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Fatigue behaviors of Square-to-Square Hollow Section T-joint with corner crack. I: Experimental studies

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Abstract: Four full-size square-to-square hollow section (SSHS) T-joints were subjected to static and fatigue tests under combined loads. Static tests were first carried out to investigate the hot spot stress (HSS) distribution along the brace-chord intersections. Fatigue tests were then performed until extensive cracks appeared and the cracks development were monitored by the alternating current potential drop (ACPD) technique. The cracked joints were then opened up and the shapes of the crack surfaces were measured. Fatigue test results and crack geometry measurements showed that under cyclic loading, cracks will be initiated at one of the four corners of the brace-chord intersection and propagate mainly in the direction parallel to the chord wall. Furthermore, branches and secondary cracks, which seldom appear in circular hollow section (CHS) joints, were formed near the end of the test. The test results also indicated that a more stringent criterion should be used to define the fatigue life the joint. Finally, the shapes of the surface cracks of the tested joints were found to be more complicated than that for CHS joints and any of the existing geometrical model used in numerical modeling of CHS joint is deemed to be inadequate.

Keywords: Combined loads; Cracking; Fatigue failures; Rectangular hollow sections; T joints.

1. INTRODUCTION

Rectangular hollow sections (RHS) are frequently employed in the constructions of many onshore structures such as cranes and bridges. During the design of these structures, one of the major concerns is the fatigue behavior under cyclic loadings. Many studies were carried out to study the fatigue performance of RHS joints [1-4] and the results were concluded in the CIDECT design guideline [5]. In these studies, the fatigue life was assessed by the HSS method. In this approach, the HSS range of the joint is first determined and then checked against a set of S-N curves for the estimation of fatigue life. Results obtained were summarized as equations for the calculation of the *stress concentration factors* (SCF) under axial (AX) and in-plane bending (IPB) loads. However, no equation is available for out-of-plane bending (OPB) load. While the HSS method is simple and reliable, it can only estimate the fatigue life of an *uncracked* joint. If surface cracks already exist in a joint, the *fracture mechanics method* (FMM) is required to estimate its remaining fatigue life. The FMM has been proven to be a reliable approach to assess the residual life of CHS joints with an existing crack [6-8]. However, it seems that few research reports can be found in the literature for the fatigue study of cracked RHS joints using the FMM. The main reason for this is that a successful application of the FMM depends on the correct modeling of the geometry of the cracks. Towards this end, despite that such models are available for CHS T, Y and K-joints [9-12], no similar model exist for cracked RHS joints. Therefore, a benchmark study that provides such information will be important for the fatigue assessment of cracked RHS joints.

The main objectives of this study are (i) to carry out an investigation on the geometrical details of surface cracks in welded SSHS joints and (ii) to suggest a realistic geometrical model for the fatigue analysis of welded SSHS joints. Four full-size SSHS T-joints subjected to combined cyclic loading were tested until fatigue failure. The SSHS T-joints were selected instead of the more general RHS joints because they are the most commonly used joints in practice. Findings obtained in this study are reported in two parts. In this paper, concentration will be focused on the experimental aspects of the study and the results obtained will provide information to describe the crack development (propagation, crack path, surface front) in SSHS joints. In the accompanying paper [13], focus will be

given to the development of a numerical modeling for the fatigue analysis and residual life estimation.

2. SCOPE OF TEST, SETUP AND SPECIMEN DETAILS

The experimental investigation of the four full-size SSHS T-joints was carried out in three phases. Firstly, the joints were subjected to static loads so that the HSS locations and the values of SCF were compared with the existing guideline [2]. Secondly, combined cyclic loads were applied to the specimens until fatigue failure and the results were validated against the UK DEN S-N curve [5]. During the cyclic loading phase, crack initiation and development were monitored by the ACPD technique [14]. Finally, the tested joints were opened up so that the crack surfaces were exposed and their shapes measured.

