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EXPERIMENTS ON 3-D CRACK GROWTH IN UNIAXIAL COMPRESSION

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A study of spatial crack propagation under uniaxial compression was undertaken in a brittle transparent plastic with artificially induced internal cracks. The specific issue addressed was whether there was a qualitative difference between 2-D and 3-D crack propagation.

Fracture of heterogeneous materials (e.g., rocks) under uniaxial compression is produced by propagation of internal cracks towards the load, some of which propagate so extensively that they eventually split the material into columns. Experimental and theoretical studies of this phenomenon based on 2-D models (plates with through cracks) showed that the extensive crack growth towards compression emerged from pre-existing (initial) defects such as through cracks in plates inclined to the compression axis, or cylindrical pores (e.g., [1-10]). The main point of these studies is that a single 2-D microdefect is capable of producing extensive crack growth sufficient to cause fracture.

In reality however, pre-existing cracks are three-dimensional, which can result in a more complicated mechanism of their growth. A limited number of experiments: Adams and Sines [4] and Cannon et al. [11], have been reported on studies of the growth of inclined disk-like cracks in uniaxially compressed transparent samples (from PMMA - polimethilmethacrylate plastic). However, the dimensions of the PMMA samples used in these experiments were not sufficient to investigate the extensive crack growth.

In order to study mechanisms of fracture in uniaxial compression, further experiments are required using sufficiently large samples which would provide enough room for extensive crack growth. In addition, the spatial interaction of several growing cracks has to be investigated. This paper reports the results of such experiments.

1. Sample preparation and experimental technique. In the experiments, parallelepiped samples made from transparent casting polyester resin "Polylite 61-209" with cross-section dimensions of 55 mm x 55 mm, and a height of 120 mm were used. When frozen to -17°C, this material is perfectly brittle, deforms without barrelling and has linear stress-strain behaviour up to its burst-like fracture. The mechanical properties evaluated during the tests are: Young's modulus $\cong$4GPa; uniaxial compressive strength $\cong$140MPa; fracture toughness $\cong$0.6MPa·m$^{1/2}$.

Two methods of modelling the internal initial disk-like cracks were adopted:
(1) *embedding* a thin disk-like inclusion into the resin block during casting. The inclusion consisted of two aluminium foil disks greased and put together and held within the sample by two cotton threads;
(2) *cutting* two semi-circular slots of 0.3 mm thickness in two halves of the sample and then gluing the halves together (this method was used in [4]). In order to ensure the contact between the opposite faces of the crack, teflon or greased foil disks were inserted into the slots (According to the 2-D analysis [9], the initial cracks, i.e. voids with contacted lips are the strongest drivers of the extensive crack growth).

The cracks were 10 and 12 mm in diameter and inclined to the loading axis at 30° and 45°.

After freezing at -17°C, the samples were uniaxially loaded by Instron loading machine in the displacement controlled regime at a loading rate of 0.4 mm/min. Two types of end conditions were used: (a) direct contact between the loading platens and the specimen ends; and (b) teflon inserts between the specimen ends and the platens.

In order to check whether this material was suitable for studying the crack propagation, 6 preliminary tests were undertaken with samples containing 2-D (through) cracks prepared either by embedding greased aluminium strips or by cutting thin strip-like slots in two halves of the sample and then gluing the halves together. The results of these tests were in qualitative agreement with the conventional results: at first two branches emerged jump-like from the ends of the initial crack, then the branches grew in a stable manner towards the load. When the total length of the growing cracks reached approximately the sample width, the crack propagation became unstable resulting in splitting of the sample.

