Non-Penetrating Impact Simulation of Stitched Resin Film Infused Composites

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Abbreviation List:

CDM	Continuum damage mechanics
CODAM	Composite damage model
OCT	Over-height compact tension
S/RFI	Stitched resin film infused
UMAT	User defined material model

Keywords: Composite materials, continuum damage mechanics, impact, user-defined material model

ABSTRACT

The CODAM constitutive model has been implemented in LS-DYNA as a user-defined material model (UMAT). Using this material model, quasi-static over-height compact tension (OCT) tests on a stitched resin film infused (S/RFI) carbon/epoxy composite material were simulated, and the results demonstrated good agreement with the measured force and crack mouth opening displacement (CMOD). The same CODAM inputs were then used to simulate non-penetrating impact events on the S/RFI material. The simulations successfully predicted the peak force and event durations for targets oriented in one direction, but under-predicted the peak force and over-predicted the event duration for the opposite target orientation.

INTRODUCTION

Continuum damage mechanics (CDM) has been used recently (Floyd, 2001a; Floyd, 2001b; Mitchell, 2001; Williams, 1999; Williams, 1998b) to model large damage development and the structural response of heavily damaged fibre-reinforced polymeric composite materials. These previous studies have examined crack and damage development in notched tension test specimens, but the constitutive model used in those studies (CODAM), can be applied in many other applications. In this study, the model has been used in the simulation of non-penetrating impact events on stitched resin film infused (S/RFI) composites. The S/RFI material examined was a carbon fibre epoxy composite, stitched through its thickness with aramid fibre. The stitching of these materials is intended to limit the effect and extent of delamination in the laminate.

CODAM is a CDM based model that has been implemented as a UMAT in LS-DYNA. The model is intended for use on fibre-reinforced polymer composites that are prone to developing large amounts of damage. CODAM abstracts composites to a sub-laminate level, smearing the damage in the sub-laminates to produce an effective response. Details on CODAM can be found in the references (Floyd, 2001a; Williams, 2002; Williams, 1999; Williams, 1998a).

APPROACH

An experimental study into the behaviour of S/RFI in damage-inducing applications was performed at The University of British Columbia (Mitchell, 2001). Two of the tests used to explore this behaviour included the OCT test, and a non-penetrating impact test. Using inputs derived from the data collected in the experiments, CODAM was employed to simulate the OCT tests. The same CODAM material input data set used in the OCT simulations was subsequently used to simulate the non-penetrating impact events.

Experiments

The S/RFI carbon-epoxy laminates examined in this study consisted of two configurations. The two configurations used a sub-laminate sequence of $[+45/-45/0_2/90/0_2/-45/+45]_n$ where n = 4 (*4-stack*) or 5 (*5-stack*).

OCT Tests. The OCT test is a notched compact tension test with a geometry that has been shown to allow stable, self-similar growth of the crack from the notch tip in displacement controlled loading (Kongshavn, 1999). A schematic of the OCT test is shown in Figure 1. Results of the OCT testing on this material showed behaviour that was substantially different in the 4-stack and 5-stack specimens. The 4-stack specimens, loaded parallel to the 0° direction of the specimen, developed cracks that grew in the direction of the load, where the 5-stack specimens loaded in the same manner developed cracks that grew along the notch mid-plane. This divergent behaviour has been shown to be related to the tension of the stitching in the material (Mitchell, 2001). The 4-stack specimens were tightly stitched, and were not effective in preventing delamination. The 5-stack specimens were loosely stitched, and significantly contained the extent of delamination resulting from the OCT test.