The “orange” rig designed for static and fatigue tests of hollow section joints under AX, IPB and OPB loads or combinations of these three basic load cases is shown in Fig. 1. The rig has three actuators, namely, actuator AX, actuator IPB and actuator OPB installed at End F to apply loads along three mutually perpendicular axes. Actuators AX and IPB with capacity of 250KN were employed to apply AX and IPB loads respectively. Actuator OPB with capacity of 150KN was employed for the generation OPB load. The actuators can be operated individually or concurrently to create combined load conditions.

The dimensions and orientation of the four SSHS T-joints, together with their mechanical properties are shown in Fig. 2. The weld profiles and the specimens were prepared in according to the American Welding Society specification [15]. They were then checked using the ultrasonic technique and the test results deemed the quality of the welds acceptable.

3. PHASE 1: STATIC TEST

3.1 *Strain gauges locations*

In order to measure the strain distribution around the brace-chord intersection, 24 and 20 sets of strain gauges were installed on the chord (G_{C1} to G_{C24}) and brace (G_{B1} to G_{B20}) respectively (Fig. 3). These locations including the five special points (A, B, C, D and E) at the four corners (CP1 to CP4) of the joint at where equations to calculate SCFs under AX and IPB loads are given in the CIDECT guide [5]. Since for a RHS joint quadratic

extrapolation is required to capture the strong non-linear strain distribution near the weld toe [2], three strain gauges were arrayed at each location along the line perpendicular to the weld toe at distances equal to $0.4t$, $0.9t$ and $1.4t$ (t is the thickness of members) from the weld toe. These *perpendicular* gauges were employed to measure the distribution of the perpendicular strain component ($\xi_{\perp}$) around the intersection. For stress calculation, at point C three more sets of *parallel* strain gauges (enlarged view in Fig. 3) were employed to measure the parallel strain components ($\xi_{\parallel}$). At all locations, the strain components at the weld toe were obtained by applying quadratic extrapolation to the three strain gauge readings. Finally, four additional strain gauges were placed at the center of the brace side to monitor the actual brace load applied.

3.2 Load application and test results

In the static test, a series of AX, IPB, OPB loads and combinations of them were applied. The basic load cases were employed to obtain the SCFs of the specimens and to validate the results against the published SCF equations [5]. Prior to the actual test, the specimen was subjected to six loading and unloading sequences. This precaution ensured the satisfactory performance of strain gauges and eliminated any drift of strain measurements due to the fabrication of the joints. In order to ensure that the joint remained elastic under static load test, the maximum static load applied was computed based on 70% of the material yield stress σ_y . During the tests, the actuators were ramped to the maximum load in several steps. At each step, the actuators were held in place and the strain readings were recorded. The loads were then increased to the next level and measurements were repeated. After reached the maximum load, the above steps were repeated by releasing the applied load in several steps to zero.

After the test, the strain gauge readings were analyzed and the *hot spot strain* (HSSN) was obtained using the quadratic extrapolation method. The *strain concentration factor* (SNCF) is calculated as

$$SNCF = \frac{HSSN}{SN_{nominal}} \quad (1)$$

where $SN_{nominal}$ is the nominal strain computed from the strain gauges readings at the center of brace sides. Assuming that the measured strains $\xi_{\perp}$ and $\xi_{||}$ are, respectively, the maximum and minimum principal strains at the weld toe, the corresponding SCF can be computed as [7]

$$SCF = SNCF \frac{(1 + \nu \xi_{||} / \xi_{\perp})}{(1 - \nu^2)} = SNCF \times SSCF \quad (2)$$

