 x 89 x 4.8	0.50	12	150	5	0.66
P12w60	89 x 89 x 4.8	0.60	12	150	5	0.77
P12w70	89 x 89 x 4.8	0.70	12	150	5	0.87
P12w75	89 x 89 x 4.8	0.75	12	150	5	0.93
P12w80	89 x 89 x 4.8	0.80	12	150	5	0.96
P12w85	89 x 89 x 4.8	0.85	12	150	5	1.00
P12w90	89 x 89 x 4.8	0.90	12	150	5	1.00
P12w100	89 x 89 x 4.8	1.00	12	150	5	1.01
P12w110	89 x 89 x 4.8	1.10	12	150	5	1.02
P12w125	89 x 89 x 4.8	1.25	12	150	5	1.02
P12w150	89 x 89 x 4.8	1.50	12	150	5	1.02

Table 6.8 Parametric study models for gusset plate thickness with end welding

Group	Model	HSS	Weld length ratio, L/w	Gusset plate thickness, t	Net section efficiency, U _n
W-P12	P12w40	89 x 89 x 4.8	0.40	12	0.68
	P12w55	89 x 89 x 4.8	0.55	12	0.85
	P12w65	89 x 89 x 4.8	0.65	12	0.96
	P12w70	89 x 89 x 4.8	0.70	12	1.00
	P12w75	89 x 89 x 4.8	0.75	12	1.00
	P12w100	89 x 89 x 4.8	1.00	12	1.00
	P12w110	89 x 89 x 4.8	1.10	12	1.00
W-P20	P20w40	89 x 89 x 4.8	0.40	20	0.74
	P20w55	89 x 89 x 4.8	0.55	20	0.92
	P20w65	89 x 89 x 4.8	0.65	20	1.00
	P20w70	89 x 89 x 4.8	0.70	20	1.00
	P20w75	89 x 89 x 4.8	0.75	20	1.00
	P20w100	89 x 89 x 4.8	1.00	20	1.00
	P20w110	89 x 89 x 4.8	1.10	20	1.00

Table 6.9 Parametric study models for aspect ratio with end welding

Group	Model	HSS	Weld length ratio, L/w	Aspect ratio, a/b	Connected section side	Net section efficiency, U_n
W40	W40r4	127 x 51 x 4.8	0.4	0.40	Short side	0.73
	W40sh	89 x 89 x 4.8	0.4	1.00		0.68
	W40h14	102 x 76 x 4.8	0.4	1.34	Long side	0.68
	W40h25	127 x 51 x 4.8	0.4	2.50	Long side	0.69
W55	W55r4	127 x 51 x 4.8	0.55	0.40	Short side	0.90
	W55sh	89 x 89 x 4.8	0.55	1.00		0.85
	W55h14	102 x 76 x 4.8	0.55	1.34	Long side	0.85
	W55h25	127 x 51 x 4.8	0.55	2.50	Long side	0.84
W70	W70r4	127 x 51 x 4.8	0.70	0.40	Short side	1.00
	W70sh	89 x 89 x 4.8	0.70	1.00		1.00
	W70h14	102 x 76 x 4.8	0.70	1.34	Long side	1.00
	W70h25	127 x 51 x 4.8	0.70	2.50	Long side	0.97
W80	W85r4	127 x 51 x 4.8	1.00	0.40	Short side	1.00
	W85sh	89 x 89 x 4.8	1.00	1.00		1.00
	W85h14	102 x 76 x 4.8	1.00	1.34	Long side	1.00
	W85h25	127 x 51 x 4.8	1.00	2.50	Long side	1.00
W100	W85r4	127 x 51 x 4.8	1.00	0.40	Short side	1.00
	W85sh	89 x 89 x 4.8	1.00	1.00		1.00
	W85h14	102 x 76 x 4.8	1.00	1.34	Long side	1.00
	W85h25	127 x 51 x 4.8	1.00	2.50	Long side	1.00

Table 6.10 Parametric study models for L/w ratio with end welding

Model	HSS	Weld length ratio, L/w	Gusset plate thickness, t (mm)	Distance between welds , w (mm)	Opening length, GS (mm)	Net section efficiency, U _n
W-P12w40	89 x 89 x 4.8	0.40	12	162	0	0.68
W-P12w55	89 x 89 x 4.8	0.55	12	162	0	0.85
W-P12w65	89 x 89 x 4.8	0.65	12	162	0	0.96
W-P12w70	89 x 89 x 4.8	0.70	12	162	0	1.00
W-P12w75	89 x 89 x 4.8	0.75	12	162	0	1.00
W-P12w100	89 x 89 x 4.8	1.00	12	162	0	1.00
W-P12w110	89 x 89 x 4.8	1.10	12	162	0	1.00

Figure 6.1 Straight segment length of the slot opening

Figure 6.2 Normalized efficiency versus L/w ratio for different HSS wall thickness with no end welding

Figure 6.3 Normalized efficiency versus L/w ratio for size factor with no end welding

Figure 6.4 Normalized efficiency versus L/w ratio for different gusset plate thicknesses with no end welding

Figure 6.5 Net section efficiency versus straight segment length for different weld length ratios with no end welding

Figure 6.6 Net section efficiency versus weld height for different weld length ratios with no end welding

Figure 6.7 Net section efficiency versus aspect ratio for different weld length ratios with no end welding

Figure 6.8 Resistance to side contraction

Figure 6.9 Net section efficiency versus weld length ratio for square HSS with no end welding

Figure 6.10 Net section efficiency versus weld length ratio for aspect ratios without end welding and stronger HSS corner

Figure 6.11 Net section efficiency versus weld length ratio for the parametric study models with 28% stronger corner and no end welding

Figure 6.12 Net section efficiency versus weld length ratio for the parametric study models with 75% stronger corner and no end welding

Figure 6.13 Net section efficiency versus net section eccentricity ratio without end welding and stronger corner

Figure 6.14 Net section efficiency versus net section eccentricity ratio for parametric study models with 28% stronger corner and no end welding

Figure 6.15 Net section efficiency versus net section eccentricity ratio for parametric study models with 75% stronger corner and no end welding

Figure 6.16 Normalized efficiency versus L/w ratio for different gusset plate thicknesses of HSS connection with end welding

Figure 6.17 Aspect ratio versus net section efficiency for HSS connection for different weld length ratios with end welding

Figure 6.18 Net section efficiency versus weld length ratio for square HSS connection with end welding