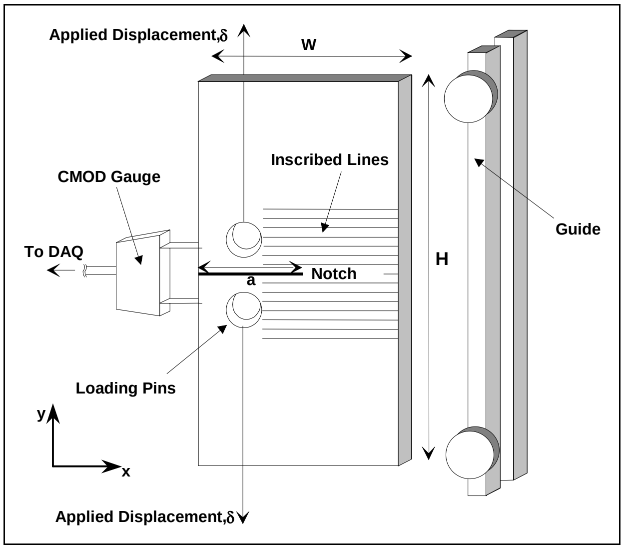


Figure 1. Schematic of the OCT test.

Impact Tests. The same material that was studied in the OCT tests was subjected to non-penetrating impact testing. These experiments involved 1” (25.4 mm) hemispherically tipped cylindrical projectiles fitted with piezoelectric load cells, launched from a gas gun. The targets were 4”x6” (101.6 mm x 152.4 mm) plates clamped over a jig with a 3”x5” (76.2 mm x 127 mm) opening.

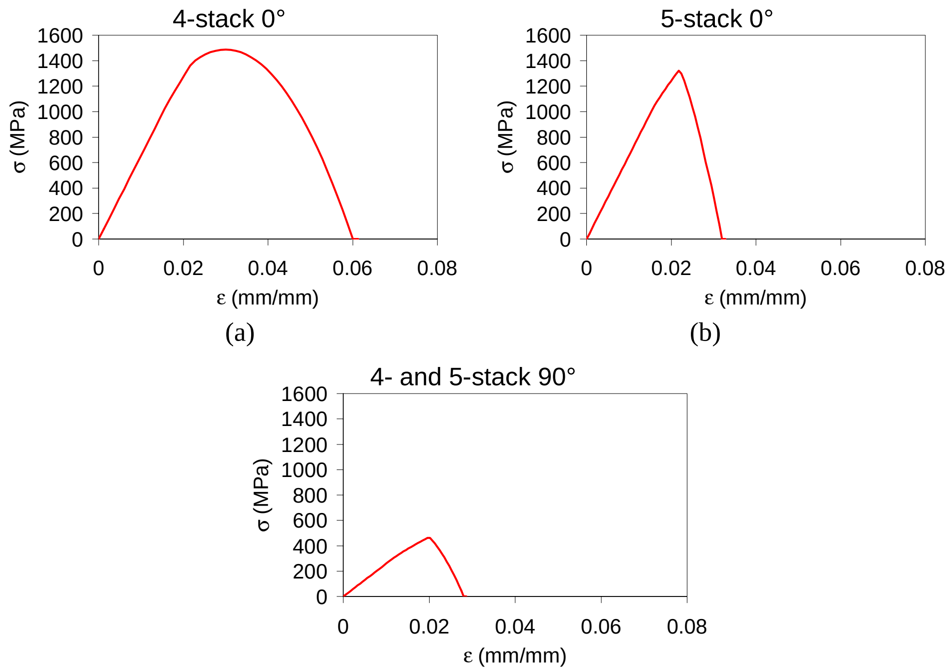
A number of tests were performed on the S/RFI material, in both the 4-stack and 5-stack configurations, with panels oriented with the 0° material direction in both the target short direction and long direction. The tests examined a range of velocities from 15.1 ft/s (4.6 m/s) to 63.3 ft/s (19.3 m/s).

Simulations

OCT Simulations. The OCT geometry was modelled with shell elements in LS-DYNA. The loading pin was assumed rigid, with perfect contact between the pin and the specimen. The displacement of the centre of the load pin was prescribed, with a displacement rate of 0.03 m/s. A small amount of global damping was included in the model to contain spurious noise.

