EXTENDING THE FRONTIERS OF FAILURE ASSESSMENT PROTOCOL FOR WELDED TUBULAR JOINTS

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This study proposes a tearing modified failure assessment diagram to predict the load levels corresponding to different crack extensions in fracture test under monotonic and cyclic loadings. This approach integrates the experimentally measured *J-R* curve to take the crack growth into consideration when conducting the ductile tearing assessment. The proposed assessment has a good estimation on the load versus crack extension, P-Δa, relationship for single-edge-notched tension, SE(T), specimens made of aluminum alloy 6061-T6511 subjected to monotonic and cyclic loadings. Subsequently, this study extends the proposed method to the welded tubular joints made of Q345 steel under in-plane bending through modified failure assessment diagrams derived from fracture specimens. The predictions on the P-Δa relationship, based on the material fracture resistances, agree well with the ultimate load resistance evaluated by standard BS ISO 14346. This proposed procedure provides a basic approach to estimate the P-Δa relationship for large-scale structural components under reversed loadings, and to upscale the material fracture resistance into ductile tearing characteristics for the integrity assessment on large-scale engineering asset.

Keywords: tubular joint; ductile tearing assessment diagram; cyclic fracture resistance; reversed loading.

1 Introduction

Extreme environmental actions, such as seismic loadings and extreme waves, cause decreases in both load resistance and fracture resistance compared to those under monotonic loadings. Previous efforts have revealed this deterioration by measuring the fracture resistance curve, namely *J-R* curve, for fracture specimens under cyclic loadings (Seok *et al*. 1991, Singh *et al.* 2003). To prevent the unstable fracture failure under such extreme actions, an engineering approach to evaluate the ductile tearing of the cracked structure is necessary. Failure assessment diagram (FAD) outlined in standard BS 7910 (2013) provides a practical approach for the integrity assessment on large-scale engineering structures subjected to monotonic loadings. The FAD allows the ductile tearing assessment for stable tearing using the failure assessment curve derived from the numerical model on the flawed structure with a stationary crack. Qian *et al*. (2013) have applied the FAD into the ductile tearing assessment on a high-strength steel X-joint subjected to in-plane bending, and predicted successfully the load (P) causing the unstable fracture failure. However, the assessment for the structures subjected to reversed loadings has yet to be developed.

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This study proposes a tearing modified FAD to evaluate the ductile tearing process during the fracture tests under monotonic and cyclic loadings. The construction of the modified FAD integrates the *J-R* curve to take the crack extension into the assessment. This research validates the modified FAD in evaluating the P-Δa relationship for fracture specimens made of different materials under monotonic and cyclic loadings, and upscales the material fracture resistance to the fracture responses of circular hollow section (CHS) X-joints subjected to in-plane bending to predict the P-Δa relationship. The modified FAD provides a basic approach for ductile tearing assessment on engineering structures subjected to reversed loadings.

2 Ductile Tearing Assessment Procedure

Standard BS 7910 (2013) suggests an option 3 procedure to build the FAD, consisting of the load ratio L_r and the fracture ratio K_r, specific to a particular material and geometry using both elastic and elastic-plastic numerical analysis of the cracked structure. The modified FAD based ductile tearing assessment follows a similar principle of this option 3 but takes the crack extension into consideration by integrating the fracture resistance curve. The ductile tearing assessment follows the three-step evaluation:

(i) Construct the modified FAD with the load-deformation (P-δ) curve of the fracture test;
(ii) Build the assessment curves corresponding to various crack extensions.
(iii) The intersection point between the modified FAD and assessment curve indicates the load level corresponding to the crack extension of the assessment curve.

The modified FAD construction requires: (1) *J-R* curve; (2) linear-elastic solution on K_I or J_e; and (3) expression for ultimate load resistance P_u. The procedure for the modified FAD construction follows the steps below from the first pair of data in the experimental P-δ curve:

(i) Measure the crack size a corresponding to the current P-δ data, and determine the crack extension Δa;
(ii) Calculate the K_I according to the current P and a, and transfer the K_I into the linear-elastic crack driving force J_e by Eq. (1),

$$J_e = K_\mathrm{I}^{\,2}(1-\nu^2)/E \tag{1}$$

(iii) Obtain the fracture resistance J_R from the *J-R* curve based on the current Δa;
(iv) Determine the K_r by the J_e and J_R through the following equation,

$$K_r = \sqrt{J_e / J_R} \tag{2}$$

(v) Evaluate the ultimate load P_u based on the current crack size, and determine the load ratio L_r by the equation below,

$$L_r = P / P_u \tag{3}$$

(vi) Repeat from step (ii) to step (vi) until the experimental data violating the validation of the *J-R* curve, and draw the modified FAD by connecting all the data pairs of (L_r, K_r).

