Test Validated Multi-Scale Simulation of a Composite Bumper Under Impact Loading

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Abstract

In a recent USAMP-DOE Validation of Material Models study sought to evaluate efficacy of computational software against physical test. The undertaking started with material characterization and sub-element verification in Phase I and continued to full bumper assembly evaluations. A multiscale ICME building block approach for calibration, verification, and validations resulted in good agreement between test and simulation and served as the foundation for the blind prediction of a composite bumper under impact loading. Comparisons show that simulations, utilizing LS-DYNA® User Material with GENOA's Multi-Scale Progressive Failure Analysis (MS-PFA), under predicted test displacement vs time and generally over-predicted force curves. Under prediction in displacement was attributed to variation in boundary conditions between test and simulation. Discrepancy in force was assumed to be due to rigid simulation joints/boundary conditions, voids/defects/waviness in physical part, and discrepancy in as-designed vs as-built part. Another factor for discrepancy was that as-designed CAD model was different than as-built physical model, causing more failure/crush/deformation in test since distortion could place undesired higher moments on assembly resulting in increased stresses at fittings. Predictions are improved with direct input of void shape/size and fabric waviness as part of analytical de-homogenized approach which scales to component level without excessive cost in CPU time.

1.0 Introduction

Advanced hybrid (continuous, chopped) composite structures are finding wide-spread applications in the automotive industry (**Figure 1**), primarily due to their high specific stiffness and strength, in addition to their improved impact performance, when compared to conventional metallic alloys. This is further assisted by the increased confidence gained through extensive developments in composite structural design, analysis, and manufacturing, allowing advanced composites to be used in modern commercial fleet, particularly in their primary structures [1][2].

Structural responses of composites to dynamic and critical loading conditions is complex. Failure in composite structures range from tensile and compressive matrix and fibre failure to delamination of the individual plies that is caused by inter and intra-laminar cracks. Composites exhibit anisotropic behaviour with generally high longitudinal and transverse strengths. However, they also sustain substantial damage along the through-thickness axis due to their poor strength properties in that direction.

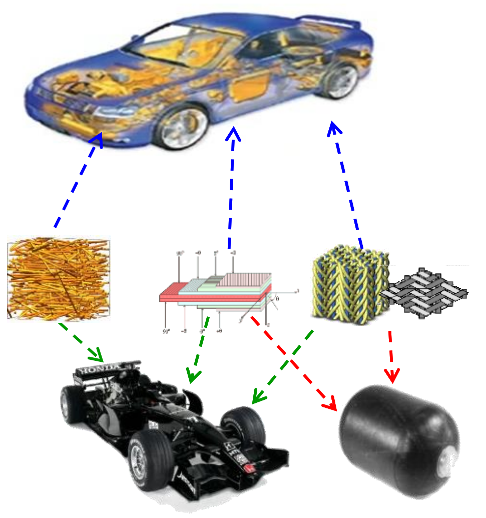


Figure 1. Advanced Hybrid Composite: Continuous and Chopped Fiber (SMC)

Commonly used structural design software's have difficulties predicting manufacturing parameters and constituent properties of short or long fiber reinforced polymer composites to meet mandated design requirements.

The objective of the present work is two-fold. The first is to implement a *computational methodology* able to predict both the effective stiffness and strength of unidirectional and weave continuous fiber and randomly oriented short fiber composites from injection and compression molding. Finally, to cast those properties into a useful model for applications on devices undergoing crushing, thus, allowing the prediction of their performance under different service loadings.

Accurate prediction of failure in composite structures is imperative in determining the fail-safe envelops. Although, a variety of failure criteria has been developed, there are still many uncertainties associated with the damage and degradation mechanisms of the composite structures that need to be effectively addressed. Of particular interest to manufacturers is delamination prediction, which is a common failure mode in low-to-medium energy impact events and can lead to catastrophic events in composite structures. Delamination cannot be detected visually and accurate prediction of its occurrence and specific location within laminates is also difficult.

In low-velocity/energy impact range, delaminations can occur at various locations through the thickness of the laminate. It is particularly common between neighbouring plies with different fibre orientation, which translates into a large stiffness mismatch within the adjacent layers.

Lower impact velocities, or impacts onto relatively flexible composite laminates, result in delaminations occurring predominantly near the bottom layers of the structure. This is due to higher tensile stresses induced through bending. At higher velocities, the impulse during the impact occurs over a shorter time thus resulting in a higher impact force. Therefore, there is a tendency of local deformation at the impacted surface causing delaminations there. This is depicted in **Figure 2.**

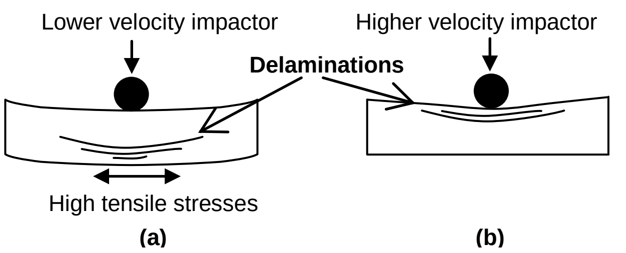


Figure 2. Delaminations Caused by (a) Low and (b) Medium Energy Impacts

There are many complexities in physically measuring the damage initiation and growth in composites. Computational analysis methods are increasingly being employed to model composite behaviour as an alternative to numerous experimental tests, which also show a degree of variability within themselves.

