Challenges in Dynamic Fracture Toughness Testing. Validity of Current Standard Methods and Validation of Improved Testing Methods

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Many materials demonstrate sensitivity to strain-rate. Appropriate experimental test data enable strain rate dependent material models. This work investigates methods for fracture toughness testing at elevated loading rates. Challenges in standard methods have been identified and potential solutions shown. Specific testing, using SA508-III pressure vessel steel, highlight these challenges and improvement with geometric constraint.

Current Standards for Fracture Testing

Many bodies present standards for fracture toughness testing; ASTM, ISO, EN, BS and ESIS procedures have been compared [1–8]. All quasi-static fracture toughness testing (by stress intensity factor K_{IC} or J-integral J_{IC}), agree in principle. Emphasis is put into different aspects of testing, but methods show no major conflicts. ASTM Standards describe procedures for more geometry types. British and ISO Standards apply more detail to pre-cracking methods and alignment tolerances.

Standard methods for fracture toughness include elevated strain rates - denoted as 'rapid' across standards. Rapid test methods have been noted in appendices to ASTM (E1820-Ap.14&17 [4], E399-Ap.10 [8]) and British Standards (7448-3-Ap.A [5]). BS ISO also have a standard dedicated to high-rate fracture testing utilising Charpy impact on pre-cracked samples and also agree on procedures. Rapid considerations use the same equations as static. Crack growth is calculated by normalisation method (for full fracture) or by interrupted multi-specimen tests. Interrupted Charpy tests employ so called 'low-blow' testing, where various input energies are used, all lower than the energy for full fracture. Strain gauges on the specimen have been recommended to monitor applied load. This aims to sample a region of elastic strain; BS state a position half width from the crack tip. [2,4,5,8] Finally, standards set a minimum time of test (t_m). ASTM E399 [8] set $t_m > 1\ ms$. ASTM E1820 [4] set by Eq.1. British Standards set $t_m > 3\tau$. This follows work by Nakamura [9], showing inertial effects of dynamic tests can be considered negligible after a given time ($t_m > 2\tau$ – Eq.2), therefore static calculations remain valid. In SA508-III steel Charpy samples, these equate to 70 μs, from Eq.1 [4] and 210 μs form Eq.2 [9]. This shows a 1000 μs limit to be relevant but conservative.

$$t_m > 2\pi \Big/ \sqrt{Sample\ Stiffness \big/ Effective\ Mass} \tag{1}$$

$$\tau = DS\frac{H}{C_0} \cong 23.8\, H \big/ C_0 \ \{for\ SEN(B)\} \tag{2}$$

Challenges in Standard Dynamic Testing Methods

Sub-sized specimens are recommended for high speed. This aligns tests to available testing rigs (usually Charpy testing) and load capacities of high-rate instrumentation. Such small samples are prone to ***plastic collapse*** (dominance by global yielding over local crack tip stresses). Hence, results are not representative of plane strain fracture toughness. Tests carried out on SA508-III RPV steel demonstrated plastic collapse under most test conditions. Standards acknowledge this issue, stating *"such tests do not comply to valid specimen sizes but can be used as part of research and quality control"* (ASTM-E1820-23b [4]).

Charpy pendulums and drop-weight test rigs have a set energy input, hence a ***non-constant speed during test***. This leads to specimen experiencing a reduction in strain-rate as a test proceeds.

Elevated speeds also make ***crack growth monitoring*** difficult and uncertain. This is less relevant for linear elastic assessment (K_{IC}) but essential for assessment with elastic-plastic assessment (J_{IC}). Most methods of crack length determination (such as normalisation) rely on calibration factors; these can be unreliable. Interrupted fracture testing is common in static tests for direct measurement crack length. Drop weight testing with a ridged stopper risks the integrity of the machine and can put additional stress waves through the sample. Charpy tests using the 'low-blow' method leads to testing at different rates.

These challenges and their impact on uncertainty drives the need for over-conservatism in component design. This limits component service life further than needed and increases component costs.

Recommended Improvements on Test Method

Raise Constraint - Increase size and/or add side-grooves. The challenge of specimen plastic collapse can the remedies by increasing the geometric constraint on the sample, promoting fracture. Linear-elastic calculations for SA508-III steel, investigating equations for toughness and failure assessment criteria, predict valid fracture could be obtained with specimens over 20mm in width (twice the scale of traditional Charpy samples). Constraint can be increase with use of side grooves. This is another deviation from the traditional Charpy specimen but can be used to increase constraint without up-scaling specimen volume and machine capacity. Results from dynamic tests, with high constraint geometries (side grooves) have been conducted and compared toughness results, demonstrating the higher validity of high constraint sub-sized fracture tests.

Interrupted fracture with active speed control. Many other challenges may be reduced with construction of a novel interrupted three-point-bending rig, for use on a servo-hydraulic high speed testing machine. Interrupted tensile testing has shown success [10], observing deformation after high-speed straining. This offers a method with less variation, active drive to control speed during test, open optical access for non-contact measurement, and the capability to interrupt tests for direct measurement of crack growth. A design for this rig has been developed and prototypes tested. Fracture tests using this method will compared to current standard methods (Charpy tests) and validity assesses, in future works.

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