Elastic material data for the S/RFI material was supplied with the panels by the manufacturer. The initial CODAM inputs for this material were based on assumptions of the behaviour of the material, in terms of the strain at the initiation and saturation of matrix and fibre cracking, as well as the relative contributions of the matrix and fibre damage to the effective stiffness of the material. Distinctions were made between the 4-stack and 5-stack inputs to account for the tendency of the 4-stack specimens to delaminate.

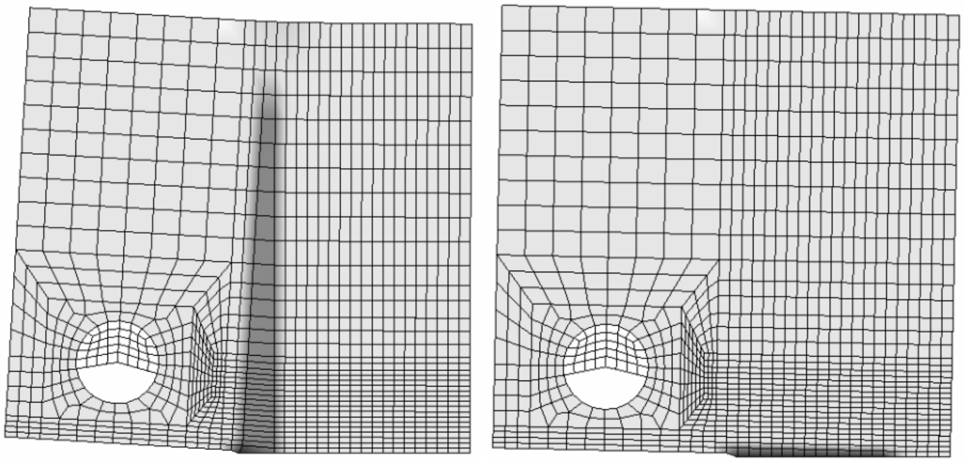
The OCT tests were simulated with this initial data set. Results of the simulation showed reasonable agreement with the experimental results; however to match as closely as possible the apparent stiffness of the system, the maximum force in the test, and the correct crack-growth behaviour, further refinement of the inputs was required. Figure 2 (a-c) shows the equivalent 1D stress-strain curves used as input for the CODAM model, while Figure 3 (a,b) demonstrates the difference in the damage growth between the 4-stack and 5-stack specimens. Figure 4 (a-d) shows the correlation of the experimental load-CMOD curve with the predicted load-CMOD curve.



(a) (b)

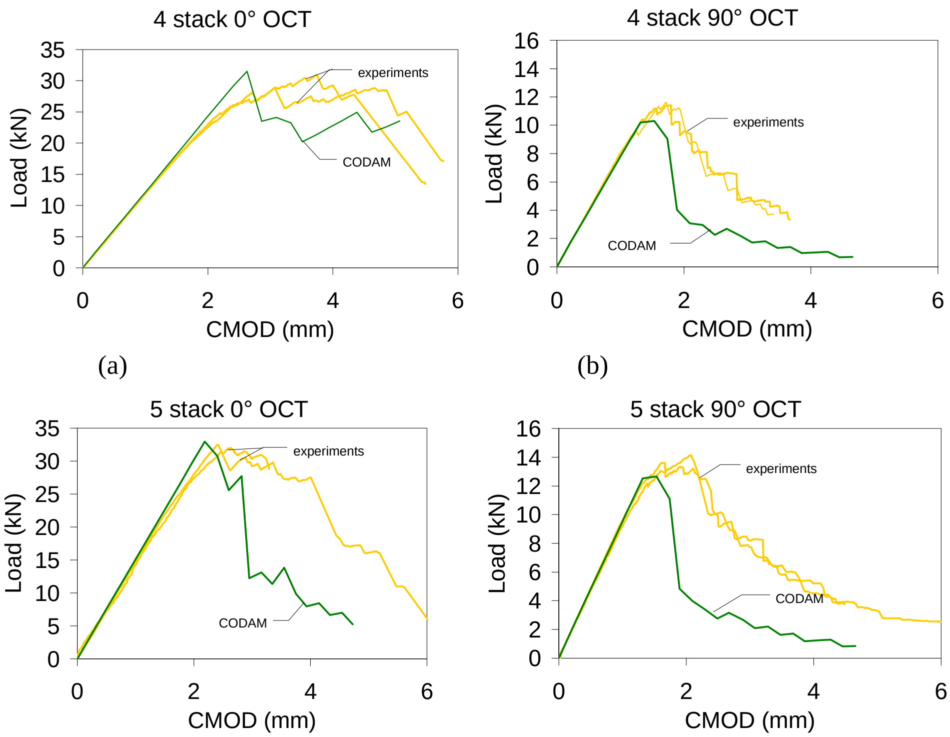
(c)