Based on the modified FAD derived by the above procedure, the ductile tearing assessment, presented in Fig. 1, builds assessment curves to evaluate the load levels corresponding to various crack extensions. The development of the assessment curve of Δa_i follows the steps below based on a measured *J-R* curve:

(i) Define a series of loads $\{P_i\}$ and calculate corresponding $\{L_{ri}\}$;
(ii) Calculate the linear-elastic crack driving force $\{J_{ei}\}$ corresponding to $\{P_i\}$ and Δa_i;
(iii) Calculate the $\{K_{ri}\}$ by Eq. (2) using $\{J_{ei}\}$ and the fracture resistance J_{Ri} at Δa_i;

(iv) Plot the assessment curve l_{ACi} by connecting data pairs of (K_{ri}, L_{ri}) as shown in Fig. 1b; The intersection point p_{ACi} between the modified FAD and assessment curve l_{ACi} indicates the load level at the current crack extension Δa_i. The ductile tearing assessment finally plots P-Δa relationship during the fracture test based on different postulated crack extensions.

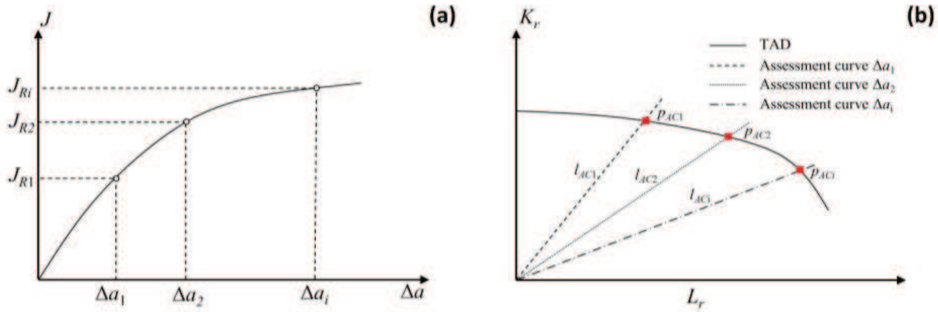

Figure 1. (a) Experimentally measured *J-R* curve; and (b) Ductile tearing assessment.

3 Validation on SE(T) Specimens under Monotonic and Reversed Loadings

This section validates the modified FAD in the ductile tearing assessment for clamped SE(T) specimens made of aluminum-alloy 6061-T6511 under monotonic and cyclic loadings reported by Liu *et al.* (2019). The material has a Young's modulus of 68GPa, yield strength of 280 MPa and ultimate strength of 340 MPa. Figure 2a presents the configuration of the specimen. This fracture test imposes displacement-controlled monotonic and reversed loadings to the clamped SE(T) specimens. This study validates the modified FAD in ductile tearing assessment through specimens with initial crack sizes of 14.4 mm and 14.2 mm subjected to monotonic and cyclic loadings respectively.

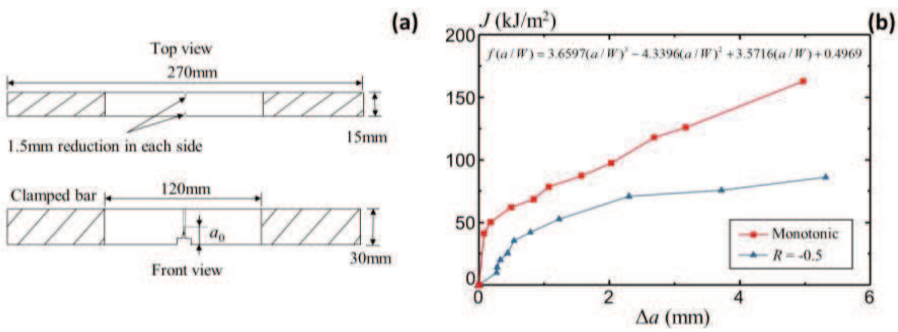

Figure 2. (a) Configuration of SE(T) specimen; and (b) *J-R* curves under different loadings.

