USE OF LS-DYNA SHELL ELEMENTS IN THE ANALYSIS OF COMPOSITE PLATES WITH UNBALANCED AND UNSYMMETRIC LAYUPS

Saiphon Charoenphan, Lawrence C. Bank, Michael E. Plesha[1]
Engineering Mechanics and Astronautics Program
Department of Engineering Physics
and
Department of Civil and Environmental Engineering
University of Wisconsin-Madison
Madison, WI 53706

Keywords:
Composite Materials, Coupling, Failure, Multidirectional laminates

[1] To whom all correspondence should be addressed. The University of Wisconsin-Madison, Dept. of Engineering Physics, Engineering Research Bldg., 1500 Engineering Dr., Madison, WI 53706. Tel: (608) 262-5741, e-mail: plesha@engr.wisc.edu

ABSTRACT

In order to obtain the desired coupling between deformation modes that can occur in composite material plates having unbalanced and/or unsymmetric lamination schemes, the appropriate shell element formulation must be selected from the available formulations in LS-DYNA. An investigative study was conducted to determine which of the shell element formulations in LS-DYNA 950 can be used for modeling such plates prior to performing in-depth studies on the behavior of more complex composite material structures. Unbalanced/symmetric and balanced/unsymmetric lamination schemes were studied for single-element and four-element "patch" tests. The elastic response of these models to in-plane tensile loads and out-of-plane bending loading was investigated. The shell elements were used with material model 54 (MAT_ENHANCED_COMPOSITE_DAMAGE). The study focused on determining which of the shell element formulations would produce the expected coupling between deformation modes. The Belytschko-Leviathan shell formulation was found to be the best choice for coupled elastic response. Progressive failures of laminates under in-plane tensile and compressive loads were also investigated using this element formulation.

INTRODUCTION

The problem of determining an appropriate shell element formulation has been an issue for failure prediction. In several damage situations, a composite material with initially balanced/symmetric orientation will likely become unbalanced and unsymmetric, and response during progressive damage will involve coupling between deformation modes. Thus, it is highly desirable and perhaps essential that a plate finite element to be used for such simulations be able to accurately reproduce coupled deformation. The composite damage model material 54 was used to investigate material failures in this study.

LS-DYNA offers many element formulations for four node isoparametric shell elements including Hughes-Liu (ELFORM1), Belytschko-Tsay (ELFORM2), Belytschko-Leviathan (ELFORM8), Belytschko-Wong-Chiang (ELFORM10) and Fast co-rotational Hughes-Liu (ELFORM11). All of these elements employ one-point quadrature and hence, are very efficient. The Hughes-Liu (Hallquist, 1998), Belytschko-Wong-Chiang (Belytschko, 1992) and Belytschko-Leviathan (Belytschko, 1994) elements have the ability to replicate geometric warping. In this paper, performance of these elements was compared for both elastic response and failure prediction.

Additional useful information on performance of LS-DYNA shell elements for applications to layered composite materials is reported in Murray (1989), Murray and Schwer (1993) and Schweizerhof et al (1998). Murray (1989) verified DYNA3D's composite damage material model (Material 54). Comparisons with analytical solutions for tensile and compressive failures of fiber and matrix, and progressive failure, were made for symmetric composite materials. Failure of unsymmetric composite materials was not reported. This work concluded that the Chang-Chang failure criterion implemented in DYNA3D provided accurate results, but recommended that modifications be made to the failure criteria and degradation rules. Murray and Schwer (1993) evaluated constitutive behavior using the Belytschko-Lin-Tsay element. Comparisons with analytical and experimental results showed good agreement for element performance in reproducing coupled response between bending, extensional, shearing and twisting deformations, included transverse shear in thick laminated plates. Schweizerhof et al (1998) tested composite damage (Material 54) with options DFAILT, DFAILC, FBRT and YCFAC on a single layer plate subjected to tension, compression or shear and indicated sudden, physically incorrect change of material behavior after initiation of damage. A new material model (Material 58) was introduced for multilayered composites that provides a smoother progression of damage.