Figure 6.19 Net section efficiency versus weld length ratio for the parametric study models with end welding and entirely flat material

Figure 6.20 Net section efficiency versus weld length ratio for the parametric study models with end welding and 28% stronger corner material

Figure 6.21 Net section efficiency versus weld length ratio for different gusset plates

Figure 6.22 Outstanding HSS section efficiency versus outstanding weld length ratio for different gusset plates

Figure 6.23 Net section efficiency versus weld length ratio for different weld heights with no end welding

Figure 6.24 Outstanding HSS efficiency versus outstanding HSS weld length ratio for different weld heights with no end welding

Figure 6.25 Feasible combinations of A_n/A_g and L/w for full strength slotted HSS connections

CHAPTER 7 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

A literature review on shear lag in the tension connections was carried out in Chapter 2 with emphasis on slotted HSS connections. It was found that only a few studies have so far been carried out to investigate the effect of shear lag on slotted square and rectangular HSS connections. Results from these limited studies showed that provisions to account for shear lag in the design standards are overly conservative when applied to a slotted HSS connection. A few procedures to determine the true stress versus true strain relationship of the material were also discussed.

The overall testing program consisted of slotted square and rectangular HSS connections with and without end welding. Only four slotted HSS specimens with end welding and three connection configurations were tested in this study. The other twenty six HSS specimens with no end welding that formed a part of the overall testing program were tested by Huang (2005). Both HSS 89 x 89 x 4.8 and HSS 127 x 51 x 4.8 were tested.

Tension coupons fabricated from the gusset plate and HSS were tested to obtain material properties for analyzing the test results and performing finite element analyses. Tension coupons from both the flat part and the corner of HSS were machined and tested. The performance of the HSS test specimen was evaluated using the actual material strength obtained from coupon tests. The net section efficiency from the test was compared to the efficiency calculated according to the provisions for shear lag on slotted tension member in design standards.

An iterative procedure was adopted to determine the true stress versus true plastic strain relationship of the material beyond the peak load. Since material properties vary across the HSS section, the HSS was idealized as having two regions of distinct material properties with one region being the HSS corner and the other being the flat part of HSS. A true stress versus true plastic strain relationship for the HSS corner was assumed through numerical simulations of the HSS connection. The average measured equivalent plastic strain at fracture from tension coupon tests was used as the critical limit to signify the material failure in the finite element analysis.

Studies on element type, critical equivalent plastic strain limit and finite element mesh were carried out in developing the finite element models for slotted square and rectangular HSS connections. Results of the numerical simulation were compared to test results from the testing program and Korol (1996) to validate these models.

Based on the validated finite element models, a finite element analyses parametric study was carried out to investigate effects of various parameters have on the strength of HSS connections. Parameters such as weld length ratio, gusset plate thickness, size of slot opening, slot orientation, weld height, size factor and HSS wall thickness were studied. Slotted square and rectangular HSS connections with and without end welding were examined in the study. Results from the parametric study were used in developing guidelines for designing an economical full-strength HSS connection, and to provide recommendations on improving the provisions for shear lag on slotted HSS connections in design standards.

7.2 Conclusions

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

- 1) This study confirmed findings from previous research that provisions for shear lag prescribed in CSA S16.1-01 and ANSI/AISC-360-05 are overly conservative when applied to slotted square and rectangular HSS tension members with and without end welding. Two equations for calculating the net section efficiency were proposed. One equation is a function of the weld length ratio and the other is a function of net section eccentricity ratio. The net section efficiency has a better correlation with the weld length ratio than with the net section eccentricity ratio.
- 2) The weld length is the main factor that affects shear lag. For a slotted HSS connection, the maximum net section efficiency can be achieved with a L/w ratio greater than 0.95 for a connection without end welding and 0.8 for a connection with end welding, as long as a fillet weld of reasonable height is provided. The net section capacity increases almost linearly with the L/w ratio up to 0.95 for the connection without end welding and 0.8 for the one with end welding, and remains constant thereafter. In general, the net section efficiency of unity is achieved after these limits.
- 3) Due to the cold-forming process, the corner has an increase in the ultimate strength but a decrease in the ductility. The strength increase in the corner of HSS contributes to the measured net section efficiency from the test to exceeding unity.
- 4) The HSS connection with end welding is always stronger than the one without end welding if other geometrical parameters being equal. Thus, providing end welding and a ratio of L/w greater than 0.8 ensure that full strength of HSS can be developed.

At a ratio greater than 0.8, the failure of a slotted HSS tension member with end welding is at the mid-length and significant ductility can be achieved.

- 5) A connection with the rectangular HSS slotted on its short side has a better net section efficiency than a rectangular HSS slotted on its long side or a square HSS. This is attributed to the greater effectiveness of the restraint provided by the gusset plate against transverse contraction of the HSS. Thus, the rectangular HSS should always be slotted on its short side to better utilize the strength.
- 6) The thickness of gusset plate is found to have a minor effect on the net section efficiency of a slotted HSS connection without end welding but have a significant effect on the connection with end welding. In the parametric study, the net section efficiency of a square HSS connection with end welding and 20 mm gusset plate is 9% higher than the one with 12 mm gusset plate at a L/w ratio of 0.4.
- 7) The straight segment length of the slot opening is found to reduce the net section efficiency of a HSS connection without end welding when it is too short. This effect can be ignored when the straight segment length of at least roughly half the gusset plate thickness is provided or the fillet weld extends a weld height beyond the end of the gusset plate.
- 8) The weld height is found to affect the net section efficiency of a slotted HSS connection when the weld length ratio is low. In general, it can be ignored when the weld length ratio is greater than 1.0. As the weld height increases from 2 mm to 12 mm, the net section efficiency increases by 12% for square HSS connections at weld length ratios of 0.4 and 0.75. Thus, a weld height of at least 1.3 times the HSS wall thickness and

1.7% of the circumference of HSS along the centreline should be used with the proposed efficiency equations when the L/w ratio is less than 1.

- 9) Using thicker HSS wall or scaling up the HSS connection proportionally will not affect the net section efficiency of the HSS connection.
- 10) The shear lag effect on the net section efficiency can be better characterized by considering the part of the HSS outside the weld toe alone.
- 11) The minimum A_n/A_g ratio is limited to 0.915 or the maximum gusset plate thickness is limited to 4.25% of the circumference along the centreline of HSS in order to fully utilize strength of a slotted HSS tension member with no end welding in the design based on CSA-S16.1-01 for a grade 350W steel. Alternatively, a weld length ratio of 0.8 together with end welding are provided to ensure that failure occurs away from the slotted end. For other grades of steel and design standards, a more economical design of a full-strength slotted HSS tension member with and without end welding can also be achieved by using the proposed net section efficiency equations.

