

Design of a Novel Test Apparatus for Multi-Sample Interrupted Dynamic Fracture Tests

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Introduction

Dynamic fracture toughness is known to differ from quasi-static conditions. Experimental characterisation of dynamic fracture is vital to ensure structural integrity, at high strain rates, and predict component lifespan. In this project a 3-point-bending rig capable of high-speed testing was designed that halts at a predetermined displacement, without the sample experiencing additional displacement by machine momentum. This work enables evaluation of the critical J-integral (J_c) of single edge notch bending (SEN(B)) samples, at varying strain rates. A set of objectives were defined:

- 1) Review state of the art theory of fracture mechanics and high strain rate testing to compile experimental requirements.
- 2) Investigate literature for current experimental methods.
- 3) Create test rig concepts and select the most appropriate design.
- 4) Develop designs by critical analysis.
- 5) Interrogate the experimental prototype to validate repeatability, accuracy and calibrate instruments.

State-Of-The-Art Review

Fracture Toughness Determination. Critical toughness properties show a material's resistance to fracture. **Stress Concentration Factor (K).** A key parameter in fracture analysis is the critical stress intensity factor, K_{IC} . Pioneered by Irwin [1], critical stress concentration (K_{IC}) denotes the critical stress (or crack length) that fracture will occur. This is geometry dependent and assumes purely linear elastic materials [2]. This is simply calculated by linear assumption to load at fracture. For a standard SEN(B) sample to be valid, it must be under plane strain conditions (condition shown in Eq.1 [2]). Samples made from 508 steel, characterised by Rait [3], would need to be over 1m in width to be valid. This is infeasible for lab tests. Smaller samples may not be accurate but demonstrate trends in material properties.

$$a, B \text{ \& } (a_0 - W) \geq 25 \frac{1}{3\pi} \left(\frac{k_{IC}}{\sigma_y} \right)^2 \approx 2.5 \left(\frac{k_{IC}}{\sigma_y} \right)^2 = 2.5 \left(\frac{350.73 \times 10^6}{539.50 \times 10^6} \right)^2 = 1.06m \text{ [2,3]} \quad (1)$$

J-Integral (J). Rice [4] modelled J-integral to describe energy per unit crack growth. This is calculated, experimentally, as the area under load and displacement histories. This assumes non-linear elastic-plastic deformation and small-scale yielding, releasing the requirement of plane strain conditions and permitting the use of suitably sized samples. Load history can be used to identify crack initiation time by observing a sharp drop in load as the point of crack initiation [5]. This drop may not be clearly defined and requires clean signals with low noise and high sample rates. The standard method to identify critical J-integral (J_{IC}) [6] (in Quasi-static testing) is to use multiple interrupted tests to produce a resistance curve - plotting J against crack growth. J_{IC} is extrapolated at near zero crack growth (0.2mm) [1]. For this application, experimentation must *record load and displacement histories at a range of strain rates.*

Dynamic Considerations.

High strain-rate systems include (in order of maximum achievable strain rate); screw driven, servo-hydraulic, drop-weight and explosive testing [7]. This project focuses on servo-hydraulic device. The system available to this group is an INSTRON VHS. It can be accelerated up to 20.0m/s, in either tensile or compression configuration. In-built instrumentation includes a linear displacement transducer and 100kN dynamic load cell. The system is enclosed in a frame, rated to 20kN. The test rig is required to *physically fit within frame* and be *actuated by the machine's piston.*

Intrinsic Challenges. Tests with high-speed motion introduce complexity to experimental procedures. Tests in motion require a *flat velocity profile*. Stress does not come to equilibrium but propagates as a wave. Reflected waves and impactful loading cause ringing (noise in data); this is minimised by *damping components that impact* and *tailoring the natural frequency to allow desired load profile*. Motion of cables can also add signal noise – *sensors are preferable stationary*. Dynamic loading has inertial effects and load imbalance. British standards (BS26203) recommend detecting load close to the sample [8] - *minimising mass between the sample and load cell*. Additionally, non-contact measurement minimises inertial effects.

Interrupted Testing Challenges. Interrupted fracture tests require the loading of a sample to be instantly ceased but high momentum equipment needs a considerable deceleration time / displacement. This introduces the main challenge of the project; *load on the sample must stop at predetermined displacements, to arrest crack growth.* To evaluate J at various lengths of crack growth, *displacement must be variable.*

Current Concepts.

High-speed interrupted fracture SEN(B) tests were not identified in literature but rate effects have been researched from total fracture of SEN(B) samples [5,9,10]. Interrupted tensile tests have also been developed for characterisation of material properties. Fitoussi and Cox used mechanical fuses to interrupt the test at a set load [11,12]. Dongfang et.al. interrupted tensile Hopkinson bar tests by containing the samples motion [13]. Displacement control allows for accurate data near the end of a test, where small variations in load lead to large variation in displacement – limiting repeatability. However, containment would overload a servo-hydraulic machine. Sancho García [7] overcame this by combining physical containment and mechanical fuses. A block on the sample impacts a table to interrupt at a set displacement. A mechanical fuse is series fractures at the rated load, protecting the system.

Concept Generation

The application of this project was to run three-point-bending, interrupt fracture tests on a Servo-hydraulic VHS instrumented testing system. Evaluation of load and displacement show J-integral at various crack growth and determine critical dynamic J-integral. *Experimental needs* were identified from similar methods and understanding of theory. These were expanded, via a requirements and objectives tree exercise, to produce a test specification document.

Ongoing Work. The work presented in this project shows an iterative concept generation project. Initial brainstorming and morphological design were developed to add detail and rank against specifications (Pugh matrix). In-silico development included dimensioning the model, motion simulation (assessing velocity and displacement profiles), stress analysis (for dimensioning, material selection and assess compliance) and modal analysis (damping, load and rate limitations). Functional prototypes were built to assess functionality and develop for manufacturability.

Further Work. Following selection of appropriate designs and final developments, a technical prototype is to be trailed. A systematic review of repeatability will be completed to validate the operational functionality of the experimental set-up. Tests on light foam blocks provide negligible resistance but deform by machine motion. High speed photography portrays velocity profile and foam indentation corresponds to load line displacement. Repeated foam tests assess variation. Signal to noise ratio from instrumentation during these tests can show effective range of the set up.

Tests on metallic samples, with known properties mark a final stage of rig development, assessing repeatability, accuracy, and signal clarity in a similar way to foam tests. Data from these tests point to system calibration and opportunities for further development.

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