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COMPRESSIVE FRACTURE OF MASONRY - EXPERIMENTAL STUDY

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ABSTRACT

Engineering materials contain flaws such as cracks, pores, voids and fissures. Compressive failure of brittle materials is characterized by multiple cracks propagating parallel to the direction of compressive stress. These cracks develop through mode I cracking from the pre-existing flaws in the material. In this paper, a method that was used to study compressive fracture of masonry through a single crack is reported. Pre-set cracks with different shapes of crack tip were placed in specimens, which were then subjected to compression. Both masonry and concrete specimens were tested. Comparisons were conducted between compressive fracture with a single crack and with multiple cracks.

KEYWORDS: Compression, Fracture

INTRODUCTION

It is widely accepted that flaws such as cracks, pores, voids and fissures exist in materials even prior to the application of load [1, 2]. The location, orientation, sizes and shapes of flaws are distributed throughout the material. When a crack grows in size, the crack surfaces can displace relative to one another in three independent modes, i.e. Modes I (opening), II (sliding) and III (tearing). Fracture mechanics is a topic that deals with the propagation of cracks leading to specimen failure. An underlying premise of fracture mechanics methodologies is that materials do contain flaws. These flaws act as stress raisers in tension and produce local tensile stresses in compressive stress fields.

Engineering materials such as concrete, masonry and rock are mainly subjected to compressive loads. Many experimental investigations [3-9] have provided considerable data on brittle fracture in compression and various theoretical models [10-14] have been developed to explain crack propagation in compression. Brittle fracture in compression has received considerable attention. Most compressive fracture experiments involve multiple cracking. 2-D inclined cracks have been used as the source for studies on single crack propagation under uniaxial compression. The crack that grows from such a source kinks towards the direction of uniaxial compression. However, the theory used to explain this behaviour cannot explain propagation from an initially zero width crack parallel to the direction of the uniaxial compression. In reality, multiple visible cracks parallel to the uniaxial compressive load are always seen. This begs two questions. What is the difference between compressive fracture with a single crack and that with multiple cracks parallel to the direction of compression? Is it possible to conduct compressive fracture tests with one single crack parallel to the uniaxial compression?

In this paper, a method is reported that was used to study compressive fracture with a single crack. Both masonry and concrete specimens with different shapes of pre-set crack tips were tested. Comparisons can now be made between compressive fracture with a single crack and with multiple cracks.

ESSENTIAL FEATURES OF COMPRESSIVE FRACTURE

Fracture in compression is different from tensile fracture [9, 14, 15]. Tensile fracture is generally typified by a single crack propagating perpendicular to the direction of maximum tensile stress, whereas compressive failure is generally typified by multiple cracks propagating parallel to the direction of compressive stress, as shown in Figure 1(a). In tension, as the crack increases in length, the cross-section of the unbroken area left to resist the load decreases: the average stress over this area and the stress intensity at the crack tip increase. The energy release rate is at least maintained, and under these circumstances, the crack continues to propagate in what is deemed to be an unstable fashion. In contrast, in compression, as the cracks increase in length, the cross-sectional area to resist the load remains essentially the same. The average stress appears not to change. Close to final failure, the cracks coalesce to form macrocracks, which in turn create columns of material in the specimen. These columns spall off or buckle away from adjacent more highly confined or more lightly stressed zones, and the specimen fails.

In addition to the more obvious macroscopic differences between tensile and compressive failure, there are two fundamental issues which make the analysis of compressive failure more difficult. First, in analyses of tensile fracture, cracks are modelled as being infinitely thin. Crack length is the important parameter, and crack width typically has no impact on the solution. However, in a uniaxial compressive stress field, an infinitely thin crack parallel to the direction of compression does not alter the stress field. As the infinitely thin crack increases in length, the stress field remains unaltered and consequently there is no reduction in strain energy in the material. Hence, the most commonly used assumption for analyzing tensile failure is simply not applicable to compressive failure.

Secondly, there is an asymmetric relationship between the bond force and interatomic spacing, as shown in Figure 1(b). In order for a crack to propagate, interatomic bonds must be broken. The relationship between bond force and interatomic spacing reveals quite clearly that only tension can break a bond. Hence, for a crack to propagate in a compressive stress field, tension must be generated, as shown in Figure 2. This is completely different from the tension fracture situation, where there is no necessity to generate compression.

