〔特別講演〕

CTOA of an Extending Crack in a Ductile Material

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A CTOA resistance curve for mild steel was used to predict rapid crack propagation in a rupturing, subscale and full scale pressurized pipes. A CTOA resistance curve, which has a steady state value of 6° , for 0.8-mm thick 2024-T3 aluminum was also used to propagate cracks in elastic-plastic finite element (FE) models of the fracture specimens and specimens with simulated multiple site damage (MSD). The CTOA of curved crack growth in this thin 2024-T3 scattered between 4° to 8° but the resultant CTOD, which is the vector sum of the mode-I COD and the mode-II crack sliding displacement (CSD), remained a constant 0.16 mm. The CTOA of a rapidly propagating crack in 1.6-mm thick, 7075-T6 SEN specimens increased from 4.5° at a low crack velocity to a constant 7° at a higher and the terminal crack velocity.

Keywords: Stable crack growth; Dynamic crack growth; CTOA; COD; Moiré interferometry, Finite element analysis.

1. Introduction

Despite its popular acceptance, the plasticity modified linear elastic fracture mechanics (LEFM) is not an effective criterion in the presence of large scale yielding. A ductile fracture criterion, which relates to the plastic strain field in the crack tip plastic zone, is the crack tip bluntness and was quantified by the crack opening displacement (COD) criterion advanced by Wells [1]. This COD criterion, which was initially related to Irwin's plastic zone estimate [2], r_p , and later to the Dugdale plastic zone [3], was promoted mainly by The Welding Institute in the 60's and 70's [4] for fracture assessment of thick-walled pressure vessels. Since the COD along a surface crack front in a thick plate cannot be readily measured and must be computed, its acceptance was hindered by the lack of an easily accessible three-dimensional elastic-plastic finite element code with the sensitivity to accurately map the crack tip bluntness. Another crack tip parameter is the crack tip opening angle (CTOA) which uniquely characterize the crack tip strain field [5] which in theory can be readily measured on the surface and computed in the interior of a three-dimensional crack. Shih et al [5] as well as Kaninnen et al [6] in the 70's concluded that the CTOA was a computationally attractive parameter and an alternative to the J-integral criterion which subsequently

dominated the ductile fracture research of the 80's and 90's.

2. Pipe Fracture

The CTOA criterion was used in the 80's by the author and his colleagues to analyze axial crack propagation in a subscale gas transmission line [7]. The rupturing profile of a propagating crack in a pressurized 2-in-diameter, Schedule 10, carbon steel pipe was recorded with a high-speed framing camera and was processed through a special software [8] which yielded the CTOA and the flap motion. The CTOA was also computed using a split-ring model of the pipe, one dimensional thermal hydraulic depressurization code and the measured crack propagation history. The excellent agreement between the measured and the computed CTOA versus crack velocity relations, as shown in Fig. 1, demonstrated that the CTOA was an effective static and dynamic fracture parameter for pipe rupture. The CTOA criterion was also used in a ring model of the rupturing pipe and a thermal hydraulic depressurization code to simulate the large-scale burst tests of 48-inch diameter x 0.720-inch thick, X70 line pipes [9]. Figure 2 shows an excellent agreement between the measured crack velocity history and that predicted by the ring model [10].

Fig. 1 CTOA versus crack velocity.

Fig. 2 Crack velocity of a rupturing pipe.

2. Stable Crack Growth

A renewed research efforts [11-13] in the CTOA criterion was undertaken in the early 90's in response to the NASA Aircraft Integrity Program. The elastic-plastic, plane stress state of a thin aluminum aircraft skin considered in this Program was ideally suited for the CTOA criterion. In the following, the author's and his colleagues' assessment [14, 15, 16] of the utility of CTOA for correlating stable crack growth in thin aluminum fracture specimens are presented.

2.1 Experimental Procedure

2.1.1 SEN and CN specimens

The experimental procedure consisted of measuring the two orthogonal displacement fields with moiré interferometry using a coarse cross diffraction grating of

40 or 60 lines/mm. Single edge notch (SEN) and center notched (CN) tension fracture specimens as well as CN fracture specimens with multiple site damage (MSD) were machined from 2024-T3 clad aluminum sheet of thickness 0.8 mm. Starter cracks were fatigued at $\sigma_{\max} = 0.3 \sigma_y$ and a stress ratio $R = 0.1$ or saw cut and sharpened with a razor blade. All cracks were oriented in the L-T direction.

2.1.2 Biaxial specimens

2024-T3 aluminum, cruciform shaped SEN fracture specimen was used for mode II crack propagation. This cruciform specimen simulated the unequal axial load imposed by the one-sided flapping of the fuselage skin of a propagating crack along a lap splice joint. Crack arrester in a pressurized fuselage was simulated with a tear strap, which was either epoxy bonded, bonded and riveted at spacing 12.5 mm apart or integrally machined (machined pad-up) onto the specimen, at the far edge.

2.1.3 MSD specimens

Among the multiple of tests conducted, only the results of the MSD5 specimens with a center/lead crack and four holes with MSD cracks will be reported in this paper. Figure 3 shows the MSD3 and MSD5 specimens configurations.

