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FOREWORD

This research memorandum has been written under contract NONR-3219 (01) (X). The memorandum was prepared by Dr. J. O. Outwater, Principal Investigator under this contract, and Mr. Gerry and summarizes part of the work to date on the compressive strength of glass. It was carried out under technical direction of the U. S. Naval Research Laboratory.

Mr. Joseph A. Kies of the U. S. Naval Research Laboratory and Messrs. Trono and Trupp of the University of Vermont were of great help in the undertaking. The author also wishes to acknowledge the valued advice and encouragement of many others.

The Effects of High Uniaxial Compressive Stress on Glass

by

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ABSTRACT

Necked Pyrex rods were used to obtain the values of uniaxial compression stress on glass. Stresses up to 547,000 psi were measured and some unusual phenomena were noted: instead of splintering, the glass failed by giving a coherent mass and at the same time set up tensile waves in the specimen. Light was emitted on failure. No creep was observed either under direct uniaxial stress of between 400,000 and 500,000 psi of 1 sec. duration or in the areas of stress concentration around a cylindrical hole drilled through the point of highest stress. The results of this work tend to substantiate a time dependent plastic flow theory.

INTRODUCTION

There are several references to the compressive strengths of materials but very few indeed actually refer to the compressive strength as such. The reason is not hard to see: Materials do not fail in compression. Instead they fail in tension or shear and the simple uniaxial compression of a glass cylinder will merely cause the edges to spall off before the specimen is split giving a reproducible but trivial value of compressive strength.

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In this paper we have attempted to avoid tensile or shear failures and have obtained values of compression up to 547,000 psi - perhaps the highest values of uniaxial compression ever obtained on any material - and show a novel form of failure where the glass, instead of splintering is reduced to a coherent powder and simultaneously emits light as it fails.

The more direct forms of failure are also observed and the crack trajectory around a flaw is shown. Six specimens were held at a uniaxial compressive stress of over 400,000 psi and no creep was observed.

FRACTURE CRITERIA

The fracture criteria for materials under combined loading are generally in accord with Griffith (1) who stated that the "general condition for rupture will be the attachment of a specific tensile stress at the edge of one of the cracks." This concept was confirmed by Erdogan and Sih (2) who showed that a slit in a brittle material would grow in the direction determined by local fracture considerations. When the stress concentration is reduced, then the crack will stop.

This criterion is difficult to reconcile with compressive failure. If the loading is directly compressive, then there will be no tensile stresses and hence no crack extension forces at the edges of cracks. If we try to adopt a shear criterion, as is usual for ductile materials, then we can explain compressive failure as a shear failure. This is, however, not the observed fact with glass as pure shear, such as is produced by torsion, never results in a typical shear fracture surface. It always appears to be tensile.

Mulville and Kies (3) showed that tensile stresses could be induced at the edges of the cavities under conditions of compressive loading and these tensile stresses could initiate and extend the failing cracks if they were of sufficient magnitude. Kies further showed that the magnitude of the tensile stresses induced was substantially independent of the size of the cavities and depended primarily on the radius of curvature of the ends. This brings the compressive failure into the realm of tensile failure even under hydrostatic conditions.

In addition to direct consideration of brittle failure of glass we are faced with the possibility of glass being in fact a ductile material and its yielding before fracture under certain conditions. Marsh (4) gave evidence of its ductility but was not able to show any flow under conditions of direct uniaxial stress. He postulated that flow would occur at stresses above 500,000 psi for load applications of duration of about 1 sec. We obtained values above this but have not direct evidence of creep or flow though the mode of failure at very high values of stress is completely different from that at lower values. It suggests that, since these stresses are of the order of magnitude of flow stresses, flow may actually be occurring resulting in a different mode of failure though no creep, as such, is noted.

EXPERIMENTAL METHOD

If we are to determine the true value of compressive stress, then we must load the specimen uniaxially and exclude lateral forces. To do this it is only necessary to load a cylinder between two parallel plates. The loading will be applied to the ends and it will be strictly uniaxial. Unfortunately it is not as simple as it sounds: the rod, instead of failing by simple uniaxial compression will merely split at the ends and splinter in detail as is typical of the form of fracture for many compressive tests with brittle materials. The reason is that there will be stress concentrations at the edge of the specimen where it contacts the anvil and the stress under this concentration will cause it to break. If it were possible to estimate the magnitude of the concentration, then we could estimate the stresses at that point.