where $\nu=0.3$ is the Poisson's ratio and $SSCF$ is the *stress-strain conversion factor*. From Eqn. 2, for the situation that $\xi_{\perp}$ is the only non-zero strain component and $\xi_{||}=0$, one has $SSCF=1/0.91 \approx 1.10$ which is the value proposed by Dutta [16]. In order to check the validity of this value, experimental mean values based on parallel strain gauges (G_{C3} , G_{C11} , G_{C15} and G_{C23}) readings at the corners (Fig. 3) under the basic loading cases were computed and listed in Table 1. It can be seen that *all* the experimental SSCFs are higher than 1.1, equivalent to a range of 16% ($SSCF=1.152$) to 34% ($SSCF=1.211$) of the ratio $\xi_{||}/\xi_{\perp}$. This implies that due to the presence of sharp corners, $\xi_{||} \neq 0$ and adopting $SSCF=1.1$ will underestimate the SCFs. Hence, for RHS joints a value of $SSCF=1.2$ appears to be more appropriate.

3.3 SCF computation

For basic load cases, the SSCF and strain obtained from the test can be directly used for the deduction of SCF values. The experimental SCF values measured at the five selected points on chord (D, C and B) and brace (E and A) at the corners under different basic load cases are tabulated in Table 2. The experimental SCF values listed in Table 2 are the averages at the corners and they were computed from the SNCFs by using the corresponding SSCFs listed in Table 1. The SCFs at these points obtained by using the equations given by van Wingerde [2] and adopted in the CIDECT guide [5] are also listed in Table 2. It can be seen that the two sets of SCFs roughly agree at point B, but not at other points. Note that in the CIDECT guide, one equation is provided for both points A and E and no equation is given for the case of OPB load. A closer examination of the results indicates that:

- (1) In all the load cases, SCFs at chord are greater than that at brace.

- (2) At point E, values predicted by the equations are too high and different equations should be used at points A and E.
- (2) For both AX and IPB cases, the peak SCFs values appear at points B or C. For the OPB case, the maximum SCFs values appear at point B.
- (3) For the AX and IPB load cases, the SCFs at point B are higher than that at point D, except for Specimen I under AX load where they are practically equal.

From the above observations, one can predicted that under cyclic loading, *even without any OPB load*, surface crack will be initiated at region between point B and D on the chord surface and will propagate mainly in the direction parallel to the chord wall (i.e. along the lines CP1-CP2 or CP3-CP4).

For the combined load cases, $\sigma(\mathbf{p})$, the stress at a given point $\mathbf{p}$ at the weld toe is calculated by the superposition method [7] such that

$$\sigma(\mathbf{p}) = \text{SCF}_{\text{AX}}(\mathbf{p}) \times \sigma_{\text{n-AX}} + \text{SCF}_{\text{IPB}}(\mathbf{p}) \times \sigma_{\text{n-IPB}} + \text{SCF}_{\text{OPB}}(\mathbf{p}) \times \sigma_{\text{n-OPB}} \quad (3)$$

where $\text{SCF}_{\text{AX}}(\mathbf{p})$, $\text{SCF}_{\text{IPB}}(\mathbf{p})$ and $\text{SCF}_{\text{OPB}}(\mathbf{p})$ are, respectively, the SCFs at point $\mathbf{p}$ for the AX, IPB and OPB loads. $\sigma_{\text{n-AX}}$, $\sigma_{\text{n-IPB}}$ and $\sigma_{\text{n-OPB}}$ are the corresponding nominal stresses. In order to check the validity of Eqn. 3, the stress distributions obtained from combined load cases were compared with the corresponding results computed by using Eqn. 3. The results showed that in all the combined load cases and specimens tested, the stress distributions obtained by the superposition method agree well with the experimental measurements. An example for Specimen I with $\sigma_{\text{n-AX}}=1.58\text{MPa}$, $\sigma_{\text{n-IPB}}=6.72\text{MPa}$ and $\sigma_{\text{n-OPB}}=6.79\text{MPa}$ is shown in Fig. 4. Hence, it can be concluded that the superposition method can be applied to the case of RHS joints.

