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MODELING FOREIGN OBJECT DAMAGE TO CVI MI SIC/IBN/SIC AND OXIDE/OXIDE CERAMIC COMPOSITE COMPONENTS IN GAS TURBINE ENGINES AT AMBIENT AND ELEVATED TEMPERATURES

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ABSTRACT

The inherent toughness of ceramic matrix composites (CMCs) in advanced gas-turbine engines must be predictable under impact from small foreign objects to lower the amount of full scale testing needed to produce robust designs. Fiber/matrix/architecture properties of the composites, and a damage evolution based progressive failure code that can be used for a full range of composite architectures (GENOA) coupled with an explicit FEM impact code (LS-DYNA) were used to simulate impact and residual 4pt flexural strength of the ceramic engine components. This approach uses physics-based mechanics coupled at the micro and macro scale boundaries. The benefit of this technique is that the root cause of damage advancement at the micromechanical level could be understood and simulations could be performed to assess better damage tolerance structures. Steel projectiles with a diameter of 1.59 mm were used to impact the composites at speeds from 100-400 m/s (Mach 0.3-1.2) and the results shown to compare to prior test data for 2-D 5H Sylramic iBN CVI MI SiC at 25^{0}C and 1316^{0}C and for 2-D 8H N720/AS ceramic composites at 25^{0}C. Simulations also gave insight to the micromechanical damage progression and were comparable with test data.

Keywords: Foreign object damage (FOD), ceramic matrix composites (CMCs), ballistic, impact mechanics, D&DT, aeroengine, gas turbine, SiC/SiC, oxide/oxide

1. INTRODUCTION

Ceramic matrix composite components in advanced gas-turbine engines increase efficiency of the engine by allowing higher operating temperatures (~1204°C), can reduce emissions, and lower engine weight. These factors impact military aircraft fuel consumption and agility. Ceramics have been proven airworthiness for modestly loaded parts like combustor liners, turbine blades, vanes and shrouds, nozzles and heat exchangers. One major concern is the residual strength of CMC's after impact with small foreign objects traveling at speeds around Mach 1, which can be determined by experiments of simulation.

Prior to this work, impact tests were performed on 2-D 5H Sylramic iBN CVI MI SiC at 25^{0}C and 1316^{0}C and for 2-D 8H N720/AS ceramic composites at 25^{0}C [1,2]. The steel projectiles had a diameter of 1.59 mm impact the composites at speeds from 100-400 m/s (Mach 0.3-1.2). Full and partial support was considered. Room temperature 4pt bend tests were performed post impact. These tests observations of damage size and cross sections at the impact site give an understanding of physical mechanisms associated with impact.

The technical objective of this work is to demonstrate a physics-based numerical model for Foreign Object Damage (FOD) and residual strength in continuous ceramic fiber-reinforced ceramic matrix composites and to compare results with prior test data.

2. SIMULATION METHOD

The complexity of CMC FOD can be attributed to the complex nature of impact dynamics coupled with the complexity of CMC architecture/constituent properties and failure modes. This simulation couples three industry approved software: LS-DYNA (impact) with GENOA (CMC property and failure prediction), and MD-NASTRAN (post impact, 4pt bend). The method includes the ability to change boundary conditions and use pre-determined residual stress and damage for the post impact bend simulation.

LS-DYNA is a well known finite element software for simulating explicit dynamic events. It tends to overpredict peak loading of dynamic events and can not accurately control the residual after-peak load) due to the complex behavior and variety of failure mechanisms in composite structures (FIGURE 1). MD-NASTRAN is an ideal finite element software for simulating the flexure tests. GENOA is a progressive failure analysis code which utilizes (1) micro and macro composite mechanics analysis, (2) finite element (FEA) analysis, and (3) damage evaluation methods (Fig. 1). GENOA is designed for prediction of the strength, durability and damage tolerance (D&DT), life assessment and reliability of an aerospace, military or automotive structural component. The numerical simulation method also provides detailed information of micro-macro stress fields, micro-macro damage development and failure mechanisms involved in the simulated structure. GENOA is used once with DYNA as the FE solver for the impact analysis, with the end residual stresses and damage state saved and used is then used in a subsequent GENOA/MD-NASTRAN analysis for the post FOD 4pt bend test. GENOA writes input decks for both LS-DYNA and MD-NASTRAN thus it can be used to account for damage by changing the composite ABD matrix, to increase the time or load step when needed, and the change the mesh. It can also interface with ANSYS, ABAQUS, and comes with its own MHOST FE solver.