ELASTIC PLATE RESPONSE

Patch tests of composite plates subjected to coupled deformations are reported in this section. In all analyses, the plate has dimensions 100 mm x 100 mm x 3.175 mm thickness and is subjected to quasi-static loads that are increased linearly with time. No damping was employed. Composite materials having five identical layers were modeled by defining five though-thickness integration points for the shell element (one integration point for each layer). Deformations and stresses obtained from the model were compared to analytical solutions.

The composite plates were composed of five layers of identical unidirectionally reinforced orthotropic material, with layups as specified below. For each layer: $\rho = 1.908(10)^3$ kg/m^3, E_X = 39.08 GPa, E_Y = 10.37 GPa, ν_{YX} = 0.0761 and G_{XY} = 3.332 GPa where X, Y and Z refer to principal material directions in the layer, with X being the fiber direction. The magnitude of applied loads is small enough to assure linear elastic material response.

In-plane shear

Coupling of tensile loading with in-plane shear deformation was tested in this study by applying a tensile edge load to a plate with unbalanced/symmetric composite material having orientations [30°/30°/0°/30°/30°] related to the x-direction. Support conditions and loading of the model are shown in Figure 1. For both the single element and four element models, all the elements provided stresses that agreed with the analytical solution.

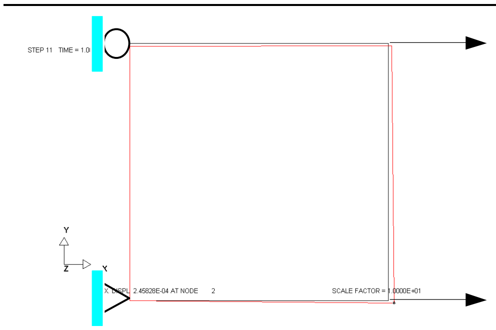
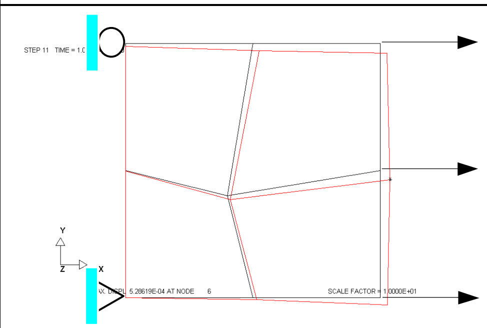
One element model	Four element model
	

Figure 1. In-plane shear deformation produced by tensile loading in an unbalanced/symmetric composite plate.

Out-of-plane twisting

With balanced/ unsymmetric composite material, tension loading is expected to produce out-of-plane twisting deformation (κ_{xy}) due to the effect of coupling contained in the compliance matrix ($\mathbf{b}^T$) for the layup. The plate has [-30°/-30°/0°/30°/30°] orientation, and support conditions and loading are shown in Figure 2.