2. Growth of a single 3-D crack in compression. Altogether, 23 samples with single cracks were tested. The typical result is shown in Fig. 1. At approximately one third of the compressive strength two branches (wings) emerged from the upper and lower parts of the crack contour and then grew in a stable manner (stepwise). This was similar to the observations [4, 11] on the crack growth in PMMA. Then the wings started to wrap around the initial crack, which eventually stopped the crack growth. The maximum length of a wing that could be achieved was approximately 1-1.5 times the radius of the initial crack. Further loading could only result in brittle, burst-like failure of the sample. This pattern of crack growth was consistent for both techniques of crack preparation, both crack diameters and angles of inclination and for both direct contact and loading through teflon inserts. The pattern was also independent of the location of the initial cracks with respect to the lateral surfaces of the sample (see Fig. 1 showing crack near a lateral surface).

In order to verify that the results obtained from the experiments on resin samples were due to the crack propagation characteristics and not influenced by the material properties, 20 experiments were conducted to failure on cement and sand/cement mortar blocks with embedded inclusions modelling internal 3-D cracks. Investigation of the failed samples revealed only non-extensive growth of the artificial cracks. As for the resin samples, the mortar samples had failed independently of the artificial cracks.

3. Qualitative difference in the style of crack propagation in 2-D and 3-D cases. An initial 2-D (through) crack inclined to the axis of compression can cause the extensive growth of the branches sufficient to produce fracture of the sample (when the growing crack becomes comparable with the sample dimensions).

A 3-D (internal) crack cannot extensively grow in uniaxial compression. The wings branched from the initial crack, can at most grow to the size comparable with the initial crack dimensions which is insufficient to cause fracture.

Since real materials contain a multitude of initial cracks the mechanism of macroscopic crack growth should be sought in interaction between the initial (micro) cracks.

4. Growth and interaction of pairs of 3-D cracks. The following three types of arrangements of initial crack were tested.

Parallel horizontally aligned inclined cracks. Fig. 2 shows the typical pattern of crack growth (only 2 samples with this arrangement were tested). It is seen that the crack interaction restricts the growth of the wings compared to the case of a single crack.

Parallel vertically aligned inclined cracks. This crack arrangement was tested on 7 samples. Due to technical difficulties, only the method of embedding was used for preparing the initial cracks. Fig. 3 is typical of the observations in this case. It is seen that the crack interaction amplifies growth of the wings although not sufficiently to produce fracture.

Coplanar horizontally aligned inclined cracks. In this case the initial cracks first grow independently as single cracks. Then, depending on the distance between the cracks, a third, large tensile crack is emerged tending to split the sample along the loading axis (the tensile crack shown in Fig. 4 consists of larger upper and smaller lower parts). Similar results arise when the initial cracks are inclined at the same angle but in opposite directions.

The table shows the dependence of the emerging of the third (macro) crack on the ratio, S/d, of the distance between the initial cracks to their diameter for all 22 samples tested. It is seen that $S=d$, is the critical distance beyond which the third crack cannot be produced.

The dimensions, orientation (in the horizontal plane) and initiation of the third crack (for $S=d$) suffer random variations probably attributed to residual stresses remaining in the resin after curing. In particular the dimensions can vary from a crack smaller than that shown in Fig. 4 to large cracks actually splitting the sample. However, the appearance of the third crack does not depend on the technique of preparation of the initial cracks and angle of their inclination to the loading direction provided that the angle is approximately the same for both initial cracks. The third cracks have also been observed in 7 samples with the initial cracks inclined in opposite directions (but at the same angle). The initial cracks also need not be aligned horizontally. In a sample with cracks situated along an inclined line as sketched in Fig. 5, a large tensile crack emerged splitting the sample.

Almost all samples with this crack arrangements were tested in direct contact: the presence of teflon inserts resulted in splitting of the sample and thereby did not allow further observations.

The common feature of the arrangements producing the third crack is that the wings are sub-coplanar. The mechanism of initiating the third crack could result from the additional tensile stresses acting on the vertical plane passing approximately through the wings. These stresses are the superposition of stress disturbances induced by opening of the wings (Fig. 5). When the distance between the cracks is sufficiently small, the magnitude of these additional stresses becomes high enough to break the material and produce the third crack. The additional stresses are superimposed on the random residual ones existing in the material. This combination eventually produces the observed variety of shapes dimensions and orientations of the third crack.