This, however, is not practical as it depends on the conditions of the surface both of the specimen and of the anvil.

To avoid the splitting off of the edges of the specimen and to ensure that the specimen would fail in the middle, the specimens were necked down at their center so that the axial stress at the center would be about ten times that at the ends. Now, instead of splitting, the stress at the central portion would cause it to fail at that section. By examining the stress distribution, it was apparent that the actual stress was uniaxial and uniform at the central portion and could be computed directly from measured load and area of cross-section. The lateral stresses induced by the curvature were less than 2% of the axial stresses and are ignored. To ensure that the necked specimens would not fail by local buckling, the necks were drawn in two stages and the ends were clamped firmly in a V-block fixture shown in Fig. 1. Values of compression were obtained up to 547,000 psi. 35 specimens of Pyrex glass annealed at 1060°F for two hours were tested. They gave an average compressive strength of 478,400 psi and a standard deviation of 46,700 psi when loaded at the crosshead rate of .1 in. per minute. Some unusual phenomena were noted:

1. The mode of failure often changed when the compressive load exceeded about 450,000 psi uniaxial compression leading to a coherent structure rather than splintering.
2. Glass exhibited triboluminescence upon failure.
3. Estimated tensile stresses exceeding an estimated 700,000 psi were supported in the interior of glass rods before a crack appeared. This estimate is based on continuum theory.
4. No creep could be observed after loading to between 400,000 and 500,000 psi for 1 sec.

MODES OF FAILURE UNDER HIGH COMPRESSIVE LOADING

When glass is compressed to failure the typical fracture results in an explosive splintering of the specimen. Such a fracture is shown in Fig. 2. When the specimen and its loading is controlled so that the loading exceeds about 450,000 psi then quite a different form of fracture occurs: This is shown in Fig. 3. Here, instead of the glass forming thin splinters, the cracks are transverse to the specimen and appear as if they resulted from a tensile standing wave excited by incipient fracture. The central portion, where the stress was highest, did not explode and scatter itself. Instead it turned to a fine powder and remained essentially intact as shown in Fig. 3. This is an extraordinary phenomenon and quite unexpected. It suggests that the strain energy in the glass during loading is relieved by the formation of surface during failure. The postulate of ductile failure suggested by Marsh (4) is contradicted in that ductile failure and the relatively low rate of straining would preclude the explosive shortening indicated by the formation of tensile cracks in the specimen. The values of strength do, however, correspond well with his predictions and it may well be that the different mode of failure is, in fact, a flow initiated phenomenon.

TRIBOLUMINESCENCE

During the actual failure of the necked-down glass specimen a camera was left open during the failure of a necked-down specimen and the light generated by the failure resulted in the photographs of Figs. 4 and 5. Fig. 4 also has an exposure made before fracture.

It can be seen that the light is generated, not from the point of greatest stress but from the areas adjacent. The point of greatest stress at the narrowest part of the neck is a band of darkness. The reasons for this phenomenon are not understood.

LACK OF CREEP

Six specimens were loaded to values over 400,000 psi at the neck held for 1 sec. and then unloaded. Their original and final lengths were noted and no change in length was observable. Measurement was done to an accuracy of 0.0001 in. over a total length of 2 ins. This implied that a maximum creep of less than .001 in/in. over the neck of the specimen during load. While this does not forbid the existence of creep, it demonstrates that it is small at stress loads that are below Marsh's yield values.

THE EFFECTS OF COMPRESSION ON GLASS

In an attempt to show the dependence of failure upon a flaw in the glass, a hole of diameter .025 in. was drilled in the neck of a specimen so that it penetrated approximately half way through the neck. The specimen was axially loaded and the loading was stopped just as an incipient crack developed in the neck.