Finite Element (FE) methods are popular in structural analyses, and have been increasingly applied to the analysis of composite materials. The various failure modes in composite structures have been established and incorporated into commercial FE codes. However, the ability to accurately capture delamination damage between composite plies within a composite structure is still being heavily investigated. This is because the delamination does not occur within the plies that make up the structure. Rather they occur in between the plies and traditionally FE has not had the capability to conduct interface analysis.

Nevertheless, recently this capability has become available and various methods have been undertaken to capture delamination. There has been an ever-increasing trend to model delamination using a mixture of shell and 3D elements. Alfano et al. [3] have also conducted an investigation into capturing damage of composite materials using interface elements with others adding strain rate effects [4]. Housner and Sokolinski applied damage degradation on shuttle Columbia accident investigation [5]. Another breakthrough has been the implementation of explicit solvers as investigated by many authors like [3][6][7][8][9] who has provided the tools and methods to be able to conduct non-linear analysis determining the onset of delamination.

Figure 3 shows the schematic view of the de-homogenized vs. homogenized multi-scale modeling approaches currently available. Both feed into FE models. As shown, homogenization is based on a numerically (FE based) generated RVE unit cell, considering the smeared fiber orientation and length without the effect of defects. It is time consuming and limited in its progressive failure modeling capabilities. Conversely, de-homogenization is fast since it is based on an analytical generated RVE unit cell, considering the through-thickness fiber orientation and length and including the effect of defects, allowing fiber, matrix, and interphase stress re-distribution and damage evolution. Results from the micro-scale are then used to 'build' up the complete laminate up to the macro-level. Often referred to as the 'building-block' approach, this modelling approach results in substantially quicker and more accurate solutions when compared to current FE methods.

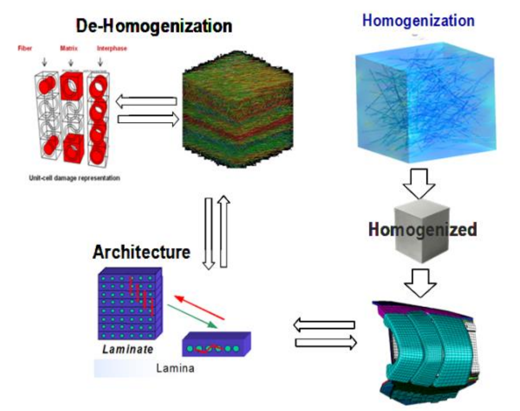


Figure 3. Schematic View of De-Homogenized vs. Homogenized Multi-Scale Modeling

Multi-scale modeling goes down to the nano-/micro-level, where failure originates and scaled back up with damage states at every timestep. This methodology also has a capability dedicated to the prediction of the performance of chopped fiber composites. Material Characterization and Qualification (MCQ) - Chopped software predicts composite randomly oriented fiber orientation, strength, stiffness, through the material thickness, by reverse engineering the material constituents' properties (fiber and matrix). By the replication of measured performance from the ASTM coupon tests, the computational analytical capability also considers the effect of defects including: (**a**) void shape size/distribution, (**b**) fiber waviness, (**c**) agglomeration, and (**d**) interphase. After characterization, a multi-scale progressive failure analysis (MS-PFA) is performed to evaluate the structural durability and damage tolerance of CFRP composite tubes and then the hybrid CFRP SFRP bumper assembly in order to track the damage and fracture evolution and to determine: when, where, and why the failure occurs, and what can be done to resolve it [6][7].

2.0 Methodology

2.1 Material Characterization & Qualification (MCQ) of Continuous Fiber

In composites, damage initiates at the fiber/matrix interface or constituent level. It is of the importance that any damage analysis considers the constituent material properties and that failure is assessed at the constituent level. However, the measurement of transversely anisotropic properties of fiber and matrix components is often not feasible. The lack of this constituent property knowledge hinders the use of micromechanics based theories to evaluate damage evolution in composites.

The last decade has seen an increase in research of modelling fibre-reinforced composites with a micro-mechanics based constitutive modelling approach. These methods consider the mechanics of the material at the micro level by considering the constitutive equations of each of the constituent phases, namely the fibre and matrix, which in this work were reverse engineered using coupon test data. This differs to the conventional FE methodologies that analyse the composite structures at the ply level. Unlike FE methods, the micro-mechanics based constitutive modelling approach is not mesh dependent since it considers the stress-strain relationships at the individual constituent level. The unit cell approach is used, whereby an

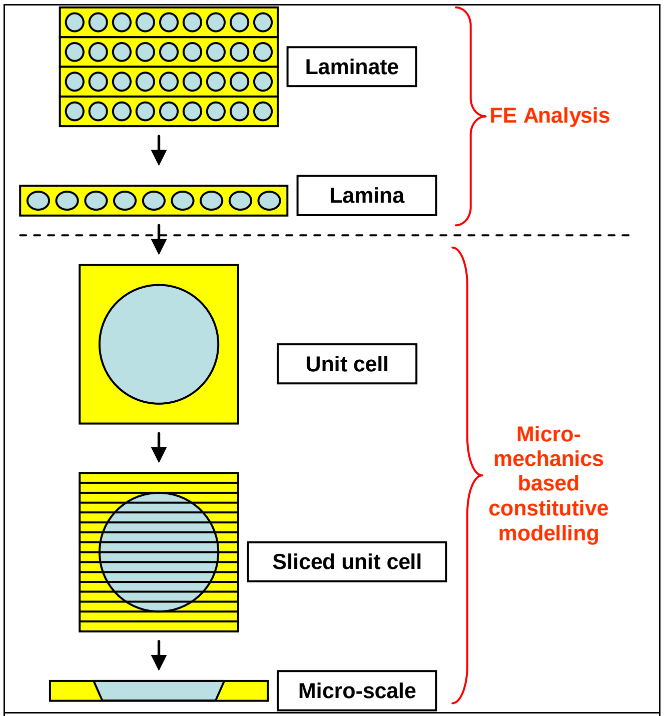


Figure 4. Augmentation of FE Analysis Using Micro-mechanics Based Constitutive Modelling