In uniaxial compressive stress, multiple visible cracks propagate essentially parallel to the direction of axial loading. Furthermore, failure of masonry under any type of loading is associated with the development of at least one visible crack. For a crack to be visible to the naked eye, the surfaces must separate. The separation mechanism is that tensile stresses break interatomic bonds and pull the surfaces apart.

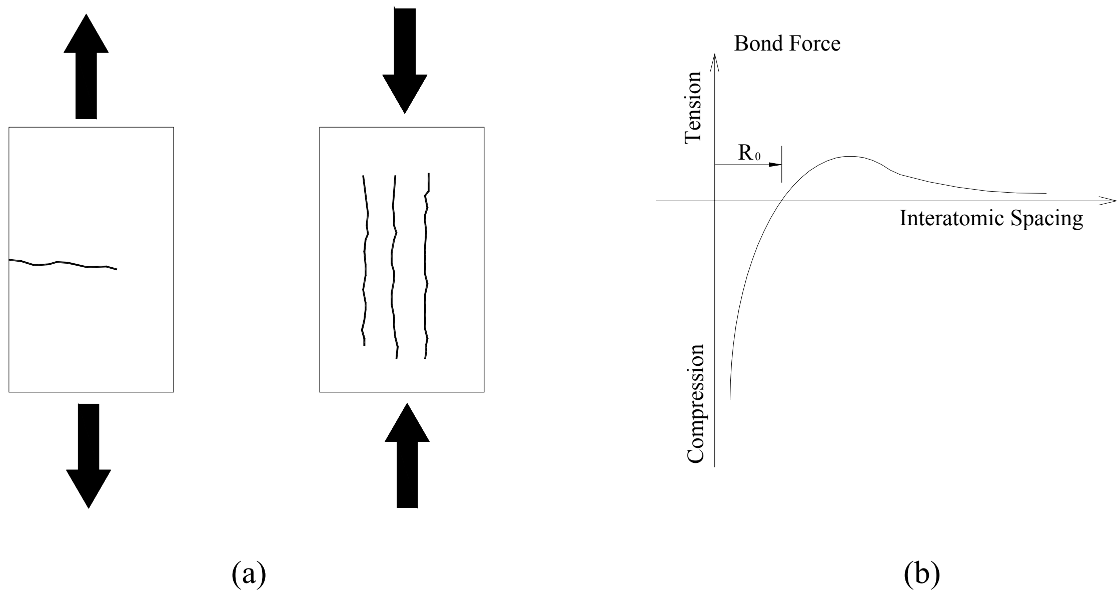


Figure 1-(a) Uniaxial Tensile Failure with a Single Crack Perpendicular to the Tension and Compressive Failure with Multiple Cracks Parallel to the Compression (b) The Bond Force - Interatomic Spacing Relationship

Therefore, from the preceding observations, for a crack to propagate two conditions must be met. First, there must be a stress large enough to break bonds (stress criterion); and second, there must be a balance between the strain energy lost and the surface/internal energy gained as the crack propagates (energy criterion).

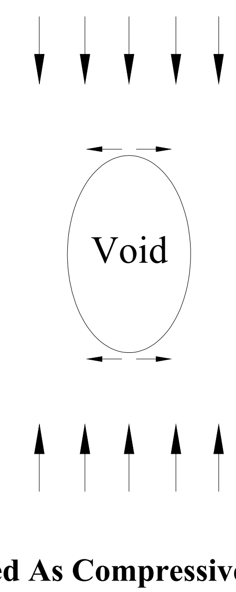


Figure 2-Tension Is Generated As Compressive Stress Flows Around a Void

COMPRESSIVE FRACTURE TESING OF MASONRY

Specimens

Two types of specimens (masonry and concrete) were used, as shown in Fig. 3. Three types of solid clay brick (63 mm x 90 mm x 119 mm) were used in this test.: Granville Gray Titan Solid (A), Cinnamon Titan Solid (B) and Columbia Solid (C), all manufactured by I-XL Industries, Medicine Hat, Alberta. The material properties of the bricks, determined according to CAN3-A82.2-M78 (1978) [16], are given in Table 1. Specimen details are listed in Table 2. Seven unit-high masonry specimens were manufactured with Type S and Type N mortars (CAN A179-04 (2004)) [17]. For masonry specimens, the pre-set cracks were formed in the units with a saw prior to construction to crack depths of 1/3 and 1/2 of the brick height. Notches were formed in the concrete specimens through a metal strip in the mould. The concrete was made from Type 10 Ordinary Portland Cement and pea gravel, and had a nominal compressive strength of 35 MPa.

