CTOA AS A DYNAMIC FRACTURE CRITERION

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ABSTRACT

A CTOA resistance curve for mild steel was used to predict rapid crack propagation in rupturing, sub- and full-scale pressurized pipes. The dynamic CTOA in the sub-scale pipe was a constant 5^{o} at crack velocity of 185 to 305 m/s and increased to 27^{o} at crack arrest. A scaled up version of a numerical model was then used to reproduce the crack velocity histories in pressurized APL 5L70, OD 48-in and 0.72-in thick pipes. The dynamic CTOA in 1.6-mm thick, 7075-T6 SEN specimens increased from 4.5^{o} at a low crack velocity to a constant 7^{o} at a higher and terminal crack velocity. The dynamic CTOA of 2024-T3 SEN specimens started at a high of 10^{o} and arrested at a low of 6^{o} after a maximum crack velocity of 2.5 m/s.

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痴plastic zone estimate [2], r_y, and later to the Dugdale plastic zone [3], was promoted mainly by The Welding Institute in the 60痴and 70痴[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 characterizes the crack tip strain field [5] and 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痴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' and 90痴

2. PIPE FRACTURE

The CTOA criterion was used in the 80痴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 (wall thickness 1.0 mm), carbon steel pipe was recorded with a high-speed framing camera and was processed through a software [8] which yielded the CTOA and the crack flap motion. The pipe was pre-grooved to model a brittle crack propagation. Figure 1 shows the CTOA dependency on the crack velocity in this fracturing pressurized pipe.

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. Figure 2 shows ring model which represents the fracturing pressurized pipe by a series of discontinuous rings. These rings deform elastic-plastically under fluid pressure and inertia load. The ring width was determined to be $0.1 \cdot D$, where D is the pipe diameter, by numerical experiments to match the measured CTOA versus crack velocity relation of Figure 1. The fluid pressure was estimated by a one dimensional thermal-hydraulic code with an axisymmetric radial outflow through each open ring. Figure 1 also shows the CTOA computed by the ring model. Figure 3 shows the predicted depressurization and the two pressure transducer responses at a downstream location in the fracturing subsized pipe.

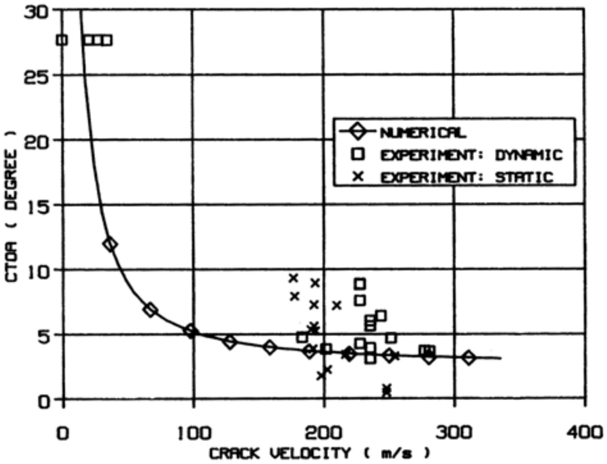

Figure 1: CTOA versus crack velocity in subsized pipe.

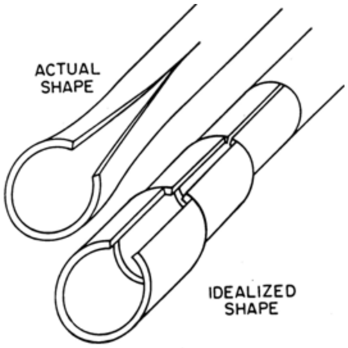

Figure 2: Ring model of a fracturing pipe.

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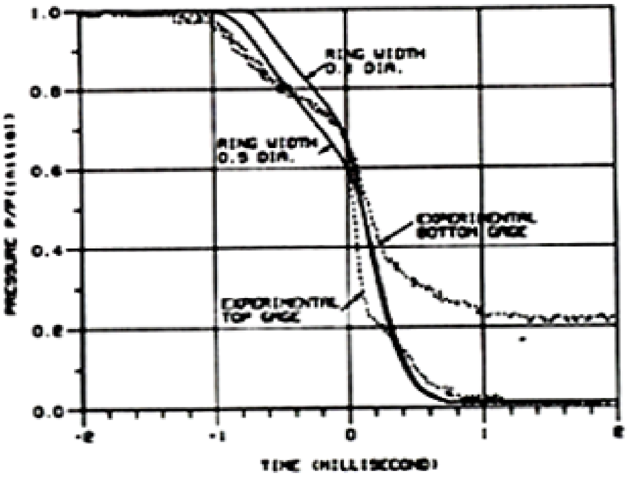

Figure 3: Depressurization in fracturing subsized pipe

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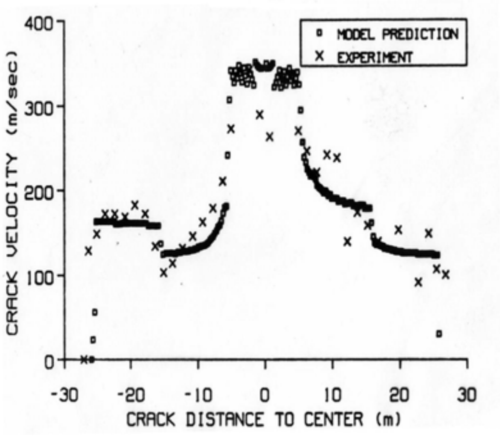
The CTOA criterion together with the ring model and the thermal hydraulic depressurization code were used to simulate the large-scale burst tests of 48-inch diameter x 0.720-inch thick, X70 line pipes [9]. After a parametric study with the ring model, a CTOA value of 6.4 degrees for a steady state crack velocity was used. Figures 4 and 5 show the Japanese test results on the crack velocity and pressure history as well as the corresponding values predicted by the ring model and the one dimensional depressurization code [10]. The excellent agreement between the measured and computed values demonstrated that the CTOA was an effective dynamic fracture parameter for pipe rupture.