To build the modified FAD for the clamped SE(T) specimen, there are requirements on the solution for the K_I, experimentally measured *J-R* curves and the expression for the ultimate load resistance. Liu *et al*. (2019) adopt the following expression for K_I,

$$K_I = f(a/W)\sqrt{\pi a}\cdot\sigma = f(a/W)\sqrt{\pi a}\cdot[P/(W\sqrt{BB_N})] \tag{4}$$

where $f(a/W)$ is a dimensionless parameter depending on the crack size of the specimen shown in Fig. 2b, and σ refers to the remote tensile stress for the side-grooved SE(T) specimen based on the effective thickness, B refers to the total thickness, and B_N denotes the net thickness excluding the side grooves, W indicates the width of the specimen. This study predicts the ultimate load resistance P_u through the following equation,

$$P_u = (W - a)B\sigma_u \tag{5}$$

where σ_u indicates the ultimate strength of the material.

The modified FAD for the SE(T) specimen under the monotonic loading can be constructed as shown in Fig. 3a. Figure 3b compares the experimental and evaluated P-Δa curves. The maximum difference in the load level is about 6.35% corresponding to the crack extension of 0.5 mm, while the difference decreases to about 3% as the crack grows further. The good agreement validates the modified FAD in the ductile tearing assessment for the monotonic loading case.

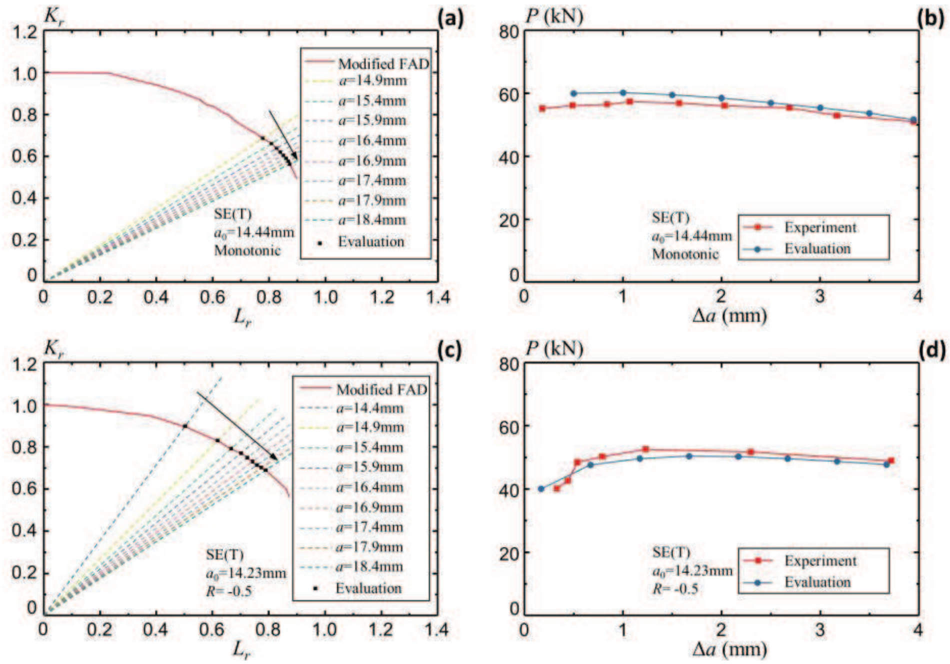

Figure 3. (a) Ductile tearing assessment for SE(T) specimen under monotonic loading; (b) Comparison on experimental and evaluated P-Δa curves under monotonic loading; (c) Ductile tearing assessment for SE(T) specimen with R=-0.5; and (d) Comparison on experimental and evaluated P-Δa curves with R=-0.5.

The modified FAD construction for the clamped SE(T) specimens subjected to cyclic loadings utilizes the cyclic J-R curve based on the envelope assumption which treats the envelope of the cyclic P-δ curve as a monotonic record. Liu *et al*. (2019) have validated the envelope assumption in the cyclic J-R curve calculation for the reported SE(T) specimen. Figure 3c plots the modified FAD for the SE(T) specimens with R of −0.5. Figure 3d compares the experimental and evaluated P-Δa curves. The modified FAD provides a reasonable estimation on the P-Δa relationships where the difference between the experimental and evaluated curves remains within 5%.