2.1 Micro and Macro Composite Progressive Failure Analysis

The overall flow of GENOA is shown in (Fig 2 and 3). These charts apply to both the GENOA/LS-DYNA impact analysis and the GENOA/MD-NASTRAN 4 pt bend simulation. The computations begin with an FE model and all composite architectures, fiber/matrix/interphases, and defects known and stored in GENOA format (shown with a ★ Fig 2). The composite properties are computed using micromechanics formulations developed at NASA [6]. Then the composite properties are integrated through the entire structure to form the structural overall stiffness for finite element (FE) analysis (Fig. 4, Ref 7). The finite element module is utilized. FE results are fed to the composite micromechanics module in GENOA to check for damage/microcracks/fracture. If there is damage the fiber/matrix/interphase properties are degraded and the FE analysis is run at the same load step. Once there is no additional damage, the load is increased and the process continues until the structure fractures and is no longer able to sustain load. This process is also shown in Figure 3.

2.2 Damage Evaluation

Determination of failure is at the micro (composite constituent) level [6, 8]. The FEM macro stress and strain in each element are broken down to the microscopic (constituent) level in the micro mechanics module to determine the damage and/or fracture. The micro failure is transferred into the macro composite mechanics module to reflect the property changes resulting from such damage.

GENOA's approach to failure evaluation involves comparison of computed constituent properties with criteria of stress limits, distortion energies, degree of relative ply rotation, and global scalar-damage. These failure criteria are given in TABLE 1. The first 9 criteria are stress limits computed by the micromechanical equations in GENOA based on a material's constituent stiffness and strength values [1]. In addition to the 9 failure criteria based on stress limits, interply delamination due to relative rotation of plies, modified distortion energy (MDE) and other combined failure criterion can be used. Strain theories and user defined theories can also be used.

TABLE 1 FAILURE MODES IN DAMAGE EVALUATION

Mode	Description
Longitudinal Tensile	Fiber tensile strength and the fiber volume ratio.
Longitudinal Compressive	1. Rule of mixtures based on fiber compressive strength and fiber volume ratio 2. Fiber microbuckling based on matrix shear modulus and fiber volume ratio, and 3. Compressive shear failure or kink band formation that is mainly based on ply intralaminar shear strength and matrix tensile strength.
Transverse Tensile	Matrix modulus, matrix tensile strength, and fiber volume ratio.
Transverse Compressive	Matrix compressive strength, matrix modulus, and fiber volume ratio.
Normal Tensile	Plies are separating due to normal tension
Normal Compressive	Due to very high surface pressure
In Plane Shear	Failure due to in plane shear with reference to laminate coordinates
Transverse Normal Shear	Shear Failure due to shear stress acting on transverse cross section oriented in normal direction of the ply
Longitudinal Normal Shear	Shear Failure due to shear stress acting on longitudinal cross section oriented in a normal direction of the ply
Combined Failure Criterion	Modified from Distortion Energy for anisotropic materials, User Defined, Puck, Tsai Wu, Tsai Hill, Hoffman, and Hashin.
Relative Rotation Criterion	Considers failure if the adjacent plies rotate excessively with respect to one another
Strain Invariant Failure Theory	SIFT, Principal strains, and Ply strain limit

3. FINITE ELEMENT MODELS

Several of the finite elements models used for the impact and other material characterization tests are shown in FIGURE 5. The size of the impact/bend model was 6,000 solid elements. It is a coarse mesh since there are many cycles within each time interval for GENOA to compute the damage and its effects. This adds time on top of a typical LS-DYNA analysis. The PFDA (GENOA/LS-DYNA) models typically take about 6-12 hours to run on a 32-bit Intel Duo Core E7300 @ 2.66GHz. The more damage accumulation, the more time it takes since GENOA will call LS-DYNA to rerun the previous time interval with damaged materials until no additional damage is reached. Some of the other models were up to 20,000 elements.

4. MATERIAL PROPERTIES

One material in consideration is a 2-D 5 harness satin cloth of Sylramic fibers, coated with a BN interface, then SiC vapor infiltrated (CVI) and Si melt-infiltrated (MI). The constituent properties of this system were used in prior work [9] at from room to 1450°C. The sample beams were 8 [0/90º] plies stacked 2.2 mm thick with the other dimensions being 45mm (length) and 8mm (width). The composite was fabricated by GE Power System Composites (Newark, DL; vintage '02) with the fibers in tow form coming from Dow Corning (Midland, MI) / COIC (San Diego, CA). The composite was 34 vol% SiC fibers, 5 vol% BN coating, and 58 vol% SiC coating, SiC particulates, and silicon, and about 2%–3% porosity.