7.3 Recommendations

- 1) The study has demonstrated that the material properties are not uniform over the entire cross-section of square and rectangular HSS. The higher strength at the HSS corner contributes significantly to the capacity of the HSS connection. Thus, a thorough study on the material properties variation over the HSS cross-section is needed in order to better utilize the increased strength in the design.
- 2) It was found that a slotted HSS connection with end welding in general has a better net section efficiency than the one without end welding with all other geometrical parameters being equal. Thus, separate equations should be developed for

connections with and without weld welding, or an improved unified equation may be developed. This should be carried out in conjunction with testing of more slotted square and rectangular HSS specimens with end welding.

- 3) In the validation of the finite element model, there was some uncertainties with regards to results reported by Korol (1996). Thus, a few more specimens at low weld length ratios should be tested to clarify these uncertainties.
- 4) The parametric study shows that weld height affects the net section efficiency when the weld length ratio is below 1. Thus, specimens with different weld height should be tested to confirm results of the parametric study since all specimens in this testing program have roughly the same weld height.
- 5) The current testing program focuses only on cold-formed non-stress relieved sections. Hot-formed and cold-formed stress relieved HSS specimens should be tested to verify the validity of the proposed model.

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APPENDIX A TEST OF HSS SPECIMENS (PHASE 1)

Data from phase 1 of the testing program carried out by Huang (2005) are summarized below.

A.1 Specimen details

A total of twenty six specimens consisting of six rectangular and twenty square specimens were tested. As shown in Figure A.1, each specimen was fabricated by welding gusset plates to the slots at both ends of a HSS member. These specimens consisted of sixteen different configurations, which were different combinations of weld length (in term of the L/w ratio), gusset plate thickness, slot opening length and slot orientation. Duplicate specimen was fabricated for each of the square specimens. The measured dimensions of all twenty six specimens are listed in Tables A.1 and A.2, and the calculated geometric ratios are listed in Table A.3. Values shown in Tables A.1 and A.2 are the average of both ends of the specimen. It should be pointed out that the thickness of HSS in Table A.1 is the average thickness of the flat part of HSS. The corner of HSS was found to be thicker than its flat part as a result of cold-forming. The measured corner thickness of HSS and average outside corner radius were listed in Table 3.3.

The net section area (A_n) of the test specimen can be calculated with

$$A_n = (c - 2\pi \cdot r) \cdot t' + 2\pi \left(r - \frac{t_c}{2} \right) \cdot t_c - 2 \cdot GW \cdot t', \quad (A.1)$$

where c is the measured outside circumference, r is the corner outside radius, t' is the thickness of the flat of HSS, t_c is the averaged corner thickness, and GW is the width of the opening. The weld length (L) is taken as the length of the straight segment of the

longitudinal weld, and the distance between the welds (w) is taken as the circumferential distance along the centerline between the edges of the slot at opposite sides of the HSS section. The calculated geometrical ratios and net section area are listed in Table A.3

The distance from the centroid of one-half of the HSS net section area to the centreline of the gusset plate is taken according to ANSI/AISC-360-05 as

$$\bar{x} = \frac{a^2 + 2ab}{4(a + b)}, \quad (\text{A.2})$$

where a is the overall height of the HSS and b is the overall width of the HSS, as shown in Figure A.1. As proposed by Huang (2005), the eccentricity ($\bar{x}$) of a square HSS with an equal circumferential length be used as the lower limit. The modified net section eccentricity is denoted by $\bar{x}^*$. Both net section eccentricities are listed in Table A.3.

A.2 Net section efficiency

The net section efficiency (U_n) in the table is calculated from

$$U_n = \frac{P_{u\text{Test}}}{A_n F_u}, \quad (\text{A.3})$$

where

$P_{u\text{Test}}$ = the peak static test load,

A_n = the net area of the cross-section, and

F_u = the ultimate tensile strength of the test specimens

Net section efficiencies (U_n) of the specimens are shown in Table A.4.

Table A.1 Measured HSS gross section properties

Test specimen	HSS				
	Circumference, c (mm)	Width, a (mm)	Width, b (mm)	Thickness, t' (mm)	Weld distance, w (mm)
RL5G05P16	343.00	127.04	51.63	4.52	147.21
RS5G05P16	343.00	51.39	127.30	4.50	145.92
SM5G05P16	343.00	89.61	89.77	4.42	146.58
SM5G05P16R	343.00	89.50	89.54	4.41	147.20
RL4G05P16	343.00	127.15	51.59	4.50	147.88
RS4G05P16	343.50	51.45	127.41	4.50	146.98
SM4G05P16	343.00	89.36	89.56	4.39	147.25
SM4G05P16R	343.00	89.61	89.51	4.40	146.19
RL3G05P16	343.00	127.08	51.46	4.47	147.38
RS3G05P16	343.00	51.32	127.21	4.50	145.97
SM3G05P16	343.00	89.93	89.67	4.40	147.12
SM3G05P16R	342.50	89.42	89.51	4.42	147.18
SM3G05P12	342.50	89.38	89.56	4.42	150.54
SM3G05P12R	343.00	89.56	89.50	4.42	151.06
SM5G05P12	343.00	89.52	89.53	4.41	150.98
SM5G05P12R	343.50	89.90	89.57	4.41	150.86
SM3G05P20	342.00	88.82	88.95	4.46	143.43
SM3G05P20R	344.00	89.39	90.10	4.45	144.32
SM5G05P20	343.00	89.56	89.59	4.42	144.00
SM5G05P20R	342.00	89.23	89.55	4.43	143.69
SM3G25P16	342.50	89.43	89.55	4.40	147.32
SM3G25P16R	343.50	89.37	89.70	4.42	147.35
SM3G50P16	342.00	89.18	89.63	4.41	148.46
SM3G50P16R	343.00	89.37	89.70	4.42	147.83
SM5G50P16	343.00	89.21	89.64	4.41	147.53
SM5G50P16R	343.00	89.40	89.69	4.41	147.61

Table A.2 Measured connection geometries

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 A.3 Calculated geometric properties of the specimen

