

Strain Concentration Factors in Rectangular Hollow Section Truss Gap K-Connections—An Experimental Study

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ABSTRACT

Recent recommendations proposed for stress and strain concentration factors to be used in fatigue design of rectangular hollow section connections (which are based on isolated connection tests and finite element modelling) have been assessed for the first time by measuring strain concentration factors in large-scale, rectangular hollow section, complete trusses. Two Warren trusses with welded gap K-connections have been tested elastically and extensive strain measurements have been made around three connections with different-size welds. From the strain data, strain (or stress) concentration factors were determined according to accepted methods and compared with values predicted by current parametric formulae recommended by researchers at Delft University of Technology, University of Karlsruhe and Nanyang Technological Institute. The agreement between these formulae and test results is not particularly good across the full range of weld sizes examined. Hence, the primary issue raised by this experimental work is that weld size should be included in the validity range of these formulae.

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NOTATION

а	Theoretical throat thickness of weld
b _i	External width of square or rectangular hollow section (RHS) member i ($i=0.1.2$) 90° to plane of truss
В	Constant used in eqn (1) according to IIW^{11}
ρ	Node eccentricity for a connection - positive being towards
C	the outside of the truss (see Fig. 7)
$f(\tau)$	$\tau = t_i/t_0$
F_{y}	Yield stress
g	Gap between web members on the chord face (ignoring welds)
<i>g</i> ′	Non-dimensional gap size $= g/t_0$
h _i	External depth of square or rectangular hollow section (RHS) member i ($i=0,1,2$), in plane of truss
Н	Distance between the fillet weld toe and the first strain gauge
:	Subscript to denote member of connections is 0 designates
l	subscript to denote member of connection; $i=0$ designates chord; $i=1$ refers to the compression web; $i=2$ refers to the
	tension web; $i=i$ refers to the overlapping web for K- and N type overlap connections
K	Notch stress/strain factor
N N	Fatigue life (number of cycles to foilure)
D	Stress ratio between minimum and maximum nominal stress
R .	in a load cycle for constant amplitude fatigue loading
S _i	Effective leg length of weld along member i
S _r	Stress range or difference between maximum and minimum stress in a load cycle for constant amplitude fatigue loading
S _{r-hs}	Hot spot stress range = $S_r \times SCF$
SCF	Stress concentration factor (Karlsruhe definition) = $\sigma_{\rm hs}/\sigma_{\rm ab}$
SCF'	Stress concentration factor (Delft definition) = $\sigma_{\rm hs}/\sigma'_{\rm nom}$
SNCF	Strain concentration factor (Karlsruhe definition) = $\varepsilon_{hs}/\varepsilon_{ab}$
SNCF'	Strain concentration factor (Delft definition) = $\varepsilon_{hs}/\varepsilon'_{nom}$
t _i	Thickness of hollow section member i ($i=0,1,2$)
x	Distance measured from the fillet weld root
α	Angle between 'web 2' and chord member according to Soh et $al.^{14}$ and Soh and Soh ¹⁵
β	Average width ratio between web member(s) and chord =
	$(b_1 + b_2)/2b_0$
γ	Width to thickness ratio of chord member $= b_0/2t_0$
$\varepsilon_{a}, \varepsilon_{b}$	Axial and bending strain, respectively, in HSS web or chord member

Eab	Nominal axial strain in the web member near connection
Eac	Nominal (prestressing) axial strain in chord near connection
Ehs	Hot spot strain near the weld toe
€ _{mb}	Nominal bending strain in the web member at reference position (see Fig. 3)
Emc	Nominal (prestressing) bending strain in chord near connec- tion
Enom	Axial strain in web member $= \varepsilon_{ab}$
ϵ'_{nom}	Maximum strain (axial plus bending) in web member at reference position (weld toe, see Fig. 3)
\mathcal{E}_{\perp}	Strain measured in five element strain gauge chain, perpen- dicular to weld direction
$\boldsymbol{\mathcal{E}}_{\parallel}$	Strain perpendicular to five element strain gauge chain, paral- lel to weld direction
θ	Angle between 'web 1' and chord member according to Soh et $al.^{14}$ and Soh and Soh ¹⁵
θ_1, θ_2	Angle between compression web member and chord, and tension web member and chord, respectively
ξ	Gap to web width ratio $= g/b_{1,2}$
σ_{ab}	Nominal axial stress in the web member near connection
$\sigma_{ m hs}$	Hot spot stress at weld toe
$\sigma'_{\sf nom}$	Maximum stress (axial plus bending) in web member at reference position (weld toe, see Fig. 3)
τ	Thickness ratio between web member and chord member = $t_{1,2}/t_0$

INTRODUCTION

Stress/strain concentrations in tubular connections are the result of a complex structural interaction between two (or more) flexible, welded tubes. Peak stresses/strains in rectangular hollow section (RHS) connections are more pronounced than circular hollow section (CHS) connections since the effect of axial forces and bending moments occurs at the same point. Axial forces and in-plane bending moments in the web member of a planar truss connection are transmitted through the body of the weld to the chord face. As the chord connecting face is relatively flexible, transverse distortions (e.g. bulging) of the chord face occur, particularly for low web member to chord width ratios. The large mass of weld ensures structural compatibility and results in local bending of the web member walls. This complex three-dimensional behaviour is further

complicated by the shape of the RHS members which are stiffer in their corners than in the midface. The result is a highly uneven distribution of loading to the stiffer parts, which accounts for why the greatest strain concentrations have been found near the weld toes at the corners of the RHS web member, as shown in Fig. 1. For T- and X-connections, gauge lines C and/or D govern, while for gap K- and N-connections, gauge lines A and B in the gap region govern.¹

Unfortunately, it is not possible to measure these stress/strain maxima exactly at the weld toes because of physical restrictions. Surface strain measurements in RHS connections are usually obtained from electrical resistance strain gauges attached to the outer surfaces of steel tubes. Because the hot spot strain occurs at the weld toe, it is necessary to extrapolate the strain from two or more points. The magnitude of the hot spot strain then depends on:

- (i) the position at which it is measured, and
- (ii) the gradient and nature of the curve used in the extrapolation.