4 Ductile Tearing Assessment on CHS X-joints

This section presents the ductile tearing assessment on CHS X-joints made of Q345 subjected to in-plane bending. Figure 4a shows the configuration of the X-joint and details in the prefabricated crack. The joint entails a machined notch of 8 mm. Before the fracture test, a fatigue pre-cracking procedure advances the crack size to 11 mm. Figure 4a indicates the loading and constraints. This study utilizes the modified FAD constructed by fracture specimens made of S355 steel which has similar material property as Q345 steel to evaluate the P-Δa relationship for the joint. Parool *et al.* (2017) have conducted monotonic fracture test on the single-edge-notched bending, SE(B), and SE(T) specimens made of S355 steel which has a Young's Modulus of 210 GPa, yield strength of 365 MPa and ultimate strength of 635 MPa. Both specimens have the same configuration as shown in Figure 4b. The initial crack sizes of the SE(B) and SE(T) specimen are 13.07 mm and 13.13 mm respectively.

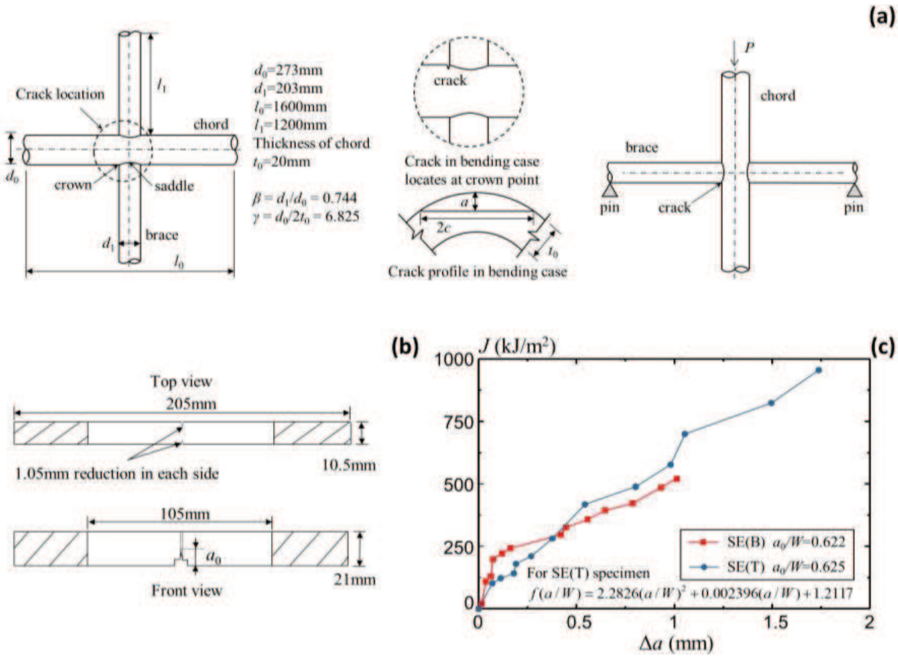

Figure 4. (a) Information on the CHS X-joint under in-plane bending; (b) Configuration of fracture specimen; and (c) *J-R* curves of fracture specimens.

This study builds the modified FAD based on SE(B) and SE(T) specimens with *J-R* curves shown in Fig 4c. The K_I solution for the SE(T) specimen has the same form reported by Liu *et al*. (2019) but adopts a different equation for $f(a/W)$ shown in Fig 4c. The ultimate load resistance prediction on SE(T) specimen uses the Eq. (5). This study calculates the K_I for SE(B) specimens through the expression provided in ASTM E1820 (2018). The prediction on the ultimate load resistance for the SE(B) specimen follows Eq. (6) recommended by standard ASTM E1820 (2018),

$$P_u = (W-a)^2 B\sigma_u / S \tag{6}$$

where S indicates the span of the SE(B) specimen.

The assessment curve for the joint couples the fracture resistance curves of fracture specimens presented in Fig. 4c and linear-elastic crack driving force of joints as follows,

$$J_e = \frac{f(\frac{a}{W})\left(P/A_c\right)^2 a}{E} \tag{7}$$

where A_c indicates the cross-sectional area of chord. The dimensionless function $f(a/W)$ follows the equation below,