Thus, *the interaction between two initial cracks is capable of producing a large separate fracture*. It can be expected that interaction of a multitude of initial cracks (as in real heterogeneous materials) can produce even more extensive fractures.

5. Growth of a multitude of 3-D cracks. It was found that casting the resin with overdoses of the catalyst (7-9% instead of 0.5-1.5% recommended by the manufacturer) together with heating at about 60°C produces a multitude of internal cracks (Fig. 6a). This allowed experiments on multi-crack propagation in uniaxial compression (altogether 9 samples were tested).

The crack growth was observed almost immediately after beginning of the load and resulted in appearance of few vertical cracks tending to split the sample (Fig. 6b; all the tests were stopped before the possible splitting to preserve the samples). Thus, *the* *interaction of a multitude of initial cracks produces large fractures tending to split the sample.*

6. Conclusion. The tests demonstrated that unlike 2-D cracking, there are intrinsic limits on 3-D crack growth. It is suggested that the brittle fracture results from new macrocracks initiated parallel to the loading direction by tensile stresses induced on the corresponding planes by opening of the fully developed wings branching from pre-existing cracks.

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S/d	Number of tests	Appearance of the third crack
0.5	4	In all samples
0.8	4	In all samples
1	9	In all samples, except of two
1.5	3	Never appears
2	2	Never appears

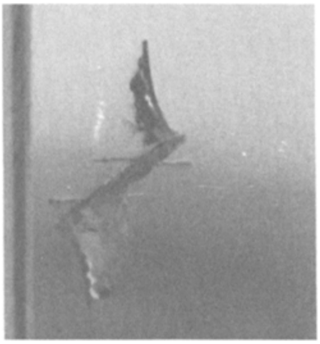

Fig. 1. Fragment of a sample with single wing crack. Two horizontal lines are threads holding the inclusion.

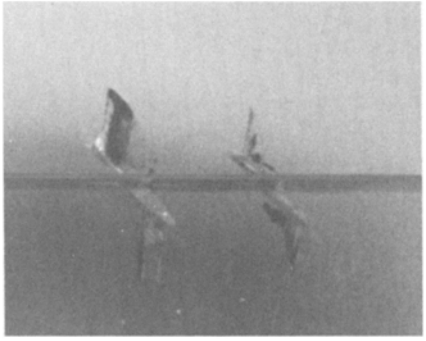

Fig. 2. Fragment of a sample with horizontally aligned parallel cracks (prepared by cutting).