Fig. 3 MSD3 and MSD5 specimens.

Special buckling guides were used to prevent the MSD and biaxial fracture specimens from buckling while allowing access for moiré interferometry analysis of the translating crack tip region

2.1.4 Moiré interferometry

The test section of the specimen was covered with a crossed moiré diffraction grating of 40 lines/mm over a

region of 50 x 100 mm. This coarse moiré grating was necessary due to the large scale plastic yielding, which resulted in moiré fringe patterns too dense to resolve by the traditional high density grating. The fringe patterns corresponded to two orthogonal u- and v-displacement fields and which, unlike the traditional moiré interferometry, could be viewed from any angular orientation. The CTOA was determined from the crack opening displacement (COD), which was obtained from the moiré data, at a distance 1 mm from the crack tip.

2.2 Numerical Procedure

Finite element (FE) models of the SEN, CN, biaxial and MSD specimens were used in the generation and propagation modes to verify the appropriateness of CTOA as a ductile fracture criterion. Graded finite elements with the smallest element of 0.25 mm were distributed through the FE model. The finite element analysis was based on the incremental theory of plasticity using the measured equivalent stress-strain relation of the 2024-T3 aluminum plate. For the generation analysis, the moiré displacement data recorded during crack growth was used as the input boundary condition together with the measured instantaneous crack length to compute the CTOA. For propagation analysis, the experimentally established CTOA resistance curve was used to propagate cracks in a finite element model of a MSD5 specimen. The FE model consisted of one half or one quarter of a truncated specimen depending on the number of plane of symmetry where the measured displacements obtained by moiré interferometry was prescribed on the truncated boundaries.

3. Results

3.1 CTOA resistance curve

During the initial stage ($\Delta a = 1-2$ mm) of crack tunneling and shear lip formation, the measured CTOA was scattered in the range of 10 to 15 degrees as shown in Fig. 4. All CTOA's had the same profile of being very large at the initial crack growth. Although a constant 5 to 6 degrees is typically used throughout the crack growth process [11-13], such constant CTOA, as marked in Fig. 4, of 5 or 6 degrees would under predict the load in the initial stage of crack growth.

In 2-D finite element analysis, the crack tunneling process and the transformation process from a horizontal crack to the shear lip condition is not modeled. Nevertheless, the experimentally determined CTOA correlated reasonably well with the FE computed CTOA (Fig. 4). For specimen CN 10, the predicted load vs. crack extension is shown on Fig. 5. With the assumption of a constant critical CTOA of 6 degree, the predicted reaction load was approximately 20% lower than the test value at the initial stage of crack growth ($\Delta a < 3$ mm). The correlation between the predicted and the measured reaction loads improved as the crack extend. The

predicted maximum load was 5 percent lower than the test value. The applied displacement versus crack growth plot is shown in Fig. 5. When the crack was propagated per the measured CTOA (i.e. with large CTOA at the first

Fig. 4 Measured CTOA.

(a) Reaction load vs. crack growth.

(b) Applied displacement vs. crack growth.

Fig. 5 FE crack growth simulation in CN 10

stage of crack growth), the predicted reaction load correlated with the test value improved. The maximum load remained to be 5 percent lower than the test value.

3.2.2 Biaxial fracture specimens

Figure 6 shows the experimentally determined crack tip opening displacement (CTOD), which is the vector sum of the mode I and mode II crack tip displacements at at distance 1mm from the crack tip, and the crack tip sliding displacement (CTSD). The CTSD is the mode II crack tip displacement. The CTOD reached a constant

Fig. 6 CTOD and CTSD of a curving crack.

value of about 0.18 mm during crack extension and the CTSD was about 0.4 mm despite the varying instantaneous crack curvature or the crack kinking angle. These results suggest that crack curving is relatively insensitive to the magnitude of CTSD and are in qualitative agreement with the extensive test results of [20]. Unlike the pure mode I crack extension data [11-14], the CTOA, as shown in Fig. 7 did not jump from a maximum value of about 15° but oscillated about its steady state value of about 5.5°. This is the same steady state CTOA reached in the SEN, CN and compact (CT) specimens of [14] and are close to that represented in [11-13] for 2024-T3 CN and CT specimens of 2.3 mm thick.

Fig. 7 CTOA of a curving crack

3.2.3 MSD specimens

Crack growth simulation based on the CTOA criterion was performed for specimens CN10 of width 254 mm and MSD5_08. To simulate crack growth, displacement was applied at the top of the specimen and cracks were propagated when the CTOA reached the critical value of 6 degrees. With the displacement held constant, the CTOA was examined again for crack extension. If the CTOA remained greater than 6 degrees, the crack was extended again, and the CTOA was evaluated again. The crack continued to extend until the CTOA dropped below 6 degrees. Additional displacement was applied until the CTOA was greater than 6 degrees where upon another node was released to extend the crack. This procedure was repeated until no additional displacement was required to propagate the crack. At that point, instability was assumed to have occurred.

