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# FATIGUE STRENGTH OF LONGITUDINAL WELDED JOINTS WITH STEEL CORRUGATED PLATES

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## ABSTRACT

In this paper the fatigue strength of welded joints with corrugated plates is studied to supplement the understanding of that related to corrugated web beams under fatigue loading. The experimental failure modes and S-N relationships of test specimens are studied and compared with those of beam tests reported in the literature. The effective notch stress analysis via finite element analysis is also applied to evaluate the fatigue crack at the weld root or the weld toe in the vicinity of the fold intersecting region of the corrugated web. The applicability of this analysis is verified and the local stress concentration related fatigue crack modes are discussed.

**Keywords:** Fatigue strength, corrugated plate, stress concentration, notch stress analysis.

## 1. INTRODUCTION

Welded H-beams with steel corrugated webs have gained increasing application in recent highway bridge projects. Ordinary shapes of corrugated webs, joining flange plates by fillet welds, consist of folds parallel and inclined to the longitudinal direction of the beam. For beam flange plates tested under tensile stress condition, it is obvious that less disturbance to the stress flow occurs with the inclined folds than that with transverse stiffeners, and it is therefore to be expected that the form of this structural detail will give a better fatigue performance than traditional H-beams with welding stiffeners. This expectation has been verified in early fatigue tests by former researchers (Harrison 1965; Korashy & Varga 1979) but it is noted that the fatigue failure induced by the local stress concentration related to web-to-flange welded joints in the steel corrugated web beams still occurs. Besides, the fatigue design basis for welded details of steel corrugated beams are still not sufficient to satisfy current application in the industry.

Present understanding of the fatigue strength of steel corrugated web beams is mostly attained by experimental testing of beam specimens (e.g. Ibrahim et al. 2006; Sause et al. 2006) and numerical

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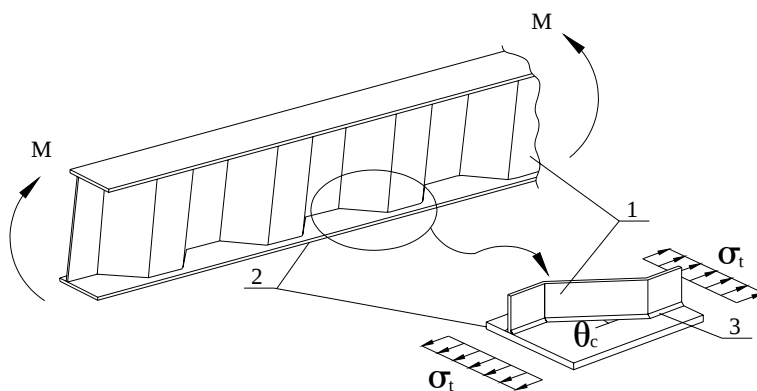
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methods. Despite that the test specimens in beam form are apparently simple, the experimental tests are limited by costs and testing machines. As a result, the data of existing beam tests and numerical modelling are still not sufficient for design. On the other hand, however, the use of welded joints or the attachment welded to the surface of the main plate (e.g. I, T, and H shape attachments) to separately account for the effect of details, such as web-to-flange welds, welded stiffeners and so forth, on the fatigue behaviour of the structure has been well documented in the literature and a considerable amount of research has been conducted. With this in mind, the fatigue behaviour of web-to-flange joints in the corrugated web beams may also be considered specifically by joining together corrugated plate, including parallel fold and inclined fold of an unit corrugation, with the main plate. If this idea is feasible, previously reported fatigue data based on the corrugated web beam tests could be well supplemented to some extent.