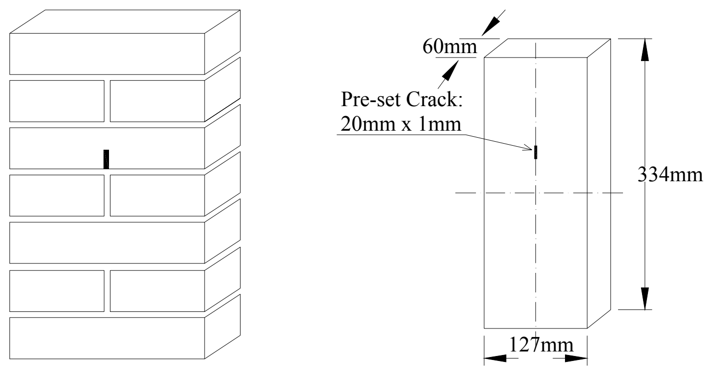


Figure 3 –Specimens with the Pre-set Cracks

Table 1-Material Properties of the Three Bricks

Brick type	Absorption (%)	Compressive strength (MPa)	Modulus of rupture (MPa)
A	8.0	60.6	5.3
B	7.7	93.0	7.2
C	10.3	72.8	6.7

Table 2-Specimen Details: 6 Specimens of Each Type Were Tested

Specimen	Notch-to-depth Ratio (a_0/H)	Specimen	Notch-to-depth Ratio (a_0/H)
AN-A1	10.5	CN-A1	10.5
AN-A2	31.5	CN-A2	31.5
AS-A1	10.5	CS-A1	10.5
AS-A2	31.5	CS-A2	31.5
BN-A1	10.5	AN	0
BN-A2	31.5	AS	0
BS-A1	10.5	BN	0
BS-A2	31.5	BS	0
CN	0	CS	0

Shape of Crack Tip

In order to investigate the effect of the shape of the crack tip on crack initiation, different shapes of crack tip were used. For concrete specimens, U and V shapes were used, while for masonry specimens, U, V and circular shapes were used, as shown in Figure 4. The U and V shapes were made in the masonry with a masonry saw and a jack saw. The circular shape (cylindrical in 3-D) was made with a 9.5 mm (3/8 inch) drill bit.

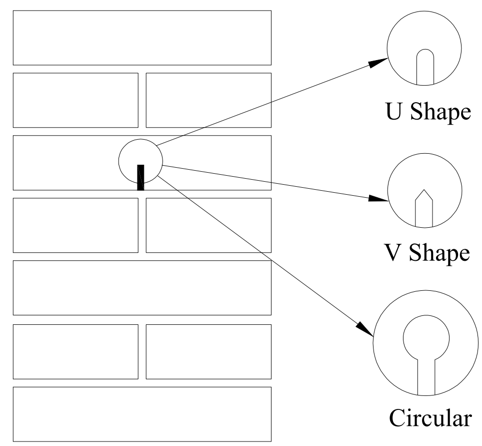


Figure 4-Different Shapes of Crack Tip

Position of the Pre-set Crack

The strains and stresses in a specimen compressed between two steel platens in a testing machine are not uniform [18]. Friction between the specimen and the platen restrains the lateral movement of the specimen at the platen-specimen interface, providing the well-known ‘platen restraint’. The vertical stress distributions at the platen interface and some depth are shown in Figure 5 [18]. Therefore, the pre-set crack was placed in the central high stress area in order to ensure that first cracking occurred at the pre-set crack tip.