It is convenient to define the position by the weld leg length (i.e. by the toe of the weld) as this can be easily measured, to an accuracy of ± 1 mm. Gradients must be evaluated using 'best' approximations of data obtained from chains of strain gauges. These data must be collected from gauges located within prescribed distances from the weld toe where the influence of notch strain (caused by a specific flaw at the weld toe) is small, and the stress/strain gradient is often nearly linear. In Europe (Delft University of Technology and University of Karlsruhe), the prescribed location for the first strain gauge is $0.4t_i$ (but at least 4 mm) from the weld toe. Hence, the



Fig. 1. Lines considered for the measurement of hot spot strain.¹

extrapolated hot spot stress/strain, $\sigma_{\rm hs}/\varepsilon_{\rm hs}$ is basically defined as a geometrical stress/strain due to the intersection of two idealized shells. These distances, together with the most popular methods of extrapolation (namely, linear and quadratic) are now reasonably well established and are summarized in Fig. 2.¹

Based on the above definition of hot spot stress/strain, the stress/strain concentration factor, SCF'/SNCF', according to Wardenier² or Delft University of Technology, is defined as:

$$SCF'/SNCF' = \frac{\text{due to geometric discontinuity somewhere in the joint}}{\text{nominal stress/strain in the web member}}$$

where nominal stress/strain in the web member $(\sigma'_{nom}/\varepsilon'_{nom})$ is the maximum stress/strain due to web member axial load $(\sigma_{ab}/\varepsilon_{ab})$ and bending moment $(\sigma_{mb}/\varepsilon_{mb})$ at the meeting point (reference position) of the centreline of the web with the top face of the chord (see Fig. 3). In contrast, researchers at the University of Karlsruhe determine these factors by considering nominal stress/strain $(\sigma_{nom}/\varepsilon_{nom})$ to be just $\sigma_{ab}/\varepsilon_{ab}$, which leads to a higher factor, or SCF/SNCF.



Fig. 2. ε_{hs} determination by linear and quadratic extrapolation methods for location D on web member in truss T1, test 1 (connection 10).



Fig. 3. Determination of nominal bending strain for calculating ε'_{nom} .

Wardenier² emphasized the importance of geometrical stress in fatigue behaviour and defines this stress in the hot spot stress method, although the real hot spot stress includes a notch stress/strain factor, K_w , to amplify the geometrical stress/strain. Using the geometrical definition of hot spot stress/strain, one ignores stress/strain raisers caused by the weld (K_w) which are dependent on fabrication, and uses the reproducible geometric stresses/strains.

It is noteworthy to point out that the above-mentioned notion of hot spot stress range, S_{r-hs} , or hot spot stress/strain, $\sigma_{hs}/\varepsilon_{hs}$, is a European definition and is still a point of debate. AWS (American Welding Society) and API (American Petroleum Institute) design codes have empirical $S_{r-hs}-N$ fatigue design curves based on measured hot spot strains and cycles to failure, of welded test specimens which have the microscopic notch effects, i.e. K_w factor, built into the data base.³ Therefore, such a definition would lead to a higher and more 'optimistic' $S_{r-hs}-N$ curve than a European one. At this time there is still a lot of dispute over the different $S_{r-hs}-N$ curves which are still in a state of development.

FATIGUE DESIGN FOR HOLLOW STRUCTURAL SECTION JOINTS—LITERATURE SURVEY

A great deal of research has now been undertaken to determine SCF and SNCF for welded tubular (circular) connections due to fatigue problems associated with connection design in offshore steel jacket-type structures. This has taken the form of experimental measurement of strains in the vicinity of the joint, finite element and other numerical models, and

photoelastic techniques, with the results having been incorporated into many national design codes for offshore structures. Unlike circular tube connections, there has been a severe lack of information available for the fatigue design of RHS connections due to the absence of extensive and reliable experimental data. RHS gap connections are much more fatiguecritical than their overlap connection counterparts, yet are much easier to fabricate and hence popular, so in certain dynamically loaded RHS structures such as bridges and crane booms this lack of design guidance for fatigue performance represents a major setback.

Initial fatigue testing involving RHS was carried out by Babiker⁴ at the University of Sheffield. Test results consisted of S_r -N curves with a comparison of three gap spacings, and the general conclusion was that overlapped connections performed better than gap connections. This research was continued at the University of Sheffield by Eastwood *et al.*⁵ with additional testing of RHS-RHS N-connections that showed improved fatigue characteristics over the CHS-RHS connections. Once again the performance of an overlap connection was better than a gap connection.

A major investigation into the fatigue behaviour of RHS connections started in 1975 with collaborative research among the University of Karlsruhe, University of Liege, University of Nottingham, BSC research centre in Corby, Institut de la Soudre in Paris, TNO Institute for Building Materials and Structures in Rijswijk, and Delft University of Technology, and was sponsored by the European Community of Steel and Coal (ECSC), CIDECT, Studiengesellschaft in Germany and the testing centres themselves. The majority of testing was, for reasons of economy, carried out on isolated K- and N-connections and the validity of the results was checked in a number of truss tests.

