those cases. Solutions like the experimental cigar- and peanut-like edge shapes require a three-dimensional formulation.

References

[1]Squire, H. B., "Investigation of the Instability of a Moving Liquid Film," *British Journal of Applied Physics*, Vol. 4, June 1953, pp. 167–169.

[2]Dombrowski, N., and Fraser, R. P., "Photographic Investigation into the Disintegration of Liquid Sheets," *Philosophical Transactions*, Vol. A247, Sept. 1954, pp. 101–130.

[3]Hagerty, W. W., and Shea, J. F., "A Study of the Stability of Plane Fluid Sheets," *Journal of Applied Mechanics*, Vol. 22, Dec. 1955, pp. 509–514.

[4]Taylor, G. I., "The Dynamics of Thin Sheets of Fluid, I. Water Bells," *Proceedings of the Royal Society of London*, Vol. A253, Dec. 1959, pp. 289–295.

[5]Taylor, G. I., "The Dynamics of Thin Sheets of Fluid, II. Waves on Fluid Sheets," *Proceedings of the Royal Society of London*, Vol. A253, Dec. 1959, pp. 296–312.

[6]Taylor, G. I., "The Dynamics of Thin Sheets of Fluid, III. Disintegration of Fluid Sheets," *Proceedings of the Royal Society of London*, Vol. A253, Dec. 1959, pp. 313–321.

[7]Brown, D. R., "A Study of the Behavior of a Thin Sheet of Moving Liquid," *Journal of Fluid Mechanics*, Vol. 10, July 1961, pp. 297–305.

[8]Clark, C. J., and Dombrowski, N., "Aerodynamic Instability and Disintegration of Inviscid Liquid Sheets," *Proceedings of the Royal Society of London*, Vol. A329, May–Sept. 1972, pp. 467–478.

[9]Lin, S. P., "Stability of a Viscous Liquid Curtain," *Journal of Fluid Mechanics*, Vol. 104, March 1981, pp. 111–118.

[10]Mansour, A., and Chigier, N., "Disintegration of Liquid Sheets," *Physics of Fluids*, Vol. A2, No. 5, Nov. 1990, pp. 706–719.

[11]Lin, S. P., Lian, Z. W., and Creighton, B. J., "Absolute and Convective Instability of a Liquid Sheet," *Journal of Fluid Mechanics*, Vol. 220, Nov. 1990, pp. 673–689.

[12]Rangel, R. H., and Sirignano, W. A., "The Linear and Nonlinear Shear Instability of a Fluid Sheet," *Physics of Fluids*, Vol. A3, No. 10, 1991, pp. 2392–2400.

[13]Chubb, D. L., and White, K. A., "Liquid Sheet Radiator," AIAA Paper 87-1525, July 1987; see also NASA TM-89841, July 1987.

[14]Chubb, D. L., and Calfo, F. D., "Scaling Results for the Liquid Sheet Radiator," *Proceedings of 24th Intersociety Energy Conversion Engineering Conference* (Washington, DC), Institute of Electrical and Electronics Engineers, New York, 1989, pp. 45–50; see also NASA TM-102100, Aug. 1989.

[15]Chubb, D. L., McConley, M. W., McMaster, M. S., and Afjen, A. A., "A Study of Thin Liquid Sheet Flows," NASA TM-106323, Aug. 1993.

Effect of Damage on the Impact Response of Composite Laminates

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Introduction

IMPACT is a key issue in the design of composite structures and may be the limiting design issue in many cases. It is therefore essential that a complete understanding of the response of composite structures to impact be obtained. This comprises two separate issues: damage resistance and damage tolerance.[1] Damage resistance is a measure of the damage incurred by a material/structure due to a particular event (in this case impact). Damage tolerance is the measure of the ability of a material/structure to "perform" (given particular performance requirements) in the presence of damage. The first issue, damage resistance, is directly related to impact. The second issue, damage tolerance, has only a secondary relationship to the impact event since it is the amount and distribution of the damage present that directly determines the damage tolerance, not the particulars of the impact event.[2] The impact event is related to damage tolerance through the damage resistance. Understanding and analyzing the damage resistance of composite structures is therefore important to determine the damage caused by a particular impact scenario. This damage state can then be used to assess the damage tolerance and thus the capability of the structure to continue to meet performance requirements.