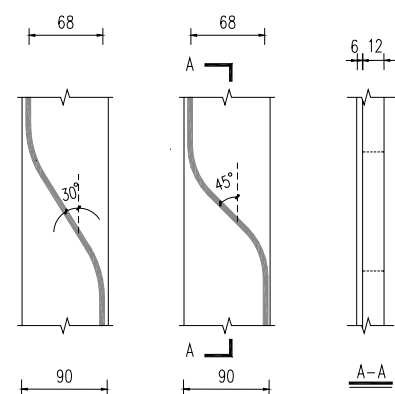
This paper gives a brief overview of a fatigue experimental study performed on the tensile plates with corrugated plates. The corrugation angle related to the inclined fold is varied to study its effect on the fatigue strength. The results of fatigue test in this study are then compared to those of related beam tests reported in the literature. Based on the effective notch stress approach, the fatigue failure of the web-to-flange welded joint are further evaluated and discussed by considering the fatigue crack initiation location and the stress distribution at the weld toe and the weld root.

## 2. EXPERIMENTAL PROCEDURE

In the case of a steel corrugated web beam in bending, the load induced fatigue of welded areas are represented by a web-to-flange welded joint in which a corrugated plate (1) is connected with a main plate (2) using fillet welds (3), as shown in Fig.1. Given the longitudinal flexibility of the corrugated web is far greater with respect to the flange plate, the overall bending moment is assumed to be carried primarily by the longitudinal flange plate. In this regard, the stress concentration is considered on the main plate subjected to repetitive primary stress excluding the cases regarding the defects of local welds or corrugation webs.



**Figure 1: Web-to-flange welded joint details in a steel corrugated web beam in bending**



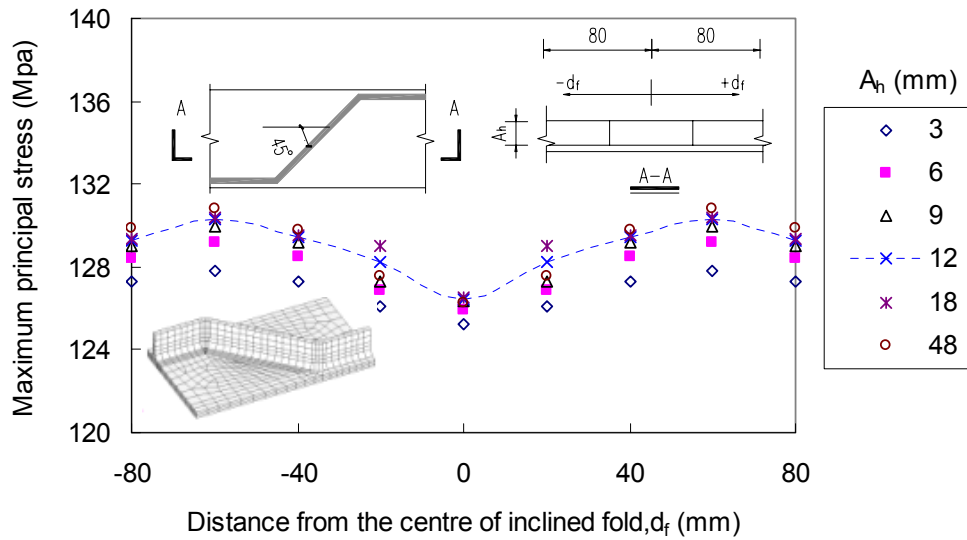
**Figure 2: Dimension of test specimens**

As shown in Fig.2, in all specimens, plates in corrugated shape are fillet welded to main plates in tension. The design weld leg length is 3 mm for all fillet welds. The corrugation angle ( $\theta_c$ ), which is defined as the angle of the inclined fold to the longitudinal direction of the beam, was considered as  $30^\circ$  and  $45^\circ$  for following comparison. The steel of the specimens conforms to Q345 steel of the Chinese national standard GB/T700, and related mechanical properties and chemical composition are described in Table 1. CO<sub>2</sub> shielded semiautomatic Gas Metal Arc Welding (GMAW) was performed for all fillet welds jointing flange plates and corrugated webs. The welding stop-starts are avoided during welding process. After fabrication, the specimens were finished by grinding in accordance with related specifications.