Results from the test programme are compiled by Noordhoek *et al.*⁶ and also reported by Wardenier and Dutta.⁷ They were later published in CIDECT's Monograph No. 7 (Dutta *et al.*⁸) and by Wardenier.² Although the programme was extensive, only some information was available for a hot spot stress design method; consequently, the classification method was recommended for fatigue design and was only applicable to square hollow section connections.

A Canadian testing programme on the fatigue strength of nine short span trusses was carried out by Ogle and Kulak⁹ at the University of Alberta. Two truss configurations were studied; six trusses had overlapped K-connections while three trusses had gapped K-connections. The aim of this research was to establish fatigue guidelines for HSS connections which were non-existent in the Canadian national standard, CAN/CSA-S16.1.¹⁰ The experimental S_r-N curves were based on a classification approach for fatigue similar to Noordhoek *et al.*⁶ General conclusions again substantiated that overlap K-connections have significantly longer fatigue lives than gap K-connections, and that fatigue lives of full sized truss specimens might be less than the lives of isolated connection specimens.

The hot spot stress method for square and rectangular tube connections was first tentatively recommended by the IIW Subcommission XV-E.¹¹ In these recommendations SCF values were given for different connection types as a function of the thickness ratio of the tubes being joined, with a minimum SCF value of 3.0 for RHS. These SCF values could then be multiplied by the nominal axial stress in the web member, σ_{ab} , to determine the hot spot stress range (S_{r-hs}), and hence the fatigue life from a set of S_{r-hs} -N curves. For simple, planar K- and N-connections of square hollow sections, the SCF for loading in the web member could be determined by:

$$SCF = B \times f(\tau)$$
where $f(\tau) = \tau = t_i/t_0 \ge \tau_{\text{limit}}$,
and $B = 6.0$ for K- and N-connections with gap and $\tau_{\text{limit}} = 0.5$
 $B = 3.6$ for K-connections with overlap and $\tau_{\text{limit}} = 0.83$
 $B = 4.3$ for N-connections with overlap and $\tau_{\text{limit}} = 0.7$

The range of validity is shown in Table 1 and the basic $S_{r,hs}$ -N design curves are shown in Fig. 4. The design procedure also involves an additional factor (see Table 2) that accounts for bending stresses in web members caused by the stiffness distribution at a connection, which is used to amplify the axial stresses (σ_{ab}) in web members calculated from a

Parameter	Range of validity
θ_1, θ_2	40°–90°
b_i, h_i	$b_i = h_i (i = 1 \text{ or } 2)$
b_0/t_0	≤25
b_1, b_2	$b_1 \approx b_2$
$\beta = b_i/b_0$	$0.5 \leq \beta \leq 1.0$
Gap connections	$0.5(b_0 - b_i) \le g \le 1.1(b_0 - b_i)$
Overlap connections	$50\% \leq \text{overlap} \leq 100\%$
Steel grade	Fe 360 ($F_y = 235$ MPa) and Fe 510 ($F_y = 355$ MPa)

 TABLE 1

 Range of Validity of CIDECT⁸ and IIW¹¹ S_r-N Curves



Fig. 4. S_{r-hs} curves according to IIW.¹¹

 TABLE 2

 Additional Factors on the Axial Stresses for Square Hollow Sections when Bending Moments are Unknown (IIW¹¹)

Type of joint		Chords	Verticals	Diagonals
Gap connections	K type	1.5	1.0	1.5
-	N type	1.5	2.2	1.6
Overlap connections	K type	1.5	1.0	1.3
-	N type	1.5	2.0	1.4

pin-jointed truss analysis. Hence, in the case of RHS gapped K-connections the hot spot stress would be:

$$S_{r,hs}$$
 = web member mean axial stress $\times 1.5 \times 6 \times f(\tau)$ (2)

It was recognized that more accurate SCF values were necessary, based on multiple connection parameters, which translates into obtaining more accurate SNCF values by experimental or analytical research. A European collaborative project in The Netherlands (namely, Delft University and TNO Institute for Buildings Materials and Structures, Rijswijk) and Germany (namely, Mannesmannrohren-Werke A.G., Dusseldorf and University of Karlsruhe) was accordingly started in order to rectify this dearth of *SNCF* data for RHS welded truss type connections by means of undertaking finite element analyses and a limited amount of RHS isolated connection testing. Initial results from these European projects have now been published^{1,12,13} and recommended *SNCF* parametric equations are being advocated with the non-dimensional geometrical parameters β , τ , γ , ζ , g' and $\theta_{1,2}$.

Research on X- and T-connections was done exclusively at Delft University while the main work on K-connections with gap and overlap was carried out at the University of Karlsruhe. However, some supplementary work, carried out exclusively on SNCF (no fatigue testing) of a singular K-connection specimen with larger dimensions than those at the University of Karlsruhe, was also conducted by Delft University and TNO. The intention of the work was primarily to study the effect that chord axial tension and chord bending have on SNCF magnitudes for K-connections with gap. The SNCF' formulae eventually proposed by the Dutch researchers were as follows:¹

$$SNCF'_{\text{chord}}^{33\%} = (2.84 - 3.1\beta) \left(\frac{2\gamma}{12.5}\right)^{(1.02 + 1.1\beta)} \left(\frac{\tau}{0.5}\right)^{(0.8 + 0.5\beta)}$$
(3)

$$SNCF'_{\text{web}}^{33\%} = 1.0 + (1.49 - 0.9\beta) \left(\frac{2\gamma}{12.5}\right)^{(3.13 - 2.55\beta)} \left(\frac{\tau}{0.5}\right)^{(-0.25 + 1.5\beta)}$$
(4)

where
$$SNCF' = \frac{geometrical \ hot \ spot \ strain(\varepsilon_{hs})}{web \ member \ total \ strain(\varepsilon_{ab} + \varepsilon_{mb})}$$
 (5)

These SNCF' formulae are based upon non-dimensional geometrical parameters β , 2γ and τ whose validity ranges are:

 $0.4 \le \beta \le 0.6$ $12.5 \le 2\gamma \le 25$ $0.25 \le \tau \le 1.0$ e = 0

The SNCF' formulae are presented at moment percentages (surface bending strain in the web member as a percentage of the total axial plus bending strain in the web member) of 33% to be consistent with the IIW Subcommittee XV-E¹¹ multiplication factor of 1.5 (see Table 2).