Figure 2. 1D stress-strain curves representing the CODAM inputs for the OCT simulations. The angles refer to the material direction; i.e., the 4-stack 0° refers to the input for the 0° material direction for the 4-stack specimens.



(a) (b)

Figure 3. Examples of damage development in (a) the 4-stack 0° OCT tests, and (b) in the 5-stack 0° OCT tests.



(a) (b)

(c) (d)

Figure 4. Comparisons between the OCT simulations and experiments.
The angles refer to the direction of loading; i.e. 4-stack 0° refers to loading the 4-stack specimen in the 0° material direction.

Non-penetrating impact simulations. The non-penetrating impacts were simulated with the OCT-derived CODAM data set for the two configurations of the S/RFI material. The target panels were also modelled with shell elements, with six integration points through the thickness to capture the bending effects. The target was supported in the out-of-plane direction along all sides. The impactor was assumed to be rigid, and automatic surface-to-surface contact was prescribed between the two bodies. Figure 5 shows the simulation configuration.

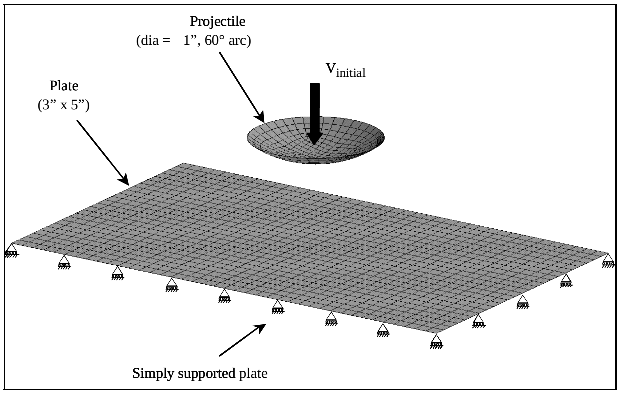


Figure 5. Schematic of the non-penetrating impact simulation.

DISCUSSION OF RESULTS

Elastic Impact

Only one of the simulations predicted no damage, a 9.4 m/s (30.9 ft/s) impact on a 5-stack specimen with the material 0° in the "short" target direction (known as a 90° impact test). The measured and simulated time histories of the contact force between the impactor and the target are shown in Figure 6. The good agreement between the simulation and the experiment in peak force and contact event duration shows that the model is valid in the undamaged elastic case.

