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DELAMINATION STUDIES OF IMPACTED COMPOSITE PLATES,(U)
AUG 76 C A ROSS, R L SIERAKOWSKI DAAG29-76-G-0085

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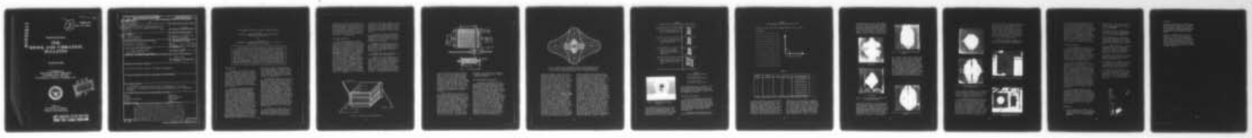

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Both steel-epoxy and fiberglass-epoxy composite crossplied plates were impacted with blunt ended cylindrical impactors at velocities below the critical penetration velocity. Failure mechanisms in the form of lamina delamination were observed for thirteen different types of ply arrangements. Lamina delamination was found to be the dominant failure mode and fiber breakage or pullout occurred only in the area in direct contact with the impactor. It was found for impacted fiberglass-epoxy plates that the number of plies within a given lamina, especially the first several laminae, are very important in the resulting progressive delamination. The extent of the damage appears to be related to kinetic energy imparted to the plate by the impactor.

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* DELAMINATION STUDIES OF IMPACTED COMPOSITE PLATES

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Both steel-epoxy and fiberglass-epoxy composite crossplied plates were impacted with blunt ended cylindrical impactors at velocities below the critical penetration velocity. Failure mechanisms in the form of lamina delamination were observed for thirteen different types of ply arrangements. Lamina delamination was found to be the dominant failure mode and fiber breakage or pullout occurred only in the area in direct contact with the impactor. It was found for impacted fiberglass-epoxy plates that the number of plies within a given lamina, especially the first several laminae, are very important in the resulting progressive delamination. The extent of the damage appears to be related to kinetic energy imparted to the plate by the impactor.

INTRODUCTION

The impact resistance of single component materials in general depends upon many material properties such as fracture strength, hardness, ductility; with particular properties being more important within certain impact velocity ranges. However, impact resistance of composite materials is not only dependent on the specific constituent material properties but also on the geometrical arrangement of the imbedded fiber arrays.

Some early experimental studies dealing with the impact resistance and penetration characteristics of composite plates have been reported. Gupta and Davids [1] have studies the penetration resistance of fiberglass plates of varying thickness and density. Further investigations on the impact resistance characteristics of fiberglass plates were conducted by Wrzesien [2] who examined the influence of placing steel sheeting in glass fiber composites. A noticeable improvement in the impact resistance of such reinforced type plates was observed. Additional studies on the impact resistance of fiberglass plates examining the influence of filament orientation and volume fraction have been reported by Ross and Sierakowski [3]. It was found that certain ply arrangements have greater impact resistance for the same volume fraction of fibers. Studies on impacted graphite-epoxy plate composites with comparison to dynamic diagnostic tests have been reported by Askins and Schwartz [4].

Most recently Hearle and Sultan [5] have examined the impact resistant properties of woven and non-woven textile materials. They have reported an improvement in penetration resistance for fiber materials having a stiffening effect at high elongations. A recent theoretical model proposed by Roylance, et al., [6], shows promise for examining the impact resistance of some textile type fiber composites. The principle thrusts of the above investigation have been directed toward examining the penetration and/or impact resistance of fiber reinforced composites. In order to understand the impact resistance mechanisms which occur during progressive failure in fiber composites, impact models and diagnostic tests have been proposed and reported on by Cristescu et al. [7,8].

In the present investigation, the above studies are extended to examine the mode of progressive failure in structurally layered fiber composites and the sequential layering effects

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dominant in controlling the impact resistant properties of such materials at velocities below the penetration limits of the specimens. The qualitative description of events occurring answers several questions raised in a previous investigation by Cristescu, et al. [7] and forms the basis of a quantitative description to be developed.