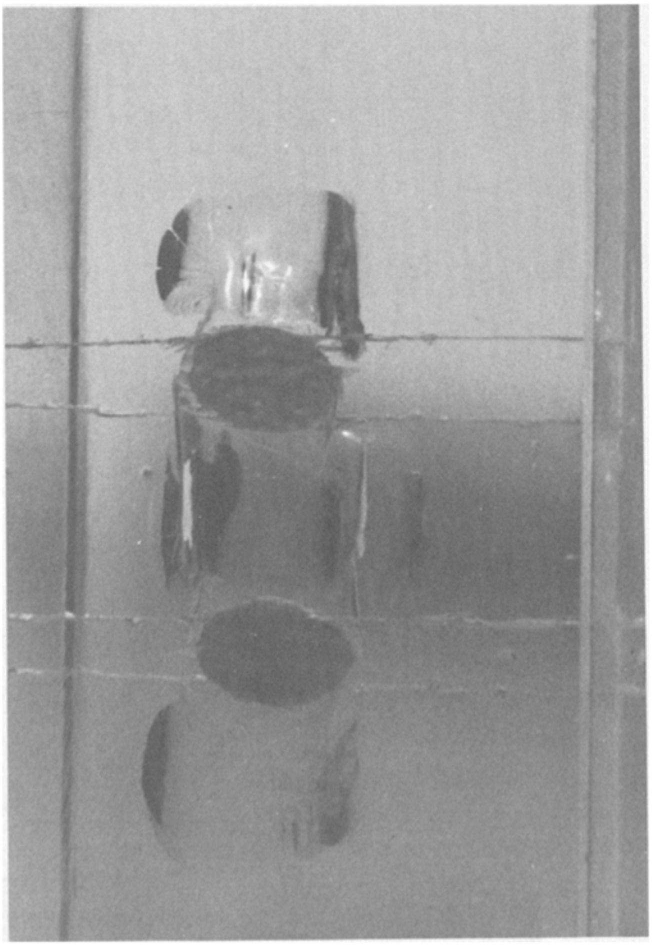

Fig. 3. Fragment of a sample with vertically aligned parallel cracks. Horizontal lines are threads holding the inclusions.

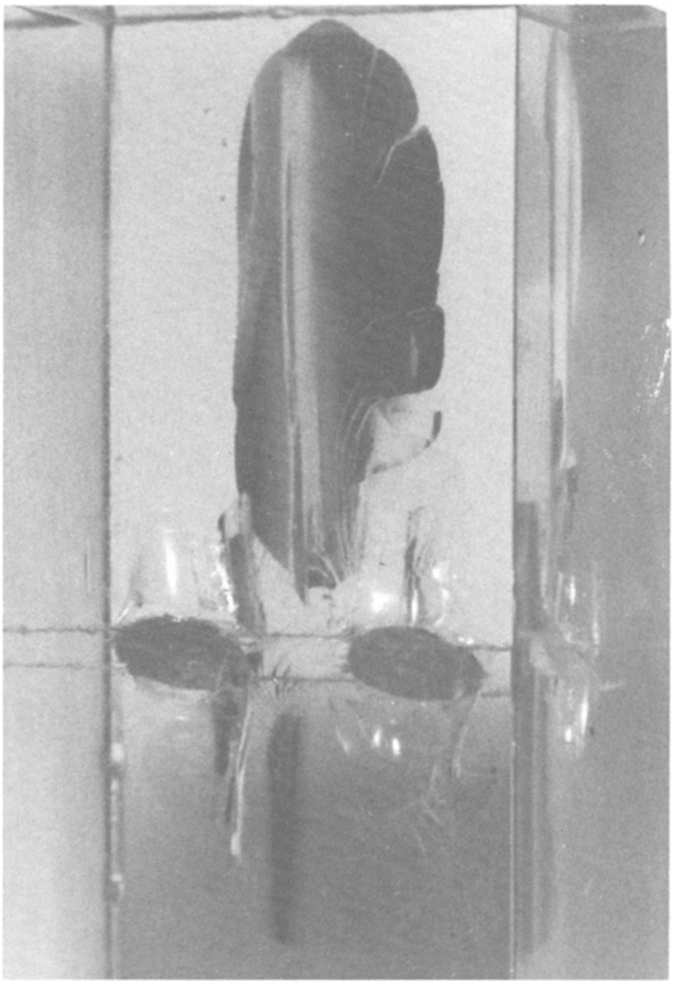

Fig. 4 Fragment of a sample with horizontally aligned coplanar cracks.