individual fibre surrounded by a matrix is considered. Once the FE results are obtained at the individual ply level, these results are decomposed using the micromechanics based constitutive model down to the micro level. This is depicted in **Figure 4**. At this level, the stresses and strains can be regarded as macroscopically uniform and therefore the rest of the laminate can be approximated based on the results from the representative unit cell. There is automatic mesh generation upon failure at the unit cell level which enhances the capability for capturing progressive failure of the composite structure.

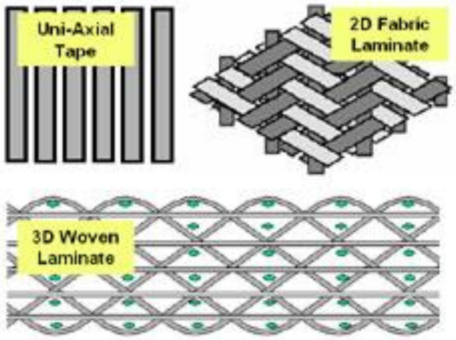


Figure 5. 1-D, 2--D and 3-D Fibre Architecture in Composite Structures [16]

Micromechanics based constitutive modelling utilizes the Material Characterization and Qualification (MCQ) software. It predicts the composite lamina, and laminate properties under manufacturing and environmental conditions. MCQ is useful during the early phases of concept/product development in evaluating the impact of changes in volume/void fraction involved in deciding on an appropriate fabrication approval or assessing environmental effects and degradation of material properties to environmental conditions. These conditions include the apparent moisture and the thermal environment and manufacturing-induced characteristics such as defect and residual strains, among others.

MCQ utilizes a composite micromechanics scheme to compute the mechanical and physical properties of a composite with 1-D, 2-D or 3-D fibre architecture as shown in **Figure 5**. An illustration of the composite modelling procedure is shown in **Figure 6** where stiffness and strength as well as physical properties of each type of reinforcement, for example filler, warp and/or through-thickness fibre, are separated into material directions based on fibre angles and contents. These are then combined with matrix properties and/or void contents to create composite unit cell properties. The modelled composite properties include stiffness, Poisson's ratios, strengths, coefficients of thermal and hygral expansion, heat conductivities and moisture diffusivities [8].

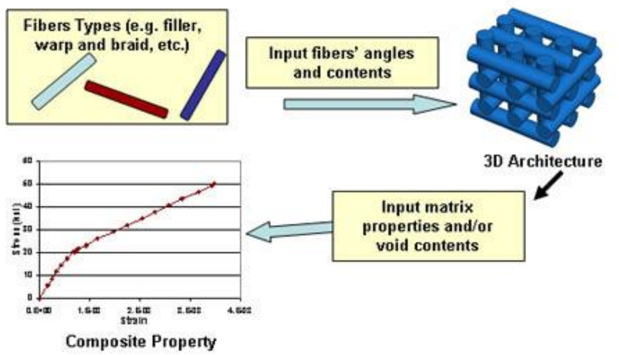


Figure 6. Micromechanics Prediction Procedure for Composite Structures

2.2 Multi-Scale Modeling of Random Chopped Fiber (De-homogenization Approach)

For modeling chopped fibers, at the *macro-scale*, the material is assumed to be *anisotropic* and *homogeneous* as a laminate, experiencing a uniform displacement in the loading direction. At the meso-scale, the laminate is then modeled as an assembly of multiple homogeneous and orthotropic lamina through its thickness. The meso-scale is then linked to a micro-scale through the use of a representative volume element, which captures the local heterogeneity of the fiber/matrix constituents and allows the analysis of the influence of local imperfections on the global behavior of the material. In this way, the fiber and polymer properties can be utilized to predict the effective orthotropic properties of the building block of the multi-axial laminate, *i.e.* the unidirectional fiber lamina. Therefore, multi-scale modeling and simulation of such composite materials have the potential to provide predictive capabilities for correlating mechanical, thermal, and electrical properties to their manufacturing processes, as well as to their structural performance.

The *Dehomogenization physics based approach* (originally proposed by Cox [11], then adopted and improved by Fukuda and Kawata [10], asserts that the elastic modulus of SFRP composites (ESFRP) is only dependent on the angle θ that fibers make with the direction (say, the 1-direction) in which the composite elastic modulus is to be evaluated (**Figure 7**). The *equivalent laminate* is idealized as the combination of unidirectional plies, each consisting of fibers having uniform length and orientation, such that it can overall replicate the same orientation distribution as that of the original short fiber composite (captured by the *second order orientation distribution tensor*). The prediction of the elastic moduli of a composite where the short fibers exhibit in-plane random orientation are based on the classical laminate analogy, which bridges the macromechanics of short fiber composites with that of laminated composites. The laminate analogy approach has been compared by Fu and Lauke [12] with other theories (namely, the *paper physics approach*, the *rule-of-thumb expression*, and the *aggregate model*), and also with existing experimental results, showing a satisfactory agreement.