For other moment percentages, the following adjustment formula was given:¹

$$SNCF'^{M\%} = \left[1 \cdot 13 - 0 \cdot 4 \left(\frac{\varepsilon_{mb}}{\varepsilon_{ab} + \varepsilon_{mb}}\right)\right] SNCF'^{33\%}$$
(6)

These formulae are described by the authors¹ as qualitative and the work carried out at the University of Karlsruhe¹³ was meant to expand upon the Delft study.

The experimental part of the Karlsruhe investigation consisted of 12 overlap K-connections and 24 gap K-connections. The objective of the test programme was to measure the *SNCF* in the critical areas of the connection, in order to be able to make comparisons with the results of the numerical investigation using the finite element method (FEM). In the case of K-connections with gap, 55 FEM analyses were performed. In addition, fatigue tests were carried out to determine $S_{r-hs}-N$ curves. The results of the analysis produced the following parametric formulae:¹³

$$SNCF_{chord} = \tau(0.00288\gamma^3 + g') + 5.21\xi(1 - 0.178\xi^2 g') - 0.1515\beta^3 g'^2 - 1.57$$
(7)

$$SNCF_{web} = 3 \cdot 3\tau (2 - \tau) + 0 \cdot 305 \xi \gamma^2 (0 \cdot 3 - 0 \cdot 01 \xi \gamma) + 0 \cdot 04 \gamma \beta (6 \cdot 38 - \gamma \beta^2) - 3 \cdot 8(\gamma g'/100)^2 - 2 \cdot 0$$
(8)

The validity ranges for these formulae are:

$0.4 \leq \beta \leq 1.0$	$0.4 \leq \tau \leq 1.0$	$12.5 \leq 2\gamma \leq 25$
$1.6 \leq q' \leq 7.1$	0·25≤ <i>ξ</i> ≤0·75	$35^\circ < \theta < 60^\circ$

Equations (7) and (8) are considered valid for a range of $35^{\circ} < \theta < 60^{\circ}$ although the formulae are based upon $\theta = 45^{\circ}$ (angle used in test specimens). In general, the equations are critically dependent on parameters β and τ while the size of gap or overlap related to web width (ξ) is next in degree of influence. Since specimens had different values of eccentricity the possible influence of internal moments on *SNCF* could have been determined; however, the parameter was not isolated in the test series and its effect is implicitly contained in the experimental *SNCF* values.

As mentioned before, the definition of SNCF in eqns (7) and (8) differs from the Delft definition, and is according to:

$$SNCF = \frac{geometrical \ hot \ spot \ strain(\varepsilon_{hs})}{web \ member \ axial \ strain(\varepsilon_{ab})}$$
(9)

Therefore, according to eqn (9) the bending moments occurring in the experiments and FEM analyses are indirectly included. The bending moments in the test specimens did vary and the values measured in the gap K-connection tests ranged from $\varepsilon_{mb}/(\varepsilon_{ab} + \varepsilon_{mb})$ of 11.3% to 62.6%.

Another parametric study on T and K square RHS connections by the FEM was carried out by Soh *et al.*¹⁴ and Soh and Soh¹⁵ at Nanyang Technological Institute, Singapore. It involved a comprehensive study of 18 K-connections and 11 T-connections. The difference in load cases between FEM work at Nanyang and Delft or Karlsruhe is illustrated by Fig. 5. FEM work by the investigators at Delft and Karlsruhe considered loading conditions that were isolated into nine single load cases, from



Fig. 5. Comparison of load cases and connection modelling considered by Delft/Karlsruhe Universities with Nanyang Technological Institute.

which two SNCF formulae were developed, one for the web member and one for the chord member. In contrast, the results of the analysis for the K-connection at Nanyang are given by 21 SCF formulae (three Kconnection members times seven loading conditions). For example, three equations are given for the type 1 axial loading case (see Fig. 5), which take on the following form:

$$SCF_{web1} = 0.8917(t_1/t_0)^{0.514}(b_0/2t_0)^{0.833}(b_1/b_0)^{0.527} (L/b_0)^{0.025}(g/b_0)^{-0.052}(\sin\theta)^{1.346}$$
(10)

$$SCF_{web2} = 0.5840(t_2/t_0)^{0.514} (b_0/2t_0)^{0.833} (b_2/b_0)^{0.527} (L/b_0)^{0.025} (g/b_0)^{-0.052} (\sin \theta)^{0.125}$$
(11)

$$SCF_{chord} = 0.3998(t_{1,2}/t_0)^{1\cdot111}(b_0/2t_0)^{1\cdot233}(b_{1,2}/b_0)^{0\cdot557} (L/b_0)^{-0\cdot121}(g/b_0)^{-0\cdot031}(\sin\theta)^{1\cdot231}$$
(12)

where web 1 has an angle of inclination of θ (see Fig. 5), L is the length of the chord under study, $t_1 = t_2$ and $b_1 = b_2$.