A number of authors[1,3–9] have presented analysis techniques to determine the response of composite structures to impact. These analyses generally determine the force, deflection, and strain (and stress) time histories of the composite structure during the impact event. In some cases, the resulting damage is also predicted. Although these analysis techniques vary from the finite element method to Rayleigh-Ritz and other schemes, they all share one item in common: they do not account for the fact that the damage that occurs during the impact event is a progressive phenomenon.

The condition of a composite laminate is not constant throughout the impact event. As damage occurs during the impact event, the parameters that govern the response may change. This can influence the overall response which will alter the force, deflection, and stress and strain histories. This, in turn, can have an effect on the total amount of damage incurred during the impact event. It is therefore essential to understand how impact response parameters change as damage occurs.

The objective of this work is, therefore, to determine the effect that damage in the composite structure has on the impact response of the structure. Although quantitative measurements and assessments are made, the ultimate goal is to determine, on a qualitative basis, whether it is necessary to account for this change in impact parameters, due to damage, in models of the event and how this should be done when necessary. This overall qualitative assessment is made based on the quantitative measurements.

Approach

The impact response of laminated composites is often analyzed by segmenting the problem into the different response phenomena that occur.[1] This generally involves considering the "global" and "local" responses of the laminate promoted by the impactor. In this context, global response refers to the dynamic structural response of the laminated configuration,[10] whereas the local response refers to the indentation caused by the impactor.[11,12] Although both phenomena occur simultaneously during the impact event, the complexity of the problem is reduced by analyzing each phenomenon separately.

The effect of damage on the impact response was considered by looking at the effect of damage on both the global and local responses. The global response was assessed by conducting an impact test and measuring the force vs time and plate center deflection vs time histories. The local response was evaluated by conducting static indentation tests and measuring the load vs indentation.

All tests were conducted on AS4/3501-6 graphite/epoxy $[\pm 45/0]_{2S}$ plates 89 mm in width with a span of 251 mm. Tests were carried out on virgin (undamaged) and on predamaged specimens. Damage in the predamaged specimens was introduced by impacting laminates with a 1.53-kg impactor rod with a 12.7-mm-diam hemispherical tup at a velocity of 4.0 m/s. The amount of damage was determined from visual and dye-penetrant-enhanced x-ray techniques. This damage generally consisted of small matrix cracks on the back surface and internal damage, consisting of ma-

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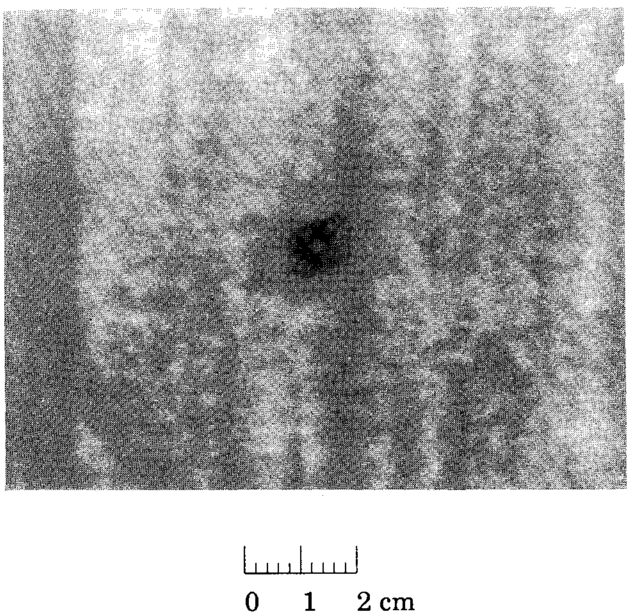

Fig. 1 X-ray photograph of damage in predamaged specimens.