If the stress around a cylindrical hole placed in a uniform stress field, S, is analysed it is shown by Wahl and Beeuwkes (5) that there is stress concentration of 3S at the transverse edge of the hole diminishing in a predictable manner from this point. This stress concentration does not depend on the size of the hole but merely on its presence in an elastic continuum. If now a smaller hole in the form of a microscopic void existed near the transverse edge of the hole, then there would again be a multiplying factor of about 45/22 on the stress at that point provided the size of the smaller void was sufficiently small so that the stress field near the larger hole would not be affected by the influence of the smaller one. Such a field is shown schematically in Fig. 6.

Under these circumstances we can expect a compressive stress of about 6.14S near the edge of the smaller hole in the longitudinal direction and about 2.04S at the upper edge of the smaller hole and this latter stress would be acting in tension.

Such stresses can be very large indeed and their results can be seen in Fig. 7. Here a necked specimen with a 0.025 in. diameter hole drilled part way through the neck was subjected to such a stress that the longitudinal stress at the neck was 115,000 psi. The crack, instead of starting at the upper edge of the hole from the tensile stress of 115,000 psi that continuum theory predicts, started at a point away from the edge of the hole, skirted the hole and then continued in a longitudinal manner. The load was relieved by a flake coming off the side of the specimen before the specimen failed entirely. It will be noted that a second and similar hole had been started near the principal hole.

There are several observations that can be made on the behavior of glass from this specimen: the transverse edge of the hole was exposed to a compression stress of about 345,000 psi and yet exhibited no crack. If plastic flow had occurred, then we could expect a crack to appear at this point of compressive loading when the load was removed. The crack would be perpendicular to the direction of applied compressive loading. This is not the case and the crack develops parallel to the compressive loading and nucleates at a point away from the edge of the hole. This suggests a mechanism of a smaller void producing a tensile stress sufficient to cause fracture. In this case the fracture would be parallel to the length of the rod as is actually observed. If these cracks are indeed nucleated by a flaw in the interior near the zone of high compression, then a compressive concentration would again occur near the void that we could again expect to cause compressive flow. If this occurred, then there would again be a crack perpendicular to the length of the rod upon unloading. This is not the case hence we apparently again have strong evidence that such flow does not occur, however, again we are in a stress-time domain where yield need not occur.

The fact that the crack nucleated in the interior of the glass rather than at the surface indicates that cracks can indeed nucleate at interior points but the tensile stress required is greater than that needed at the surface.

An additional observation is also possible from Fig. 7. On the two surfaces of the specimen on each side of the transverse hole, there appears a roughness where small splinters of glass have spalled off during compression leaving a rough surface. This effect was not observed with necked specimens that had been compressed to failure. The surface would be quite smooth in all cases so it would be reasonable to attribute the failure in the drilled specimen to the surface flaws created by the handling during drilling. The undrilled specimens would be transferred from the extending apparatus directly to the compression fixture with precautions being taken to avoid touching or in any way damaging the surface.

DISCUSSION

It is significant that strengths of the order of magnitude of those predicted by Marsh should occur with specimens under compression and a novel form of fracture be demonstrated at those values. The mode of failure gave a coherent, white mass of glass instead of the usual splintering. The fact of the splintering suggests that the glass is failing by splinter spalling off the top of the specimen where it is in contact with the anvil as shown in Figs. 8 and 2 or it may be failing by buckling. Buckling can occur even with carefully clamped and necked specimens and they fail at consistently lower strength values of about 300,000 psi. The fact that the specimens were in fact buckling was only detectable by high speed photography at 4000 frames per second when a configuration shown in Fig. 9 was obtained immediately before failure. The buckling was sudden and quite undetectable by ordinary observation. When the experiment was modified, so that splintering and buckling did not occur, then we got consistently higher strength values.

Marsh suggests that there is a time dependence for yielding and that the yielding might be sudden when it does occur. This we can confirm by noting no creep at values between 400,000 and 500,000 psi which are below the predicted yield limits whereas the yield was sudden enough when it did occur, to give tensile cracks in the specimen and such a release of energy that a flash of light resulted.