SPECIMEN FABRICATION

Some of the terms used to describe the various elements of a composite plate are included at this point to clarify the fabrication process described in this section and the failure mechanisms described in later sections. Attention is also directed to Figure 1 for further clarification. A plate or laminate is defined to be a flat piece of composite material, containing one or more layers and/or lamina, whose thickness is small compared to the other dimensions. A lamina represents a given thickness of a composite plate or laminate, containing one or more layers whose fibers are all aligned in the same direction. A layer or ply is defined as a given thickness of a composite plate or laminate containing only one filament thickness. A fiber or filament represents the reinforcing phase of the material and is held in place by the matrix. All the filaments or fibers used in this study are continuous and are uniaxially aligned in each layer with a 90° orientation difference between lamina. Plates having a 90° orientation difference between laminae are usually referred to as cross plied plates.

Two types of plate test specimens were fabricated to be representative of an extensible and inextensible fiber imbedded in a brittle matrix as shown schematically in Figure 2. The plate materials studied were:

Fibers - Owens-Corning Fiberglass, Type ECG-150 precision-controlled roving, density 2540 kg/m³ and elastic modulus 72.4 GPa; Stainless-steel type 304, density 7833 kg/m³ and elastic modulus 206.2 GPa.

Matrix - Shell Epon 828 Epoxy, and Magnolia Plastics Curing Agent D.

Several size plate configurations of different cross ply orientations were prepared of nominal dimensions .15m square and .30m square and containing fifty per cent by volume fraction of fiber. A special 6061-T6 aluminum plate fixture attached to a lathe assembly was used in preparing the specimens, with lathe speed and cross feed adjusted to insure controlled fiber spacing. Layer spacing was controlled