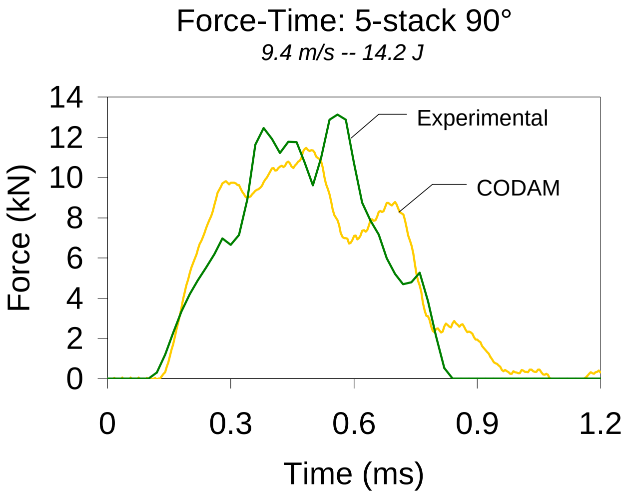
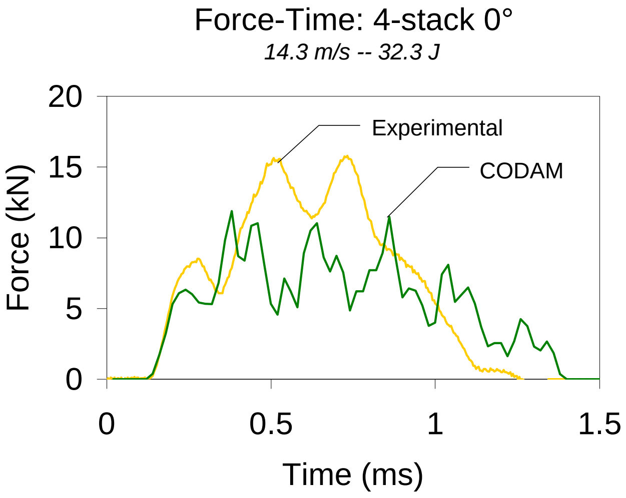


Figure 6. Contact force histories for low-velocity, elastic impact, on a 5-stack 90° specimen.

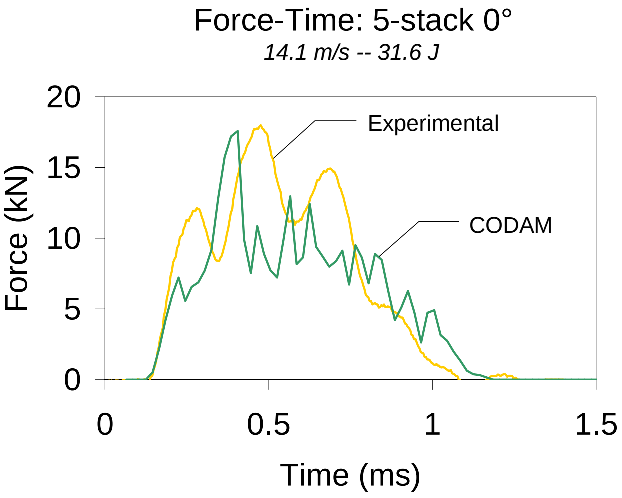
Damage Inducing Impact

In the simulations involving projectile velocities that are sufficient to cause damage in the targets, there are four configurations to consider. Each target was impacted with the 0° material direction in the target long and short directions. Further, each orientation was tested with both the 4- and 5-stack laminates.

0° Impact Orientation. In this configuration, the 0° material direction is oriented in the long direction of the target. Representative impactor force histories are shown in Figure 7. In all simulated velocities for this orientation, for both the 4-stack and 5-stack laminates, the mean peak force is under-predicted, and the event duration is slightly over-predicted. Both of these observations indicate that the simulations over-predict the amount or effect of damage in the target.



(a)



(b)

Figure 7. Impactor force histories for 4-stack 0° (a) and 5-stack 0° (b) simulations, with comparisons to the experiments.

Figure 8 shows a plot of the average damage in an impact target for a 0° impact. In all of the 0° impact simulations and experiments, damage grew in this manner, in the centre of the target, parallel to the material 0° direction.