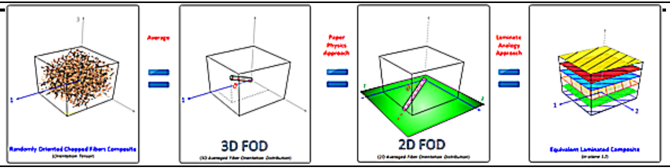


Figure 7. Orientation Tensor Determination (OTD).

2.3 Multi-Scale Progressive Failure Analysis (MS-PFA)

Composite micromechanics formulation and inputs from MCQ-Composites are integrated into LS_DYNA FE structural analysis with non-linear stress-strain plasticity considerations and damage progression tracking in order to study damage mechanisms at the structural level via GENOA software [9]. This FE module tracks damage initiation and growth within the structure. In the present work, micro-mechanics formulation from MCQ-Composites and GENOA is integrated into LS-DYNA environment through a user material subroutine that allows stress, strain, and damage tracking at the constituent level for each element of the model. The material subroutine is developed for both LS-DYNA/Explicit (USERMAT). Failure is properly assessed at the fiber, matrix or interface scale. Damage information is stored as history variable from LS-DYNA. Thus the methodology augments FEA analysis, with a full-hierarchical modeling that goes down to the micro-scale of sub-divided unit cells composed of fiber bundles and their surrounding matrix. The damage tracking is decomposed from global structural level to micro-scale level. The stresses and strain at the micro level are calculated using a mechanics-of-material-approach from the finite element analysis (FEA) results of the macro-mechanical analysis at each load increment. Displacements, stresses, and strains derived from the structural scale FEA solution at a node or element of the finite element model are passed to the laminate and lamina scales using laminate theory. Stresses and strains at the micro-scale are derived from the lamina scale stresses using micro-stress theory. The latter is interrogated for damage using a set of failure criteria.

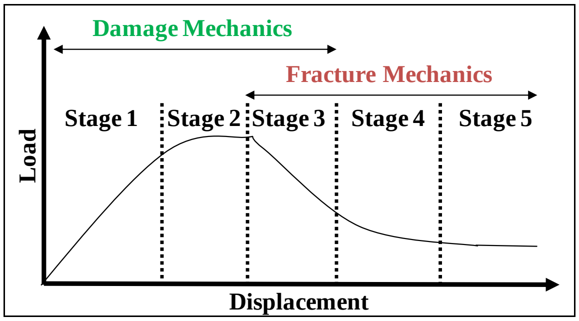
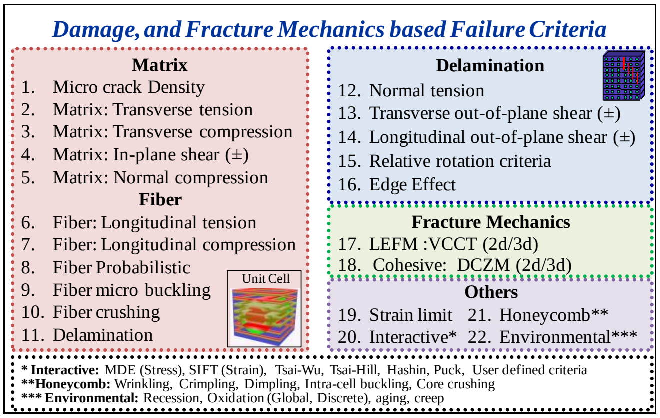


Figure 8. Overlap of Damage and Fracture Mechanics


Damage, and Fracture Mechanics based Failure Criteria

Matrix
1. Micro crack Density
2. Matrix: Transverse tension
3. Matrix: Transverse compression
4. Matrix: In-plane shear (±)
5. Matrix: Normal compression

Fiber
6. Fiber: Longitudinal tension
7. Fiber: Longitudinal compression
8. Fiber Probabilistic
9. Fiber micro buckling
10. Fiber crushing
11. Delamination

Delamination
12. Normal tension
13. Transverse out-of-plane shear (±)
14. Longitudinal out-of-plane shear (±)
15. Relative rotation criteria
16. Edge Effect

Fracture Mechanics
17. LEFM :VCCT (2d/3d)
18. Cohesive: DCZM (2d/3d)

Others
19. Strain limit 21. Honeycomb**
20. Interactive* 22. Environmental***

* **Interactive:** MDE (Stress), SIFT (Strain), Tsai-Wu, Tsai-Hill, Hashin, Puck, User defined criteria
****Honeycomb:** Wrinkling, Crimpling, Dimpling, Intra-cell buckling, Core crushing
*** **Environmental:** Recession, Oxidation (Global, Discrete), aging, creep

Figure 9. Multi-Scale Damage (Translaminar and Interlaminar), and fracture (Mode I-II) in MS-PFA

Typically there are five stages of load displacement curve and the overlap between damage and fracture mechanics (**Figure 8**). Damage mechanics and mechanisms (**Figure 9**), predicts the translaminar and interlaminar damage evolution and qualitative damage and fracture pattern, while fracture mechanics predicts the delamination growth. The key is to analyze the entire load-displacement curve observed in **Figure 8** using an integrated damage and fracture method. This method can be described in three different steps: 1) Damage

Mechanics - simulates stages 1-5 with PFA to predict crack path. Estimates damage evolution type as well as damage and failure initiation and damage propagation; 2) Fracture Mechanics - simulates stages 3-5 with VCCT/DCZM. This might involve preparing a coarser FE model with pre-defined crack path (predicted via PFA damage mechanics simulation or test). This simulates the load drop damage and failure. 3) Combined PFA+VCCT/DCZM – simulates all stages 1-5 to account for damage accumulation/mode switching (damage/fracture mechanics) for improved predictions.