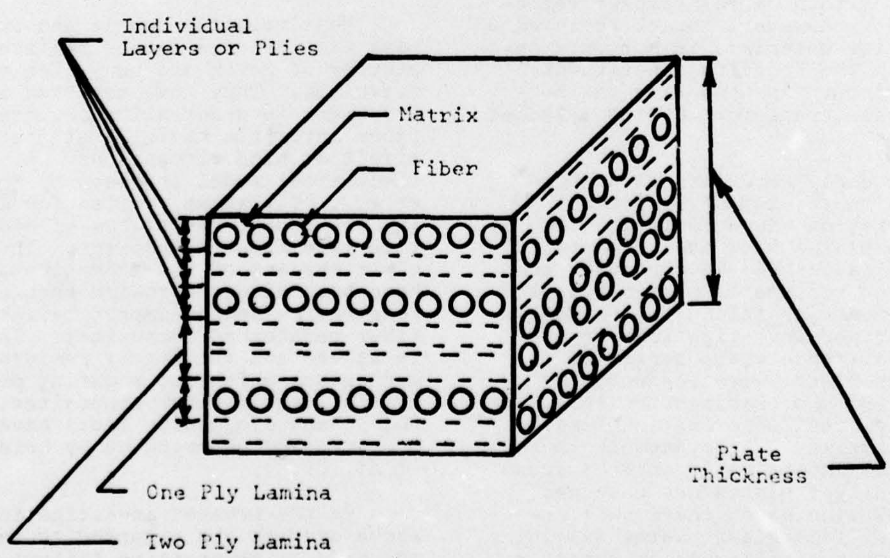


Fig. 1 - Composite plate nomenclature

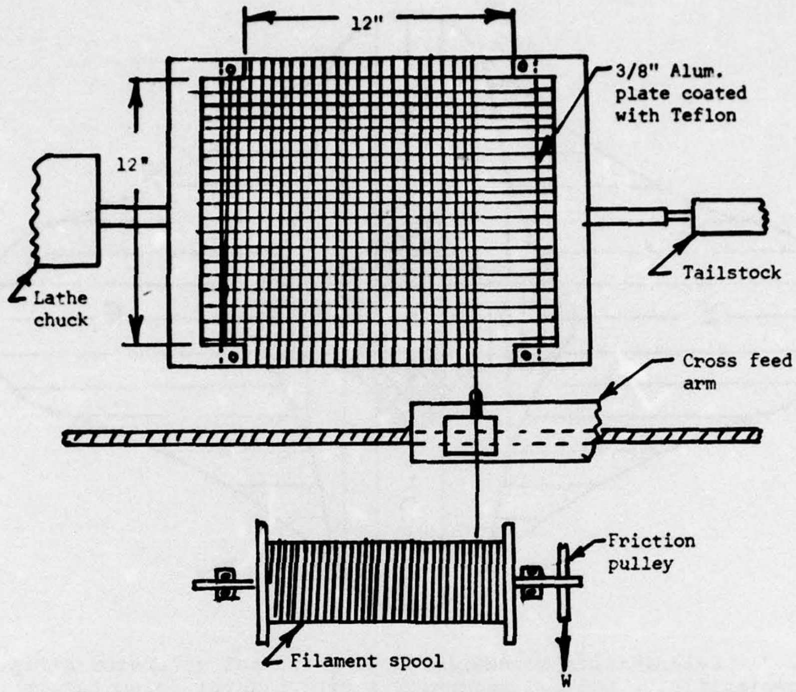


Fig. 2 - Winding assembly

by use of shim stock placed along the edges of the mandrel assembly (nominally 4×10^{-4}m). For the steel-epoxy specimens, the epoxy matrix material was poured over the wound steel wire assembly with the edges of the assembly sealed for leakage, while for the fiberglass specimens the epoxy matrix was brushed on after each successive layer had been wound. In order to construct a specific laminate, (0° - 90° ply orientations) the mandrel assembly was rotated as necessary in the holder assembly.

After completing the plate lay up, which consisted of 15 layers total thickness of approximately $.67 \times 10^{-2}$m, cover plates of either aluminum (6061-T6) or wood, of nominal dimensions comparable to the mandrel were clamped to the specimen and adjusted to predetermined thickness stops. Both cover plates and mandrel assembly were sprayed with teflon release agent to insure easy removal of the fabricated specimens from the mandrel assembly. The mold assembly was then placed in a furnace to cure at 150°F for 2 hours and then air cooled. In addition to the .15m square and .30m square plate specimens, some smaller bar specimens of nominal dimensions .15m x .025m x .005m were prepared.

TEST BACKGROUND AND PROCEDURES

It has been recognized that impacted composite plates may fail due to existence of several different failure mechanisms occurring separately or in some combination such as: shear cut-out of a plug; fiber debonding, stretching, and/or breaking and fiber pull out; delamination; and matrix failure. In a previous paper [7] a delamination mechanism was introduced and described as an important feature which may account for the improved impact resistance of a class of multilamina plates having several fiber layers in each lamina. Elements of this mechanism have been also observed for other than fiberglass composite systems in [4]. The essential features of this mechanism shown in Figure 3, for the case of moderate impact velocities (i.e., below plate penetration), consist of an initial shearing action as the penetrator cuts through the first layers of the composite, followed by delamination of