CONCLUSIONS

1. Uniaxial compressive strengths of 547,000 psi have been obtained on pyrex glass.
2. A novel mode of failure has been observed at these high levels of compressive stress suggesting ductile failure.
3. Triboluminescence has been observed upon failure under these high compressive stresses.
4. No creep has been observed under compressive stresses between 400,000 and 500,000 psi for 1 sec.
5. Compressive stress concentrations exceeding 345,000 psi can be estimated around drilled holes and cracks are caused in the interior of rods by induced tensile stresses at voids.
6. Values obtained and the phenomena observed serve to substantiate Marsh's theory of plastic flow.

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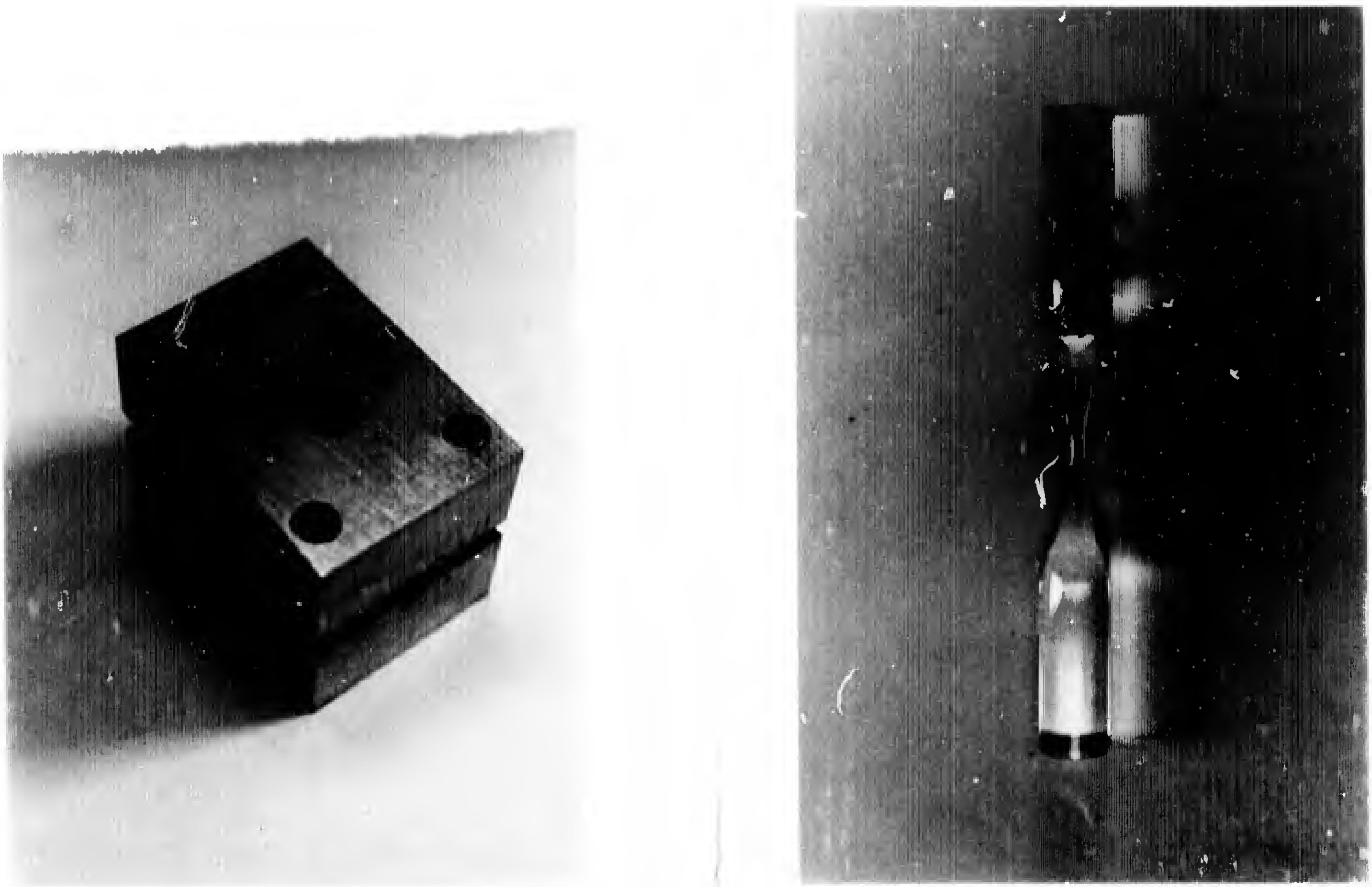

Fig. 1. Holding fixture to prevent buckling and typical double necked specimen.