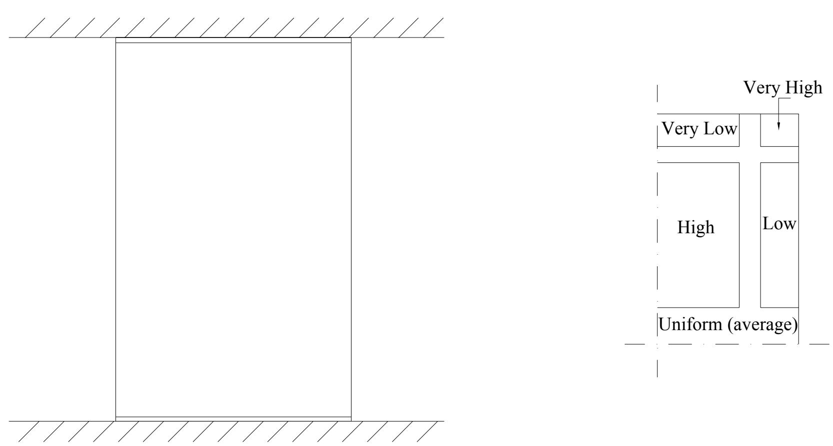


Figure 5 – Vertical Stress Distributions in Testing Machine

Test Arrangement
The test arrangement is shown in Figure 6. The specimens were tested in a closed-loop, electro hydraulic MTS Test Machine. Specimens were capped with fibre board. Displacement was applied at a loading rate of about 50 kN/min. The applied load, crack mouth opening displacement (CMOD), and the vertical deformation of the specimen over a 300 mm gauge length were monitored. The CMOD and the deformation of the specimen were measured using an MTS clip gauge and LVDT's, respectively.

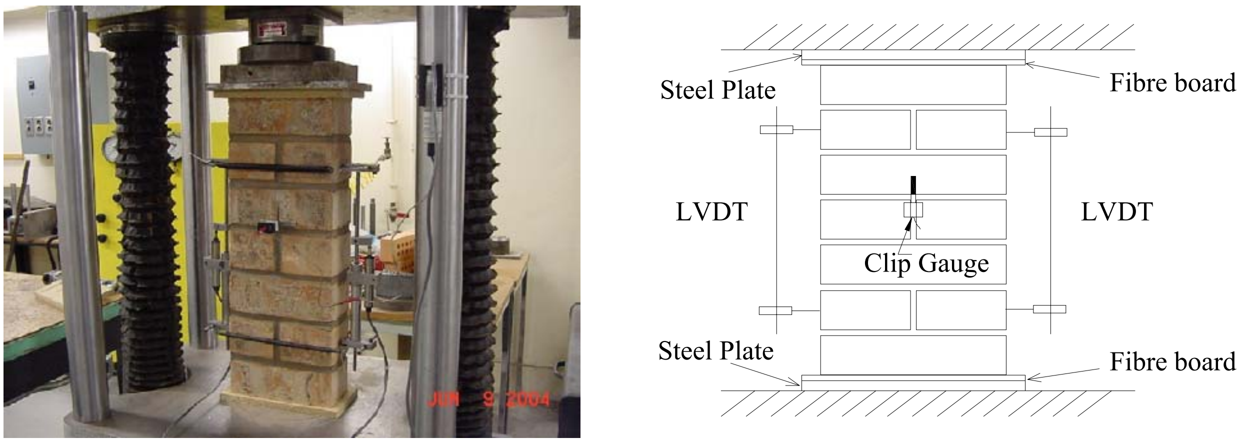


Figure 6 – Test Setup

EXPERIMENTAL RESULTS AND DISCUSSIONS

Failure Modes

<u>Specimens without Pre-set Crack</u>

First, specimens without a pre-set crack were tested. Failure was typical for compressive testing with failure occurring through multiple cracks (emanating from different flaws) propagating parallel to the direction of compressive stress, accompanied by local crushing and spalling in the specimen. These tests were performed to establish a baseline against which the failure of specimens with pre-set cracks could be compared.

<u>Specimens with V and U Shape Crack Tips</u>

The failure of specimens with V and U shaped crack tips was like that of specimens without the pre-set crack, as shown in Figure 7. Cracking started at the weakest point instead of the pre-set crack tip. This meant that these crack tips were not of a critical enough shape to drive specimen cracking from that point, rather than from any other pre-existing flaw in the specimen. Thus, a more critical shape of flaw was required to initiate a single crack for failure.