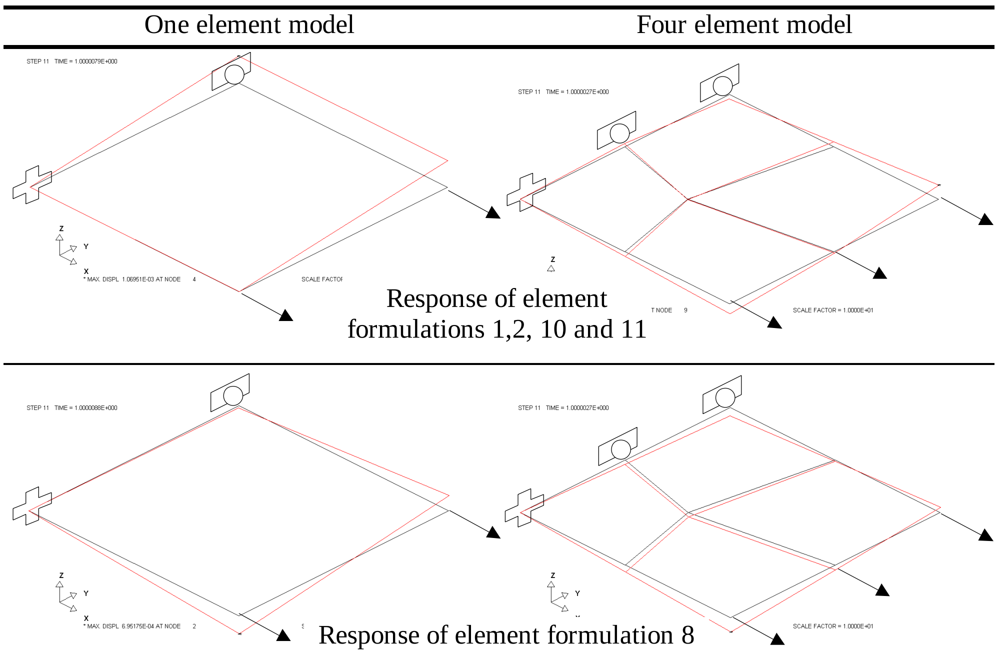


Figure 2. Twisting deformation produced by tensile loading of a balanced/symmetric composite plate. Element formulations 1, 2, 8, 10, and 11 refer to the LS-DYNA elements Hughes-Liu (ELFORM1), Belytschko-Tsay (ELFORM2), Belytschko-Leviathan (ELFORM8), Belytschko-Wong-Chiang (ELFORM10) and Fast Co-rotational Hughes-Liu (ELFORM11), respectively.

In the single element models, only the Belytschko-Leviathan element provided correct curvatures and stresses. In the four element models, all elements showed the ability to model this twisting mode. However, the Belytschko-Leviathan element provided the most accurate curvature. Comparison of the response shown in Figure 2 for element formulations 1, 2, 10 and 11, with element formulation 8, shows some notable differences.

The last set of tests to be discussed assesses element capability to produce out-of-plane twisting due to bending loading in unbalanced/symmetric composite material where all curvature modes (κ_x, κ_y and κ_{xy}) are expected to be displayed. Transverse loads were applied to a [30°/30°/0°/30°/30°] plate with the support conditions shown in Figure 3. As before, only the Belytschko-Leviathan element provided the correct response for a one element model. However, results for the four element models show all elements to be capable of reproducing the expected coupling.

FAILURE PREDICTION

Failure tests in tension and compression of multidirectional composite material plates are reported in this section. These tests were useful to help assess the capability and accuracy of these elements to model damage subject to simple loading conditions where membrane forces are expected to be high. A single element plate with dimensions 100 mm x 100 mm x 3.175 mm was modeled using shell element formulation 8 (Belytschko-Leviathan) and was subjected to quasi-static in-plane tension or compression loads.

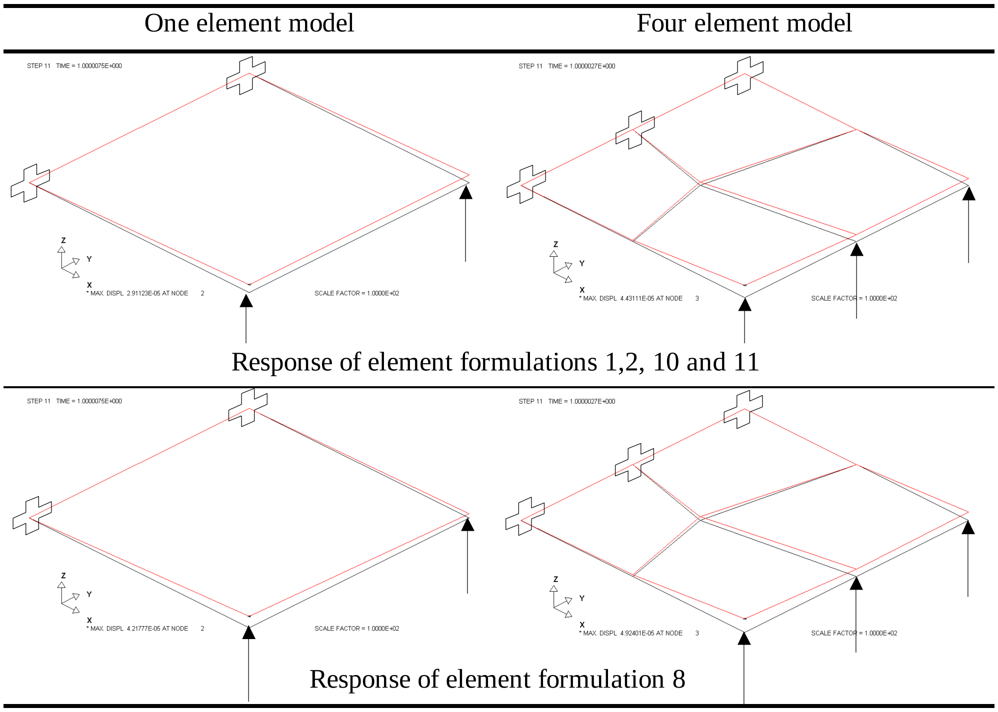
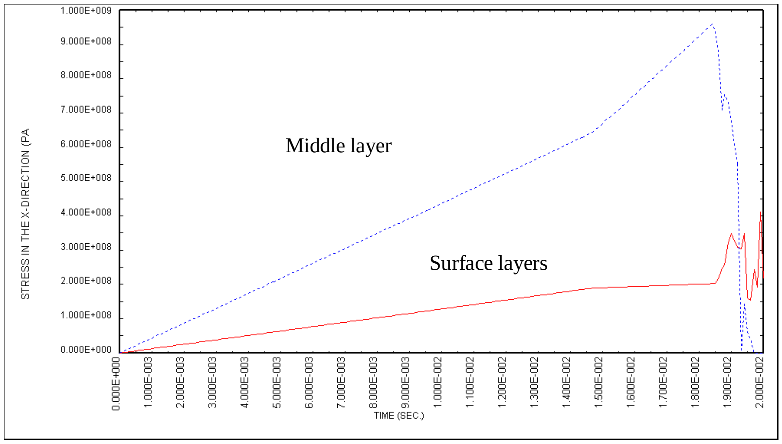