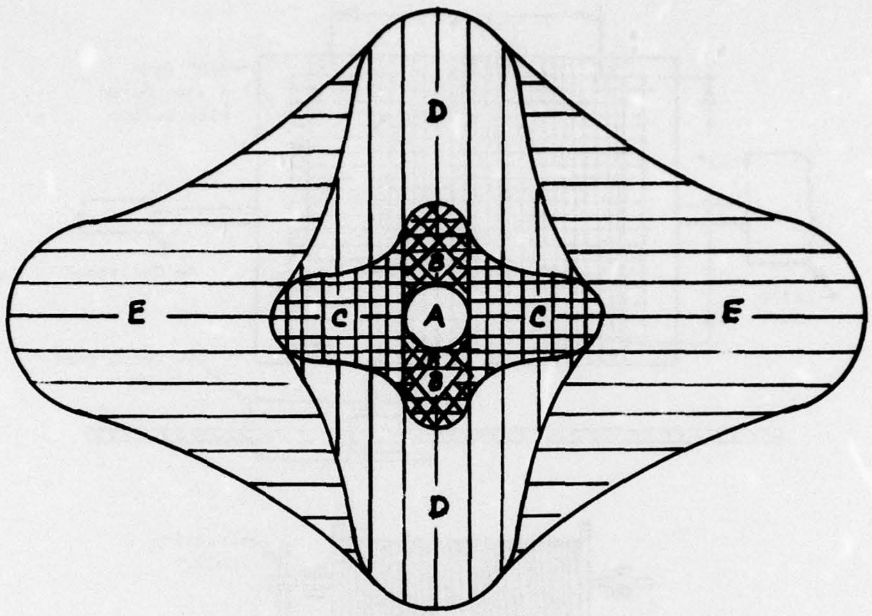
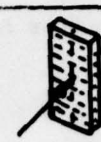
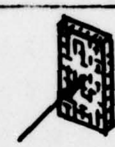
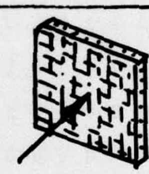


Fig. 3 - Delamination schematic showing initial generator strip. A projectile; B initial generator strip; C first delamination area; D second delamination area; E third delamination area

successive laminae. Upon impact the projectile pushes a strip of the first lamina one projectile diameter wide rearward and the length of this strip is partially dependent on the time for the projectile to cut through the first lamina. This first stage of the delamination process, area B of Figure 3, in turn loads transversely the second lamina along the length of this strip and generates a delamination in the second lamina. The generation of the delamination process in the second lamina by a strip in the first lamina leads to the term first generator strip to define this strip. Subsequent generator strips are formed as delamination occurs rearward from one lamina to another. The successive lengths of these generator strips appear to follow some type of arithmetic or geometric progression, with limiting repeated delamination determined by the total number of lamina and by the plate boundary. An important feature of this failure mechanism is that the sequence of events occur in a front to back manner as opposed to monolithic materials in which spalling occurs due to reflected tensile waves. To examine many of these questions an extensive series of impact tests using 2.54cm x .97cm diameter blunt ended penetrators have been performed on plates of various ply arrangements to examine (a) the successive stages as they develop in the delamination mechanism, (b) the influence of sequential lamina stacking on controlling the generator strip mechanism and (c) the effect of changes in fiber length on the observed delamination mechanisms. Initial testing reported on in [8] described some diagnostic type tests which were conducted in this study in order to better understand the mechanism of sequential lamina delamination. Controlled coupon specimens of nominal size (.25m x .1m x .005m) with three lamina consisting of different fiber numbers and orientation were impact tested at low velocities as shown in Table I. For these tests the top lamina or top and bottom lamina, were machined away to observe the threshold loading for noting the tendency to form a generator strip. For the specimens tested, an impact velocity of 12.7m/sec was found necessary to initiate the tendency for formation of a generator strip. Since for the most part the steel epoxy specimens appeared to show a symmetrical fracture pattern as shown in Figure 4,

TABLE 1
Specimen Types Used for Dynamic Impact Tests

a). Single fiber sandwiched between two multifilament lamina in a matrix; steel and glass fiber	
b). Three fibers sandwiched between two multifilament lamina in a matrix; steel fiber	
c). Multiple fibers sandwiched between two multifilament lamina in a matrix; steel and glass fiber	
d). Impact tests on 0°-90° cross-plied multifilament in a matrix plate; steel-epoxy and glass epoxy	