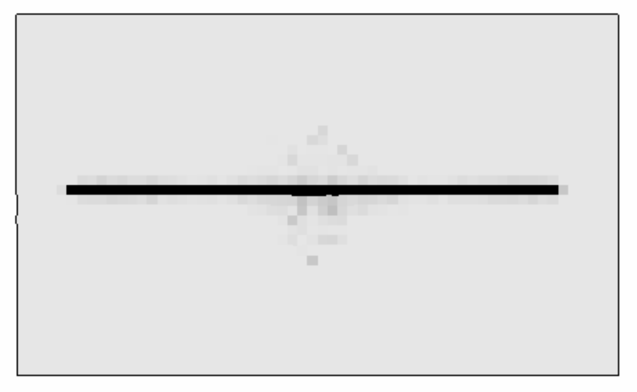
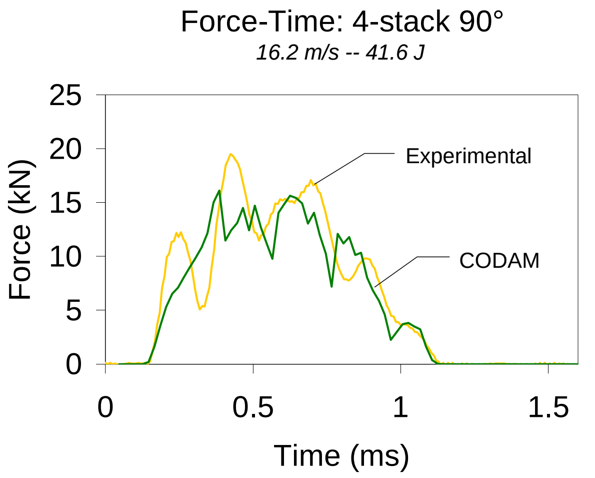
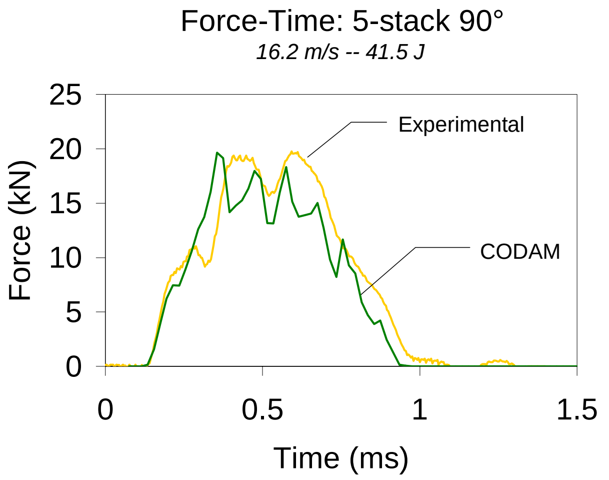


Figure 8. Plot of average damage in a 4-stack, 0° target, impacted at 14.3 m/s (32.3 J).



(a)



(b)

Figure 9. Impactor force histories for 4-stack 90° (a) and 5-stack 90° (b) simulations, with comparisons to the experiments.

90° Impact Orientation. In this configuration, the 0° material direction is oriented in the short direction of the target. Representative impactor force histories are shown in Figure 9. In these cases, the peak forces and the duration of the impact events are predicted quite well by the simulations.

Figure 10 shows a plot of the average damage in an impact target for a 90° impact. As in the 0° impacts, all of the 90° impact simulations and experiments exhibited damage that grew in the centre of the target, parallel to the material 0° direction.

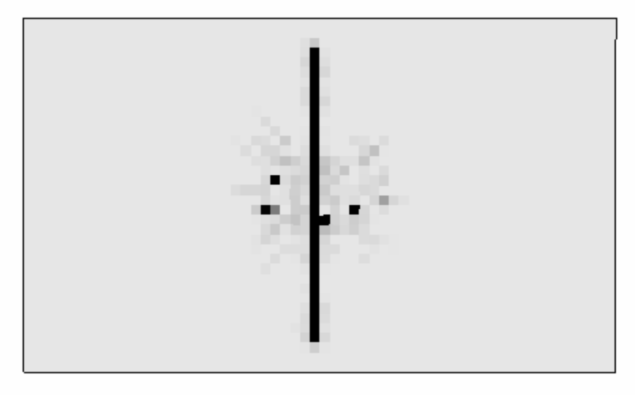


Figure 10. Plot of average damage in a 4-stack, 90° target, impacted at 16.2 m/s (41.6 J).

Discussion

To demonstrate the effect of the constitutive model, the 4-stack 90° impact simulation shown above (16.2 m/s or 53.1 ft/s) was run with an elastic (non-damaging) material input. The results of this are shown in Figure 11. This figure clearly shows that a constitutive model that includes progressive damage captures the whole impact event much better than the elastic model.