The analysis is performed progressively, enabling the analysis of damage initiation and progression through the failure criteria available in MCQ-Composites and thus the LSDYNA User Material. Damage is assessed at each ply through the thickness by making use of the integration points and composite modeling available from LS-DYNA software. The ply fracture mechanisms decompose to include fiber failure under tension, compression (crushing, micro-buckling and de-bonding), and delamination. It allows 2 or 3-D architectural details (through-the-thickness fibers, resin rich interphase layer between weave plies, fiber volume ratio, void shape, size and location, cure conditions, etc.) and degradation of constituent material properties at increased loading based on detected damage.

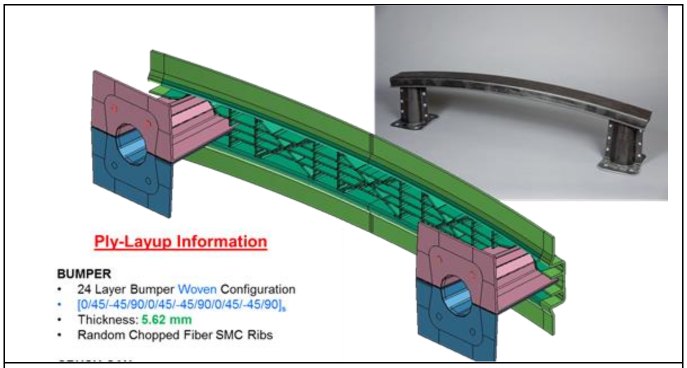


Figure 10. Hybrid Bumper Composite Construction, (SMC, Continuous)

3.0 Results and Discussion

A low speed impact of a hybrid woven and chopped fiber composite bumper automotive structure (**Figure 10**) is analysed using a leading micro-mechanics based constitutive modeller integrated with LS-DYNA The simulation results are then compared with experimental results. The bumper construction utilized: (**i**) 24 layers woven configuration [0/45/-45/90/0/45/-45/90/0/45/90]s, layer thickness - 5.42 mm; and (**ii**) Random chopped fiber SMC (Sheet Mold Compound) ribs.

3.1 Multi-Scale Material Modeling

Calibration and Verification of Fiber/Matrix Constituent Properties

Material properties was reverse engineered and strain behavior was predicted based on UD-lamina properties. Provided experimental UD-lamina data was used to reverse engineer effective fiber and matrix properties needed in the micro-mechanics-based finite element analysis code. Fiber volume ratio, void volume ratio and material non-linearity were taken into account. All calibration were done through the in-plane directions: a) Longitudinal (tension, compression, **b**) Transverse (tension and compression), and c) Shear. The analytical architecture model was then build in MCQ using constituent properties and compared with tensile test of a plain woven $[0/90]_6$ (**Table 1**). Verification of woven material model in the LS-DYNA User Mat are compared with MCQ material and test. Good agreement between analytical solution (MCQ and LS DYNA User Mat) and test is achieved as shown in **Figure 11**. Once the process of validation is completed fiber/matrix properties are frozen and implemented to FE model for impact simulation.

Table1. Weave Properties Calibration

Woven 0/90				
Material		Carbon/Epoxy		
Property	Units	Test	MCQ	% Error
E11	[GPa]	53.3	56.01	5.08
E22	[GPa]	53.1	55.7	4.90
E33	[GPa]		9.97	-
G12	[GPa]	4.5	4.53	0.67
G13	[GPa]		3.3	-
G23	[GPa]		3.39	-
v12	[-]	0.055	0.041	-25.45
v13	[-]		0.54	-
v23	[-]		0.55	-
S11T	[MPa]	598	640.6	7.12
S11C	[MPa]	619	587.1	-5.15
S22T	[MPa]	764	705.8	-7.62
S22C	[MPa]	415	486	17.11
S33T	[MPa]			-
S33C	[MPa]			-
S12S (5%)	[MPa]	110	71.97	-34.57
S13S	[MPa]			-
S23S	[MPa]	-		-

SMC Material Modeling

Nano assisted Micro-mechanics in MCQ Composites was used to predict the chopped fiber properties. Reverse optimization was performed to derive an equivalent set of mechanical properties mimicking the continuous (fiber/matrix) inputs (the previously mentioned paper physics approach) to the user material from the chopped fiber coupon test data in flow, cross flow and shear. In addition, (orientation and thickness) was derived in order to develop the user material card for the FEM model (**Table 2**).