4. PHASE 2: FATIGUE TEST

4.1 Cyclic loads and ACPD probe locations

In fatigue test, sinusoidal constant-amplitude loads which are combinations of the three basic cases were applied. The cyclic loading patterns applied to the four specimens are summarized in Fig. 5. These cyclic loads were selected in such a way that the resulted HSS

at the weld toe are in the range of $[0.75\sigma_y, 0.85\sigma_y]$ so that the specimens could be failed in a realistic numbers of load cycles (500k-2500k). All the actuators were preset under load control condition. For all load cases, the minimum magnitude of the applied load was zero while the maximum loads generated peak SCFs at one of the corners on the chord (Fig. 6). ACPD probes were attached to the joints to record crack development on the chord surface. As surface cracks are expected to initiate at the peak HSS region, based on the stress distributions shown in Fig. 6, 32 ACPD probes were concentrated at region around CP3 for Specimens I and IV and around CP4 for Specimens II and III (Figs. 7 to 10). For Specimen I, the distance between two adjacent probes was either 10mm or 20mm. For Specimens II to IV, a uniform probe interval of 10mm was adopted. The ACPD probes were connected to the U10 Crack Microgauge [17] which can detect cracks with a minimum depth of 0.1mm. The U10 Crack Microgauge was then connected to a PC running the FLAIR software [18] for instrument control, data storage and graphical outputs. According to the manufacturer's specification, with 10mm probe spacing and a smooth crack front, the relative error of an isolated measurement on an existing crack is typically less than 10%.

4.2 Geometrical parameters

In order to facilitate the description of the fatigue testing results, definitions of some parameters used in the description of the geometry of a surface crack are needed. As shown in Fig. 11a, a surface crack is initiated at the peak HSS point $\mathbf{p}$ and *propagates* along the weld toe while *penetrates* into the chord face. Assuming that after a number of load cycles, the two endpoints $\mathbf{p}_1$ and $\mathbf{p}_2$ mark the extent of the crack. The *crack length*, l is then defined as the length of the curve $\mathbf{p}_1\mathbf{p}_2$. To describe the level of penetration into the chord face, a typical cross-section $l'-l'$ which cuts across the crack at point $\mathbf{O}'$ in such a way that it is perpendicular to the weld toe at $\mathbf{O}'$ is examined. A local coordinate system $x'-z'$ is set up with origin at $\mathbf{O}'$ and the deepest point at this section is denoted as $\mathbf{d}'$ (Fig. 11b). The *curved crack depth*, a' is defined as the length of the curve $\mathbf{O}'\mathbf{d}'$. In addition, the *projected cracked depth*, a , is defined as the projected length of the curve $\mathbf{O}'\mathbf{d}'$ on the z' axis. For a typical point $\mathbf{q}'$ on the curve $\mathbf{O}'\mathbf{d}'$, the angle $\theta_s(z')$ is defined as the angle between the line $\mathbf{O}'\mathbf{q}'$ and the z' axis. In general, since the crack profile is a curve, $a' \geq a$ and it is possible that $a'/t_0 > 1$ while $a/t_0 \leq 1$. The shape of the curve $\mathbf{O}'\mathbf{d}'$ also varies along the crack length so

that its shape at point **p** (Fig. 11a) is different from that at section $I'-I'$. Furthermore, it is possible that maximum values of a' and a could appear at different sections. The crack may penetrate through the chord (i.e. $a=t_0$) at one section while at another section, a' may attend a maximum value but still with $a/t_0 < 1$.