**Table 1: Chemical composition and mechanical properties of steel**

| Type | Chemical composition (%) |                |                |       |       | Mechanical properties |                       |                |
|------|--------------------------|----------------|----------------|-------|-------|-----------------------|-----------------------|----------------|
|      | C                        | S <sub>i</sub> | M <sub>n</sub> | P     | S     | Yield stress (MPa)    | Ultimate stress (Mpa) | Elongation (%) |
| Q345 | 0.16                     | 0.33           | 1.36           | 0.035 | 0.022 | 400                   | 555                   | 33             |

The welded joints were tested by a Shimadzu 4890 fatigue testing machine of 200 kN capacity and monitored by a Shimadzu Gluon test execution version 2.50c software. A special plate fixture device was adopted to grip the tensile plate with the corrugated attachment. Constant amplitude sinusoidal stress cycles with a frequency of 8Hz were conducted during the fatigue test. The levels of stress range between 120Mpa and 200Mpa were selected and the stress ratio was set at 0.1 for all test. The fatigue life was determined as the test specimen was tested to rupture. The actual measured cross-sectional dimensions were used for the calculation of nominal stress of testing specimens.



**Figure 3: Maximum principal stress along the longitudinal direction of the flange surface**

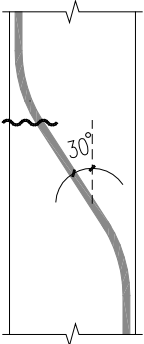
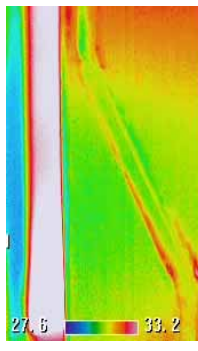
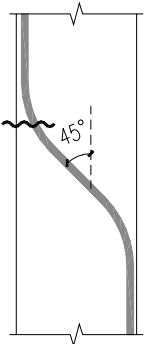
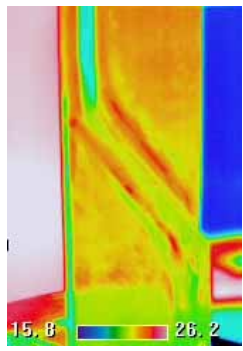
Since the local corrugated web and its connecting fillet welds are strained by the load in the stressed main plate, the effect of the height of the corrugated plate ( $A_h$ ) on the maximum principal stress along the longitudinal direction of the flange surface is compared via finite element analysis in

Fig.3. It is seen that the variation of stress becomes non-significant as  $A_h$  increases to 12mm which is equal to four times of the weld leg length. In this regard,  $A_h$  is chosen as 12mm for all specimens.

### 3. FATIGUE TEST RESULTS

Typical fatigue crack modes of tested specimens are schematically shown in Table 2. Apart from several specimens failed resulting from plate edge and weld defect, most tested specimens exhibit failure near the location where the parallel fold and the inclined fold of the corrugated plate intersects. This agrees with corresponding beam test results reported in literature (Ibrahim et al. 2006). Comparing the specimens with corrugation angles at 30 degree and 45 degree, it seems that the location of fatigue crack initiation point translates moderately from the end of the inclined fold with the increase of corrugation angle. This can be attributed to the change of local stress concentration manner with the corrugation angle.

**Table 2: Comparison of fatigue crack initiation of specimens with  $\theta_c=30^\circ$  and  $45^\circ$**

| Specimen with $\theta_c=30^\circ$                                                   |                                                                                     |                                                                                     | Specimen with $\theta_c=45^\circ$                                                   |                                                                                      |                                                                                       |
|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| Crack type                                                                          | Test photo                                                                          | Thermal image                                                                       | Crack type                                                                          | Test photo                                                                           | Thermal image                                                                         |
|  |  |  |  |  |  |

To further trace stress concentration corresponding to this manner, the infrared thermographic technique was also adopted under the consideration that the non-uniformity of the stress field in the vicinity of the corrugated plate, especially the inclined fold, gives rise to unequal plastic deformation at the points of stress concentration. From the theoretical point of view, the material fracture under fatigue loading relates to the accumulation of local plastic deformation and dissipation of heat energy. As shown in Table 2, the location of highest temperature for the specimen with  $\theta_c$  at 30 degree is closer to the end of the inclined fold of the corrugated web in contrast with that with  $\theta_c$  at 45 degree. Also, relative high temperature are widely distributed along the inclined fold of the corrugated web with  $\theta_c$  at 45 degree. This result corresponds well to the fatigue crack modes of tested specimens with different  $\theta_c$ .