Impact with 1.59 mm steel pellet from 115m/s – 440m/s, (at temperatures 25°C, 1316°C, fully and partially supported), 4 point bend after impact. The bend test was so that the impact region was placed in tension. The bend test outer span was 40mm while the inner span was 20mm.

The material for this test vs analysis was a 2-D oxide/oxide (N720/AS = aluminosilicate) ceramic matrix composite. The 8 harness satin cloth was 12 plies, vacuum bagged with the AS matrix slurry and heat-treated at high temperature. There was no interphase, the porosity was about 25%, and the final specimens were 50 mm (length) x 10mm (width) and 3mm thick

The constituent properties used in the simulation of the oxide/oxide material from prior work that predicted material behavior for 2D ([0/90]) N720/A and 3D (through-thickness angle interlock) N720/A). The predicted behavior included 2D: in-plane tension, compression, and shear, inter-laminar shear and tension, in-plane bending, bi-axial tension, and 3D: in-plane and inter-laminar tensions [5]. That work also predicted component mechanical behavior post thermal cycling. Current work is determining if it was a valid assumption to use N720/A properties for simulation of N720/AS test.

5. SIMULATION RESULTS

The simulation results of the seven specimens are presented in this section.

5.1 SiC/SiC

The room temperature simulations of the full impact test (Fig 6 left) are close to the test results. They do have inconsistent error with respect to increasing impact velocities that needs to be investigated. The room temperature simulations (solid elements) of the test coupon partially held (Fig 6 right) are also close to test results and show the same inconsistent damage growth rate compared with test. The modeling strategy was changed from shell to solid elements because the fully supported case was not possible to model with shell elements and it seemed that the damage pattern was too large compared with test for the partially supported case.

Figure 7 and Figure 8 show the contact force and percent total damaged volume as the impact occurs. We see the contact force is a maximum of 4,300 N (the master surface force was negative in the impact direction which was chosen to be the output of the two contact bodies). The contact and simulation is ended in about 6μs. Key points A, B, C, and D are identified on both figures. They identify when damage initiated (A), when it propagated (B, C), and the final damage state (D). As seen in Figure 8, there is only about 3% total damaged volume over the whole coupon. Most of the damage is local to the impact site. Furthermore, most of the damage occurs at the beginning of the impact event, and when the projectile is bouncing back not much more damage occurs.

Figure 9 numerically identifies the region of damaged volume (as red=damage elements) for these time events. The percents shown for each of the damage mechanisms are with respect to the total damage volume. In (B) we see that 61.0% of all the damaged volume shown in red is due to Normal Compression (S33, out of plane); and so forth. These damages are tracked and when accumulated can lead to failure of the composite.

Figure 10 shows that the simulation data point of (Figure 6 left) was generated after isolating the regions that had fiber crushing, matrix damage, and normal compressive damage. The measurement was taken at the surface. Showing the wire mesh shows the depth and of the same damage combination. Figure 11 comes directly from [1] and is a depiction of delamination and cracking that was observed from test for all extents of the test performed.

Figure 12 comes directly from [1] and is a depiction of delamination and cracking that was observed from test for all extents of the test performed. Figure 12 (left) is an actual picture of a cross section of the damage zone for a partially supported 400m/s specimen. Figure 12 (right) shows the delamination at the end of the same event simulated. An important point to make is that while the simulation gives a good approximation to delamination and gives insight to other unseen damage mechanisms (out of plane shear,…), to make matches to such cracks path details seen in the test picture might require a higher fidelity model. Crack density (# cracks / mm) computations were active in the impact model. It was shown to reduce damage a bit (1-2%) by allowing more cracks to form locally rather than progress across the larger FE scale. Unfortunately the crack density was not one computation chosen to be printed to the database files so that I/O time was decreased. This shall be done for this case in a future rerun of the simulation. Ply level and fiber/matrix/interphase stresses, damages, strains, can also be tracked at every moment in the analysis but at this moment the focus is more on the damage which is automatically computed based on those ply and fiber/matrix/interphase level responses.