Test specimen	Weld length ratio, L/w	Net area, A_n (mm ²)	$\bar{x}/L$ (AISC-05)	$\bar{x}^*/L$ (Modified)	a/b
RL5G05P16	1.33	1325	0.21	0.21	2.46
RS5G05P16	1.34	1310	0.11	0.17	0.40
SM5G05P16	1.33	1304	0.17	0.17	1.00
SM5G05P16R	1.34	1304	0.17	0.17	1.00
RL4G05P16	1.05	1330	0.26	0.26	2.46
RS4G05P16	1.06	1327	0.14	0.22	0.40
SM4G05P16	1.06	1300	0.21	0.21	1.00
SM4G05P16R	1.08	1290	0.21	0.21	1.00
RL3G05P16	0.79	1323	0.35	0.35	2.46
RS3G05P16	0.80	1326	0.19	0.29	0.40
SM3G05P16	0.79	1302	0.29	0.29	1.00
SM3G05P16R	0.79	1305	0.29	0.29	1.00
SM3G05P12	0.79	1335	0.28	0.28	1.00
SM3G05P12R	0.78	1338	0.29	0.29	1.00
SM5G05P12	1.34	1334	0.17	0.17	1.00
SM5G05P12R	1.34	1336	0.17	0.17	1.00
SM3G05P20	0.80	1272	0.29	0.29	1.00
SM3G05P20R	0.79	1288	0.30	0.30	1.00
SM5G05P20	1.33	1273	0.18	0.18	1.00
SM5G05P20R	1.33	1275	0.18	0.18	1.00
SM3G25P16	0.80	1303	0.29	0.29	1.00
SM3G25P16R	0.79	1309	0.29	0.29	1.00
SM3G50P16	0.79	1316	0.29	0.29	1.00
SM3G50P16R	0.78	1315	0.29	0.29	1.00
SM5G50P16	1.34	1302	0.17	0.17	1.00
SM5G50P16R	1.32	1304	0.17	0.17	1.00

Table A.4 Test results

Test specimen	Weld length ratio, L/w	$\bar{x}/L$ (AISC-05)	Peak test load, P_{uTest} (kN)	Net area capacity $A_n F_u$ (kN)	Net area efficiency U_n
RL5G05P16	1.33	0.21	674.6	593.6	1.14
RS5G05P16	1.34	0.11	674.4	586.7	1.15
SM5G05P16	1.33	0.17	679.9	632.5	1.07
SM5G05P16R	1.34	0.17	673.3	632.2	1.06
RL4G05P16	1.05	0.26	676.8	595.9	1.14
RS4G05P16	1.06	0.14	652.6	594.4	1.10
SM4G05P16	1.06	0.21	677.5	630.3	1.07
SM4G05P16R	1.08	0.21	674.3	625.8	1.08
RL3G05P16	0.79	0.35	615.6	592.7	1.04
RS3G05P16	0.80	0.19	641.5	594.2	1.08
SM3G05P16	0.79	0.29	650.6	631.5	1.03
SM3G05P16R	0.79	0.29	652.6	632.9	1.03
SM3G05P12	0.79	0.28	676.4	647.3	1.04
SM3G05P12R	0.78	0.29	668.8	649.1	1.03
SM5G05P12	1.34	0.17	695.6	647.2	1.07
SM5G05P12R	1.34	0.17	690.9	647.9	1.07
SM3G05P20	0.80	0.29	621.2	616.8	1.01
SM3G05P20R	0.79	0.30	634.9	624.8	1.02
SM5G05P20	1.33	0.18	666.9	617.4	1.08
SM5G05P20R	1.33	0.18	673.8	618.3	1.09
SM3G25P16	0.80	0.29	664.0	631.9	1.05
SM3G25P16R	0.79	0.29	667.7	635.0	1.05
SM3G50P16	0.79	0.29	665.5	638.0	1.04
SM3G50P16R	0.78	0.29	650.3	637.8	1.02
SM5G50P16	1.34	0.17	670.2	631.6	1.06
SM5G50P16R	1.32	0.17	670.4	632.4	1.06

Figure A.1 The specimen geometry for phase 1.

APPENDIX B ADDITIONAL TEST DATA

HSS specimens investigated in the phase 2 were measured at both ends of the specimen. The data shown in Tables 3.2 and 3.3 are the average value of both ends. Detailed dimensions at both ends of each specimen are presented here.

Tables B.1 and B.2 present the measured data for HSS and connection at the upper end during the test. Tables B.3 and B.4 present the measured data for HSS and connection at the bottom end. Figures B.1 and B.2 show pictures of failed HSS specimens in phase 2 testing.

Table B.1 Measured HSS gross section properties at top end

Test specimen	Circumference, c (mm)	Width, a (mm)	Width, b (mm)	Thickness, t' (mm)
S10-a	342.00	88.60	89.33	4.44
S10-b	344.00	88.76	89.13	4.42
S07	343.00	88.79	89.23	4.45
R07	345.00	51.34	127.31	4.52

Table B.2 Measured connection geometry at top end

Test specimen	Gusset plate		Weld length L (mm)	Weld height	
	Width, WP(mm)	Thickness, t (mm)		Longitudinal t _w (mm)	End t _e (mm)
S10-a	254.30	16.32	170.10	10.50	11.00
S10-b	253.60	16.21	172.00	10.00	11.50
S07	254.10	16.23	122.00	11.00	10.50
R07	254.10	16.14	125.20	10.50	9.50

Table B.3 Measured HSS gross section properties at bottom end

Test specimen	Circumference, c (mm)	Width, a (mm)	Width, b (mm)	Thickness, t' (mm)
S10-a	342.00	88.69	89.21	4.41
S10-b	344.00	88.84	89.23	4.44
S07	343.00	88.92	89.12	4.43
R07	345.00	51.78	127.21	4.54

Table B.4 Measured connection geometry at bottom end

Test specimen	Gusset plate		Weld length L (mm)	Weld height	
	Width, WP(mm)	Thickness, t (mm)		Longitudinal t _w (mm)	End t _e (mm)
S10-a	254.70	16.72	170.40	11.50	11.00
S10-b	254.10	16.83	172.70	11.00	11.50
S07	254.50	16.73	123.50	11.00	11.20
R07	254.50	16.64	126.20	11.50	11.50

S10-a

S10-b

Figure B.1 Failures of S10-a and S10-b.

S07

R07

Figure B.2 Failures of S07 and R07.