The fatigue test results of welded joints in  $\text{Log}(N)$  versus  $\text{Log}(\Delta S)$  relationship are summarised in Fig.4, in which  $N$  and  $\Delta S$  denote fatigue life and stress range in Mpa respectively. The method of

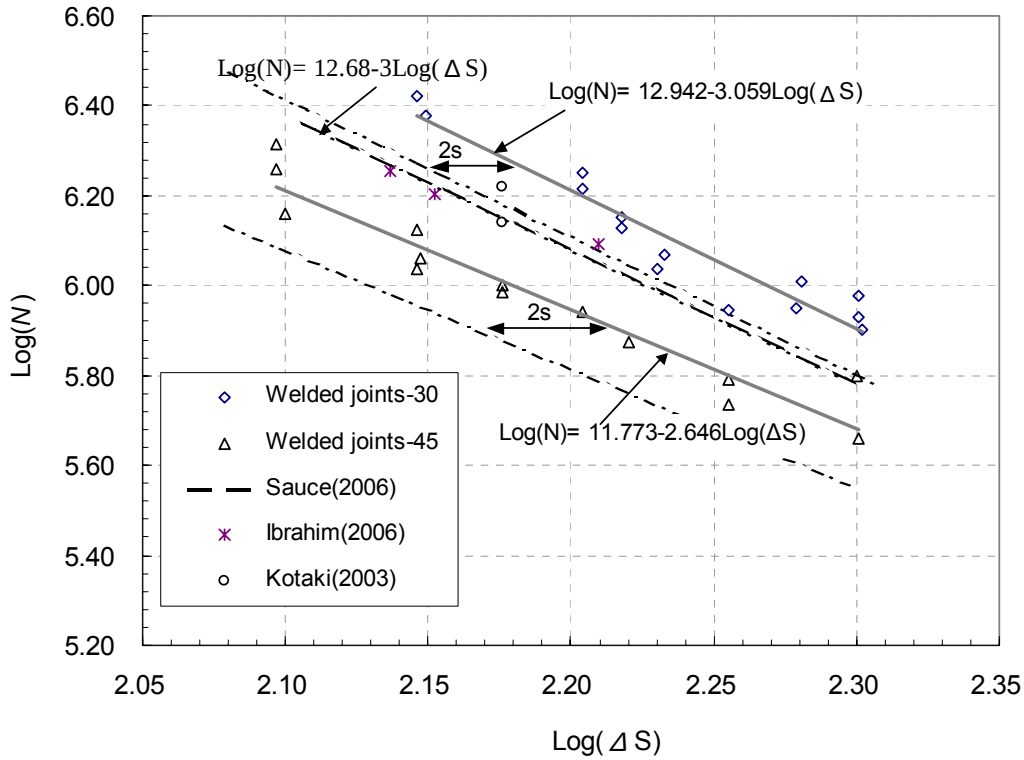
least squares was used in the test result post-processing to produce the best fit mean  $\text{Log}(N)$  versus  $\text{Log}(\Delta S)$  curve. The mean regression line for the welded joints with  $\theta_c$  at 30 degree can be given by:

$$\text{Log}(N) = 12.942 - 3.059\text{Log}(\Delta S) \quad (1)$$

and, those with  $\theta_c$  at 45 degree can be expressed as:

$$\text{Log}(N) = 11.773 - 2.646\text{Log}(\Delta S) \quad (2)$$

The standard deviations (SD) were also calculated to account for the scatter in fatigue lives obtained in the experimental data. A  $\text{Log}(N)$ - $\text{Log}(\Delta S)$  curve corresponding to two standard deviations below the mean (M-2SD) was plotted for each group of specimens to represent 95% confidence limit. This transformation can also be regarded as a lower bound curve for the purpose of fatigue design.