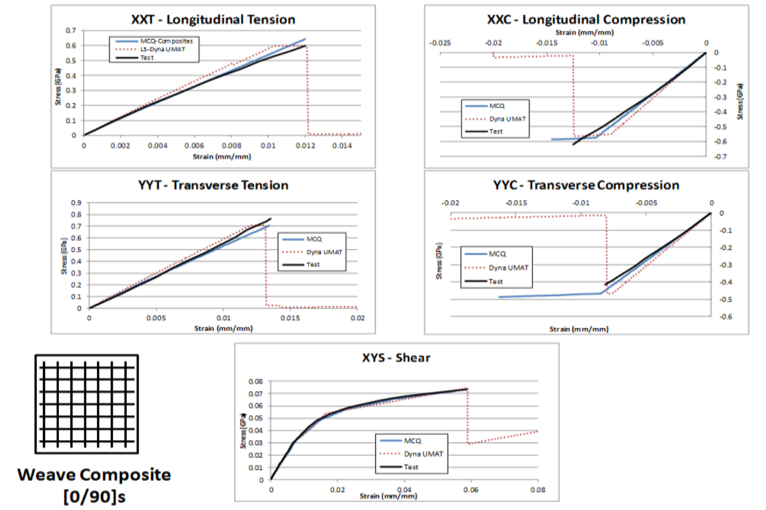


Figure 11. LS-DYNA Material modeling verification through five ASTM standards, Tension, compression and shear ASTM tests for each direction for [0/90]6 laminate

Table 2. SMC Equivalent Fiber/Matrix, and Orientation Tensor

MCQ-Chopped

Step 1

Test Validation using ply properties

Software: MCQ-Chopped

Input: Vendor provided fiber/matrix properties, fiber geometry and content, flow/cross-flow stress strain curves

Output: Aligned layer non linear ply properties, orientation angle through thickness and longitudinal/transverse/shear stress-strain curves for validation

MCQ-Composites

Step 2

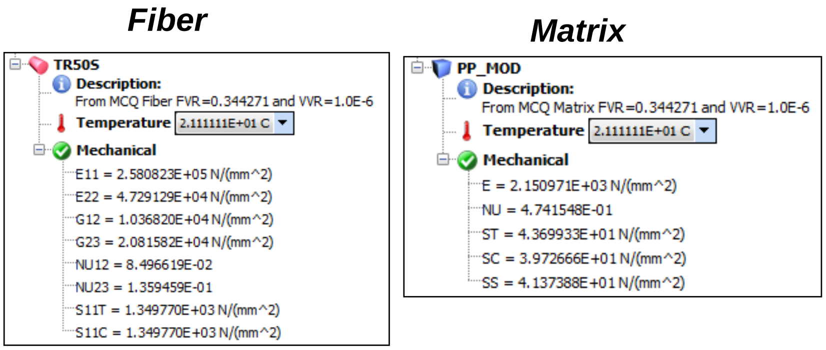
Test Validation using effective fiber/matrix properties

Software: MCQ-Composite

Input: Aligned layer ply properties from MCQ-Chopped, fiber/matrix modulus, flow stress strain curves

Output: effective fiber/matrix non-linear properties and longitudinal/transverse/shear stress-strain curves for validation

a) Nano assisted Micro-Mechanics to derive Effective Chopped fiber properties



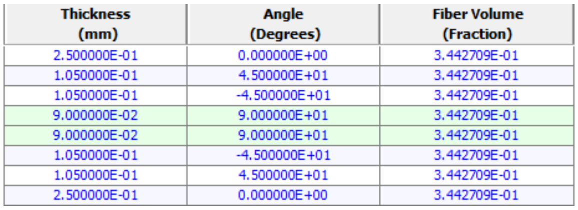
Fiber

TR50S
Description:
From MCQ Fiber FVR=0.344271 and VVR=1.0E-6
Temperature 2.111111E+01 C
Mechanical
E11 = 2.580823E+05 N/(mm^2)
E22 = 4.729129E+04 N/(mm^2)
G12 = 1.036820E+04 N/(mm^2)
G23 = 2.081582E+04 N/(mm^2)
NU12 = 8.496619E-02
NU23 = 1.359459E-01
S11T = 1.349770E+03 N/(mm^2)
S11C = 1.349770E+03 N/(mm^2)

Matrix

PP_MOD
Description:
From MCQ Matrix FVR=0.344271 and VVR=1.0E-6
Temperature 2.111111E+01 C
Mechanical
E = 2.150971E+03 N/(mm^2)
NU = 4.741548E-01
ST = 4.369933E+01 N/(mm^2)
SC = 3.972666E+01 N/(mm^2)
SS = 4.137388E+01 N/(mm^2)

b) MCQ-Composites effective properties



Thickness (mm)	Angle (Degrees)	Fiber Volume (Fraction)
2.500000E-01	0.000000E+00	3.442709E-01
1.050000E-01	4.500000E+01	3.442709E-01
1.050000E-01	-4.500000E+01	3.442709E-01
9.000000E-02	9.000000E+01	3.442709E-01
9.000000E-02	9.000000E+01	3.442709E-01
1.050000E-01	-4.500000E+01	3.442709E-01
1.050000E-01	4.500000E+01	3.442709E-01
2.500000E-01	0.000000E+00	3.442709E-01