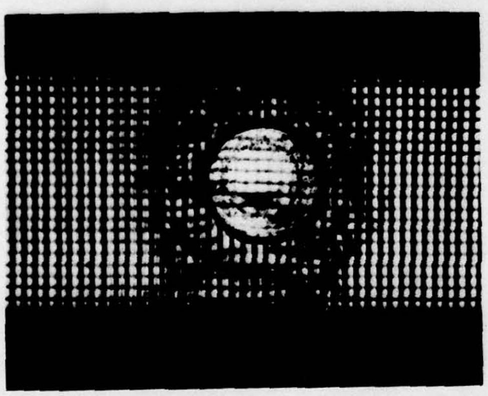


Fig. 4 - Impacted Steel Epoxy Specimen

the remainder of the tests were conducted on fiberglass specimens. For this reason, fiberglass plate specimens of different geometries have been selected for further study, as indicated in Table 2, with the tested

TABLE 2
Plate Geometries Studied

(a) Square Plate
(.15 m x .15 m x .006 m)

(b) Square Plate
(.30 m x .30 m x .006 m)

ply arrangements given in Table 3. All plates were fixed along all edges and were impacted with similar blunt ended penetrators of mass 14.8g, length 2.54cm and diameter of .97cm.

DISCUSSION AND RESULTS

In the delamination mechanism described here, the influence of reflected dilatational and shear waves from the lamina interfaces and interlamina shear waves appears to be minimal. Therefore principal attention has been focused upon the generator strip mechanism and stacking sequence importance in ply delamination.

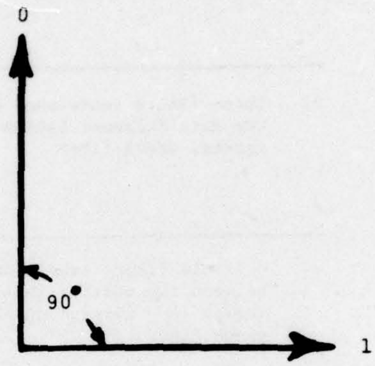
To examine these mechanisms the plate configurations indicated in Table

TABLE 3
Ply Arrangements for Glass Roving Plates

Sequence as shown runs from impacted side to back of plate

Pure Epoxy

1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
1	0	0	1	1	1	0	0	0	0	1	1	1	1	1
1	1	0	1	1	0	1	1	0	1	1	0	1	1	0
1	1	0	0	1	1	0	0	1	1	0	0	1	1	0
1	1	1	0	1	1	1	0	1	1	1	0	1	1	1
1	1	1	0	0	1	1	1	0	0	1	1	1	0	0
1	1	1	0	0	0	1	1	1	0	0	0	1	1	1
1	1	1	0	0	0	0	1	1	1	0	0	0	0	1
1	1	1	1	0	0	0	0	1	1	1	1	0	0	0
1	1	1	1	1	0	1	1	1	1	1	0	1	1	1
1	1	1	1	1	0	0	0	0	0	1	1	1	1	1
1	1	1	1	1	1	1	1	0	0	0	0	0	0	0



Filament directions

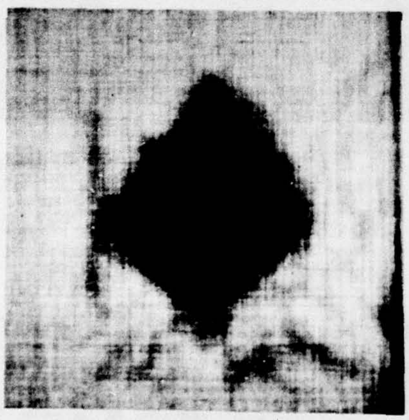
TABLE 4

Plate Type	No. of Lamina	Strip length (m)	Ply Arrangement[a]
a	4	.119	111100001111000
b	5	.038	100111000011111
c	5	.114	111000111000111
d	6	.127	111001110011100
e	7	.114	111011101110111
f	8	.091	110011001100110
g	15	.043	101010101010101

a) Layer or ply sequence runs from impacted side to back of plate.