APPENDIX C TENSION COUPON TEST

Tension coupon tests were carried out to obtain material properties of the test specimen. Tests of tension coupons for phase 1 materials were carried out by Huang (2005). Since tension coupons of cold-formed HSS have no well defined yield plateau, the yield strength of the HSS is calculated using the 0.2% offset method. The definitions of yield strength (F_y) and ultimate strength (F_u) for HSS coupons are shown in Figure C.1. The yield strength of the gusset plate is taken as the proportional limit or the end of the yield plateau of the engineering stress versus engineering strain curve. The yield strength (F_y) and ultimate strength (F_u) of all the tested tension coupons for both phases of tests are listed in Table C.1.

Two material ductility values are also reported. One is the percentage elongation over a 50.0 mm 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 of the coupon at fracture. Three cross-section areas at fracture (A_f , A_{fcor} and A_{fmid}) are presented in Table C.1. A typical cross-section of a rectangular coupon at the necking region was shown in Figure 2.5. The cross-section area A , A_{cor} and A_{mid} at the necking region are defined by (2.33) in Section 2.4.

The engineering stress versus extensometer strain curves of coupons for phase 1 materials are shown in Figures C.2 to C.5 except that for the rectangular HSS. The engineering stress versus extensometer strain curve of rectangular HSS is presented in Figure 3.14 because the rectangular HSS used in both testing phases have the same material properties. 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 coupon fracture. True stress versus true plastic strain relationship for each material is in Tables C.2 and C.3.

Table C.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_{fcor}	A_o/A_{fmid}		
HSS 89 x 89 (phase 1)						
S12	28.9	2.19	2.04	2.35	403	482.9
S16	30.3	2.19	1.95	2.38	408	485.0
S20	24.8	2.01	1.84	2.21	396	488.0
Average	28.0	2.11	1.94	2.31	402	485.3
HSS 89 x 89 (phase 2)						
S1	28.6	2.40	2.10	2.81	370	443.7
S2	32.3	1.96	1.80	2.14	377	434.2
S3	30.0	2.26	1.97	2.64	365	445.1
S4	26.0	2.19	1.92	2.54	367	435.5
Average	29.2	2.20	1.95	2.53	370	439.6
HSS 127 x 51						
R1	33.2	2.31	2.03	2.67	376.0	446.9
R2	34.1	2.35	2.05	2.74	383.0	450.8
R4	33.2	2.19	2.01	2.41	387.0	447.6
R5	33.7	2.32	2.04	2.67	375.0	448.9
Average	33.5	2.29	2.04	2.62	380.3	449.0
12 mm plate (phase 1)						
P121	36.1	2.15	2.05	2.26	313.0	493.9
P122	35.5	2.22	2.17	2.28	318.0	495.7
P123	33.5	2.06	1.95	2.17	327.0	494.9
Average	35.0	2.14	2.06	2.24	319.3	494.8
16 mm plate (phase 1)						
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 (phase 1)						
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
Average	39.6	2.14	1.98	2.34	288.7	457.3

Table C.1 Continue

Coupon	Elongation (%)	Cross section area ratio			Yield strength, F_y (MPa)	Ultimate strength, F_u (MPa)
		A_o/A_f	A_o/A_{fcor}	A_o/A_{fmid}		
16 mm plate (phase 2)						
NP161	32.5	2.49	2.30	2.72	378.7	564.4
NP162	33.3	2.22	2.03	2.46	379.7	560.1
NP163	35.0	2.05	1.91	2.22	382.7	559.3
Average	33.6	2.25	2.08	2.47	380.4	561.3

Table C.2 True stress versus true plastic strain data for HSS

127 x 51 x 4.8		89 x 89 x 4.8 (phase 1)		89 x 89 x 4.8 (phase 2)	
True plastic strain (mm/mm)	True stress (MPa)	True plastic strain (mm/mm)	True stress (MPa)	True plastic strain (mm/mm)	True stress (MPa)
0.0000	370.0	0.0000	398.0	0.0000	370.0
0.0057	405.5	0.0007	407.4	0.0110	395.0
0.0106	411.0	0.0011	431.8	0.0132	405.0
0.0271	431.9	0.0028	437.3	0.0261	416.0
0.0379	443.7	0.0085	452.1	0.0385	429.5
0.0523	457.7	0.0136	462.3	0.0511	442.6
0.0641	468.0	0.0272	482.6	0.0598	450.6
0.0818	481.9	0.0473	503.2	0.0696	459.1
0.0966	492.4	0.0580	511.7	0.0850	470.9
0.1101	501.2	0.0692	519.3	0.0964	479.3
0.1477	523.1	0.0809	526.4	0.1124	491.0
0.1651	532.1	0.1027	537.7	0.1257	498.5
0.1790	538.8	0.1220	548.3	0.1377	504.9
0.1900	543.4	0.1300	552.4	0.1600	516.0
0.2000	547.5	0.1500	562.0	0.2000	533.8
0.3500	595.1	0.1700	570.9	0.2300	545.7
0.4000	607.5	0.2000	583.1	0.2500	553.1
0.5000	629.0	0.2500	600.9	0.3000	570.1
0.6000	647.3	0.4000	642.6	0.4000	595.2
0.7000	663.4	0.5000	664.4	0.5000	618.2
0.8000	677.8	0.6000	683.1	0.6000	637.9
0.9000	690.7	0.7000	699.5	0.7000	655.4
1.0000	702.6	0.8000	714.2	0.8000	671.0
1.2000	723.6	0.9000	727.5	0.9000	685.3
1.4000	742.0	1.0000	739.7	1.0000	698.3
		1.4000	780.5	1.4000	742.1