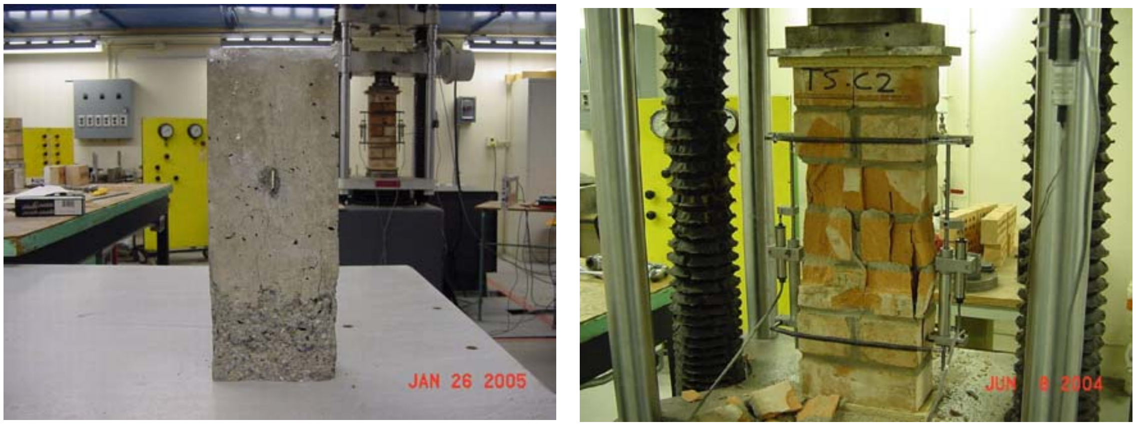


Figure 7 – Multiple Cracks in Specimens with U and V Shaped Crack Tips

<u>Specimens with a Circular Crack Tip</u>

The effect of the size and shape of the flaws on crack initiation and propagation in compressive stress fields has been investigated previously [13,14]. These factors have been shown to be important with respect to crack initiation and propagation. The most critical shape for a flaw or void for initiating failure in compression has been shown to be a spheroidal void [13,14,15]. However, creation of a specific spheroidal void in a specimen is not a practical proposition. Another set of critical shapes for inducing crack propagation in compression are cylindrical (cigar) shaped voids, which thus have a circular crack tip when viewed in 2-D. It is quite simple to create a cylindrical void in a specimen by simply drilling a hole through it. Hence, holes were drilled to change the shape of the crack tip to circular in some specimens. Close observation at the apex of the hole during each test showed that first cracking always began there. The single crack propagated in a stable fashion with increasing load. At the peak load, the single crack divided the specimen suddenly into two pieces, as shown in Figure 8.

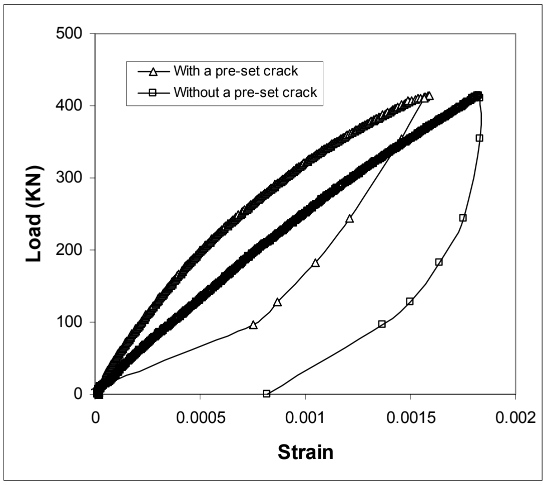
Figure 8 – Crack with Circular Tip in a Specimen, and the Failed Specimen