4, which constitute a part of the listing in Table 3, are discussed. For studies of these plates a fixed impact velocity of 110 m/sec was used. In comparison impact failure of pure epoxy plates occurred at 28 m/sec and for fiberglass epoxy plates with a single lamina (all fifteen fiber layers in the same direction) failure occurred at 60 m/sec. The second column of Table 4 indicates the total number of representative lamina with different numbers of individual layers for plates identified for convenience by the symbols a through g. If we compare plates b and g each of which start with a single initial layer (a 1 type direction lamina containing only one layer), and approximately the same generator strip length, the resultant delamination in case b is found to be greater than in g due to the additional thickness of the second lamina in b which allowed development of the generator strip through the additional plies contained within each lamina of b as shown in Figure 5. Further if we examine plate e, Figure 6, which has a single ply lamina alternating between

(Plate b)



(Plate g)

Fig. 5 - Ply delamination for plates b and g respectively

multi-ply laminae, we note that the initial generator strip is approximately three times that developed in plates types b and g. However, because of the single ply alternating secondary lamina, the delamination in the direction perpendicular to the initial multi-ply lamina direction is not fully developed as shown in Figure 6. If we compare

Fig. 6 - Ply delamination for plate type e

plate types e and c with the same number of plies in the first lamina (impact side), with one plate containing more plies or layers in the second lamina, that is c versus e, we can observe a greater overall delamination occurring in case c as shown in Figure 7. Comparison of delamination patterns of plates type c, d, and e indicates that the second lamina stacking sequence constrains the resultant delamination growth once the generator strip has developed. Plate types a and f further reinforce this observation with

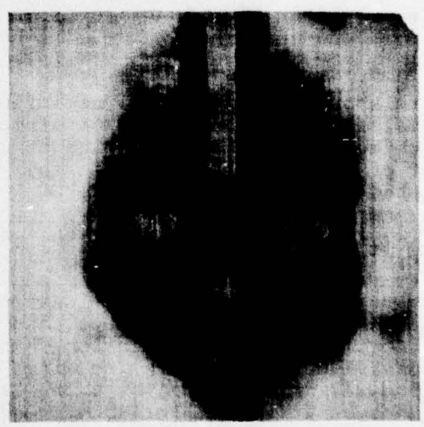


Fig. 7 - Ply delamination for plate type c

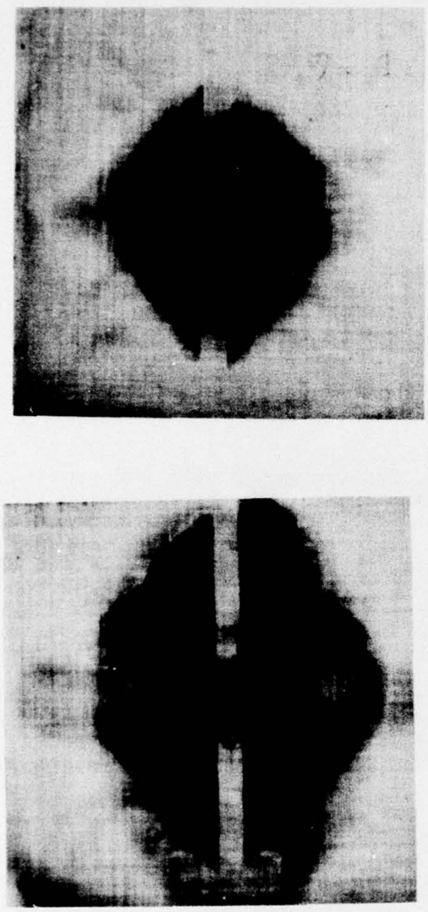


Fig. 8 - Delamination on plate types f and a respectively

results shown in Figure 8. The influence of development of the generator strip through multiple plies of lamina on the extent of damage is apparent in the elongated damaged area of plate c.

Two additional aspects of the generator strip mechanism were investigated as they relate to the specimen size necessary to observe the delamination sequence; edge boundary effects, and the effect of changing fiber length on progressive delamination. The first question was investigated by using large specimens as indicated in Table 2. Impacting such specimens with penetrators used in the smaller plate studies and at comparable impact velocities (110 m/sec) produced the same equivalent damage level. This is evident in Figure 9 which shows a typical impacted large plate of type c from Table 4. As to changing fiber length, several circular holder assemblies of varying diameter (.010, .013, .015m), Figure 10, were used to change the fiber length during impact using penetrators projected at 110 m/sec. Once again the same delamination mechanism was evident.