For the MSD5_08 specimen, where the MSD crack was 2.5 mm and the ligament between the center crack and the first MSD crack was 12.7 mm, the cracks were propagated based on a constant CTOA value of 6 degree. The predicted versus measured reaction load is shown in Fig. 8. Similar to the CN10 case, the predicted reaction load at the initial stage of crack growth was lower than the test value. The predicted maximum load was 10% lower than the test value. The CTOA criterion, however, did not predict instability. Additional displacement was needed to propagate the crack even though the center crack had extend 7mm and the MSD crack extended 4 mm with only 1 mm of ligament left between the cracks. The analysis was stopped at that point and the cracks were assumed to have linked.

Fig. 8 Experimental and FE CTOA of MD5 specimens

3.2.4 Summary

The CTOA criterion is a local fracture parameter and the angle is constant during steady state crack growth. However, during the initial stage of crack growth where crack tunneling and shear lip formation exist, the measured CTOA is larger than steady state CTOA and is scattered. The residual strength predictions using the CTOA criterion were within 5% to 10% of test results. However, for problems where fracture occurs after a few mm of crack extension, the CTOA criterion may not be very reliable.

The above crack growth simulation demonstrated that the CTOA could predict crack growth of ductile material and that it may be used to predict the residual strength of structures containing MSD. However, the prediction at the initial stage of crack growth was approximately 20% lower than the test value when a constant critical CTOA value was assumed. For problems where the structure will fail immediately after crack growth initiation, assuming a constant CTOA value may lead to under predicting of the residual strength.

4. Dynamic fracture

4.1 Experimental procedure

In this study, dynamic moiré interferometry, which yielded the dynamic CTOA, was used to determine the

transient displacement fields perpendicular and parallel to the running crack in 7075-T6 aluminum alloy, SEN specimen. The SEN specimen was either fatigue precracked or blunt notched for low and high crack velocity tests, respectively. Four frames of the moiré fringe patterns corresponding to either the vertical or horizontal displacements were recorded by an IMACON 790 camera. The framing rate was also fixed to either 10,000 or 100,000 frames per second. As a result, multiple recordings of identically loaded SEN specimens at different delay timings were used to capture the entire fracture event that lasted about 1.2 milliseconds. Despite all efforts to generate reproducible tests, no two dynamic fracture tests are identical and thus the final composite fracture event was constructed with due consideration of the load-time histories and the varying crack opening profiles of each fracture test. The measured crack tip displacement field was used to compute the CTOA.

4.2 Dynamic CTOA

As mentioned previously, a multitude of tests were assembled to construct a continuous crack propagation history. The successive crack opening profiles associated

with these different tests is shown by Fig. 9. A remnant of the blunting of the fatigued crack tip prior to rapid crack propagation is evident through out the entire crack

Fig. 9 Crack profile of a propagating crack. 7075-T6 SEN specimen.

propagation history. This initial crack tip blunting is quantified in Fig. 10 which shows the CTOA dropping

Fig. 10 CTOA variation with crack extension. 7075-T6 SEN specimen.

from its initial high value to a constant angle of 4° with crack extension in the first series of experiment. The data identified as the *first series* is from fatigue precracked specimens and the *second series* refers to the data from the blunt notched specimens. The steady state CTOA in the second series is a higher 7.5° . When the CTOA is plotted in terms of the crack velocity in Fig. 11, it passes

Fig. 11 CTOA variation with crack velocity. 7075-T6 SEN specimen.

through a minimum value at an intermediate crack velocity of about 100 m/s.

4.3 Discussion

Literature on dynamic fracture show that the LEFM based dynamic strain energy release rate, G_{ID} with respect to crack velocity of somewhat brittle material exhibits a characteristic gamma-shaped curve. To check this conclusion, the CTOD at a crack tip distance of $r = 1$ mm was used to compute the dynamic fracture toughness, K_{ID} , and hence the strain energy release rate, G_{ID} , based on LEFM for the first and second series of dynamic fracture tests of 7075-T6 aluminum specimens. The same procedure was also used to compute the G_{ID} for the blunt-notched 7075-T6 SEN specimens of 1967[17]. These three tests yielded the characteristic gamma shaped G_{ID} versus crack velocity relation of Fig. 12.

Fig. 12 G_{ID} versus crack velocity. 7075-T6 SEN specimen.

The distinct difference in the G and CTOA responses at the terminal velocity, suggests that the traditional practice of characterizing dynamic fracture of somewhat ductile material through the G_{ID} versus crack velocity relation based on LEFM could be misleading. The LEFM approach results in a terminal velocity, which is insensitive to the variation in the driving force, G_{ID} , while the CTOA approach, based on elastic-plastic fracture mechanics (EPFM), suggests that the terminal crack velocity is a consequence of the saturation of the dissipated plastic energy.

5. Conclusions

1. The CTOA resistance curve can be used to characterize stable crack growth in thin aluminum fracture specimens.
2. Under mixed modes I and II crack tip deformation, the resultant CTOD remains constant.
3. Dynamic ductile crack propagation can be characterized by CTOA.

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