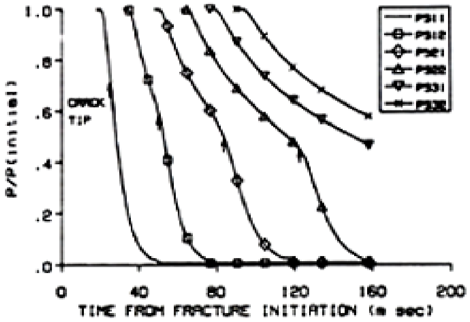


Figure 4: Crack velocity history of a rupturing full scale pipe.

Figure 5: Depressurization history of a rupturing full scale pipe.

3. ALUMINUM FRACTURE SPECIMENS

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.

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 Figure 6 [11, 12]. A remnant of the blunting of the fatigued crack tip prior to rapid crack propagation is evident through out the entire crack propagation history. This initial crack tip blunting is quantified in Figure 7 which shows the CTOA dropping from its initial high value to a constant angle of 4^o 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^o. When the CTOA is plotted in terms of the crack velocity in Figure 7, it passed through a minimum value at an intermediate crack velocity of about 100 m/s.

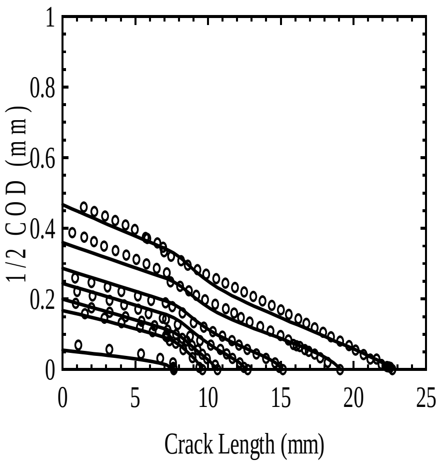


Figure 6: Crack profile of a propagating crack.
7075-T6 SEN specimen.
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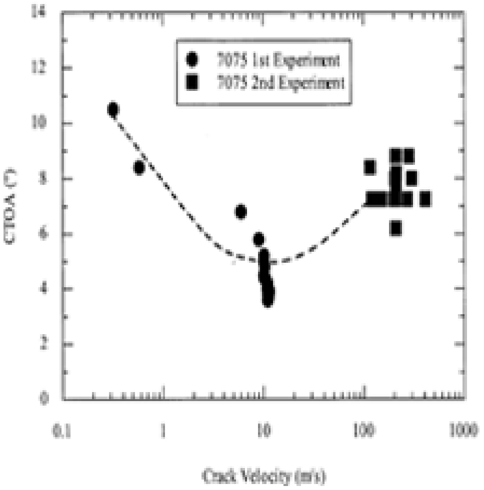

Figure 7: CTOA variation with crack extension.
7075-T6 SEN specimen.

The variation of dynamic CTOA of the 2024-T3 SEN specimens with sharp starter cracks resembled a fast stable crack growth with a maximum crack velocity of only 2.5 m/s. In retrospect, dynamic fracture tests of this ductile material should have been conducted with a severe blunt starter crack. As shown in Figure 8, the crack started to run after initial blunting of 10^o and arrested at a lower CTOA of 6^o.

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[13]. These three tests yielded the characteristic gamma shaped G_{ID} versus crack velocity relation of Fig. 9. 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.

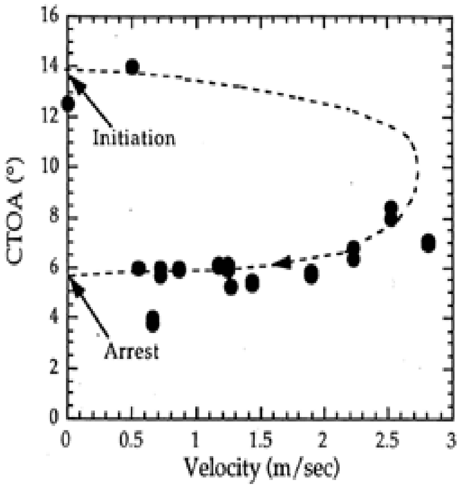

Figure 8: CTOA variation with crack velocity.
2024-T3 SEN specimens.

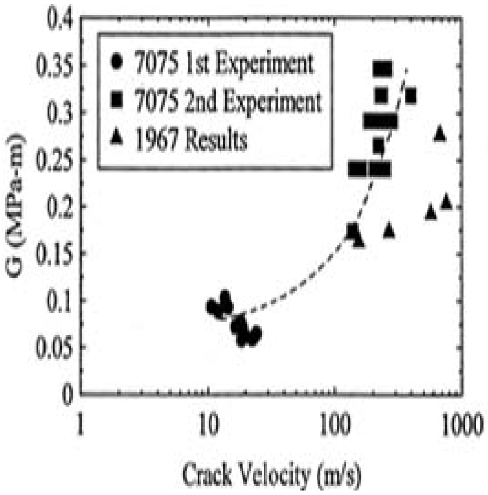

Figure 9: G_{ID} variation with crack velocity.
7075-T6 SEN specimens.

4. CONCLUSION

The CTOA resistance curve can be used to characterize dynamic crack growth in pressurize steel pipes and thin aluminum fracture specimens.

5. ACKNOWLEDGEMENTS

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