SCF parametric formulae of Soh and Soh¹⁵ distinguish between the two web members at a K-connection with 'web 1' being the one having an angle of inclination = θ , while 'web 2' has an angle of inclination, α . As shown in eqns (10)–(12), the parametric formulae include θ as a parameter but not α . In their parametric study, Soh and Soh¹⁵ assumed $\alpha = 45^{\circ}$ for 'web 2', but it is unclear if this member is in tension or compression. For the sake of comparison (see Table 7) 'web 2' has been assumed to be the tensile web member.

Revised international recommendations will soon be prepared by the IIW Tubular Structures Committee, but the aforementioned studies need to be first assessed by SCF/SNCF measurements on large-scale RHS welded connections in complete trusses, which is the topic of the next section.

EXPERIMENTAL WORK

Two large-scale, 12.0 m and 12.2 m span, simply-supported RHS Warren trusses as shown in Figs 6 and 7 have been tested elastically under single panel point loading to produce strain data for three RHS gap K-connections. Figures 6(c) and (b) illustrate the main difference between truss T1 and truss T2; i.e. the chord depth $h_0 = 305 \text{ mm}$ (with e = 7.5 mm)



Fig. 6. Details of RHS trusses T1 and T2 tested, with measured member dimensions.



Fig. 7. Overall view of truss T2 tested.

and $h_0 = 204 \text{ mm}$ (with e = 58.3 mm), respectively. Horizontal dimensions for truss T1 differ slightly from those in truss T2 due to two 50% overlapped connections (nos 3 and 11) in truss T2; otherwise, all

connections are gapped with a gap size (g) of 38 mm. Other pertinent SCNF non-dimensional parameters for both trusses are almost identical $(\tau = 1.0, \beta = 0.625, g' = 3.2, 2\gamma = 17)$. Hot spot strain measurements were taken at three gap K-connections along 'measurement lines' which co-incided with the inside wall line of the web member. The specified locations for strain gauge chains and their typical response are shown by Figs 8 and 9, respectively. The data collected during a typical test are shown in Fig. 10 and Table 3. Figure 10 shows the truss loading location relative to the instrumented connection along with the measured strains,







Fig. 9. SNCF strain gauge response showing initial cracking of weld at toe of joint at HSS web corner (truss T1, test 1).



Fig. 10. Strain gauge data from connection 10 in truss T1 during test 1.

forces and bending moments in the truss members near the connection. Axial and bending strains in the chord member are denoted by ε_{ac} and ε_{mc} , respectively. The axial strain, ε_{ab} , the bending strain, ε_{b} , bending strain at the reference position, ε_{mb} , and axial (ε_{ab}) plus bending (ε_{mb}) strain, ε'_{nom} , in both web members are also shown by this figure. ε_{ab} is the average of two strain gauges located at a distance of $2 \cdot 5b_{1,2}$ up the web member from the chord face (measured along the web centreline). As shown by Fig. 3, ε_{mb} involves a linear extrapolation of the bending strain, ε_{b} , at the strain gauge location to the chord face/web centreline position, which is added to ε_{ab} to give ε'_{nom} , as follows:

$$\varepsilon'_{nom} = \varepsilon_{ab} + 1.444\varepsilon_b = \varepsilon_{ab} + \varepsilon_{mb} \tag{13}$$

	x (mm)	Strain (με)		x (mm)	Strain (με)		x (mm)	Strain (με)
B	$S_2 = 5.9$		Н	$S_2 = 7.6$		С	$S_0 = 8.5$	
	H = 6.0			H = 6.0			$H \simeq 5.5$	
B 1	11.9	1086	H1	13.6	290	C1	14.0	272
B 2	14.9	796	H2	16.6	229	C2	17.0	189
B 3	17.9	653	H3	19.6	190	C3	20.0	124
B 4	20.9	573	H4	22.6	150	C4	23.0	44
B 5	23.9	503	H5	25.6	134	C5	26.0	30
D	$S_2 = 6.3$		Α	$S_0 = 6.7$		E	$S_0 = 7.6$	
	H = 7.5			H = 4.5			H = 5.5	
D1	13.8	891	A1	11.2	581	E1	13-1	489
D2	16.8	728	A2	14.2	317	E2	16-1	338
D3	19.8	618	A3	17.2	88	E3	19·1	239
D4	22.8	566	A4	20.2	-128	E4	22.1	158
D5	25.8	520	A5	23.2	-333	E5	25.1	99
F	$S_2 = 7.4$		Aª	$S_0 = 8.5$		G	$S_0 = 9.6$	
	H = 5.0			H = 5.5			H = 5.0	
F1	12.4	616	A1ª	14.0	- 333	G1	14.6	30
F2	15.4	552	A2ª	17.0	- 128	G2	17.6	10
F3	18.4	408	A3ª	20.0	88	G3	20.6	-10
F4	21.4	326	A4 ^a	23.0	317	G4	23.6	-25
F5	24.4	271	A5ª	26.0	581	G5	26.6	-35

TABLE 3 SNCF Strain Gauge Data at Connection 10 in Truss T1 During Test 1

"Strains extrapolated to weld on the compression web member.



The 1.444 factor for ε_b results from the geometry of the web member, i.e. linear extrapolation of bending strain (ε_b) from two strain gauge locations along the web member to the reference position (see Fig. 3).

One final aspect of the SNCF strain gauge instrumentation was the strain gauges which were placed perpendicular to strain gauges within chains B, J and A for truss T2 tests 2 and 3. Figure 11 shows such an arrangement of strain gauges for truss T2 test 2 measuring strains perpendicular to SNCF strain gauge chains, ε_{\parallel} . Knowing the bi-axial strain situation at the weld toe, one can determine the factor to convert SNCF to SCF using strength of materials theory for stress/strain relationships.