4.3 Fatigue test results

During the fatigue test, two distinct phases can be identified [19]: The *initiation phase* is defined as the period between the first load cycle and N_2 , the cycle when the crack can be detected visually (or by the ACPD technique, i.e. $a' \approx 0.1\text{mm}$). The *propagation phase* is defined as the period between N_2 and N_3 , the cycles to through-thickness crack (TTC) formation. The propagation and penetration of the surface crack were monitored at the 32 ACPD probes locations such that the *curved crack depth*, a' , attended at different load cycles were recorded. Since in many previous studies [4, 7, 14] it was found that crack fronts generated under cyclic loading are smooth curves, after the tests were finished, six-order polynomial curve fittings were applied to the raw data to obtain smoothed profiles of surface cracks so that the deepest points (the sections with maximum a') were identified. Further analyses of the crack penetration data at the deepest points were then employed to identify different crack growth phases and the crack penetration rate. A summary of the results obtained is listed in Table 3 and the following graphs are plotted:

- (1) Crack propagation and penetration profiles: graphs of a' against l (Figs. 12 to 15).
- (2) Crack penetration curve at the deepest point: graphs of a' against N at the deepest point, where N is the number of load cycles applied (Figs. 16 and 17).
- (3) Crack penetration rate at the deepest point: graphs of da'/dN against a'/t_0 at the deepest point (Fig. 18).
- (4) Crack propagation curves: graphs of l against a' at the deepest point (Fig. 19).

4.3.1 Specimen I

For Specimen I, the combined loads applied generated a distinct peak HSS near CP3 (Fig. 6). A surface crack was initiated at a section near SI-P19 and then gradually shifted to a section near SI-P20 (Fig. 12). The initiation phase is about 25% (100k cycles) of N_f , the total numbers of cycles applied (Figs. 16 and 18). After the initiation phase, the crack

developed steadily with a' increased proportionally with N and a mid increase in the penetration rate was observed near the end of the test. This phenomenon is different from the cases of CHS T-joints [7] in which after the initiation phase, the crack penetrated into the chord rapidly. For the propagation of the crack, as predicted from the SCF results, the crack propagated towards CP4 (Fig. 8) with a final ratio of $a/l=0.08$ (Table 3).

4.3.2 Specimen II

Specimen II was designed to test the prediction that even without any OPB load, the crack will still propagate in a direction parallel to the chord wall. A relatively small amount of OPB load was applied (Fig. 5) so that the peak HSS near CP4 was only 10% higher than that at CP1 (Fig. 6). A crack was initiated at a section near SII-P17 (Fig. 13) and remained as the deepest section. When compared with Specimen I, a shorter initiation phase corresponding to 10% of N_f was recorded (Fig. 16). The penetration rate then increased until $a'/t_0 \approx 0.6$ ($a' \approx 10\text{mm}$) after which it *dropped* sharply (Fig. 18). Detail investigation showed that this was due to the deflection at End F of the specimen. When $a' \approx 10\text{mm}$, the crack was considerably long ($l \approx 150\text{mm}$, Fig. 19) and caused a deflection $\delta \approx 10\text{mm}$ at End F (Fig. 20). The AX load thus produced a secondary OPB load equivalent to $0.01\text{m} \times 75\text{kN} = 0.765\text{Nm}$ which cancelled out part of the OPB load ($-0.42\text{kN} \times 2.165\text{m} = -0.91\text{kNm}$) applied. As a result, the HSS at CP4 was reduced and the penetration rate dropped. With further load cycles applied, a second crack was developed at CP1 (Fig. 8). However, despite the absence of OPB load and the appearance of the second crack, the first crack still propagated along the line CP4-CP3 with a final ratio of $a/l=0.05$ (Table 3).

4.3.3 Specimen III

For Specimen III, no AX load was applied (Fig. 5) and the nearly identical IPB and OPB loads generated the peak HSS near CP4 (Fig. 6). As a result, a crack was initiated near SIII-P19 and shifted to SIII-P18 (Fig. 14). The initiation phase accounted for about 5% of N_f and then followed by a sharp increase in penetration rate (Fig. 18). After that the penetration rate was dropped but eventually increased again. The crack also mainly propagates along the line CP4-CP3 (Fig. 9) and with little advancement towards CP1. However, when $l \approx 120\text{mm}$ ($a' \approx 15\text{mm}$ at the deepest section), the crack tip near SIII-P23 branched out from

the weld toe (Figs. 9 and 14). Nevertheless, the crack still mainly propagated along the chord wall direction with a final ratio of $a/l=0.06$ (Table 3).