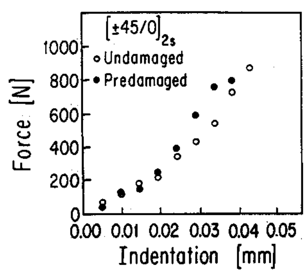

Fig. 2 Force vs indentation results for undamaged and predamaged specimens.

trix cracks and delamination, about the size of the impactor as shown in Fig. 1.

A complete description of the experimental work can be found in Refs. 13 and 14.

Results and Discussion

Local Effect—Static Indentation Tests

Load-indentation results are presented in Fig. 2 for the undamaged and predamaged specimens. Data are not reported above 900 N since cracking sounds were heard indicating that the originally undamaged specimens were no longer undamaged at that point. It is clear that more force is required to obtain the same indentation level in the case where the $[\pm 45/0]_{2S}$ laminates have damage present. This was consistent for all of the cases.

To compare the data on a more quantitative basis, the data for each specimen were fit to the relation[11]

$$R = K\alpha^n \tag{1}$$

where R is the contact force, α is the local indentation, and n is a constant that has been previously estimated to be 1.5 (Ref. 12). The value of the contact stiffness K depends on the constitutive properties of the plate and indentor, as well as the radius of the indentor. The data were fit to this relationship using a linear regression on logarithms of the data.

For the undamaged specimens, the exponent n was found to have a value of 1.14, whereas for the predamaged laminates n had a value of 1.40. The contact stiffnesses are 26.2 $kN/mm^{1.14}$ for the undamaged laminates and 78.3 $kN/mm^{1.40}$ for the predamaged laminates. Since the value of the contact stiffness is dependent on the value of the exponent n, a direct comparison is not useful when the exponent values are different, as in this case. Correlation coefficients were generally in the range of 0.9.

This analysis of the data also clearly shows that the laminates with damage are stiffer, in contact, than the undamaged laminates. This dependence of the contact stiffness on the presence of damage is attributed to the ability of the surface of the predamaged laminate to better conform to the shape of the indentor that produces a larger area of contact as illustrated in Fig. 3. The lower part of the figure shows the case of an undamaged laminate where, as the tup goes into the laminate, the surface cannot perfectly conform to the tup. If the laminate is locally more compliant (i.e., better able to conform to the tup), there will be more contact area as illustrated in the upper part of this figure. If the pressure distribution remains Hertzian, which is the normal assumption for this situation,[12,15,16] then the plate must carry more load in the damaged condition. This can be conversely stated as the total load applied by the indentor is spread out over a larger area when damage is present, thus reducing the stress level at the contact point and thus reducing the indentation for a given load. This is also consistent with the data.

If this hypothesis is correct, the difference in the response between undamaged and predamaged laminates will become more pronounced at greater indentations since the difference in contact area will increase. This is consistent with the experimental data where there is virtually no difference in the responses at lower values of indentation, but the responses begin to diverge as the indentation increases in value.

Global Effect—Impact Tests

The force and displacement vs time histories of the undamaged and predamaged $[\pm 45/0]_{2S}$ laminates are shown in Figs. 4 and 5, respectively. There is no significant difference in the force signature for the predamaged and undamaged cases, and this was true for all of the specimens tested. The lack of any difference is particularly noticeable for the displacement vs time histories.

To provide better quantitative comparison, peak values and the duration of the impact event are compared. For the undamaged

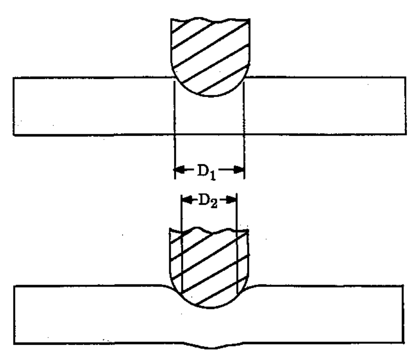

Fig. 3 Illustration of ability of upper surface to conform to tup and resulting contact area for (upper) damaged laminate and (lower) undamaged laminate.