Table C.3 True stress versus true plastic strain data for gusset plates

20 mm gusset plate		16 mm gusset plate (phase 1)		12 mm gusset plate		16 mm gusset plate (phase 2)	
True plastic strain (mm/mm)	True stress (MPa)	True plastic strain (mm/mm)	True stress (MPa)	True plastic strain (mm/mm)	True stress (MPa)	True plastic strain (mm/mm)	True stress (MPa)
0.0000	289.4	0.0000	337.7	0.0000	319.4	0.0000	380.0
0.0321	341.0	0.0085	344.2	0.0194	343.4	0.0106	386.5
0.0453	398.6	0.0321	404.9	0.0395	422.0	0.0329	491.7
0.0581	425.1	0.0626	453.8	0.0614	469.4	0.0437	519.2
0.0706	446.1	0.0844	479.9	0.0852	505.5	0.0701	566.7
0.0898	472.0	0.1082	503.7	0.1100	534.6	0.1100	614.9
0.1048	490.9	0.1285	521.3	0.1468	571.3	0.1407	642.7
0.1383	519.2	0.1520	539.4	0.1680	587.9	0.1536	652.9
0.1541	530.6	0.1800	556.2	0.1895	600.0	0.2000	684.3
0.1711	543.8	0.2000	566.7	0.2161	612.7	0.3500	755.5
0.1900	554.5	0.3500	626.2	0.3500	658.8	0.4000	773.5
0.2000	559.8	0.4000	641.4	0.4000	672.1	0.4500	789.7
0.3500	619.1	0.5000	667.6	0.4500	683.9	0.5000	804.5
0.4000	633.8	0.6000	689.7	0.5000	694.7	0.5500	818.1
0.5000	658.9	0.7000	709.1	0.6000	713.5	0.6000	830.7
0.6000	680.0	0.8000	726.3	0.7000	729.8	0.6500	842.5
0.7000	698.2	0.9000	741.8	0.8000	744.2	0.7000	853.5
0.8000	714.3	1.0000	756.0	0.9000	757.1	0.8000	873.8
0.9000	728.8	1.4000	803.2	1.0000	768.8	0.9000	892.0
1.0000	742.0			1.4000	807.1	1.0000	908.6
1.4000	785.5					1.4000	963.9

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

Figure C.2 Engineering stress versus engineering strain for HSS 89 x 89 (phase 1) tension coupons

Figure C.3 Engineering stress versus engineering strain for 12 mm gusset plate (phase 1) tension coupons

Figure C.4 Engineering stress versus engineering strain for 16 mm gusset plate (phase 1) tension coupons

Figure C.5 Engineering stress versus engineering strain for 20 mm gusset plate (phase 1) tension coupons

APPENDIX D ITERATIVE METHOD TO DETERMINE THE TRUE STRESS VERSUS TRUE PLASTIC STRAIN RELATIONSHIP

The iterative method to determine the true stress versus true plastic strain relationship of the test material after the peak load is presented in this section using the HSS 89 x 89 from phase 1 of the testing program as an example. Only data from one test coupon is used in the illustration. The true stress versus true plastic strain relationship for each trial is generated by the power-law equation defined in (4.6) to (4.8). Values of ϵ_o^p , ϵ_f^p , σ_o^t and σ_f^t are 0, 0.103, 398 MPa and 538 MPa respectively. Values of n and the corresponding C of each trial are listed Table D.1.

D.1 First guess

After the peak load, the state of stress in the region of necking is no longer uniaxial. But a rough estimate of the true stress (σ^t) and true plastic strain (ϵ^p) can still be estimated by

$$\sigma^t = \frac{F}{A}, \text{ and} \quad (D.1)$$

$$\epsilon^p = \ln\left(\frac{A_0}{A}\right) - \frac{\sigma^t}{E}, \quad (D.2)$$

where F is the load and A is the current average cross-section area defined by (2.33). But due to necking, the actual hydrostatic tension stress at the necking region is greater than one-third of the uniaxial tensile stress. For this reason, (D.1) will overestimate the actual true stress. Thus after the peak load, only 75% of the increase in true stress is considered in calibrating the first trial n . But the true plastic strain is still calculated with (D.2). Using only 75% of the increase in true stress to obtain the first trial n was found to give a close

estimate of the final n value. The first trial value of n is determined by matching the 75% true stress data as illustrated in Figure D.1. Result of the numerical simulation using values from the first estimate is shown in Figure D.2.

D.2 Iterative procedure

The last test data point of the coupon test has an engineering stress (σ_f^e) of 389.5 MPa and the change in cross-section area $(1-A/A_0)_f$ of 0.535. Figure D.2 shows that the simulation results with the first trial n overestimates the engineering stress of last test data point at $(1-A/A_0)_f$ of 0.535 by 1 MPa. It should be noted that the trial curve shown in Figure D.2 is exaggerated for clarity. Thus, the second trial n is adjusted until the generated true stress versus true plastic strain curve has a stress decrease by 2 MPa at the true plastic strain of 0.76 corresponding to the last test data point. The correction in true stress is doubled the discrepancy of engineering stress in the first trial. Results of the numerical simulation with the second trial n are shown in Figure D.2. The simulation with the second trial n underestimates the engineering stress of the last test data point by 1 MPa. The subsequent trial value of n is interpolated from the previous last two trial values by

$$n_{i+1} = \frac{n_{i-1} - n_i}{(\sigma_f^e - \sigma_i^e) - (\sigma_f^e - \sigma_{i-1}^e)} (\sigma_f^e - \sigma_i^e) + n_i, \quad (D.3)$$

where

σ_f^e = engineering stress at close to fracture,

σ_{i-1}^e = predicted stress at close to fracture at iteration $i-1$, and

σ_i^e = predicted stress at close to fracture at iteration i .

All $\sigma_f^e, \sigma_{i-1}^e$ and σ_i^e are the stress at the same deformation of $1-(A/A_o)_f$ and are listed in Table D.1. It should be noted that in an actual calculation for a material, σ_f^e and $(1-A/A_o)_f$ are the selected values that represent data from a number coupon tests and not the last test data point from one single test coupon. The third trial n is interpolated from the last two trial values based on (D.3). Figure D.2 shows the simulation stress versus change in cross-section area curve of the third trial matches that of the test. Therefore, the iteration can be stopped and n is accepted.

Table D.1 Parameters used in each of the trial

Trial, i	n	C	σ_f^e (MPa)	σ_{i-1}^e (MPa)	σ_i^e (MPa)	$1-(A/A_o)_f$
1	6.30	0.0129	389.5	—	390.5	0.535
2	6.50	0.0118	389.5	390.5	388.5	0.535
3	6.45	0.0112	389.5	388.5	389.2	0.535

Figure D.1 True stress versus true strain verves for the iterative method

Figure D.2 Engineering stress versus change in cross-section area curves for the iterative method

APPENDIX E KOROL'S TEST RESULTS

Summary of specimen details and test results from Korol (1996) are presented in

Table E.1.