Figure 3. Bending deformations in unbalanced/symmetric plates. Element formulations 1, 2, 8, 10, and 11 refer to the LS-DYNA elements Hughes-Liu (ELFORM1), Belytschko-Tsay (ELFORM2), Belytschko-Leviathan (ELFORM8), Belytschko-Wong-Chiang (ELFORM10) and Fast Co-rotational Hughes-Liu (ELFORM11), respectively.

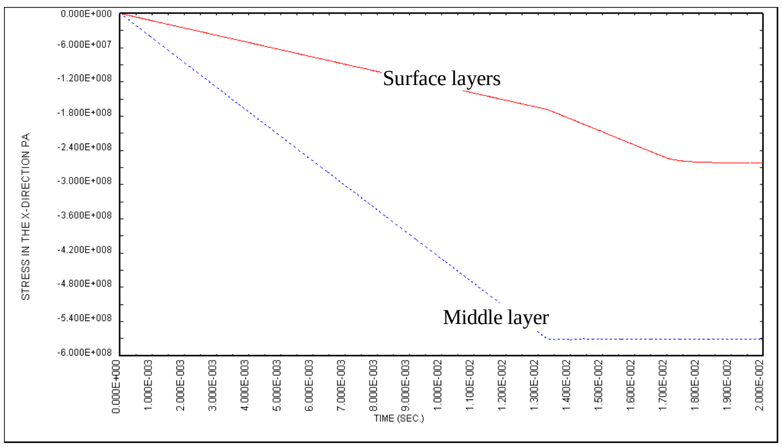
Damage material model 54 (MAT_ENHANCED_COMPOSITE_DAMAGE) with Chang/Chang failure criteria was used in the models. These criteria were also used for the analytical solutions to which the finite element results were compared. The limit strengths, referred to principal material directions of a layer, are taken to be XC = 0.5717 GPa, XT = 0.9649 GPa, YC = 0.2843 GPa, YT = 0.0579 GPa and SC (Shear strength)= 0.119 GPa. For plates loaded in compression, we usually had difficulty with out-of-plane deformations developing, which we henceforth refer to as “flip-over”. Use of mass proportional damping in the amount 50% of critical damping at the fundamental frequency of vibration for membrane behavior, approximately 7000 Hz, was found to help suppress the onset of such displacements. Additional comments are offered later.