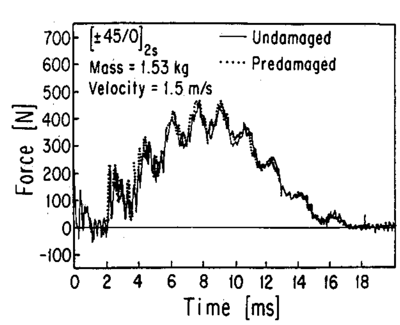

Fig. 4 Impact force vs time history for undamaged and predamaged specimens.

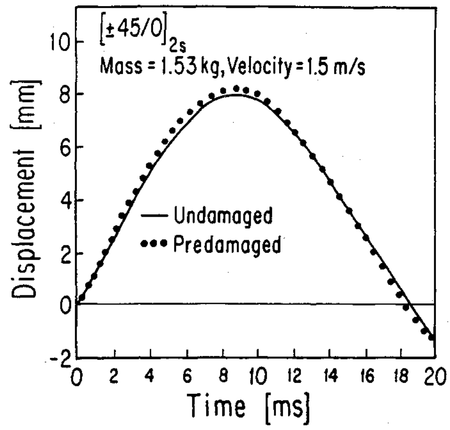

Fig. 5 Center deflection vs time history for undamaged and predamaged specimens.

laminates, the peak force varied from 440 to 496 N, whereas the peak force in the predamaged cases varied from 418 to 499 N. The peak displacement of the undamaged laminates varied from 7.9 to 8.6 mm in comparison with 8.0 to 8.5 mm for the predamaged laminates. In both cases, the duration of the impact event ranged between 18.6 and 19.1 ms.

It can therefore be concluded that the presence of local damage did not have a detectable effect on the global structural response. It should be noted that the planar size of the damage present in these cases is considerably smaller than the dimension of importance in the structural response—the span of the specimen in the test jig. The linear size of the damage was approximately the size of the tup used to create the damage: 12.7 mm in diameter. The span of the specimen was 251 mm, a factor of 20 times the damage size. Therefore, this conclusion is probably not valid as the size of the damage approaches the length critical to the structural response.

Implications

The results clearly indicate that the presence of damage, and thus the occurrence of damage during the impact event, affect the local response. The presence of damage will therefore have an effect on the stress and strain state in the laminate immediately under the impactor. This, in turn, affects the progression of damage.

It is surprising, however, that there is no notable effect on the global response as measured by either the force or displacement vs time histories. It would be expected that the displacement vs time history would be unaffected since this is a measure of the integrated structural response. Since the damage size is over an order of magnitude smaller than the important structural dimension, its effect on the important structural parameters would be minimal and would not be felt in the displacement. However, the force vs time history is both a structural global response as well as a local response. The source of the force on the plate is the indentor contact relation which is a "local" phenomenon. Since this contact relation has been affected by the presence of damage, it would be expected that the force vs time history would be affected.

Closer examination of the data reveals that the key is the peak force experienced during the impact event. As can be seen in Fig. 4, the peak force is about 400–500 N. If the force vs indentation results of Fig. 2 are considered, the behavior of the undamaged and damaged specimens has barely begun to diverge at loads of 400–500 N. Thus, the reason that no difference is seen in the global event is because the forces encountered are low. If the impact forces were high enough such that there was a difference in the static indentation response, it would be expected that a difference would also be seen in the force vs time history. Further work should therefore be conducted at higher velocities. In addition, these plates were relatively thin and deflections were large, indicating that membrane stresses may be important. Work should be conducted on thicker laminates where bending resistance is more dominant and may be more affected by the presence of damage such as delamination.

Nevertheless, the current results indicate that it may be possible to ignore the presence of damage in analyzing the impact event in a number of instances, especially if the analysis is for preliminary design purposes. Unfortunately, the loads where this may be valid cannot be determined without prior analysis or experimentation. The static indentation results, however, make it clear that the local stress and strain fields will begin to deviate from the actual case if no damage is assumed in the analysis. The next logical step in this work is thus to measure the damage present after impact of predamaged specimens and virgin specimens. This will require careful nondestructive, and possibly destructive, investigation to properly characterize the damage on a three-dimensional basis. This will allow a better assessment of the effect that the presence of damage has on the further progression of damage and the overall damage resistance of a composite structure.

