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Literature Review

Wave Propagation in Graphite Epoxy Laminates Due to Impact

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REFERENCE: Tan, T. M. and Sun, C. T., Wave Propagation in Graphite Epoxy Laminates Due to Impact, Purdue University, Lafayette, IN.

This review presents some highlights and discussion of an interim contractor's report on a continuing research program being conducted by the authors of the report at Purdue University under the sponsorship of NASA Lewis Research Center, monitored by C. C. Chamis.

The report presents the results of a study of the impact problem in composite materials. The authors begin by making the distinction between "hard object impact," wherein the short contact time results in a problem dominated by a local impact event and a stress field over the remainder of the specimen created by stress wave propagation, and "soft object impact," wherein the dynamic response of the whole structure is important. The focus of their work, and the case most generally associated with impact damage, is the hard-object case, which involves transient wave behavior.

The wave propagation analysis was approached by using the laminated plate theory developed by Whitney and Pagano [*1*], which includes the effects of transverse shear deformations and rotary inertia contributions. Harmonic plane wave solutions were developed for a symmetrically laminated composite plate for which it was assumed that

$$G_{13} = G_{23} = G_{12}.$$

The transient stress wave propagation was described as a shock wave for which the stress components, the particle velocities, and their derivatives are discontinuous. The corresponding dynamical and kinematic conditions across the wave front combined with the laminate constitutive equations (written in terms of the corresponding jump conditions across the wave front) produce five homogeneous equations the uncouple, for the example considered, into three groups that govern the extensional and in-plane shear wave fronts, the bending and twisting moment wave fronts, and the transverse shear wave front. Ray theory is used to construct the respective wave fronts.

Tan and Sun emphasize that if the dynamic load driving the wave phenomenon is caused by an impact, the most important step in analyzing the response is to construct an accurate account of the contact behavior.

The approach taken to the analysis of contact behavior was based on statical indentation tests that were used to construct "contact laws" for impacts in which permanent damage events cause energy dissipation during the impact process. A loading curve of the form

$$F = ka^n \qquad (1)$$

where the contact force F is related to the indentation a by the power n (assumed to be equal to $3/2$) and the factor k, which depends on the material properties of the target and indenter and the radius of the indenter. Figure 1 shows an example of the force-indentation data compared to the power-law approximation with $n = 3/2$. Unloading behavior was modeled by the relation

$$F = F_m(a - a_o)^q/(a_m - a_o) \qquad (2)$$

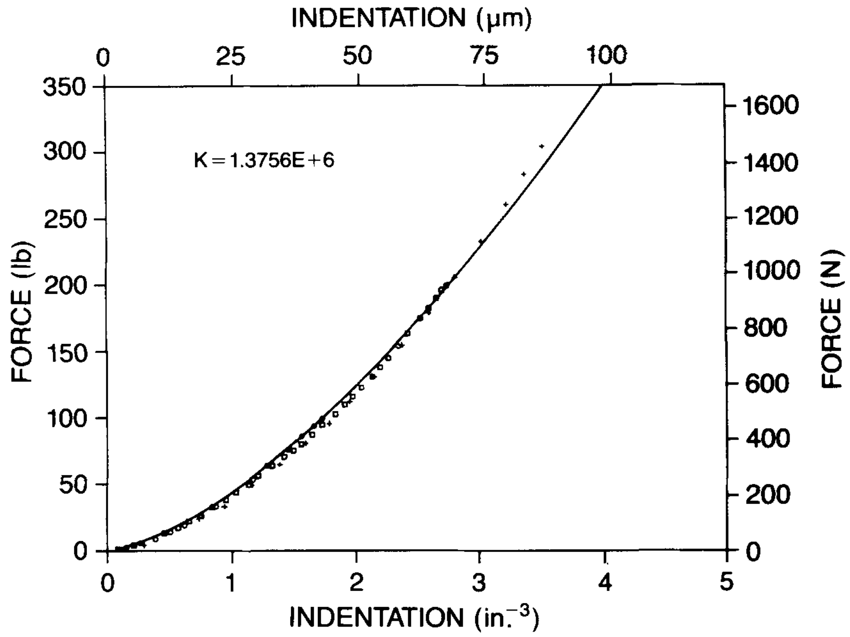

FIG. 1—*Loading curve of [90°/45°/90°/−45°/90°]$_{2s}$ specimen with 12.7-mm indenter (n = 3/2).*

where F_m is the contact force at which unloading begins, a_m is the corresponding (maximum) indentation, and a_o is the remaining permanent indentation upon total unloading. It was found that $q = 5/2$ fitted the unloading path very well. Rapid loading and unloading was used to avoid creep effects. Numerous indentation tests on beam specimens with laminations of $[0, 45, 0, -45, 0]_{2s}$ and $[0, 45, 90, -45, 90]_{2s}$ were conducted. It was found that the permanent indentation a_o was related to the maximum indentation a_m by the relation

$$a_o/a_m = 1 - (a_{cr}/a_m)^{2/5} \qquad \text{for } a_m > a_{cr} \tag{3}$$

and

$$a_o = 0 \qquad \text{for} \qquad a_m \leq a_{cr} \tag{4}$$

The value of a_{cr}, a constant related to the unloading rigidity, was found to be independent of the size of the indenter. Reloading was modeled by the equation

$$F = k_1 (a - a_o)^p \tag{5}$$

with $p = 3/2$.

The impact response of the laminated plate specimens was modeled by a finite-element scheme using 9-node isoperimetric plate elements developed by Yang [2]. The projectile was modeled by a rod element developed by Yang and Sun [3]. The matrix balance equations were solved simultaneously with the indentation laws to predict the impact response.