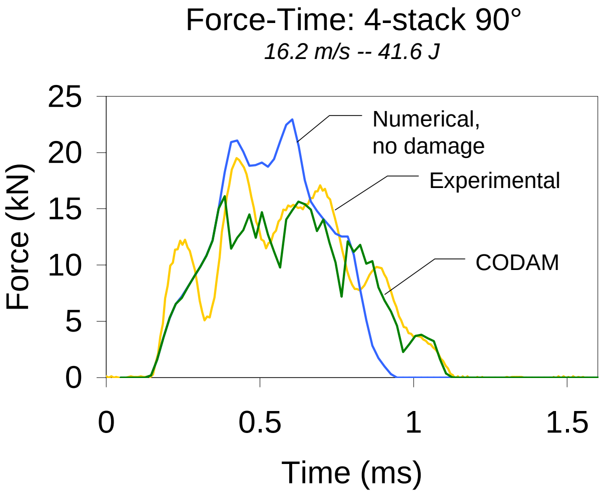
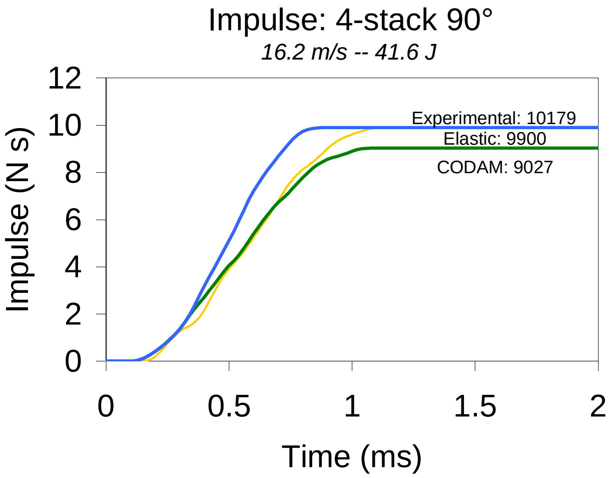
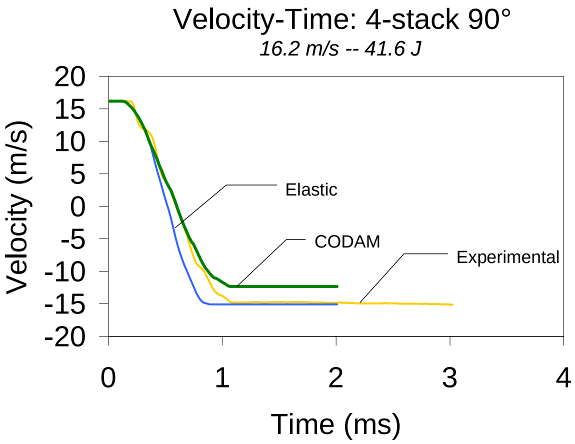


Figure 11. 4-stack 90° simulation showing the effect of using the CDM model compared to an elastic constitutive model.



(a)



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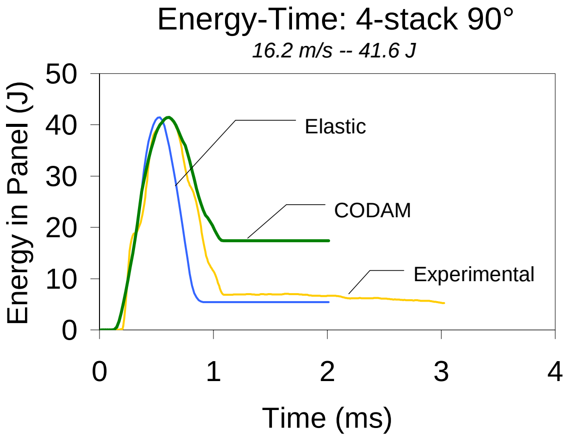
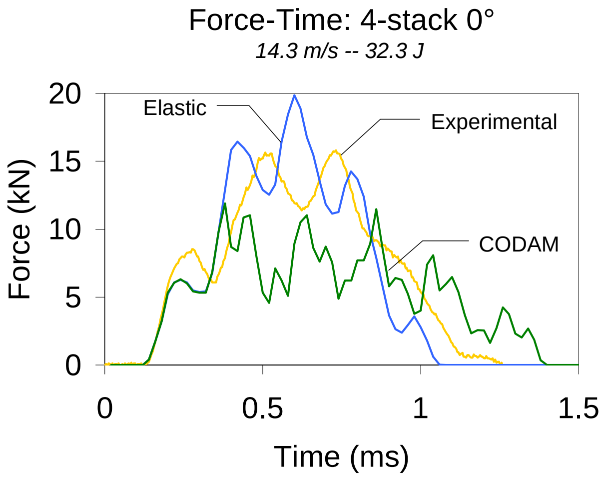


