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Graphite/Epoxy (0° /90°)$_{2s}$ 에 있어서의 Stress Rate 의 Stress-Strain 관계에 대한 영향과 Transversal Damage 의 발전 과정에 대한 고찰

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Stress Rate Effects on Stress-Strain Responses and Transversal Damage Development Observation in Graphite/Epoxy (0°/90°)$_{2s}$

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Abstract : Stress rate effect ($\dot{S}$=0.1 MP$_a$/sec. and 100 MP$_a$/sec.) for the mechanical behavior and the fracture in the graphite/epoxy cross-ply laminates T300/5208 (0° /90°)$_{2s}$ is studied. This effect is slightly shown in transversal behavior and not in longitudinal behavior. There is no stiffness reduction in longitudinal behavior due to transversal cracking in 90° plies. The fiber stiffening effects compensate the matrix damage in the stiffness variation. In addition, the transversal damage development during monotonic tensile loading with very low stress rate is examined microscopically. The experimental data shows five steps in the transversal crack development.

INTRODUCTION

Laminates of the (0°/90°)$_{2s}$ is one of the principal form of construction for advanced fiber composites used for structural applications. In this cross-ply laminates the development of transversal cracks in 90° plies would be a good indication for the damage procedure. Many efforts[1] have been made to find out what parameters influence this cracking. With relatively low 90° ply thickness, this transversal cracking would be constrained. Parvizi[1] showed this effect in cross-ply glass-reinforced epoxy resins. Similar results were presented by Bader[2] for cross-ply laminates.

Flaggs[3,4] presented the results of experimental study and theoretical analysis for the crack initiation in the 90° ply with the various ply thickness. Graphite/epoxy cross-ply laminates show multiple crackings in the 90° ply before final rupture occurs.[5] Wang[7] predicted the transversal crack density as a function of applied stress in several 90° ply thickness by the simulation method. These works have done for the systems of one 90° ply with various thickness surrounded by two 0° outer plies.

For the structure of (0°/90°)$_{2s}$, there are two 90° plies of different thickness. These two different 90° plies should interact in the crack development. Yoon[8] observed the crack density variation in this system with the incremental loadings. These results show that the matrix cracking is a main failure process observable in this monotonic tensile loading. The longitudinal behavior is dominated by the fiber characteristics. The transversal behavior is influenced by the matrix cracking. Whitney[9] showed that the longitudinal behavior of graphite/epoxy cross-ply was different with that of the glass/epoxy and the boron/epoxy. But the similarity in the transversal behavior in above three systems was shown. This facts demonstrates that the matrix characteristics influence the transversal behavior. And this transversal damage would cause the final rupture. The inherent viscoelasticity of polymer matrix can affect this transversal damage[10].

In this study, the stress rate is varied 1000 times to verify this effect for the stress-strain behavior and the rupture of the specimens. The very low stress rate with monotonic increasement without arrest was chosen to observe exactly the transversal crack development without stress redistribution due to the arrest. It would be a basis for the further theoretical prediction of the damage process in this system.

EXPERIMENTAL PROCEDURE

The material system used in this study is $(0°/90°)_{2s}$ with stacking sequence 0°/90°/0°/90°/90°/0°/90°/0°, T300/5208, graphite/epoxy (Vf=0.67), supplied by ONERA of france. Straight-sided coupon specimens are prepared from the panels using a diamond-impregnated saw. All specimens were 270 mm long and 20 mm wide. Gage length was 135 mm.

The side edges of the specimens were ground with sand paper number 600, 800, 1000 and then polished with 7, 5 and 1 micron polishing powder in order to facilitate microscopic examination. All specimens were inspected under a microscope prior to each test to examine any fabrication-induced cracks and then stored in a conditionning cabinet with R. H, 65% at 23℃.

The specimens were loaded at a constant stress rate without arrest until final rupture. The stress rates are 0.1 MP_a/sec. ($=\dot{S}_1$) and 100 MP_a/sec. ($=\dot{S}_2$). The test was done by using the hydraulic testing machine, Instron. The strain gages were used to detect the deformations of the specimens. The replication of the side edges of specimens at $\dot{S}_1$ was taken by the acetone swollen cellulose acetate in the regular interval. Microscopic observation was done for these replicas and then for the ruptured specimens.

RESULTS AND DISCUSSION

Longitudinal stress-strain curves for uniaxial tension of balanced symmetric laminates $(0°/90°)_{2s}$ are shown in Fig. 1 for two stress rates ($\dot{S}_1$ and $\dot{S}_2$). To clearly demonstrate the stress rate effect, the $\dot{S}_2$ is chosen 1000 times of $\dot{S}_1$ The specimens demonstrate the elastic behavior in the longitudinal direction nearly until the final rupture. So the Young's modulus is the most imp ortant factor to consider. The results are summarized in Table 1.

The average Young's modulus of $\dot{S}_1$ is 76.9±2.2 and that of $\dot{S}_2$ is 78.7±3.4. One can see that this difference is small in comparing with the deviations. It means that the stress rate would not alternate the Young's modulus.