Experimental impact data were produced by striking 15 by 10 cm plates suspended by strings with a rod-pendulum formed around an impact-force transducer.

Figure 2 shows a typical comparison between the calculated and observed behavior at one point on the impacted plate. Six such records are presented, all showing very good agreement. Figure 3 shows the calculated deformed configurations of the laminate plate after impact indicating sharp discontinuities in the out-of-plane displacements. The contact force history of the impact test, as measured by the impact force transducer in the indenter, was also closely matched in amplitude and contact duration by the finite-element analysis.

The authors note that their verification study was conducted for low-velocity impact (less than 380 cm/s) and may not apply to the high-velocity impact case. They also note that the nature of the impact damage was not specifically characterized or accounted for. Such damage could also be induced by stress waves created by the impact; this is especially true for the through-the-thickness wave that can lead to back-surface delamination. They also suggest that the subsequent strength and life of impacted laminates should be examined and analyzed.

The experience of this reviewer suggests that many practical impact situations fit the "low-velocity impact" focus of this report. The approach taken seems now to be well established and, as the authors suggest, could be used as a starting point for more comprehensive analysis and modeling of this important problem. Including some specific account of the damage process appears to be one possible (and attractive) next step. The authors have reported a comprehensive experimental and sound analytical treatment of the part of the problem they addressed. The report is precise and well integrated.

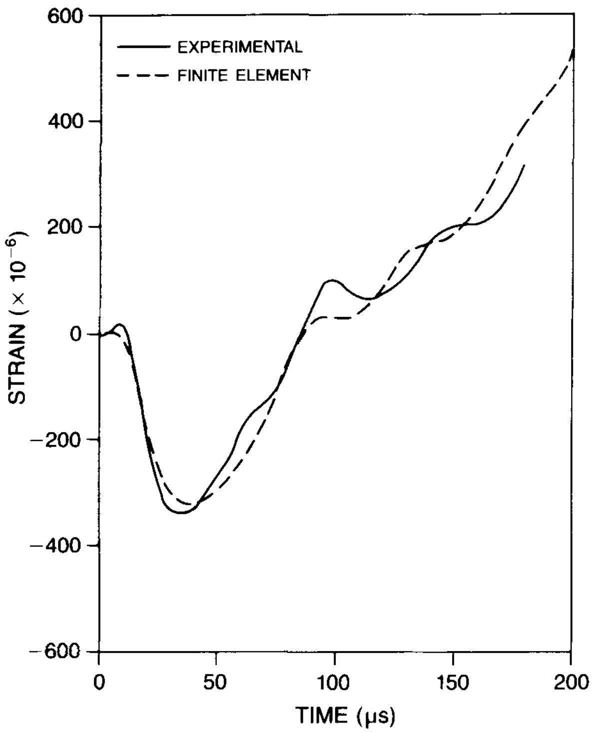

FIG. 2—*Strain response history at Gauge 3.*

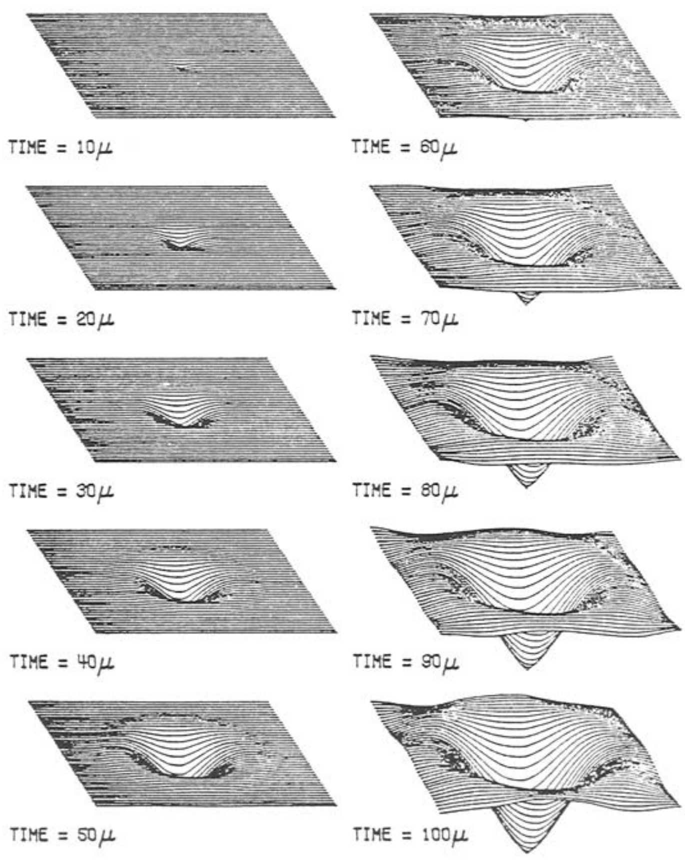

FIG. 3—*Deformed configurations of laminated plate after impact.*

More information concerning the subject report or the corresponding research program can be obtained from Professor C. T. Sun, School of Aeronautics and Astronautics, West Lafayette, IN 47907; telephone (317) 494-5130.

References

[1] Whitney, J. M. and Pagano, N. J., "Shear Deformation in Heterogeneous Anisotropic Plates," *Journal of Applied Mechanics*, Vol. 37, 1970, pp. 1031-1036.

[2] Yang, S. H., "Static and Dynamic Contact Behavior of Composite Laminates," Ph.D. Dissertation, Purdue University, 1981.

[3] Yang, T. Y. and Sun, C. T., "Finite Elements for the Vibration of Framed Shear Walls," *Journal of Sound and Vibration*, Vol. 27, No. 3, 1973, pp. 297-311.