EXPERIMENTAL TEST RESULTS

General

From the strain data described above, the following topics have been considered for analysis:

(i) Strain concentration factors (SNCF) have been determined experimentally at the three test connections and are compared to parametric formulae given by researchers at Delft University of Technology. The Netherlands and University of Karlsruhe, Germany.



Fig. 11. Strain gauges measuring ε_{\parallel} (strains perpendicular to SNCF strain gauge chains) at locations A, B and J, at connection 5 in truss T2 during test 2.

(ii) Similarly, stress concentration factors (SCF) have been determined experimentally using calculated SCF/SNCF factors and are compared to parametric formulae given by reseachers at Nanyang Technological Institute, Singapore. This comparison is restricted to two tests where ε_{\parallel} was measured, namely, truss T2 test 2 locations A, B and J, and truss T2 test 3 locations B and J.

Experimental Strain Concentration Factors (SNCF)

All SNCF results were established by normalizing measured hot spot strains, ε_{hs} , in the web member as well as the chord with respect to a nominal longitudinal strain, ε_{ab} (axial strain only), or ε'_{nom} (axial plus bending strain), in the web member. In the case of SNCF chains on the chord (i.e. A, C, E and G, as shown in Fig. 8), an adjustment was carried out according to van Wingerde¹⁶ to make experimental truss results (with varying chord loadings) consistent with isolated K-connection test results, as follows:

$$SNCF_{chord, lines C, E} = (\varepsilon_{hs} + 0.4(\varepsilon_{ac} + \varepsilon_{mc}))/\varepsilon_{ab} \text{ (or } \varepsilon'_{nom}), \text{ and}$$
 (14)

$$SNCF_{\text{chord, lines A, G}} = (\varepsilon_{\text{hs}} - 1.6(\varepsilon_{\text{ac}} + \varepsilon_{\text{mc}}))/\varepsilon_{\text{ab}} \text{ (or } \varepsilon'_{\text{nom}})$$
(15)

By normalizing with respect to ε_{ab} and ε'_{nom} , the SNCF values obtained can be directly compared to those given by parametric formulae recommended by researchers at Delft University -SNCF' using ε'_{nom} (see Ref. 1) and the University of Karlsruhe -SNCF using ε_{ab} , (see Ref. 13). For comparison with the Delft formulae, the reference position for the web member nominal bending strain is taken as the intersection of the web member centreline with the chord face (see Fig. 3).¹⁶

Figure 2 illustrates how ε_{hs} for one particular location, chain D, in truss T1 test 1 was determined from both linear and quadratic extrapolation methods. A two-step quadratic extrapolation method was used according to van Wingerde.¹⁶ Initially, measured strains are fitted with the following function:

$$a + bx + cx^2 \tag{16}$$

where a, b and c are constants, to produce two values of strain at the 'boundary' points, i.e. $0.4t_i$ and $1.4t_i$ from the weld toe (see Fig. 2). Next, the extrapolated strains at the boundary points, plus the measured strains within these two points, were again fitted with eqn (16). This curve is the

one shown in Fig. 2 and is used for the quadratic extrapolation of ε_{hs} and to establish the two strain values for the linear extrapolation.

Experimental Stress Concentration Factors (SCF)

Table 5 shows SNCF values from Table 4 (in italics) converted to SCF, so that these can be compared to predicted values by parametric formulae recommended by reseachers at Nanyang Technological Institute. This conversion is possible for truss T2 test 2 locations A, B and J and truss T2 test 3 locations B and J where two strain gauges perpendicular to the chains themselves allowed the linear extrapolation of ε_{\parallel} to the weld toe, and the derivation of an SCF/SNCF conversion factor. Table 5 gives 5 SCF/SNCF conversion factors for the respective locations in truss tests which are used as multipliers to convert SNCF' ($\varepsilon_{hs}/\varepsilon_{nom}$) or SNCF ($\varepsilon_{hs}/\varepsilon_{ab}$), for both linearly and quadratically extrapolated ε_{hs} to SCF.

EVALUATION OF TEST RESULTS

Test results showed that the maximum SNCF (or SNCF') values occur in the gap region, in either the chord member or web member wall, i.e. at location B on tension web member (or location J on compression web member) and location A in chord (see Fig. 1). This is in agreement with both Mang et al.¹³ and Puthli et al.¹ At these critical locations, the difference in SNCF values determined by quadratic and linear extrapolation procedures is fairly small, with the 'quadratic SNCF' being up to 15% greater than the 'linear SNCF'. Since truss T2 tests 2 and 3 have connections which are nominally identical except for their weld sizes, these reveal that the SNCF' (or SNCF) at a particular location depends on relative weld size (S_i/t_i) —see Table 4—with SNCF' decreasing as weld leg size increases. This is illustrated in Fig. 12 for locations B, D and F on the tension web member, and locations J and K on the compression web member. The notable influence of relative weld size (S_i/t_i) and weld profile has been observed also by other reseachers (e.g. Refs 3, 17 and 18) on connections between other structural members or tubular (CHS) connections, and is considered to a certain extent in the AWS D1.1¹⁹ code.