Whitney[9] showed that the longitudinal stress-strain curves in graphite/epoxy cross-ply are different from that of glass/epoxy and boron/epoxy laminates. Generally in fiber reinforced laminates the first crack appears in 90° ply where the load

Table 1. Results of the Monotonic Tensile Test

No.	$\dot{S}$(MP_a/sec.)	E_0 (GP_a)	S_{ult}(MP_a)
1	0.1	76.1	728
2	0.1	76.1	514
3	0.1	81.1	724
4	0.1	74.6	691
5	0.1	76.4	621
6	100	74.9	663
7	100	80.8	729
8	100	80.4	635
9	100	74.6	609
10	100	82.9	722

where E_0=Young's modulus
S_{ult}=tensile strength

is sustained only by the matrix. The glass/epoxy and boron/epoxy laminates display a knee in longitudinal stress-strain response after the 90 ply failure. It's due to the low stiffness of the reinforcing fibers. The modulus of glass fiber is about 3 times of. The matrix modulus.

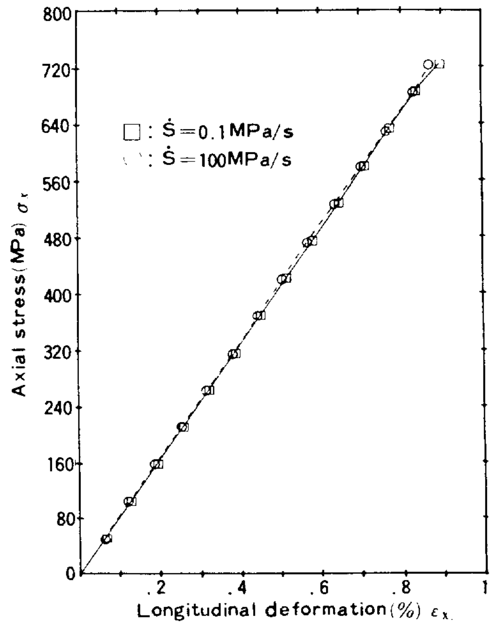

Fig. 1. Stress-strain response in monotonic tensile test.

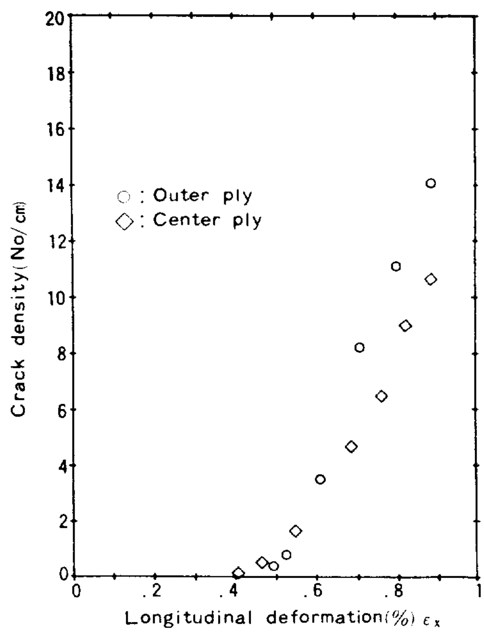

Fig. 2. Transverse crack development in monotonic tensile test.

In the case of graphite/epoxy, the anisotropic ratio E_L/E_T (longitudinal modulus/transversal modulus) is so large that 90° ply failure is not observable in longitudinal strain gage (see Fig. 1). And the fiber modulus is about 37 times of the matrix modulus. Furthermore the carbon fiber stiffenes slightly with the increasing strain. For these reasons the polymer matrix characteristics are concealed in the longitudinal behavior.

To find the correlation between the crack development in 90° ply and the transversal behavior. The replication technics were used for crack observation. The replication was done with very low stress rate, $\dot{S}_1$, without arrest to describe exactly the crack development. The total endruance of one experience is about 2 hours. The time of replication was 0.5 minutes, and then the effect of replication time is negligeable. The load level for each replication is checked with precaution. The variation of the crack density is shown in Fig. 2.

The first crack in the center ply is observed at the applied stress in the vicinity of 300 MP_a. This stress level is about 5 times of the neat resin's tensile strength. It shows that the lamination induced stress is very important for the mechanical behavior of the specimens. The stress level at first ply failure was verified by acoustic emission, which was developed in reference.[11] For the outer 90° plies one can always see the multiple cracks. Although the repeated replications one can not observe the unique crack in these plies. It's an intersting phenomenon. From the extrapolation of the data, the supposed stress level at the first crack appearance of outer 90° plies is slightly higher than that of the center ply (see Fig 2).