4.3.4 Specimen IV

For Specimen 4, equal magnitude of IPB and OPB loads were used and the AX load applied generated tensile stress along the *whole* intersection (Fig. 6). The crack was initiated at a section near SIV-P10 (Fig. 15) with a short initiation phase (2% of N_f) and then penetrated into the chord steadily (Fig. 17). As the crack continuous to grow, the surface crack turned to a TTC at SIV-P22 (Fig. 15). The initiation phase at SIV-P22 was about 85% of N_f as it took many load cycles for the crack to propagate to that location. However, after the initiation phase, the penetration rate at SIV-P22 was high (Fig. 18). Near the end of the test a second crack appeared at SIV-P29 ($\approx 75\%$ of N_f) and branches were eventually formed at both ends of the crack at SIV-P29 ($\approx 85\%$ of N_f) and SIV-P6 ($>85\%$ of N_f). However, by the time the second crack and the branches were formed, the ratio of a'/t_0 at SIV-10 was ≥ 1.0 . As expected, despite that tensile stress was developed along the whole intersection, the crack again mainly propagated along the chord wall direction (Fig. 11) with a final ratio of $a/l=0.05$ (Table 3).

4.3.5 Fatigue lives for specimens

In the previous studies of CHS joints [7, 9], the fatigue life of a joint is normally defined as N_3 , the number of cycles when TTC are formed. However, for a RHS joint, extensive crack propagation ($l \approx$ brace width) and penetration ($a \geq 1$) can occur well before a TTC is formed. In fact, for the four specimens tested, TTC was formed only in Specimen IV after more than two millions load cycles were applied. Since by the time $a'/t_0=1.0$, the surface crack is already sufficiently long and deep, there could be significant changes in the stiffness and the static strength of the joint due to the reduction of effective thickness of the chord. Hence, it is suggested that the fatigue life of a RHS joint should be defined as $N_{a'}$, the number of load cycles when $a'/t_0=1.0$. For the four specimens tested, $N_{a'}$ is about 55% to 85% of N_f (Table 3). In Fig. 21, the S-N curve [19] corresponding to the specimen chord thickness is plotted against the values of $N_{a'}$ and N_f obtained from the tests. It appears that the S-N curve is still conservative even when the more stringent criterion of $N_{a'}$ is adopted.

5. PHASE 3: CRACK GEOMETRY MEASUREMENTS

The fatigue test results and the ACPD readings indicate that for a RHS joint, the shape of the crack surface could not be described by a constant θ_s . In order to obtain more details of the crack shape, the cracked joints were cut out from the specimen and split into two parts, namely, the chord face part and the brace wall part. Plane and sections views of the crack surfaces exposed are shown in Fig. 22. Fig. 22 shows that the unsymmetrical shape of the crack surface changes along brace-chord intersection and confirms that the crack fronts generated during the fatigue test are smooth curves. Furthermore, the angle θ_s increases as the crack penetration into the chord wall. In order to gather more details, a clay molding procedure was employed to measure the section profile (shape of the curve $O'd'$ in Fig. 11) of the crack and the variations of θ_s at different sections. The molding procedure consists of the following steps:

- (1) After the crack surface was cleaned properly, soft fine clay was applied to the brace wall part (Fig. 23a).
- (2) The clay mold was then removed when it was half-dry. Thus, the shape of the crack was imprinted onto the clay mold (Figs. 23b and c).
- (3) The clay mold was allowed to dry completely. Slices of clay were trimmed off at 10mm intervals in directions perpendicular to the weld toe (Fig. 23d).
- (4) For each section, the profile was transferred to a tracing paper (Fig. 23e).
- (5) The profiles were scanned and digitalized to measure the variation of θ_s (Fig. 23f).