5.2 Oxide/Oxide

Figure 13 shows the maximum indentation of the impact event in the simulation at the impact cross section for the fully supported, RT case. There is much deformation. The Oxide/Oxide composite has a lower modulus than the SiC/SiC composite. This high deformation leads to collapsing elements and a very low DYNA time step which resulted in 12 hour simulation times using 2 parallel processors. The 300m/s simulation can be correlated with a picture of damage taken after the test also shown in the figure. Notice that the test picture, like the simulation has damage outside the diameter of the sphere of impact. It is these damage and deformed meshes that are the initial state for the subsequent flexure simulation. The frontal damage size in the simulation is compared with test for all impact velocities in Figure 14 (left). The simulation is in good agreement with test. Test shows little difference frontal damage for the fully supported and partially supported configurations. The scatter can be predicted with probabilistic impact. Figure 14 (right) shows the maximum load obtained during the 4 point bend simulation compared with test results. The simulation is in good agreement with test. Figure 15 is impact damage taken to the 4 point bend simulation for fully supported oxide/oxide specimen, the 100m/s room temperature scenario. It also shows how the fracture propagated in the 4pt bend simulation.

6. CONCLUSION

Impact simulations for both SiC/SiC and Oxide/Oxide composites have been performed and results have been obtained that are reasonably well when compared with test. Those analyses still need to be refined to lower the discrepancy. New analyses for different scenarios need to be run as well.

Shell models exhibit more damage during impact when compared with test. Shell models also over constraining the fully supported model and artificially lowering the impact stresses. The solid models show promise and have damage, delamination, and residual strength characteristics comparable with test. Using a coarse FE model to lower simulation time seems to work for macro behavior like damage, delamination, and residual strength. However, making comparisons details like crack paths in test vs simulation is difficult. Crack density formulations were used in the analysis but no such output was chosen to be kept because it increases the I/O and thus simulation time. Such output will be gathered for a future simulation. Another concern is the choice of single integration point elements in the dynamic analysis which lowers the accuracy of stresses but decreases computational time. A study should be performed about the different in stresses with a higher order element should be performed to cast light on this subject.

Unit Conversion Table

	To convert		Multiply by
Temperature	^{o}F	to ^{o}C	(^{o}F-32)/1.8
Force	lbf	to N	4.448
Stress	psi	to MPa	6.895×10^{-3}
Length	in	to mm	25.4

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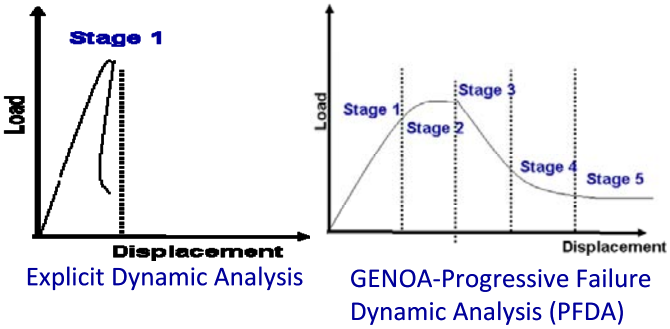

FIGURE 1 IMPACT DYNAMIC EXPLICIT ANALYSIS VS. PFDA [4]