Balanced/Symmetric Composite

A balanced/symmetric composite plate with [-45°/45°/0°/45°/-45°] orientation was subjected to tension or compression edge loading. In tension loading, initial failure was found in the outer layers (45° and –45°) at loading of 84 kN ($1.4(10)^{-2}$ sec), and was due to tensile cracking of the matrix. After the elastic properties of the matrix in these laminates were reduced to zero, the stresses remain constant. Only the middle layer carried additional load until ultimate failure occurred. In compression loading, initial failure occurred when the compressive fiber failure criterion was satisfied in the middle layer at loading of 79 kN ($1.32(10)^{-2}$ sec). Ultimate failure was found in the outer layers at 100 kN ($1.7(10)^{-2}$ sec). The results of the x-direction stresses are shown in Figure 4. These results show good agreement with the analytical solutions.



(a) Tension



(b) Compression

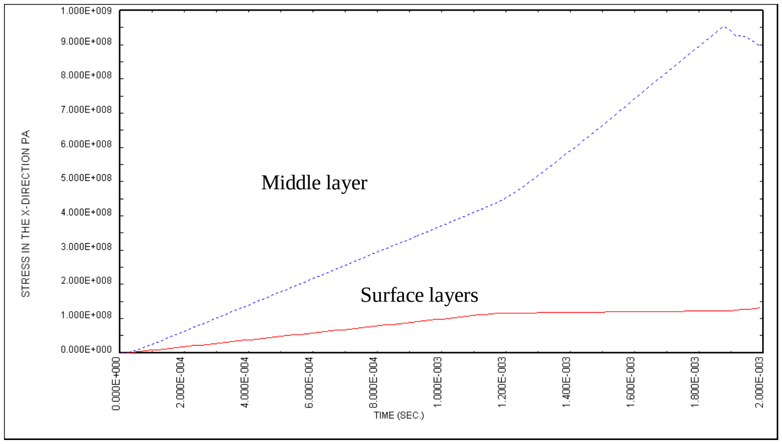
Figure 4. Plots of *x*-direction stress vs. time for (a) tension loading, and (b) compression loading, of balanced/symmetric composite plates to failure.

Unbalanced/Symmetric Composite

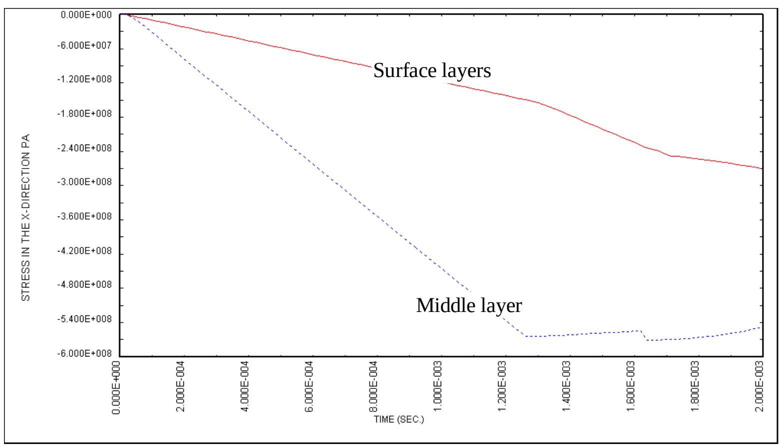
Here we consider an unbalanced/symmetric composite material plate with orientations [45°/45°/0°/45°/45°]. In tension loading, initial failure was found in the outer layers, due to tensile cracking of the matrix, at 57 kN $(1.15(10)^{-3}$ sec). Ultimate failure occurred when stress in the middle layer satisfied the tensile fiber failure criterion. In compression loading, initial failure was found in the middle layer with fiber compression failure occurring at 75 kN $(1.25(10)^{-3}$ sec), and ultimate failure was found in the outer layers with compressive matrix failure. These results agree with the analytical solution and are shown in Figure 5.

Balanced/Unsymmetric Composite

The balanced/unsymmetric composite material used in this test has orientation [-45°/-45°/0° /45°/45°]. The finite element results give good agreement with the analytical solution for tension loading. As shown in Figure 6a, initial failure was found in the outer surface layers with tensile matrix failure at 55 kN (1.1 sec). Failure then progressed from the outer layers to the next set of layers, and ultimate failure occurred in the middle layer at the mid-surface of the plates.