Table E.1 Specimens details and test results

Specimen No.	HSS	Slot orientation	Weld length, L (mm)	L/w	Net area efficiency U_n
1A	127x51x6.4	Long side	160	1.17	0.98
1B	127x51x6.4	Long side	157	1.14	1.04
2A	89x89x6.4	-	157	1.13	0.95
2B	89x89x6.4	-	162	1.17	1.00
3A	127x51x6.4	Short side	156	1.12	1.05
3B	127x51x6.4	Short side	161	1.16	1.05
4A	127x51x6.4	Long side	90	0.64	0.77
4B	127x51x6.4	Long side	89	0.63	0.82
5A	89x89x6.4	-	98	0.69	0.89
5B	89x89x6.4	-	85	0.60	0.80
6A	127x51x6.4	Short side	91	0.66	0.81
6B	127x51x6.4	Short side	88	0.64	0.86
7A	127x51x6.4	Long side	70	0.50	0.63
7B	127x51x6.4	Long side	66	0.47	0.59
8A	89x89x6.4	-	64	0.46	0.62
8B	89x89x6.4	-	69	0.50	0.70
9A	127x51x6.4	Short side	66	0.48	0.73
9B	127x51x6.4	Short side	65	0.47	0.66

APPENDIX F ADDITIONAL RESULTS FROM PARAMETRIC STUDY

Results of simulations for parametric study using flat part material properties of phase 1 HSS 89 x 89 and HSS 127 x 51 with their corresponding assumed corner material properties developed in Section 5.2.1 are listed in Tables F.1 and F.2. Results of simulations for finite element models with no end welding in Section 6.3.1.8 are listed in Table F.1 and for finite element models with end welding in Section 6.3.2.4 are listed in Table F.2. The net section efficiency for the model with material properties of HSS 127 x 51 and 75% stronger corner is denoted as $U_{n_{75}}$, and that with material properties of HSS 89 x 89 and 28% stronger corner is denoted as $U_{n_{28}}$. Results of the outstanding HSS efficiency are listed in Tables F.3 to F.5.

Table F.1 Results of simulation using different corner strength for parametric study models with no end welding

Group	Model	HSS	Weld length ratio, L/w	Aspect ratio, a/b	Net section efficiency, $U_{n_{28}}$	Net section efficiency, $U_{n_{75}}$
W40	W40r40	127 x 51 x 4.8	0.38	0.40	0.55	0.61
	W40r75	102 x 76 x 4.8	0.38	0.75	–	0.54
	W40sh	89 x 89 x 4.8	0.38	1.00	0.54	0.54
	W40h14	102 x 76 x 4.8	0.38	1.34	–	0.54
	W40h25	127 x 51 x 4.8	0.38	2.50	0.54	0.54
W60	W60r40	127 x 51 x 4.8	0.58	0.40	0.79	0.86
	W60r75	102 x 76 x 4.8	0.58	0.75	–	0.77
	W60sh	89 x 89 x 4.8	0.58	1.00	0.74	0.75
	W60h14	102 x 76 x 4.8	0.58	1.34	–	0.73
	W60h25	127 x 51 x 4.8	0.58	2.50	0.73	0.73
W75	W75r40	127 x 51 x 4.8	0.73	0.40	0.97	0.98
	W75r75	102 x 76 x 4.8	0.73	0.75	–	0.92
	W75sh	89 x 89 x 4.8	0.73	1.00	0.89	0.90
	W75h14	102 x 76 x 4.8	0.73	1.34	–	0.88
	W75h25	127 x 51 x 4.8	0.73	2.50	0.85	0.86
W85	W85r40	127 x 51 x 4.8	0.83	0.40	1.05	1.05
	W85r75	102 x 76 x 4.8	0.83	0.75	–	1.02
	W85sh	89 x 89 x 4.8	0.83	1.00	0.99	0.99
	W85h14	102 x 76 x 4.8	0.83	1.34	–	0.97
	W85h25	127 x 51 x 4.8	0.83	2.50	0.94	0.95
W100	W100r40	127 x 51 x 4.8	1.00	0.40	1.09	1.14
	W100r75	102 x 76 x 4.8	1.00	0.75	–	1.12
	W100sh	89 x 89 x 4.8	1.00	1.00	1.05	1.10
	W100h14	102 x 76 x 4.8	1.00	1.34	–	1.09
	W100h25	127 x 51 x 4.8	1.00	2.50	1.05	1.07
W125	W125r40	127 x 51 x 4.8	1.25	0.40	1.09	1.14
	W125r75	102 x 76 x 4.8	1.25	0.75	–	1.14
	W125sh	89 x 89 x 4.8	1.25	1.00	1.06	1.12
	W125h14	102 x 76 x 4.8	1.25	1.34	–	1.11
	W125h25	127 x 51 x 4.8	1.25	2.50	1.06	1.11

Table F.1 Continue

Group	Model	HSS	Weld length ratio, L/w	Aspect ratio, a/b	Net section efficiency, U _{n_28}	Net section efficiency, U _{n_75}
W150	W150r40	127 x 51 x 4.8	1.50	0.40	1.09	1.14
	W150r75	102 x 76 x 4.8	1.50	0.75	-	1.14
	W150sh	89 x 89 x 4.8	1.50	1.00	1.06	1.12
	W150h14	102 x 76 x 4.8	1.50	1.34	-	1.12
	W150h25	127 x 51 x 4.8	1.50	2.50	1.06	1.12

Table F.2 Results of simulation using different corner strength for parametric study models with end welding

Group	Model	HSS	Weld length ratio, L/w	Aspect ratio, a/b	Net section efficiency, $U_{n_{28}}$
W40	W40r40	127 x 51 x 4.8	0.40	0.40	0.82
	W40sh	89 x 89 x 4.8	0.40	1.00	0.68
	W40h14	102 x 76 x 4.8	0.40	1.34	0.69
	W40h25	127 x 51 x 4.8	0.40	2.50	0.69
W55	W40r40	127 x 51 x 4.8	0.55	0.40	1.00
	W40sh	89 x 89 x 4.8	0.55	1.00	0.86
	W40h14	102 x 76 x 4.8	0.55	1.34	0.85
	W40h25	127 x 51 x 4.8	0.55	2.50	0.84
W70	W40r40	127 x 51 x 4.8	0.70	0.40	1.04
	W40sh	89 x 89 x 4.8	0.70	1.00	1.03
	W40h14	102 x 76 x 4.8	0.70	1.34	1.01
	W40h25	127 x 51 x 4.8	0.70	2.50	0.98
W80	W40r40	127 x 51 x 4.8	0.80	0.40	1.04
	W40sh	89 x 89 x 4.8	0.80	1.00	1.04
	W40h14	102 x 76 x 4.8	0.80	1.34	1.02
	W40h25	127 x 51 x 4.8	0.80	2.50	1.00
W100	W40r40	127 x 51 x 4.8	1.00	0.40	1.04
	W40sh	89 x 89 x 4.8	1.00	1.00	1.04
	W40h14	102 x 76 x 4.8	1.00	1.34	1.04
	W40h25	127 x 51 x 4.8	1.00	2.50	1.03