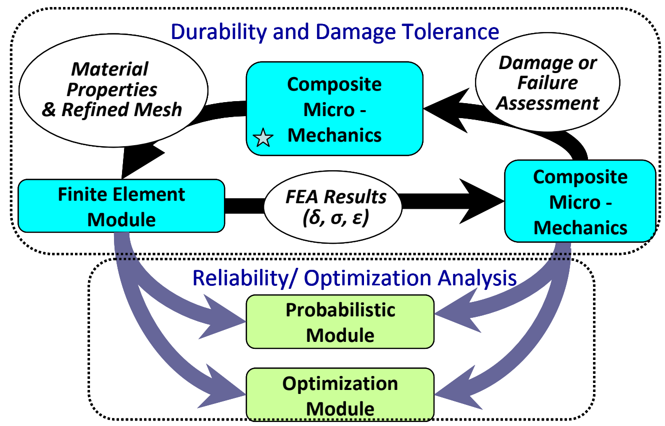

FIGURE 2 ANALYSIS PROCEDURE OF THE MULTI-SCALED FEM PROGRESSIVE FAILURE METHOD

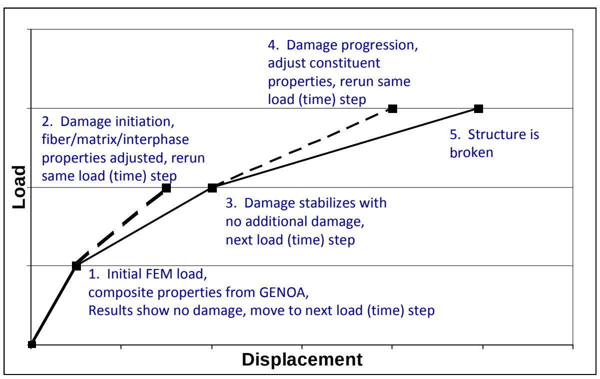

FIGURE 3 DAMAGE TRACKING EXPRESSED IN TERMS OF LOAD VS. DISPLACEMENT

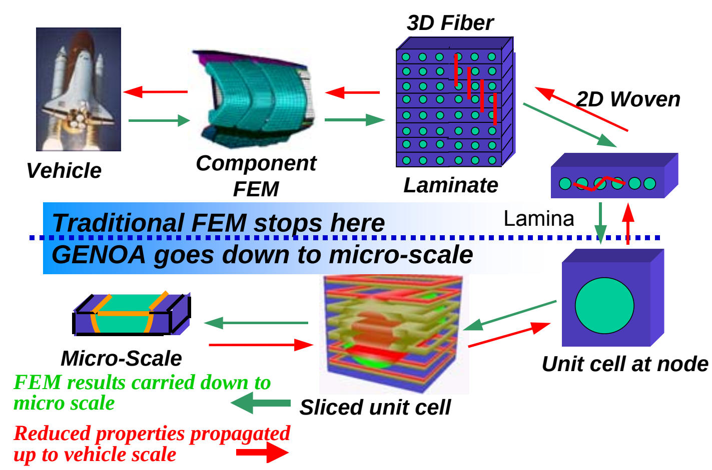

FIGURE 4 MICRO-MACRO SCALE INTERACTION IN GENOA'S PROGRESSIVE FAILURE ANALYSIS

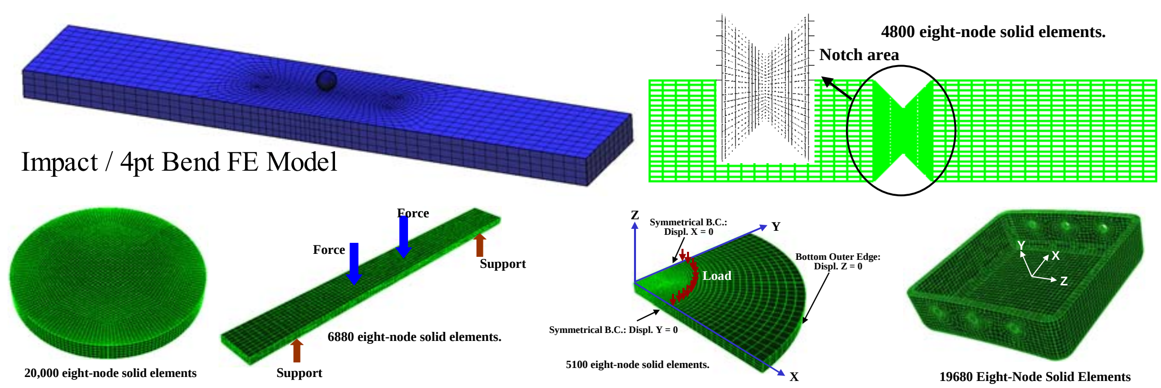

FIGURE 5 SEVERAL OF THE FE MODELS USED FOR IMPACT AND CHARACTERIZATION