It is interesting to note that this change in SNCF' (or SNCF) with weld size is only consistent for connections with the same noding eccentricity (e.g. B_2-B_3 or D_2-D_3 in Fig. 12, which are all measured on truss T2). If one compares B_1 (location B on truss T1 test 1 with $e \approx 0$) with B_2 (location

	Using ε'_{nom} and ε_{ab}
	Quadratic)
4	(Linear and
TABLE	Values (
-	he and SNCF (or SNCF')
	Experimental s _h

Test no.	Locati	uo	S _{0.1.2}	$\varepsilon_{\rm hs}(imes I)$	0-e)	SNCF' (usi	ng ε' _{nom})	SNCF (usi	ng E _{ab})
			- (mm)	Quadratic	Linear	Quadratic	Linear	Quadratic	Linear
Truss T1	Web	B	5-9	1821	1566	5-93	5.10	9-63	8.29
test 1		۵	6-3	1471	1325	4.79	4.32	7.78	10-2
connection 10		ц	7-4	826	801	2.69	2-61	4.37	4-24
		Η	7-6	443	405	1-44	1-32	2-34	2·14
	Chord	×	6.7	989	937	2-91	2.74	4·73	4-46
		Α"	10-5	- 586	-653	2.14	2-35	3.32	3-65
		C	8.5	411	409	1-42	1-41	2.30	2-29
		ш	7.6	820	723	2.75	2-43	4.47	3-95
		G	9.6	73	62	-0-07	-0.11	0.12	-0-17
Truss T2	Web	В	4-9	2254	2011	5-44	4.86	8-98	8-01
test 2		Ω	5.3	1520	1342	3-67	3-24	90 . 9	5.35
connection 5		Ц	5.6	922	902	2·23	2.18	3-67	3-59
		ŗ	16-5	- 1421	-1337	3.53	3-32	5.68	5-35
		R°	15-0	-1154	- 1050	2.86	2.61	4.62	4·20
	Chord	×	5.6	1442	1453	2-81	2.83	4-63	4.67
		٩ª	19-5	-378	-413	1.63	1-72	2.63	2-77
Truss T2	Web	æ	11-6	1961	1774	3-47	3.14	6-03	5-46
test 3		Δ	11.8	1388	1329	2.46	2-35	4.27	4:09
connection 4		Ц	10-4	1160	1034	2.05	1-83	3-57	3-18
		ľ	12.8	-2555	-2189	4-54	3-89	7-98	6-84
		K	11-4	-1710	-1552	3 0 4	2-76	5.34	4-85
	Chord	×	13.7	223	288	0-92	i Q	1.60	1.80
		٨.	14-9	- 1051	- 1017	1-34	1-28	2.35	2-25
^a Using ε'_{nom} and ε Chain A in Trus	s T2 Te	mpres sts 2 a	sion memb and 3 was	ber for SNCF' offset from th	and SNCF, r	espectively. nt line by 7.5 n	nm (63% of	t ₀) and 11 mm	(92% of t ₀),
respectively, beca Italic type, see te	tuse the ₁ xt.	gap di	stance at t	he measureme	nt line could	not accommoda	ite the five-ele	ement strain gau	ige.

SNCFs in RHS Joints

Test no.	Locatio	r r	SCF' (using SCF/	(SNCF × SNCF')	SCF (using SCF,	(SNCF × SNCF)
			Quadratic	Linear	Quadratic	Linear
Truss T2 test 2 connection 5 Truss T2 test 3 connection 4	Web Chord Web	8 ² 8 ²	1.104 × 5.44 = 6.01 1.106 × 3.53 = 3.90 1.146 × 2.81 = 3.22 1.107 × 3.47 = 3.84 1.091 × 4.54 = 4.95	1.104 × 4.86 = 5.37 1.106 × 3.32 = 3.67 1.146 × 2.83 = 3.24 1.107 × 3.14 = 3.48 1.091 × 3.89 = 4.24	1.104 × 8.98 = 9.91 1.106 × 5.68 = 6.28 1.146 × 4.63 = 5.31 1.107 × 6.03 = 6.68 1.091 × 7.98 = 8.71	1.104 × 8.01 = 8.84 1.106 × 5.35 = 5.92 1.146 × 4.67 = 5.35 1.107 × 5.46 = 6.04 1.091 × 6.84 = 7.46

^aOn compression member.

B in truss T2 test 2 with $e \approx h_0/4$) in Fig. 12, however, it can be seen that SNCF' decreases as weld leg size decreases, a reverse trend to before which must be due to the difference in noding eccentricity. These results suggest that the addition of a positive noding eccentricity in a typical gap connection has the beneficial effect of reducing the SNCF' at a particular location in a tension web member. Parametric SNCF formulae currently proposed by Delft¹ and Karlsruhe¹³ do not include the connection noding eccentricity as a parameter, although the Delft formulae (eqns (3)-(6)) are stipulated to be valid only for e=0 (Ref. 1) and the Karlsruhe formulae (eqns (7) and (8)) are quoted to have the eccentricity effect 'implicitly contained in the indicated SNCF values'.¹³

The range of validity for the Delft formulae is not met by two truss parameters; β for both trusses slightly exceeds the upper limit of 0.6 and e = 58.3 mm in truss T2 contravenes the e = 0 condition. For the sake of comparison, however, Table 6 shows the SNCF predicted by all SNCF formulae relative to the maximum critical SNCF from the truss tests (as determined by quadratic extrapolation).

Table 6 shows that the Delft SNCF parametric formulae underestimate the measured value for the web member in all cases, which is an unsafe trait. This is especially noteworthy in view of the fact that a positive



Fig. 12. Experimental SNCF' versus S/t for truss T1 test 1, truss T2 tests 2 and 3.