(a) Tension



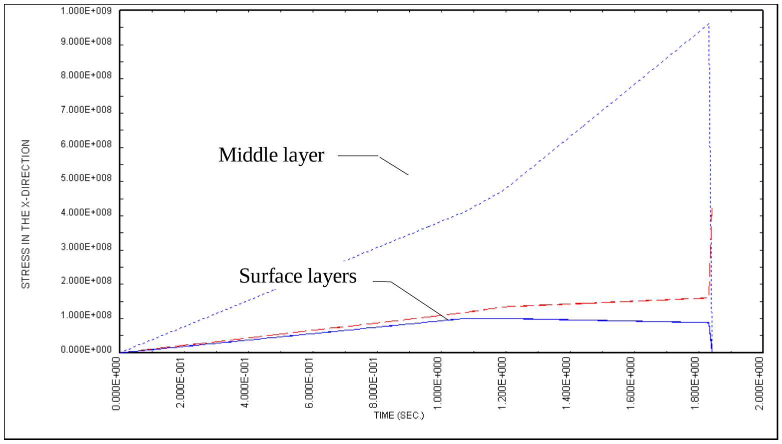
(b) Compression

Figure 5. Plots of *x*-direction stress vs. time for (a) tension loading, and (b) compression loading, of unbalanced/symmetric composite plates to failure.

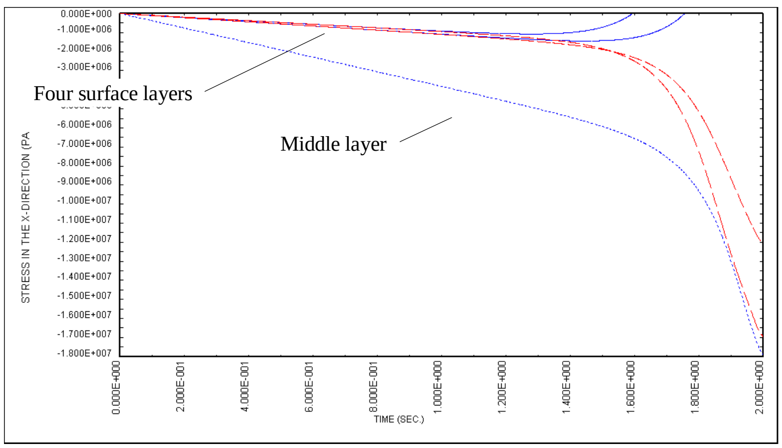
However, we have been unable to model damage due to compression loading since unstable deformations (i.e., "flip over" of the plate) occur before failure develops as shown in Figure 6b.

Comments on analysis duration

In this study, we are interested in quasi-static response of plates. Thus, it is necessary to apply loads slowly, relative to the time scales for structural vibration, and/or to use dynamic relaxation where heavy damping is employed to dissipate energy. With shells, there are two distinctly different fundamental time scales: one for membrane behavior and the other for bending/twisting behavior. The fundamental periods of vibration for membrane behavior, τ_m, and bending behavior, τ_b, were found to be about $1.4(10)^{-4}$ sec and $1.7(10)^{-2}$ sec, respectively. Membrane loading can reasonably be classified as being "slow" if it is applied over a time span that is substantially longer (e.g., several orders of magnitude) than τ_m, while slow bending loading similarly requires a time span substantially longer than τ_b. Thus, for the finite element models considered here, quasi-static simulations with bending loads require an analysis duration that is perhaps 1.7 sec or longer (using two orders of magnitude in the criterion cited above). Meanwhile, the simulations with membrane response only (i.e., in-plane tensile or compressive loading of a symmetric laminate) require an analysis duration that is perhaps 0.014 sec, or longer.



(a) Tension



(b) Compression

Figure 6. Plots of *x*-direction stress vs. time for (a) tension loading, and (b) compression loading, of balanced/unsymmetric composite plates. The response due to tension loading (a) shows failure, as expected, while we were unsuccessful in obtaining failure for compression loading (b).