Note that in step (5), in order to determine θ_s for a typical point q' on the crack profile, the coordinates (x', z') of q' , which can be determined with error $\leq 1\text{mm}$, were measured. Since $\tan(\theta_s) = x'/z'$, the error of θ_s , $e(\theta_s)$, decreases as z' increases. By using the above procedure, it is estimated that $e(\theta_s) \leq 4^\circ$ when $z' = t_0 = 16\text{mm}$. A local coordinate s' is defined to describe the variation of θ_s at different sections of the crack (Fig. 24). s' is measured from M, the intersection of the weld toe with the middle of the brace wall. For a typical point Q on the weld toe, s' is defined as the length of the curve MQ such that at points B and D, $s' = L_w$ and $L_w + \pi r_w/2$ respectively. In order to show the typical variation of θ_s along the surface crack corresponding to different a/t_0 levels, the measurements obtained for Specimen I is plotted in Fig. 25. From the measurements, it can be observed that:

- (1) In general, θ_s increases as a/t_0 increases at all sections for all the specimens.

- (2) The rate of change of θ_s is higher at the corners (within the curve BD) than between the line MB. Hence, the final range of θ_s is larger at the corners.
- (3) The initial values of θ_s fluctuate a lot when $a/t_0 < 0.2$ and smooth out as a/t_0 increases. This can be explained by the higher measurement error when z' is small.
- (4) When $a/t_0 > 0.2$, values of θ_s near the corner are greater than that between the line MB.
- (5) Peak values of θ_s occur at a section close to the quarter point C_1 of the corner of the brace (Fig. 25).

In general, the variation of θ_s is somehow depended on the welding details and loading applied. Nevertheless, it is found that the information obtained could be used to construct a reasonable geometrical model [13] for the prediction of fatigue life of a cracked SSHS joint.

6. CONCLUSIONS

In this study, four full-size SSHS joints were subjected to both static and fatigue tests. The static results obtained indicate that peak HSS occurs at the corners of the chord brace intersection. The measured SCFs are different from that predicted by the existing guideline. The results also showed that the superposition method can be used to predict the SCF distribution for combined loadings. Furthermore, it is found that a higher stress-strain convention factor of 1.2 should be used for RHS joints.

The fatigue test demonstrated that under cyclic loading, cracks will be initialized at the corners of the brace chord intersections and propagate in a direction parallel to the chord wall, even without any OPB load. Results obtained by the ACPD technique and post-failure measurements showed that the cracks surface is a smooth 3D unsymmetrical surface with curved crack profile at any cross section. The crack growth rate at the deepest point may not increase monotonically with the number of load cycles applied. Significantly long and advanced crack could appear well before a TTC is formed. Furthermore, secondary cracks and branches which seldom appear in CHS joints were formed near the end of the tests. Based on the test results, it is suggested that the fatigue life of a RHS joint should be considered as the number of load cycles when the curved crack depth is equal to the thickness of the chord.

The results obtained in this study suggested that *any* of the existing geometrical model developed for cracked CHS joints could *not* be applied for the numerical modeling of cracked RHS joints. However, the experimental results obtained could be employed for the modeling of cracked RHS joints. In the second part of this study, more details regarding the geometrical model developed and the numerical results obtained will be presented.

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Fig.1. The “Orange” rig and setting for the three actuators

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Fig. 5. Cyclic load applied to Specimens

Fig. 6. Stress distribution on chord for specimens subjected to cyclic loads

Fig. 7. A plan view for ACPD probes locations, Specimen I

Fig. 8. A plan view for ACPD probes locations, Specimen II

Fig. 11. Definitions of geometrical parameters of a surface crack

Fig. 12. Curved crack depth (a') history for Specimen I

Fig. 13. Curved crack depth (a') history for Specimen II

Fig. 14. Curved crack depth (a') history for Specimen III

Fig. 15. Curved crack depth (a') history for Specimen IV

Fig. 16. Crack penetration curves for Specimens I-III.