The decreasing stress at the onset of 90° ply cracking with increasing thickness is similar to that for cross-ply glass/epoxy.[1] This can be explained with the aid of an energy criterion.[1]

The representative transversal stress-strain res-

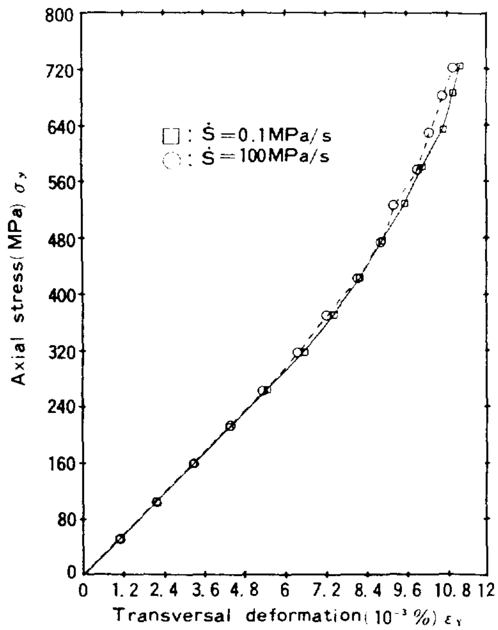

Fig. 3. Stress-strain response in monotonic tensile test.

ponse is presented in Fig 3. The transversal deformation is very low. This means that the error term could be great with usual manipulation of data. The representative data is also elastic until the first crack is the center ply at the stress level of about 300 MP_a. From this load level it demonstrates non-elastic behavior. The response with high stress rate $\dot{S}_2$ is smoother than that with low stress rate $\dot{S}_1$. The poisson's ratio of $\dot{S}_1$ has a tendency to be slightly greater than that of $\dot{S}_2$. It would be attributed to the much apparent matrix crackings effect for the transversal behavior. One can conclude that this fact requires an enough time to act. This is surely a very complex process.

For the structure used in this study, there are two different plies, 90° and 90°/90°. The damage development of these two plies should have an interaction. This fact has not been thoroughly investigated. The replications of damaged specimens at the edge were seriously examined by the microscopic observation. The replicas are fully surveyed to give an representative model of this process for the further. The sample thickness is only 1mm and it is composed of 8 plies. The one ply occupies only 0.125mm thick. But the replication was done for total gage length of 125mm. It's difficult to represent the total transversal crack development by the photographs. And the treatment of the replicas to take the photos could give an flue image. So these are abbreviated for the simplicity of the representation.

With these results one could find that the transversal crack development demonstrate the following five different steps.

(1) At the first 90°/90° ply cracking, the crack does not go through the entire ply, but has an appearance of opening at the center of the ply.

(2) External ply cracks appears secondly and they were lightly skewed.

(3) After the crackings in exernal ply, the center ply cracks go through the entire ply thickness.

(4) When the crack density is important, the light delamination occurs in the resin rich area between two cracks.

(5) Near the total failure, many little cracks suddenley observed in the central 90°/90° ply.

The preceding five steps are sketched schematically in Fig. 4. These phenomena would call further experiences and the deep comprehension of the real demage process is this complex system.

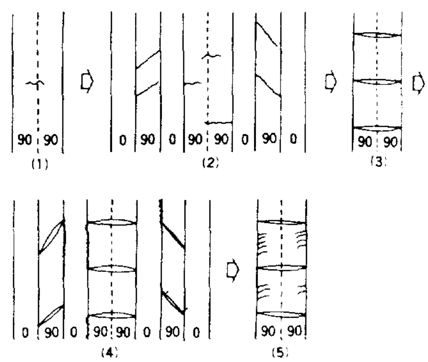

Fig. 4. Scheme of transverse crack development in graphite/epoxy $(0/90)_{2S}$.

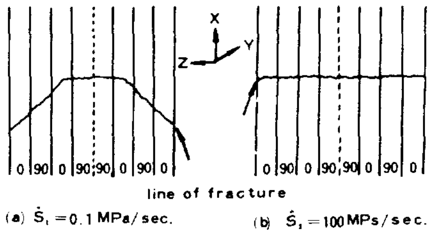

Fig. 5. Stress rate effect for fracture mode.

In the final rupture aspect, the stress rate effect was lightly shown, One could find that the rupture line has a tendency to incline with the very low stress rate, which is not observed with the very high stress rate. It is shown in Fig. 5. To review the concerning data, the tensile strength and the total longitudinal deformation could be chosen. The average tensile strength with $\dot{S}_1$ is 656±81 MPa and that of $\dot{S}_2$ is 672±47 MPa. The average total longtudinal deformation of $\dot{S}_1$ is 0.88±0.05% and that of $\dot{S}_2$ is 0.83±0.05%. The differences in these data is too small to compare with the deviations. It would be wise to suspend the difinite remark until obtaining the more precise and abundant data.

CONCLUSION

In graphite/epoxy laminates $(0°/90°)_{2s}$, there is no stiffness reduction in the longitudinal direction due to the transvesal crack development. With very low stress rate, the crack development demonstrates five different steps, The stress rate effect is observed in the transversal behavior and the final rupture. But the total strength of specimens is not effected by the time effect because of the fiber stiffening effects in this system.

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