**Figure 4: Comparison of  $\log(N)$ - $\text{Log}(\Delta S)$  relation of test results and literature data**

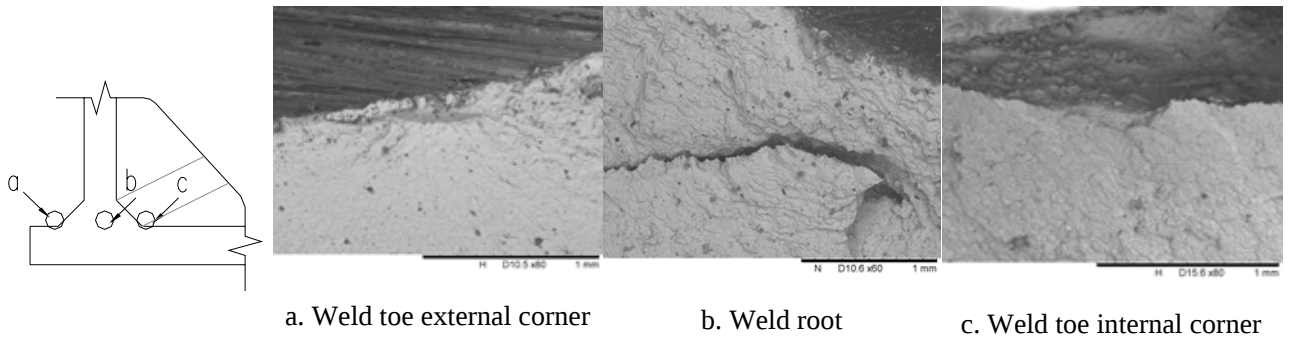
The results of related beam tests reported by Kotaki et al. (2004) and Ibrahim et al. (2006) are also added and plotted in Fig.4 with the same scale and data range for further comparison. The stress range of referred specimens with the corrugation angle of 30 degree is closer to the mean regression line expression of eq.(1). In contrast, the stress range of test specimens with  $\theta_c$  at 36.8 degree (a slope of 3:4) reported by Ibrahim et al. (2006) lies between mean regression line expressions of eq.(1) and eq.(2) corresponding to the  $\theta_c$  of 30 degree and 45 degree respectively. As such, the test results of corrugated web beams with the  $\theta_c$  (36.9 degree) conducted by Sause et al. (2006) were added for comparison. In this referred study, a best fit equation for their test data from the remaining life analysis was suggested as:

$$\text{Log}(N) = 12.68 - 3\text{Log}(\Delta S) \quad (3)$$

As can be seen from Fig.4, the referred eq.(3) almost represents the mean value between eq.(1) and eq.(2), which corresponds to the calculated stress ranges of 133.76Mpa, 148.19Mpa and 116.95Mpa respectively at 2 million cycles. This demonstrates that the equations from the regression analysis of the test tensile plates with corrugated attachments is applicable to the case of beam tests provided that the stress concentration is controlled by the corrugation angle. Notwithstanding this, it is noted that different fatigue crack propagation modes and structural details, e.g. crack initiating from a notch in the flame cut edge of the flange plate, the presence of scallops, would result in lower fatigue strengths than those predicted from linear regression analytical expressions in this study.