We studied the effect of analysis duration (i.e., amount of time used to apply loading), and usually found that an unstable deformation, called “flip over”, occurred in compression loading situations when analysis duration was of the order of 2 sec or more, which typically required 100,000 time steps or more. We note that while a particular loading duration may be slow relative to the time scale for membrane vibration, it may be fast relative to the time scale for bending vibration. Thus, of the analysis durations listed in Table 1, the three longest simulations are expected to be quasi-static from the standpoint of membrane behavior, while the shortest duration simulation could produce vibratory motion. In fact, the response solution for the shortest duration simulation does show some high frequency oscillations superimposed on the quasi-static response, but the magnitude of these oscillations is not overly objectionable. From the standpoint of bending behavior, only the longest duration simulation is likely to be quasi-static. Although membrane deformation in symmetric plates is orthogonal to bending deformation, when a very large number of time steps was used, we often encountered unexpected “flip over”. Without any damping, only the first computation reported in Table 1 (i.e., $2.0(10)^{-3}$ sec duration), provided the expected results, and simulations for the remaining analysis durations displayed flip over. Use of mass proportional damping (50% critical damping at the fundamental frequency for membrane vibration, approximately 7000 Hz) was helpful in eliminating flip over for the two intermediate duration simulations reported in Table 1, while the longest duration simulation still displayed flip over. Application of the entire load instantaneously, with reliance on damping to accomplish dynamic relaxation, further exacerbated flip over.

A possible reason for difficulties with flip over could be round off error produced in the internal force computations which are done in single precision in LS-DYNA. Internal forces are produced almost entirely by very stiff membrane behavior. Errors produced here could give rise to bending behavior, which is much softer and hence more sensitive to any spurious transverse loads that might be produced. The problem we encounter here most likely pertains to very simple finite element models where the geometry, loading and material properties are such that response is by membrane deformations only. In more typical applications, nonuniformities of any of these quantities will couple bending and membrane action, where bending is considerably more flexible than membrane behavior.

Table 1. Analysis duration, number of time steps, and results for compression loading in multidirectional balanced/symmetric composite plates. The simulation for analysis duration $2.0(10)^{-3}$ sec was undamped, while the remaining simulations used the mass proportional damping reported in the paper. The results of the simulation with $2.0(10)^{-2}$ sec duration are shown in Figure 4b.

Analysis duration (sec.)	Number of time steps	Failure prediction
2.0×10^{-3}	100	Correct
2.0×10^{-2}	1,000	Correct
2.0×10^{-1}	10,000	Correct
2.0×10^{0}	100,000	Incorrect (“flip over”)

CONCLUSION

The elastic and damage response of multidirectional composite material plates was simulated using several LS-DYNA shell element formulations in conjunction with composite damage material 54. The Belytschko-Leviathan element was found to display the expected coupling between membrane and bending/twisting deformations that occur in unbalanced and/or unsymmetric composite materials.

For problems involving compressive membrane loading in symmetric plates, wherein strictly in-plane deformations are expected, we observed that large unexpected bending deformations, called “flip-over”, developed when the number of time steps for load application became too large.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by the National Science Foundation under Grant No. CMS-9713566. We would also like to acknowledge the continuous assistance provided by James M. Kennedy and Lee P. Binderman of KBS2 Inc. in interpreting the LS-DYNA finite element code.

REFERENCES

BELYTSCHKO, T., and LEVIATHAN, I. (1994). "Physical Stabilization of the 4-node Shell Element with One-point Quadrature." *Comput. Methods Appl. Mech. Engrg.*, Vol. 113, pp. 321-350.

BELYTSCHKO, T., WONG, B.L., and CHIANG, H.Y. (1992). "Advances in One-point Quadrature Shell Elements," *Comput. Methods Appl. Mech. Engrg.*, Vol. 96, pp. 93-107.

HALLQUIST, J.O. (1998). "Belytschko-Lin-Tsay Shell." In: LS-DYNA Theoretical manual. Livermore Software Technology Corporation. pp. 6.1-6.12.

MURRAY, Y.D. (1989). "Theory and Verification of the Fiber Composite Damage Model Implemented in DYNA3D" DNA-TR-89-132, Defense Nuclear Agency, Alexandria, VA.

MURRAY, Y.D., and SCHWER, L.E. (1993). "Verification of a General Purpose Laminated Composite Shell Element Implementation: Comparisons With Analytical and Experimental Results", *Finite Elements in Analysis and Design*, Vol. 12, pp. 1-16.

SCHWEIZERHOF, K., WEIMAR, K., MUNZ, T.M and ROTTNER, T. (1998). "Crashworthiness Analysis With Enhanced Composite Material Models in LS-DYNA – Merits and Limits" Proceedings of the 5th Int'l. LS-DYNA Users Conference.