(c)

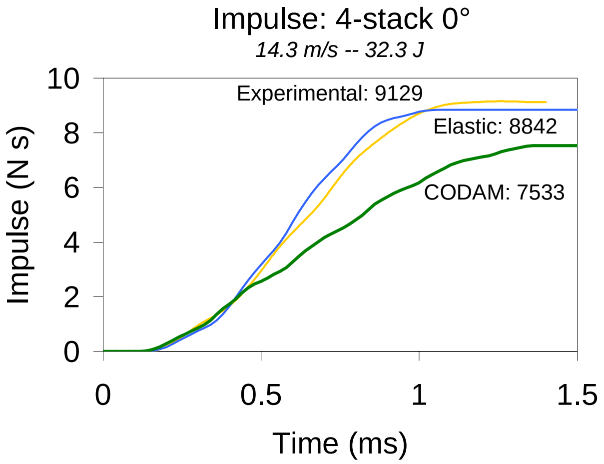
Figure 12. Additional methods of comparing the simulations to the experiment.

In addition to examining the impactor contact force histories, other comparisons can be made. For example, the impulse that the projectile delivers to the target has been examined in the 4-stack 90° impact at 16.2 m/s (53.1 ft/s). Figure 12(a) shows that examined in this manner, the elastic simulation delivers an impulse closer to that measured in the experiment, but over a shorter duration. Alternatively, the velocity history of the impactor can be examined, as shown in Figure 12(b). This figure shows that the CODAM simulation corresponds very closely to the experimental velocity, up to ~1 ms. Figure 12(c), a plot of the energy transferred to the panel, shows that the CODAM simulation transfers more energy to the panel than the elastic simulation. It is this additional transfer of energy that results in the differences shown in the impulse and velocity history plots.

A similar investigation into the 4-stack 0° impact at 14.3 m/s (46.8 ft/s) shows that the elastic model over-predicts the peak force and under-predicts the event duration, but approximates the total impulse transmitted to the panel very well. Figure 13 shows these results.



(a)



(b)

Figure 13. Contact force time history for the 4-stack 0° 14.3 m/s (46.8 ft/s) impact, showing (a) the elastic simulation, and (b) the impulse history showing the experiment, the CODAM simulation, and the elastic simulation.

The available experimental data provide little insight into the issue. The experimental impactor velocity history and the corresponding target energy history suggest that very little energy is absorbed by the target. Unfortunately, the displacement of the target and vibrations in the target were not measured. Further, detailed damage analysis of the targets was not performed, so the extent of the damage in the actual targets is not known.

SUMMARY

The CODAM constitutive model has been shown to be versatile, with the ability to satisfactorily simulate in-plane crack growth and non-penetrating impact damage development with the same data set. The CODAM model demonstrated a closer correlation with experiments in the 90° impact events, simulating the peak contact force and event duration quite closely. The model was less accurate in modelling the 0° impact events, under-predicting the peak force, and slightly over-predicting the event duration. Damage development in the CODAM simulations seems more extensive than observed experimentally, but a more detailed examination of the impacted targets is required to gain further insight into this aspect of the problem.

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