TABLE 6
Comparison of Predicted Quadratic SNCF (or SNCF') (by eqns (3)-(8)) with Maximum
Experimental SNCF (or SNCF'), Related to the Tension Web Member

Member	Method for	Experimental SNCF (max. value)/predicted SNCF				
	normalizing Strains	Truss T1 test 1	Truss T2 test 2	Truss T2 test 3		
Web	Using ε'_{nom} (Delft method)	5.93/3.35 = 1.77	5.44/3.30 = 1.65	3.47/3.22 = 1.08		
	Using ε_{ab} (Karlsruhe method)	9.63/3.50 = 2.75	8.98/3.47 = 2.59	$6 \cdot 03/3 \cdot 45 = 1 \cdot 75$		
Chord	Using ε' _{nom} (Delft method)	2.91/3.26 = 0.89	$2 \cdot 81/3 \cdot 20 = 0 \cdot 88$	$0.92/3.07 = 0.30^{a}$		
	Using ε_{ab} (Karlsruhe method)	4.73/4.50 = 1.05	$4 \cdot 63 / 4 \cdot 46 = 1 \cdot 04$	$1.60/4.35 = 0.37^{a}$		

"Chord in compression.

noding eccentricity (truss T2 tests 2 and 3) has been seen to reduce the measured in-situ SNCF on a tension web member. For the chord member, however, the Delft formulae are in reasonable agreement with the test results, except for when the chord is in compression in which case the predicted SNCF is very conservative.

For the Karlsruhe SNCF parametric formulae, the predicted SNCF values for the web member reveal a significant underestimation of the measured values. For the chord member the Karlsruhe SNCF predictions follow the same trend as for the Delft formulae.

Table 7 shows experimental SCF' relative to predicted ones given by Soh and Soh¹⁵ (see eqns (10)–(12)). These SCF parametric formulae include a parameter L, defined as the length of chord under study, which in Fig. 5 corresponds to a chord location where pin supports exist. This distance, for truss tests, has been assumed to be the distance between the midpoints of the chord member on either side of the connection, where moment is assumed to be zero (therefore, L=2410 mm for truss T2 test 2 and L=2383 for truss T2 test 3). Also, it is assumed that in the definition of SCF, Soh and Soh¹⁵ consider the 'nominal stress' in the web to include the effect of bending moment at the chord to web member interface, i.e. $\varepsilon'_{nom} = \varepsilon_{ab} + \varepsilon_{mb}$. Under these conditions Table 7 shows reasonable agreement between most experimental and predicted SCF' with the predicted SCF' for the tension web member (location B) being 22% less than the one for the compression web (location J).

Test no. Truss T2	Location		Predicted SCF	Experimental SCF'/Predicted SCF'	
				Quadratic	Linear
	Web	В	3.10	$6 \cdot 01/3 \cdot 10 = 1 \cdot 94$	5.37/3.10=1.73
test 2		Jª	3.97	3.90/3.97 = 0.98	3.67/3.97 = 0.92
connection 5	Chord	Α	3.35	$3 \cdot 22/3 \cdot 35 = 0.96$	$3 \cdot 24/3 \cdot 35 = 0.97$
Truss T2	Web	В	3.06	3.84/3.06 = 1.25	3.48/3.06 = 1.14
test 3 connection 4		Jª	3.92	4.95/3.92 = 1.26	$4 \cdot 24/3 \cdot 92 = 1 \cdot 08$

TABLE 7Comparison of Predicted SCF' with Experimental SCF' According to Soh and Soh¹⁵ (by
eqns (10)-(12))

"On compression member.

CONCLUSIONS

It has been shown that weld size relative to member thickness (S_i/t_i) has a significant influence on the gap K-connection strain or stress concentration factor (SNCF or SCF), with SNCF decreasing as weld leg size increases. It has also been observed that the addition of a positive noding eccentricity to a connection (with positive being towards the outside of the truss), tends to reduce the maximum SNCF in the tension web member.

For both the Delft¹ and Karlsruhe¹³ SNCF parametric formulae, the agreement with test results is not particularly good across the full range of weld sizes examined. However, it could be argued that only truss T2 test 3 has weld leg sizes which are representative of those which might be required in practice, for a fatigue-critical truss (at location B which was critical for the web member $S_2/t_2 = 0.96$, and at location A, $S_0/t_0 = 1.14$). The latest IIW fatigue design recommendations (IIW¹¹), for example, require fillet welds with a throat thickness of at least $1.0t_i$. Nevertheless, parametric formulae applicable over a wide range of weld sizes would be desirable. If one focuses attention solely on truss T2 test 3 in Table 6, which had the largest weld sizes, the predicted SNCF values for the tension web member agree well with the test result, when using the Delft formula, even though the e=0 condition is violated. However, for the chord member (in compression) in truss T2 test 3 the SNCF predictions by both Delft and Karlsruhe methods are still poor.

Experimental results show that chord SNCF is influenced by the location of the joint within a truss and the adjustment of SNCF for

compression chords, as evidenced by truss T2 test 3, appears to warrant further refinement.

In the case of SCF parametric formulae by Soh and Soh,¹⁵ Table 7 showed some reasonable agreement between actual measured and predicted SCF values, although the comparison is limited to five locations. SCF parametric formulae for K-connections include two additional parameters L and θ , relative to those parameters considered by Delft or Karlsruhe (see eqns (3)-(8)), and they also treat each web member separately, whereas the Delft/Karlsruhe formulae do not discern between the two members. It is interesting to note that Soh et al.¹⁴ and Soh and Soh¹⁵ overlook the European research on this matter which has consisted of substantially better experimental work to verify the theoretical work. However, in the experimental study reported herein the better agreement with measurements was provided by Soh and Soh¹⁵ rather than either of the European approaches. This may well be fortuitous as their¹⁵ finite element grid/mesh appears too coarse for accurate SCF measurements at the 'hot spot' regions. Moreover, Soh and Soh¹⁵ did not include any welds in their finite element models.

Finally, the difference between SNCF (or SCF) determined experimentally by linear and quadratic extrapolation techniques was found to be small for hot spot locations (up to 15%). The primary issue raised by this experimental work is that weld size should be included in the validity range of SNCF/SCF formulae.

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