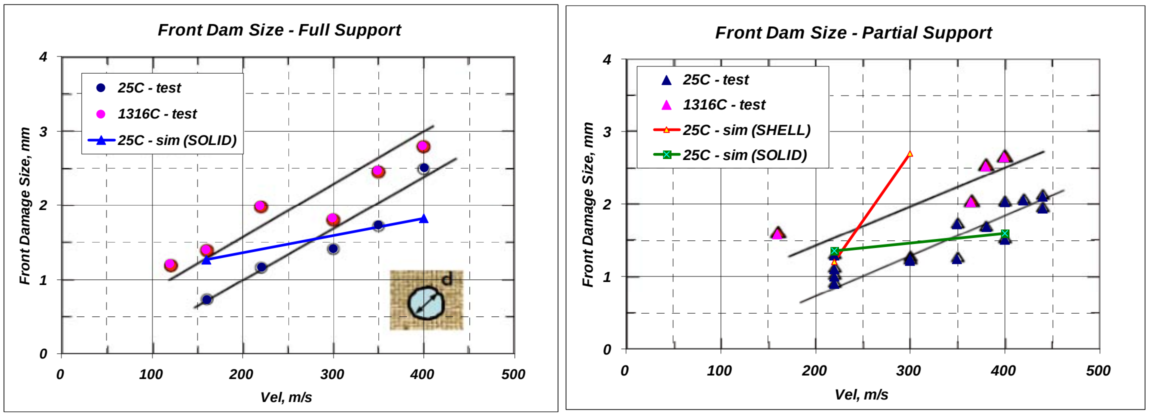

FIGURE 6 FRONTAL DAMAGE VS VELOCITY FOR SIC/SIC COMPOSITE AT ROOM AND 1316C FOR FULL (LEFT) AND PARTIAL SUPPORT (RIGHT). ROOM TEMPERATURE RESULTS COMPARED WITH TEST [1]

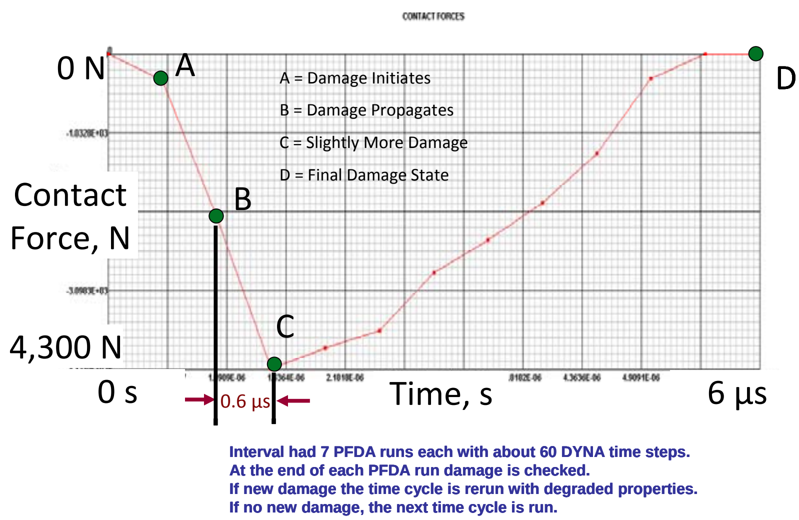

FIGURE 7 CONTACT FORCE VS TIME (FULL, 400M/S, RT)

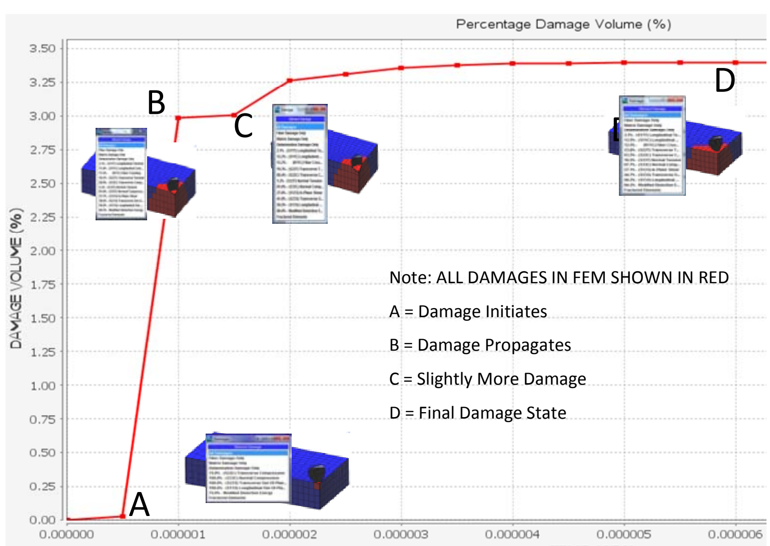

FIGURE 8 TOTAL PERCENT DAMAGED VOLUME VS TIME (FULL, 400M/S, RT) (RED = DAMAGE)