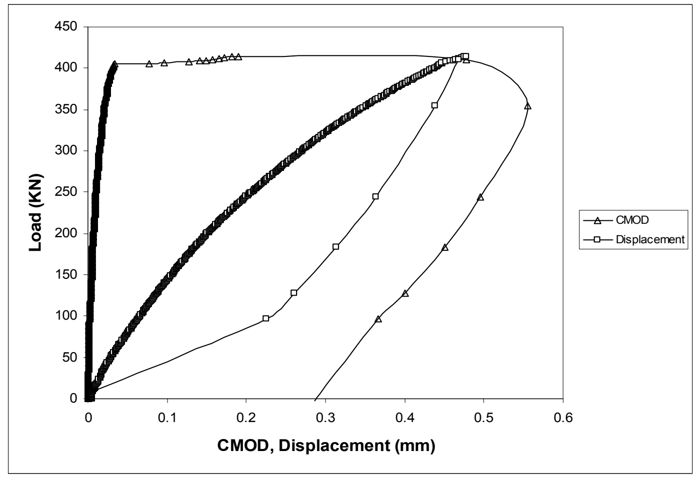
Typical Load - Deformation Curve

Only the experimental results for Brick C specimens with circular crack tips are reported (Table 3). A typical load versus deformation curve is shown in Figure 9. Specimens without a pre-set crack had higher fracture loads than those with pre-set cracks. Increasing fracture load with increasing pre-set crack length was not expected (Figure 10). The crack mouth opening displacement (CMOD) was very low (up to about 80 to 90% of the peak load). Crack extension at the pre-set crack tip then became visible, and the CMOD increased quickly until the peak load was reached. The mean values of the CMOD at failure were around 0.05 mm, with the CMOD generally being less variable than the failure strain. Failure strains in pre-set crack specimens (about 1300 and 800 με) were considerably less than in whole specimens (about 2100 με).

Table 3-Experimental Results

Specimen	Peak Load (KN)	CMOD at Failure (mm)	Strain at Failure	Comment
CN-A1-1	436	0.045	0.00203	
CN-A1-2	309	0.051	0.00133	
CN-A1-3	347	0.041	0.00160	
CN-A1-4	398	0.067	0.00090	
CN-A1-5	334	0.030	0.00060	
CN-A2-1	483	0.070	0.00080	
CN-A2-2	503	0.044	0.00107	
CN-A2-3	394	0.057	0.00083	
CN-A2-4	371	0.063	0.00070	
CN-A2-5	397	0.042	0.00073	
CS-A1-1	364	0.034	0.00107	
CS-A1-2	-	-	-	Not Fail
CS-A1-3	398	0.041	0.00103	
CS-A1-4	484	0.053	0.00190	
CS-A1-5	438	0.059	0.00120	
CS-A2-1	503	0.047	0.00043	
CS-A2-2	497	0.041	0.00077	
CS-A2-3	490	0.036	0.00067	
CS-A2-4	523	0.034	0.00203	
CS-A2-5	411	0.033	0.00143	
CS-A2-6	-	-	-	Not Fail
CN-1	470	-	0.00207	
CN-2	412	-	0.00153	
CN-3	497	-	0.00203	
CN-4	460	-	0.00230	
CN-5	501	-	0.00230	
CS-1	509	-	0.00207	
CS-2	532	-	0.00250	
CS-3	530	-	0.00213	
CS-4	-	-	-	Not Fail
CS-5	528	-	0.00207	





(a) (b)

Figure 9-Typical Load – Strain and Load - CMOD Curves for Specimens without and with a Pre-set Crack

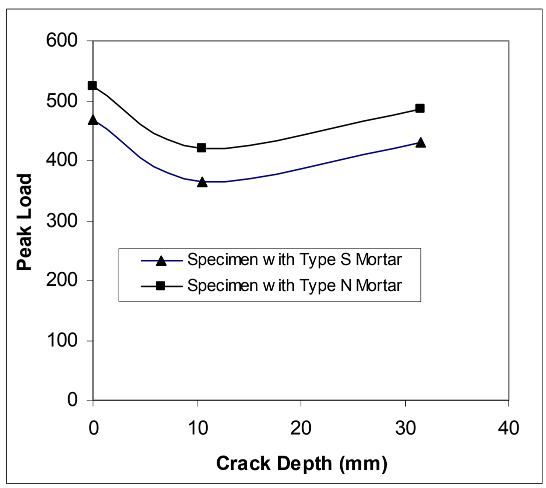


Figure 10-Peak Load versus Crack Depth

CONCLUSIONS

A new technique for compressive fracture testing to obtain a single crack using a pre-set crack with circular crack tip (i.e.: a cylindrical void drilled through the specimen) has been reported here. This experiment may provide a way to realize a relationship between fracture through a single crack and through multiple cracks under compression, both qualitatively and quantitatively, and lead to a better understanding of the driving factors of fracture in compressive stress fields. Some initial experimental results were also reported.

Further analysis and theoretical developments are required to achieve this goal, particularly concerning the relationship between fracture from a single crack and that from multiple cracks. The effects of both initial crack size and offset will need to be elucidated.

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