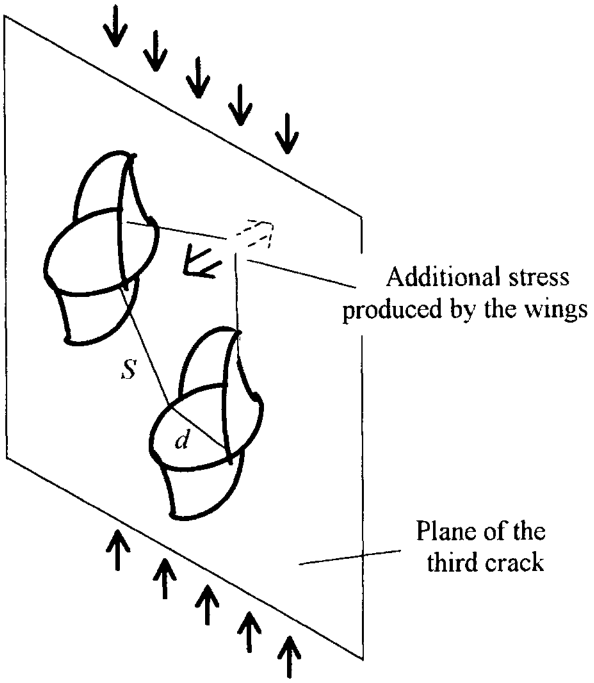

Fig. 5. The mechanism of initiation of the third crack.

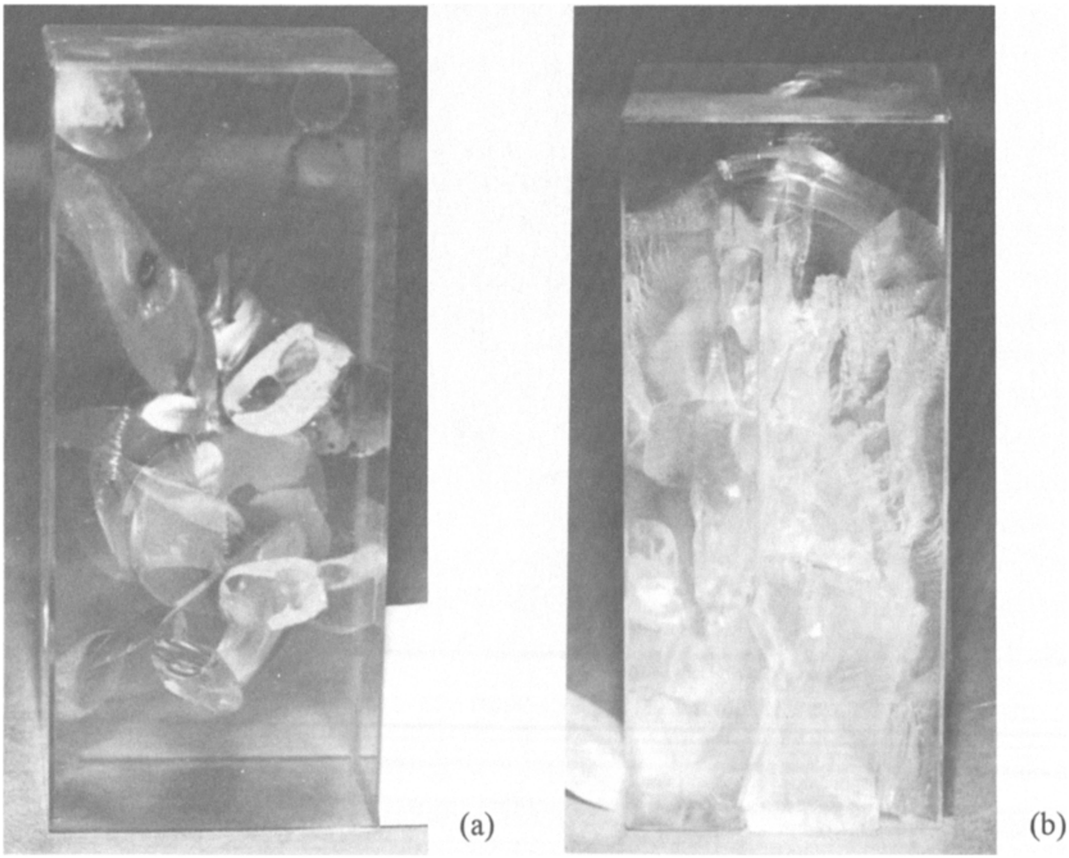

Fig. 6. Sample with many cracks: (a) before testing; (b) after testing.