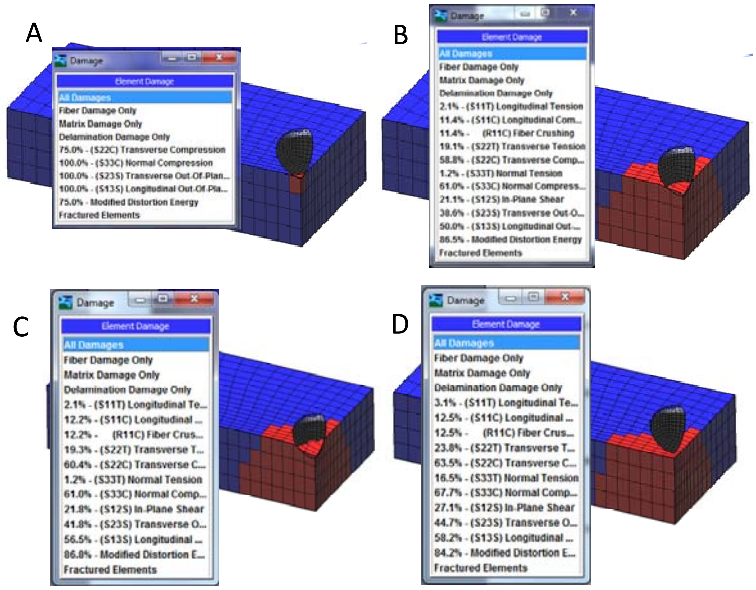

FIGURE 9 ALL DAMAGE TYPES AND THEIR PERCENT TRACKED AT 4 DIFFERENT TIMES IN THE ANALYSIS (RED = DAMAGE) (FULL, 400M/S, RT)

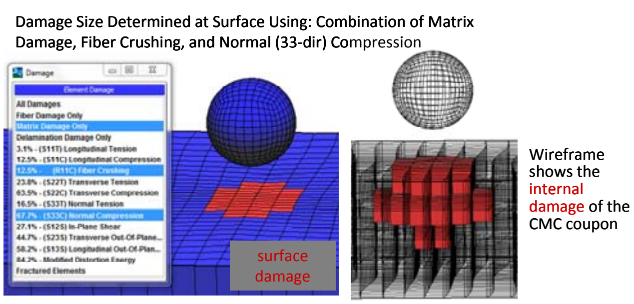

FIGURE 10 REGIONS WITH MATRIX DAMAGE, FIBER CRUSHING, AND NORMAL (33-DIR) COMPRESSION DAMAGE ISOLATED POST IMPACT EVENT FOR CORRELATION WITH TEST (RED = DAMAGE) (FULL, 400M/S, RT)

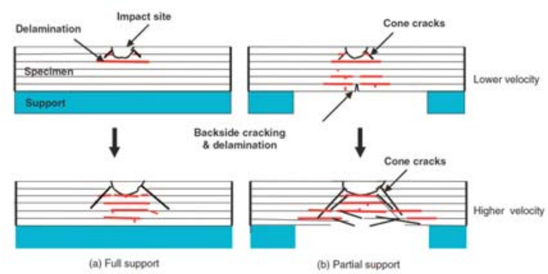

FIGURE 11 SCHEMATIC OF TEST RESULTS SHOWING DELAMINATION (RED) AND CONE CRACKS FOR DIFFERENT SUPPORTS AND VELOCITIES TESTED [FIG REF 1]

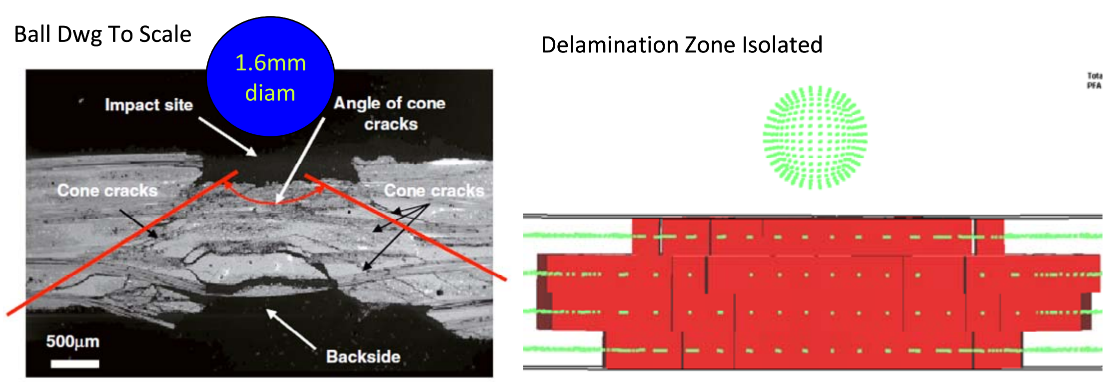

FIGURE 12 PARTIAL 400M/S, RT TEST PICTURE (LEFT) SHOWING DELAMINATION, CONE CRACKS, AND REMOVED CRACK ZONES AT CROSS SECTION OF IMPACT ZONE VS SIMULATION DELAMINATION ZONE ISOLATED (RIGHT). [LEFT FIG REF 1]