Fig. 2. Typical splintered fracture.

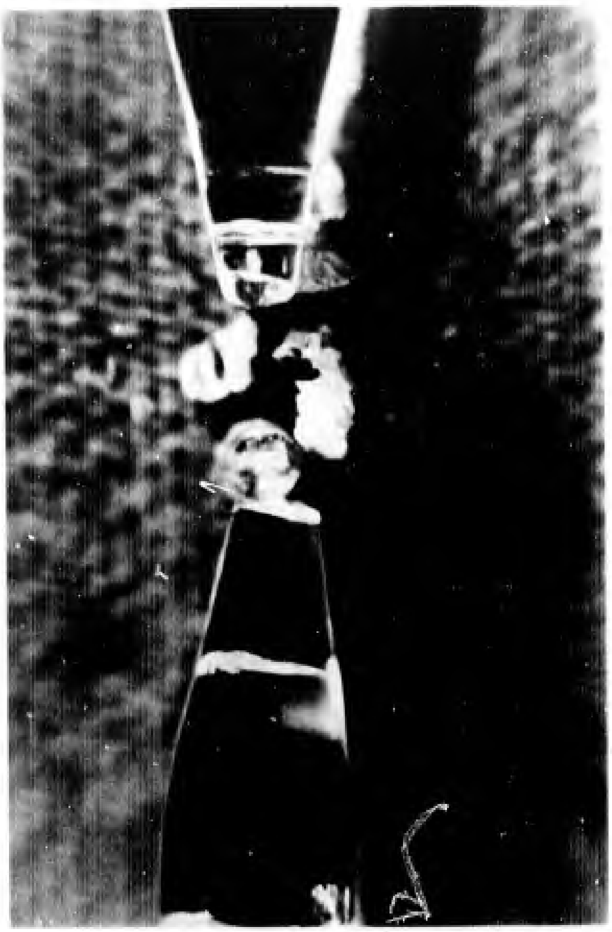

Fig. 3. Typical coherent fracture.

Fig. 4. Self-exposure of glass rod on fracture superimposed on flash photograph taken before loading.

Fig. 5. Self exposure of glass rod on fracture.