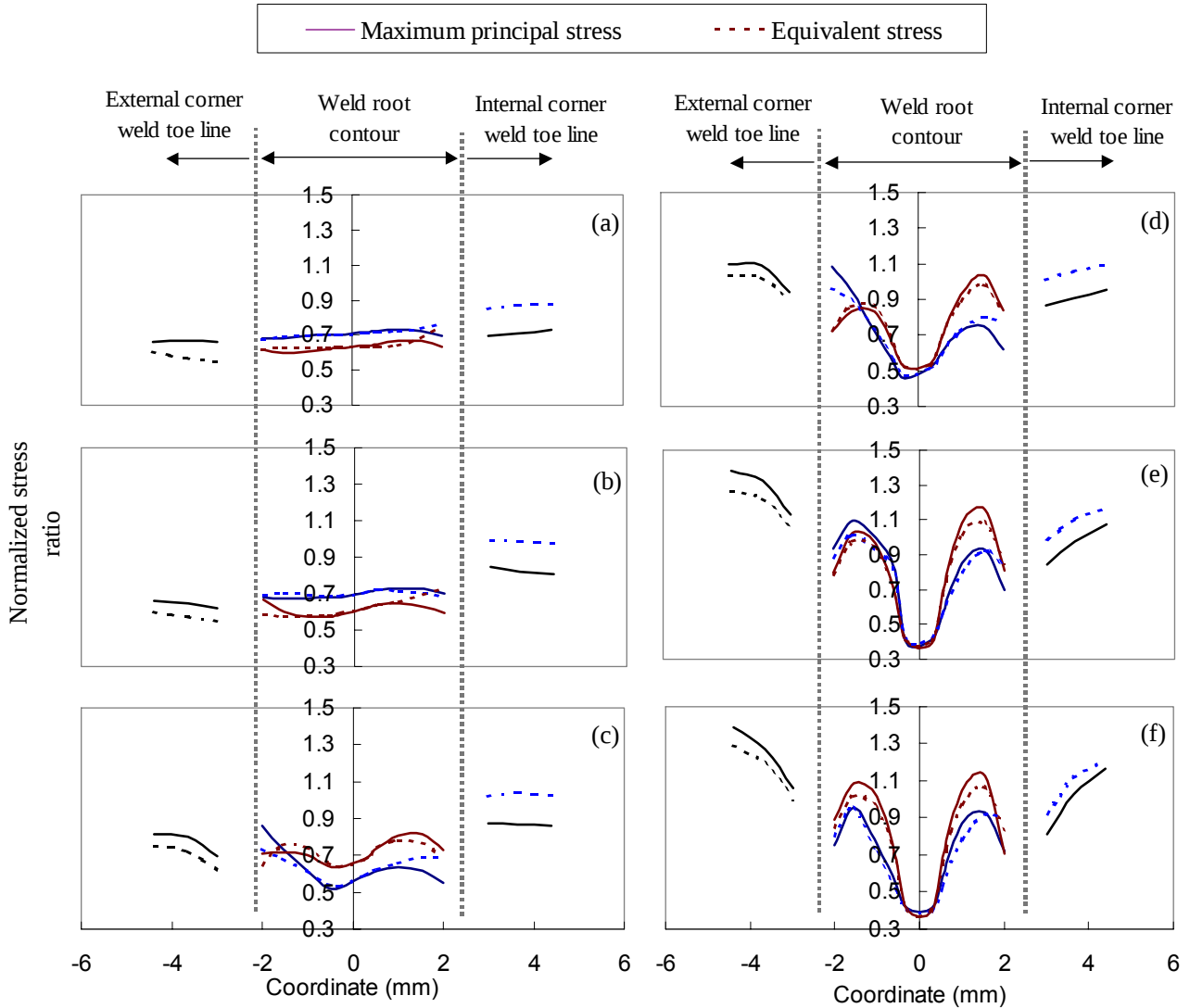
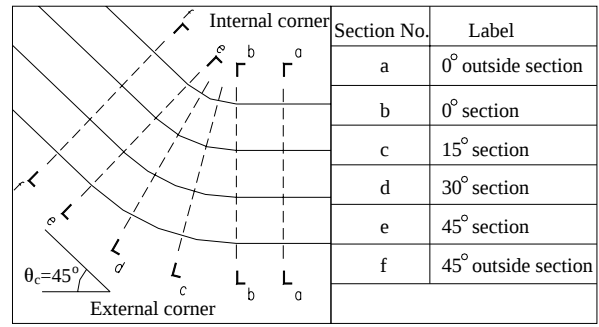
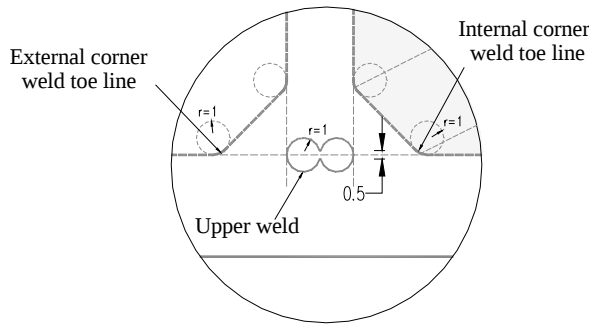
#### 4. EFFECTIVE NOTCH STRESS ANALYSIS

An illustration of typical fracture surfaces of welded joints under stress range of 160Mpa is shown in Fig.5. The fatigue cracks were identified initiating from the weld root or the weld toe corresponding to the internal and external corners of the corrugated web, perpendicular to the longitudinal stress direction. The welded joint failed as the cracks propagated through the thickness of the tensile plate.