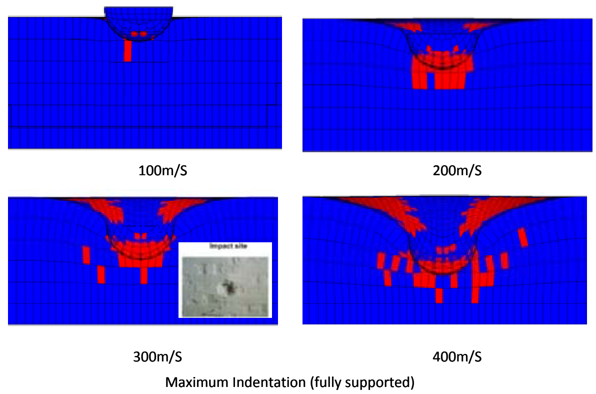

FIGURE 13 SIMULATION SHOWING MAXIMUM INDENTATION SHOWN IN A CROSS SECTION OF THE OXIDE/OXIDE SIMULATION MODEL FOR FULL, RT CASE [PIC REF 2]

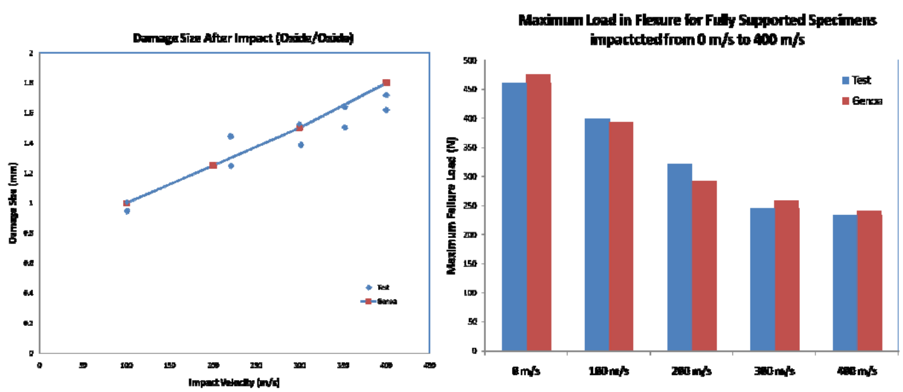

FIGURE 14 DAMAGE SIZE AFTER IMPACT (LEFT) AND POST IMPACT MAXIMUM FLEXURE LOAD (RIGHT) VS VELOCITY(100-400M/S) FOR FULLY SUPPORTED OX/OX RT SCENARIO

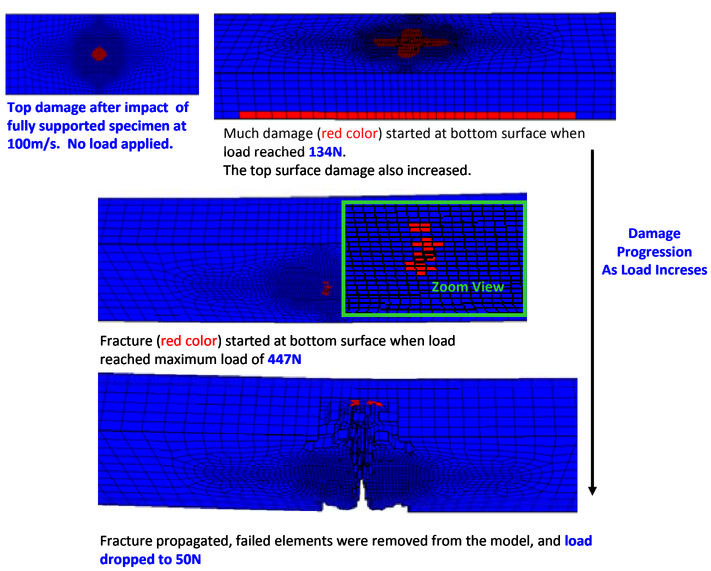

FIGURE 15 INITIAL IMPACT DAMAGE AND 4 POINT BEND DAMAGE PROGRESSION FULLY SUPPORTED OX/OX, 100M/S RT SCENARIO SHOWN FOR THE SIMULATION