Table F.3 Results of outstanding HSS efficiency for different gusset plate thickness of parametric study models with end welding

Group	Model	Distance between welds (outstanding), W_{outsd}	Weld length (L)	Weld length ratio L / W_{outsd}	P_{u_pred}	P_{u_outsd}	U_{u_outsd}
Plate 12	P12w40	138	65.0	0.47	399.6	642.5	0.62
	P12w65	138	105.5	0.76	528.5	642.5	0.82
	P12w70	138	113.5	0.82	613.8	642.5	0.95
	P12w75	138	121.5	0.88	643.5	642.5	1.00
	P12w110	138	178.5	1.29	643.5	642.5	1.00
Plate 20	P20w40	130	65.0	0.49	409.6	605.3	0.68
	P20w55	130	92.0	0.71	560.0	605.3	0.89
	P20w60	130	100.0	0.77	606.5	605.3	0.93
	P20w65	130	107.0	0.82	606.5	605.3	1.00
	P20w100	130	160.0	1.22	606.5	605.3	1.00

Table F.4 Results of outstanding HSS efficiency for different gusset plate thickness of parametric study models with no end welding

Group	Model	Distance between welds (outstanding), W_{outsd}	Weld length (L)	Weld length ratio L / W_{outsd}	P_{u_pred}	P_{u_outsd}	U_{u_outsd}
Plate 12	P12w40	138	60.0	0.43	330.6	642.5	0.51
	P12w60	138	90.0	0.65	481.0	642.5	0.75
	P12w70	138	105.5	0.76	553.4	642.5	0.86
	P12w80	138	120.5	0.87	614.5	642.5	0.95
	P12w100	138	150.5	1.09	652.5	642.5	1.01
Plate 20	P20w40	130	57.0	0.44	313.0	605.3	0.52
	P20w60	130	85.0	0.65	459.0	605.3	0.76
	P20w75	130	106.0	0.82	563.0	605.3	0.93
	P20w85	130	121.0	0.93	604.5	605.3	1.00
	P20w110	130	156.0	1.20	619.5	605.3	1.02

Table F.5 Results of outstanding HSS efficiency for different weld height of parametric study models with no end welding

Group	Model	Distance between welds (outstanding), W_{outsd}	Weld length (L)	Weld length ratio L/W_{outsd}	P_{u_pred}	P_{u_outsd}	U_{u_outsd}
W40	W40h5	140	60.0	0.43	373.6	652.8	0.51
	W40h8	134	60.0	0.45	410.9	624.8	0.75
	W40h10	130	60.0	0.46	435.8	606.2	0.86
	W40h12	126	60.0	0.48	448.2	587.6	0.95
W75	W75h5	140	112.5	0.80	637.9	652.8	0.52
	W75h8	134	112.5	0.84	673.8	624.8	0.76
	W75h10	130	112.5	0.87	693.8	606.2	0.93
	W75h12	126	112.5	0.89	701.0	587.6	1.00
W100	W100h5	140	150.0	1.07	707.6	652.8	0.52
	W100h8	134	150.0	1.12	710.4	624.8	0.76
	W100h10	130	150.0	1.15	711.7	606.2	0.93
	W100h12	126	150.0	1.19	713.2	587.6	1.00
W125	W125h5	140	188.0	1.34	709.8	652.8	0.52
	W125h8	134	188.0	1.40	709.9	624.8	0.76
	W125h10	130	188.0	1.45	712.6	606.2	0.93
	W125h12	126	188.0	1.49	713.5	587.6	1.00

APPENDIX G THE NET SECTION ECCENTRICITY CALCULATION

The net section eccentricity ($\bar{x}$) of the parametric study models with no end welding for the a/b ratios are presented here. The net section eccentricity ($\bar{x}$) is calculated according to (2.18) as specified by ANSI/AISC-360-05, and is denoted as $\bar{x}$ (AISC-05) in Table G.1. The modified net section eccentricity ($\bar{x}^*$) is determined by taking the eccentricity of a square HSS with an equal circumferential length as the lower limit when a/b ratio is less than 1. The modified net section eccentricity is denoted as $\bar{x}^*$. A more accurate way to calculate the net section eccentricity is to take the distance from the centroid of one half of the HSS net cross-section area to the face of the gusset plate rather than to the centreline of the gusset plate as specified in ANSI/AISC-360-05. The distance from the centroid of one-half of the HSS net cross-section area to the face of the gusset plate ($\bar{x}_n$) is taken as

$$\begin{aligned}\bar{x}_n &= \frac{2(a-t')(b-t') + (a-t'-t)(a-t'+t)}{4(a+b-2t'-t)} - \frac{t}{2} \\ &= \frac{(a-t')(a+2b-3t') - t^2}{4(a+b-2t'-t)} - \frac{t}{2}.\end{aligned}\tag{G.1}$$

Variables used in (G.1) are depicted in Figures 3.1. Again, a modified net section eccentricity ($\bar{x}_n^*$) is determined by taking the eccentricity ($\bar{x}_n$) of a square HSS with an equal circumferential length as the lower limit when a/b ratio is less than 1. The values of $\bar{x}_n$ and $\bar{x}_n^*$ for the parametric study models are also shown in Table G.1

Table G.1 Net section eccentricity for parametric study models with no end welding

HSS	Gusset plate thickness (t), mm	Aspect ratio, a/b	$\bar{x}$ (AISC-05)	$\bar{x}^*$ (Modified)	$\bar{x}_n$	$\bar{x}_n^*$ (Modified)
127 x 51 x 4.8	12	0.40	21.85	33.38	15.23	27.77
102 x 76 x 4.8	12	0.75	29.89	33.38	24.00	27.77
89 x 89 x 4.8	12	1.00	33.38	33.38	27.77	27.77
102 x 76 x 4.8	12	1.34	36.39	36.39	31.00	31.00
127 x 51 x 4.8	12	2.50	40.85	40.85	35.69	35.69