$$f(a/W) = -1895.16(a/W)^3 + 4075.2(a/W)^2 - 4289.69(a/W) + 2636.81 \tag{8}$$

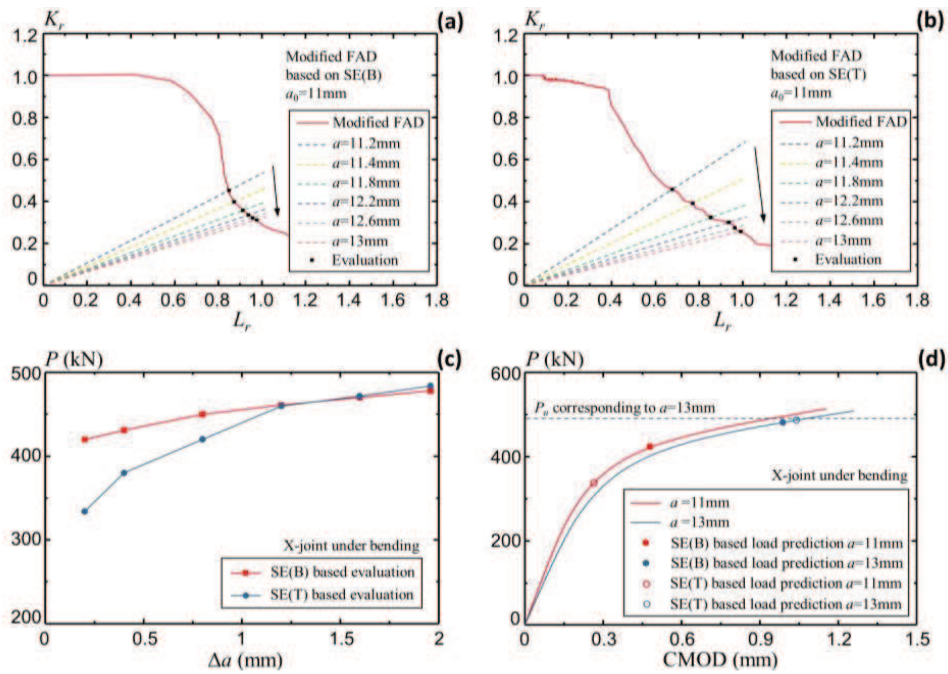

Figure 5. Ductile tearing assessment through (a) SE(B) and (b) SE(T) specimen; (c) Evaluated P-Δa relationships derived from the modified FAD based on fracture specimens; and (d) Load comparison.

The ductile tearing assessment requires the ultimate resistance evaluation to build the assessment curve for joint. This work follows the expressions recommended by standard BS ISO 14346 (2013) for the intact CHS X-joint with orthogonal brace and chord subjected to in-plane bending,

$$M_u = 4.3\beta\gamma^{0.5}\sigma_y t_0^{\,2} \tag{9}$$

Qian *et al*. (2008) demonstrate a consistent ultimate strength for the thick-wall joint through the finite element analysis. This study transfers the ultimate moment resistance into the load resistance through the elastic solution shown as follows,

$$P_u = 2M_u / l_1 \tag{10}$$

where t_0 denotes the thickness of chord, l_1 is the length of brace, β and γ refer to dimensionless geometry parameters of joint as shown in Fig. 4a, and σ_y is the yield strength equal to 465 MPa. The ultimate load resistance for the cracked joint multiplies the load resistance of the intact joint by a reduction factor A_{RF} in the following form (Cheaitani and Burdekin, 1994),

$$A_{RF} = 1 - A_{crack} / (L_w t_0) \tag{11}$$

where A_{crack} is the area of crack surface which is assumed as half ellipse, L_w equals to the weld length along the intersection between the chord and brace derived by Qian (2013).

Figure 5a and b present the assessment with SE(B) and SE(T) based modified FAD for the joint. Figure 5c compares the P-Δa relationships evaluated from both specimens. The modified FAD derived from two fracture specimens provide similar load resistances when the crack extension goes over 1 mm. Figure 5d plots the numerical load-deformation curves of joints with a stationary crack of different crack sizes, which includes the modified FAD based evaluation on the load resistance and presents similar values with the ultimate load resistance predicted by standard BS ISO 14346 (2013).

5 Conclusions and Future Work

This study proposes a modified FAD based ductile tearing assessment to evaluate the P-Δa relationship in the stable ductile tearing process. The work supports following conclusions:

(i) The modified FAD is capable in evaluating the P-Δa relationship of the fracture specimens subjected to monotonic and cyclic loadings;

(ii) The ductile tearing assessment based on the modified FAD, derived from the material fracture resistance, provides a reasonable prediction on the P-Δa relationship for X-joints under in-plane bending.

The proposed approach provides a basic way to assess the ductile tearing for cracked structures under reversed loadings. The research team is working on the experiment on X-joint presented in this report. The experiment imposes monotonic and reversed axial loading and in-plane bending on the X-joint to investigate the effect of reversed loadings on the fracture resistance of structural component and verify the modified FAD based ductile tearing assessment.

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