**Figure 5: Typical micrograph of cracks at weld toe and weld root of the specimen**

To further evaluate the web-to-flange welded joint in the critical region, the effective notch stress approach was performed for the specimen with  $\theta_c$  at 45 degree in this analysis. The notch stress was obtained via an analysis of finite element models with fictitious rounds with effective notch radius of 1mm at the weld toe and the weld root. This radius value has been verified to give consistent results for structural steels (Hobbacher 2003). Given that the stressed web-to-flange fillet welds closed to the intersection region of the longitudinal fold and the inclined fold of the corrugated web are potentially subject to fatigue failure, the effective notch sections were chosen at the angles of 0 degree, 15 degree, 30 degree, 45 degree to the cross-section perpendicular to the longitudinal fold of the corrugated web as a reference section, as shown in Fig.6. The local parts around the weld toe and the weld root were modelled using solid element and corresponding mesh was refined to allow a more accurate appraisal of the notch stress. The principal stress and equivalent stress are normalized by the nominal stress along weld toe and the weld root lines.



**Figure 6: Normalized stress ratio distribution on the notch surface**

As shown in Fig.6, regarding the notch section of the internal corner weld toe line, the magnitude of normalized principal stress is smaller than that of the normalized equivalent stress, and the reverse tends to be the case for the external corner weld toe line. In contrast, the normalized principal stress and equivalent stress are almost equivalent in the range of weld root notch. When comparing the magnitude of the notch stress of the weld toe and the weld root, the highest stress takes place at the weld toe corresponding to the internal corner of the corrugated web if the angle of the notch section

is  $0^{\circ}\sim 30^{\circ}$  with respect to the reference section. The location of this highest stress corresponds well to the crack initiation point in the test specimen (Fig.5a). On the other hand, if the notch section is located with the angle at  $30^{\circ}\sim 45^{\circ}$ , relative to the reference section, the weld toe corresponding to the external corner of the corrugated web exhibits the highest stress. The notch stress variation in the weld root range tends to be greater than that in the weld toe range, and this trend is increased with the increase of the aforementioned reference section angle. Additionally, when the reference angle is  $30^{\circ}$ , the highest notch stresses of the weld root and weld toe corresponding to the internal and external corners of the corrugated web are quite close to each other. In this case, it is expected that both the weld toe and the weld root are prone to suffer fatigue crack initiation which can be referred to the test observation in Fig.5b&c. Hence, those results indicate that it is possible to expect the fatigue crack failure arising at the weld root or weld toe corresponding to the external and internal corners of the corrugated webs with the aid of the effective notch stress approach.

## 5. CONCLUSIONS

In this study, the fatigue strength of tensile plates with corrugated plates has been investigated as a supplementary understanding of that related to corrugated web beams under fatigue loading. Based on the fatigue experiments and related finite element analysis results, the following conclusions can be drawn:

- The location of fatigue crack initiation point translates moderately from the end of the inclined fold with the increase of corrugation angle. This indicates that the fatigue cracks for the test specimens with the corrugation angle at 45 degree or larger are related to the stress concentration locating at the intersection of the longitudinal fold and the inclined fold of the corrugated web.
- The basic failure modes and S-N relationships from regression analysis of test specimens are comparable to those of beam tests which justifies the welded joints with corrugated plates in representing related structural details of corrugated web beams in the study of fatigue strength.
- The effective notch stress analysis has a good use in evaluating the fatigue crack at the weld root or the weld toe in the vicinity of the fold intersection region of the corrugated web.

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