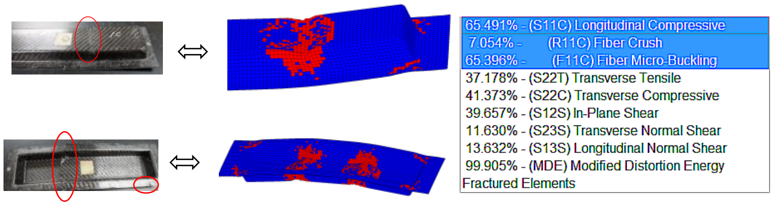
c) MCQ-Composites fictitious layup

3.2 Finite Element Analysis

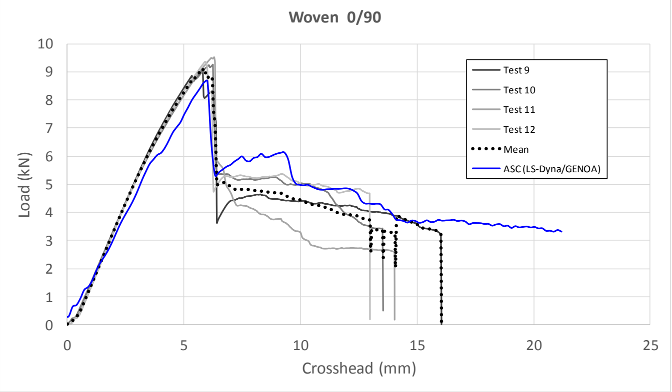
Since the bumper assembly consisted of crush cans and the bumper in bending, verifications were performed with each, forming a building block study.

Four Point Bend Simulation of Cross Ply Layup

Genoa – LS-DYNA FE based MS-PFA, integrated software was used to predict 4 point bend cross ply woven composite laminate. The model consisted of 8700 shell elements, type 2. The analysis was carried by LS-DYAN/Explicit solver jointly with Genoa/MCQ usermat subroutine. The failure mechanisms observed were fiber crush, and micro buckling, in addition to interlaminar shear (S13, S23) (**Figure 12a**). **Figure 12b** compares prediction of 4 Point Bend Simulation of Cross Ply Layup versus test. Simulations were performed using LS-DYNA version 810 and 4-processors machine and took 27 minutes.



a) Damage observed by test and simulation



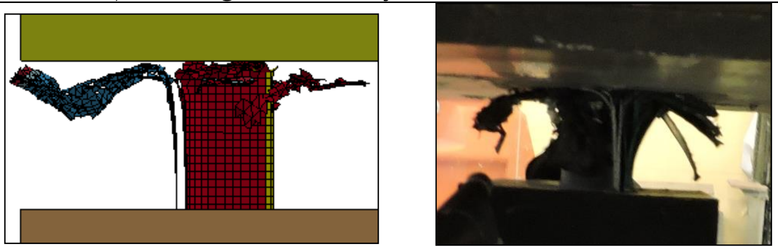
b) Load-Displacement by test and simulation

Figure 12. . 4 Point Bend Simulation of Cross Ply Layup

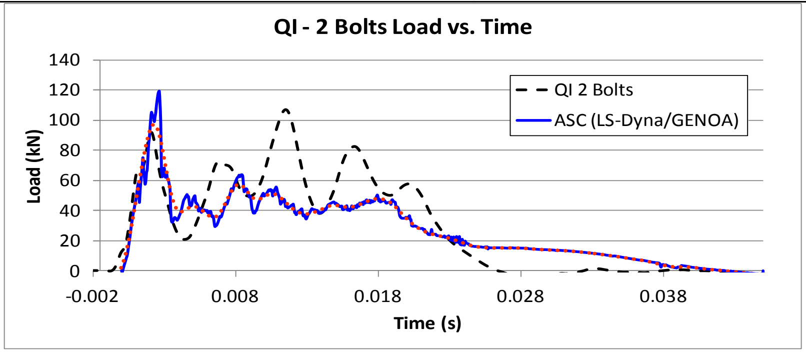
Crush Can Analysis

Crush 'can' material was 9 layers woven configuration, thickness per layer = 0.218 mm. The lay-up [0/90/45/-45/0/-45/45/90/0] was the same in the hat and the plate and was impacted with 276kg at 4m/s. **Figure 13** shows simulation shows comparable behavior with test data for (a) intrusion distance and (b) deformation. Peak load of 120kN in simulation vs 90kN test. Filtered simulation peak load would be about 95kN. In addition simulation predicted the contributing failure mechanisms were Fiber crush, and micro buckling, in addition to interlaminar shear (S13, S23).

a) Damage observed by test and simulation



b) Deformation observed by test and simulation



c) Load-Displacement by test and simulation

Figure 13. Crush Tube Simulation of Cross Ply Layup

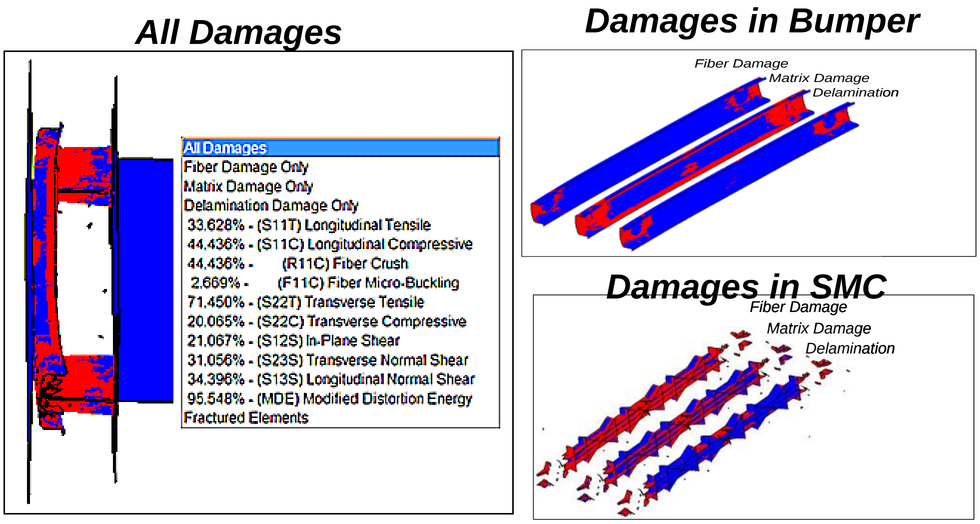
Hybrid Composite Bumper Impact Analysis

Hybrid bumper model construction (**Figure 10**) (24 woven layup, and SMC chopped fiber) was modeled using