Acknowledgment

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References

[1]Cairns, D. S., and Lagace, P. A., "A Consistent Engineering Methodology for the Treatment of Impact in Composite Materials," *Journal of Reinforced Plastics and Composites*, Vol. 11, No. 4, 1992, pp. 395–412.

[2]Cairns, D. S., and Lagace, P. A., "Residual Tensile Strength of Graphite/Epoxy and Kevlar/Epoxy Laminates with Impact Damage," *Composite Materials: Testing and Design*, Vol. 9, ASTM STP 1059, American Society for Testing and Materials, Philadelphia, PA, 1990, pp. 48–63.

[3]Gresczuk, L. B., "Response of Isotropic and Composite Materials to Particle Impact," *Foreign Object Impact Damage to Composites*, ASTM STP 568, American Society for Testing and Materials, 1975, pp. 183–211.

[4]Sun, C. T., and Chattopadhyay, S., "Dynamic Response of Anisotropic Laminated Plates Under Initial Stress to Impact of a Mass," *Journal of Applied Mechanics*, Vol. 42, Sept. 1975, pp. 693–698.

[5]Caprino, G., Visconti, I. C., and Ilio, A. D., "Elastic Behavior of Composite Structures Under Low Velocity Impact," *Composites*, Vol. 15, No. 3, 1984, pp. 231–234.

[6]Shivakumar, K. N., Elber, W., and Illg, W., "Prediction of Impact Force and Duration Due to Low-Velocity Impact on Circular Composite Laminates," *Journal of Applied Mechanics*, Vol. 52, Sept. 1985, pp. 674–680.

[7]Graves, M. J., and Koontz, J. S., "Initiation and Extent of Impact Damage in Graphite/Epoxy and Graphite/PEEK Composites," *Proceedings of the AIAA/ASME/ASCE/AHS 29th Structures, Structural Dynamics, and Materials Conference* (Williamsburg, VA), AIAA, Washington, DC, 1988, pp. 967–975.

[8]Aggour, H., and Sun, C. T., "Finite Element Analysis of a Laminated Composite Plate Subjected to Circularly Distributed Central Impact Loading," *Computers & Structures*, Vol. 28, No. 6, 1988, pp. 729–736.

[9]Wu, H. T., and Springer, G. S., "Impact Induced Stresses, Strains, and Delaminations in Composite Plates," *Journal of Composite Materials*, Vol. 22, No. 6, 1988, pp. 533–560.

[10]Cairns, D. S., and Lagace, P. A., "Transient Response of Graphite/Epoxy and Kevlar/Epoxy Laminates Subjected to Impact," *AIAA Journal*, Vol. 27, No. 11, 1989, pp. 1590–1596.

[11]Yang, S. H., and Sun, C. T., "Indentation Law for Composite Laminates," *Composite Materials: Testing and Design*, ASTM STP 787, American Society for Testing and Materials, Philadelphia, PA, 1982, pp. 425–449.

[12]Tan, T. M., and Sun, C. T., "Use of Statical Indentation Laws in the Impact Analysis of Laminated Composite Plates," *Journal of Applied Mechanics*, Vol. 52, March 1985, pp. 6–12.

[13]Lagace, P. A., Ryan, K. F., and Graves, M. J. "Effect of Damage on the Impact Response of Composite Laminates," *Proceedings of the AIAA/ASME/ASCE/AHS/ASC 32nd Structures, Structural Dynamics, and Materials Conference* (Baltimore, MD), AIAA, Washington, DC, 1991, pp. 1137–1143.

[14]Ryan, K. F., "Dynamic Response of Graphite/Epoxy Plates Subjected to Impact Loading," Massachusetts Institute of Technology, TELAC Rept. 89-13, Cambridge, MA, Sept. 1989.

[15]Cairns, D. S., and Lagace, P. A., "Thick Composite Plates Subjected to Lateral Loading," *Journal of Applied Mechanics*, Vol. 109, Sept. 1987, pp. 611–616.

[16]Conway, H. D., *Zeitschrift fuer Angewandte Mathematik und Physik*, Vol. 7, 1956, pp. 460–465.