Fig. 17. Crack penetration curve at sections SIV-P10, SIV-P22 and SIV-P29

Fig. 18. Crack penetration rate (da'/dN) for Specimens I to IV

Fig. 19. Graphs of crack length l against curved crack depth a'
 (Note: For Specimen IV, SIV-P10, values of l for $a' > 18$ mm are not recorded as the crack propagated outside range of ACPD probes)

Fig. 20. Eccentricity caused by the deflection of the brace end

Fig. 21. Fatigue test results comparing with S-N curve data

Fig. 22. Views of the chord face and the brace wall parts

(a) Fine soft clay was applied

(b) Dried clay mold was removed

(c) Crack surface imprinting on clay model

(d) Sections of the mold were prepared

(e) Transfer of cross sections to tracing papers

(f) Crack shape marked on paper scanning

Fig. 23. Procedure to measure the geometry of a surface crack

Fig. 24. Local coordinate s' for the measurement of θ_s

Fig. 25. Measured values of θ_s , Specimen III

Table 1. Mean $SSCF$ values calculated from experimental results

Specimen	Mean $SSCF$ values		
	AX	IPB	OPB
I	1.152	1.173	1.186
II	1.193	1.158	1.172
III	1.162	1.170	1.193
IV	1.178	1.181	1.211

Table 2. Experimental SCF values obtained from static test

Specimen /Location		AX			IPB			OPB
		Exp.	Eqn.	Diff.(%)	Exp.	Eqn.	Diff.(%)	Exp.
I	D	15.26	6.65	-56.4	5.32	7.05	32.52	2.29
	C	17.52	14.53	-17.11	10.45	13.2	26.3	6.38
	B	15.25	16.19	6.09	9.93	10.68	7.55	10.18
	A	12.48	9.94	-20.35	8.16	7.3	-10.54	6.59
	E	6.26	9.94	50.83	5.88	7.3	24.15	2.33
II	D	12.06	9.70	-19.50	5.94	8.35	40.57	2.26
	C	21.74	20.11	-7.50	12.56	14.45	15.05	8.51
	B	21.84	22.43	2.70	9.86	10.51	6.59	13.52
	A	9.39	12.35	31.50	4.44	6.25	40.76	4.93
	E	2.00	12.35	517.50	2.75	6.25	127.17	0.84
III	D	10.52	8.05	23.48	4.69	6.93	47.76	1.87
	C	15.40	16.69	8.38	8.25	11.99	45.33	6.62
	B	13.06	18.62	42.57	5.24	8.72	66.41	7.96
	A	10.48	12.35	17.80	4.43	6.25	41.08	5.45
	E	2.94	12.35	320.06	2.89	6.25	116.26	1.16
IV	D	11.64	7.6	-34.71	6.57	6.52	-0.76	2.45
	C	13.31	15.96	19.91	8.74	11.66	33.41	5.95
	B	14.06	17.93	27.52	8.98	8.49	-5.46	10.37
	A	11.85	13.34	12.57	6.65	6.76	1.65	6.10
	E	5.36	13.34	148.88	5.09	6.76	32.81	2.07

Note: **Exp.** = Experimental SCF values

Eqn. = SCF values predicted by using equations given in [5]

Diff. (%) = Percentage difference calculated as $100 \times (\text{Eqn.} - \text{Exp.}) / \text{Exp.}$

Maximum SCF values for each case are enclosed in boxes.

Table 3. Summary of fatigue test final results

Results	Specimen I	Specimen II	Specimen III	Specimen IV
Total no. of cycle applied N_f	407517	446508	899289	2459643
No. of cycle when $a'/t_0=1.0$, $N_{a'}$ (To the nearest 1000 cycles)	341000	277000	494000	2045000
Final l (to the nearest 5mm)	150	255	230	295
Final a' (mm)	20.03	20.53	30.14	29.29
Final a/t_0	0.75	0.79	0.89	1.0