GENOA/MCQ material models in LS DYNA user material. Shell elements type 2 were utilized. The impact conditions in **Table 3** were simulated. Strain rate effects were utilized. **Figure 14 a** shows the damage results of the full frontal case post processed in the GENOA GUI. **Figure 14 a** shows 33% longitudinal tensile failure (fiber failure) during the end of the crush event and 31-34% out of plane shear (S12S and S23). **Figure 14 a (right)** shows fiber matrix and delamination damages in the bumper and SMC. **Figure 14 b, c, d, and e** shows results vs test for several of the cases. Discrepancy (over prediction) in force was assumed to be due to rigid simulation joints/boundary conditions, voids/defects/waviness in physical part.

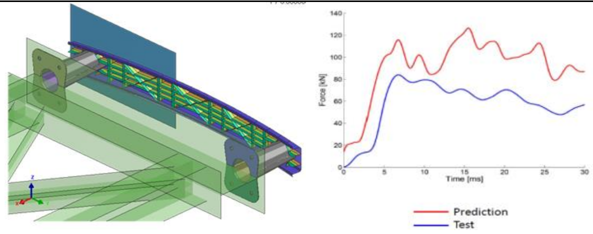
Table 3. Impact Conditions, Simulation Guidelines

	Crash Mode	Mass (kg)	Impact Velocity (m/s) (S.D.)
1	**Full Frontal**	300.00	15.30 (0.24)
2	**Frontal Offset**	323.00	9.16 (1.98)
3	**Frontal Pole**	306.00	2.54 (0.16)
6	**Frontal Angular**	323.00	5.19
4	**Low Speed Midpoint**	302.30	4.56 (0.02)
5	**Low Speed Quarter**	326.40	4.21 (0.26)

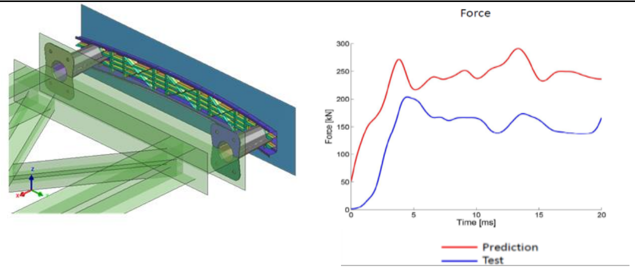


All Damages
Fiber Damage Only
Matrix Damage Only
Delamination Damage Only
33,628% - (S11T) Longitudinal Tensile
44,436% - (S11C) Longitudinal Compressive
44,436% - (R11C) Fiber Crush
2,669% - (F11C) Fiber Micro-Buckling
71,450% - (S22T) Transverse Tensile
20,065% - (S22C) Transverse Compressive
21,067% - (S12S) In-Plane Shear
31,056% - (S23S) Transverse Normal Shear
34,396% - (S13S) Longitudinal Normal Shear
95,548% - (MDE) Modified Distortion Energy
Fractured Elements

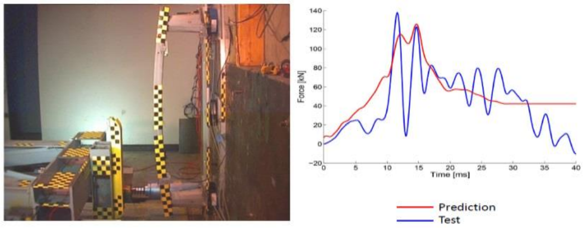
a) Damage observed by simulation



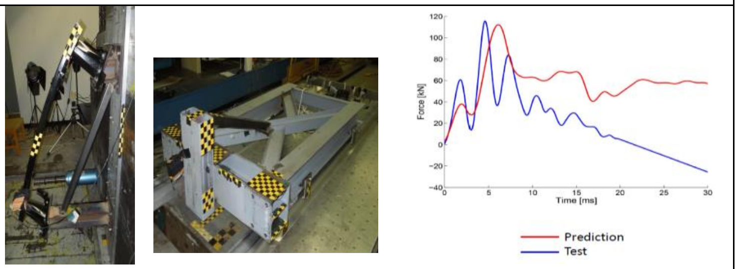
b) **Frontal Offset, Load-Time**



c) **Frontal Rigid, Load-Time**



d) **Low Speed Quarter**



e) **Frontal Angular**

Figure 14. Hybrid Composite Bumper Simulation and Test

4.0 Conclusion

Genoa using LS-DYNA/Explicit user material was able to predict load displacement and damage footprint during the impact event. Multi-scale dehomogenized approach is able to model the chopped fiber, and continuous fiber and assess damage evolution at the constituent level. A building block validation strategy was has been described and exercised from 4 point static to crush tube followed by hybrid composite bumper impact simulation. LS-DYNA User Material with GENOA's Multi-Scale Progressive Failure Analysis (MS-PFA), under predicted test displacement vs time and generally over-predicted force curves. Discrepancy in force was assumed to be due to rigid simulation joints/boundary conditions, voids/defects/waviness in physical part, and discrepancy in as-designed vs as-built part.

5.0 Acknowledgement

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