Finally, to evaluate stages in the progressive delamination sequence of events, plates of type c from Table 4

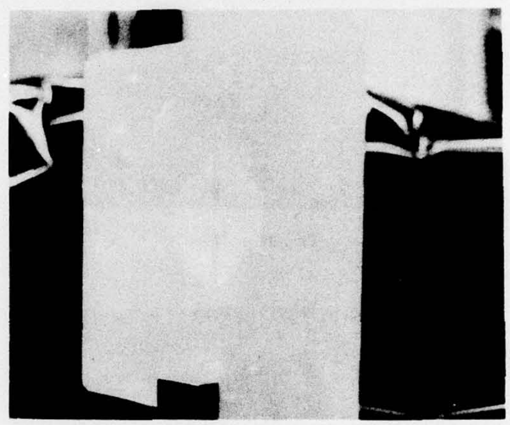


Fig. 9 - Impacted large plate specimen

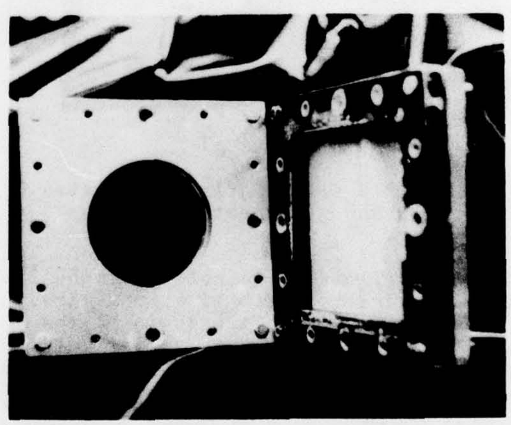


Fig. 10 - Typical specimen holder assemblies

were impacted using blunt penetrators at successive incremental impacts of 50 m/sec starting from 150 m/sec up to 450 m/sec at which point incipient penetration was evident. The generator strip mechanism was found to form with progressive delamination occurring from the impacted face to the rear of the plate in a systematic incremental progression. The progression appears first to be arithmetic until sufficient damage has occurred that boundary effects begin to influence ply delamination near the penetration velocity.

CONCLUDING REMARKS

The deformation and failure of monolithic homogeneous isotropic plate under normal impact is quite regular resulting in very symmetrical crack patterns, damaged areas, and spall patterns. For multi layered composite plates the resulting damaged area may become highly unsymmetrical by simply changing the ply arrangement or by varying some lamina thicknesses.

For static loading, the ply arrangement is very important in determining plate stiffness but in the analysis the loading direction is unimportant; whereas for impact loading plate damage is highly dependent upon the ply arrangement on the side of the plate being loaded. Also, for dynamically impacted systems it appears that the number of plies within a given lamina, particularly the first several laminae, are very important in the formation of the generator strip and the resulting progressive delamination. Specifically, this latter growth phenomenon (total damaged area) appears to be related to the amount of kinetic energy imparted to the plate by the impactor.

In this paper only the 0°-90° lamina orientation difference was investigated, however other orientation differences should produce very similar delamination sequences. The generator strip formation may not be as distinct as in the crossplied case but the load transfer and delamination of adjacent laminae are expected to be very similar to that observed in the crossplied plates.

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Discussion

Mr. Keith (Kaman Sciences): The results you showed were for point loadings on the plates; in the first part of your talk, you talked about flier plate loadings or impulsive loads, area loadings. Were the results that you obtained from the area loadings of the same tread?

Mr. Ross: I probably mislead you there. I intended to say at that point we were only in that one area and we were talking about central impact with a point load. We have not looked at the so called blast or flier plate loading; there has been some work on either boron or graphite plates under pressure loading and I think it is in the April 1975 Journal of Composite Materials.