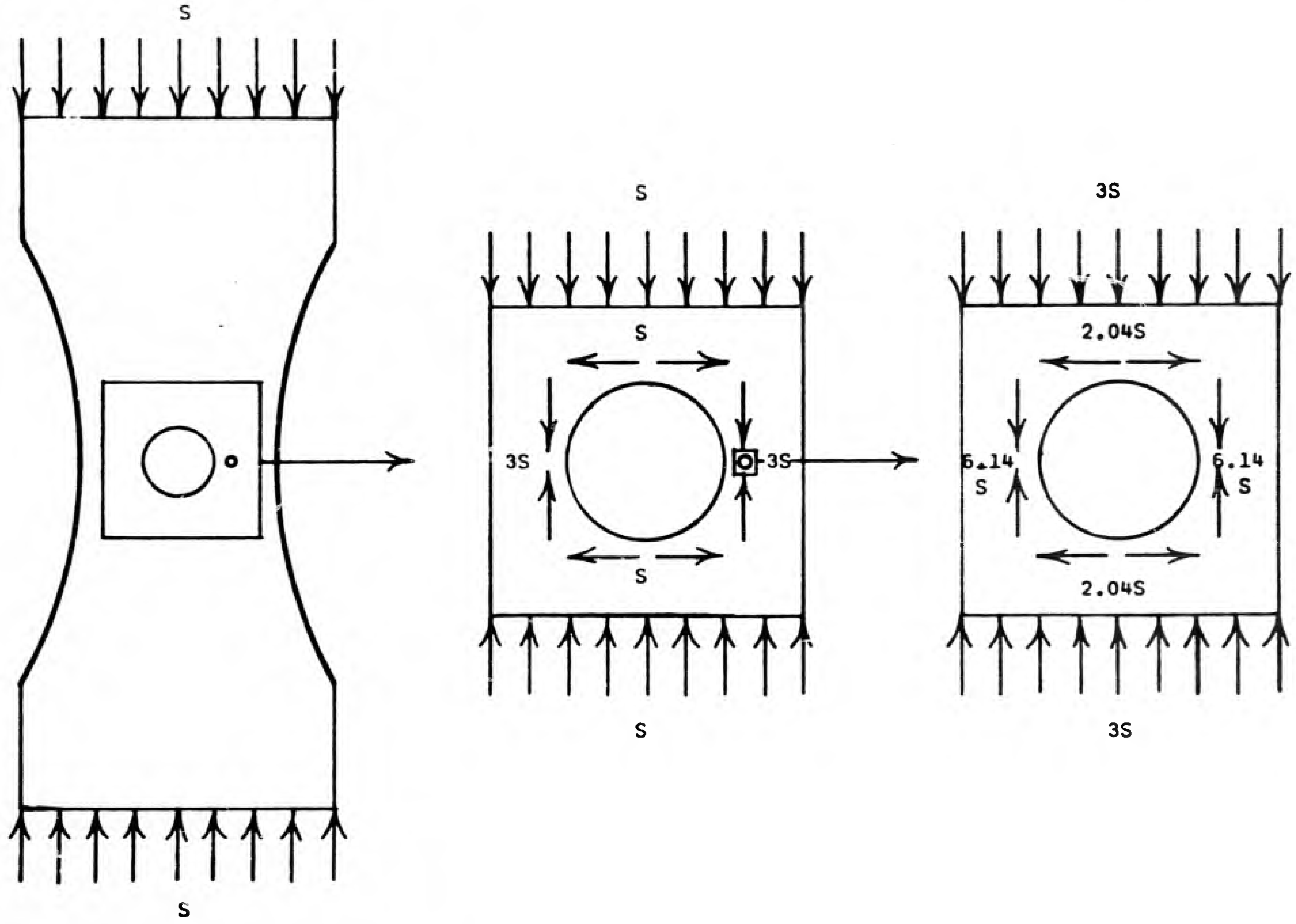

FIGURE 6 SCHEMATIC OF STRESS CONCENTRATION AROUND A CYLINDRICAL HOLE IN A NECKED CYLINDER WITH A SMALLER SPHERICAL CAVITY NEXT TO IT

Fig. 7. Crack initiation around drilled hole.

Fig. 8. Start of spalling at end of rod.

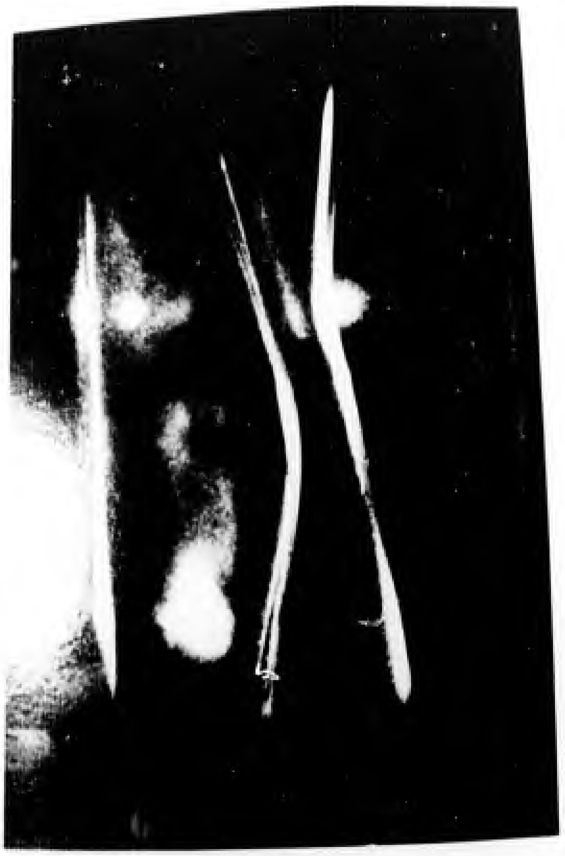

Fig. 9. Typical buckling of a necked rod immediately prior to failure.

Taken at 4000 frames per second.