

Modeling and Characterization of Crushable Composite Structures

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The crushing response and the energy absorption capacity of a quasi-isotropic C-shaped composite panel is presented to simulate the progressive damage and failure mechanisms involved in the component testing. Crushable composite structures are widely used for impact applications, as because of their great high-energy absorption capability and lower weight. Simulating the crush characteristics of composite structures is challenging, as the conventional tools fail to accurately represent the failure mechanisms at the component level. Here, a cost-effective predictive tool ‘CZone’ is applied for simulating the crushing response of composite materials. CZone for Abaqus (CZA) is an add-on capability for Abaqus/Explicit and combines with the commercially available impact modeling capabilities included within the Abaqus finite element software package.

I. Introduction

Composites are one of the versatile materials used heavily in aerospace and automotive industries these days under normal and extreme conditions. The energy absorption capability during crushing can help prevent the severe impact damage in the critical components of a structure. The failure behavior of composites is a complex phenomenon that generally cannot be described by conventional metal failure mechanisms. Several studies address the crushing response of composite panels with different geometries and the built-in composite material models in commercially available FE codes [1]-[4]. In the past, a study was conducted under the support of the National Aeronautics and Space Administration (NASA) aimed at evaluating the predictive capability of the Abaqus in-built material model to simulate the quasi-static and dynamic crushing responses of composite specimens [5]. A quasi-isotropic C-shaped composite panel was chosen to investigate the crush behavior dependency on material and model parameters. The results showed a good agreement after a calibration of those optimized parameters, but further study is needed to make the predictive model more reliable and accurate. Here, a new methodology named ‘CZone’ is explored to study the crushing behavior of the composites in details.

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Metallic crushable structures are used in various energy absorption applications like automobiles, helicopters, aircraft, trains and other transport vehicles, although composite materials hold great potential for increased energy absorption with lower-weight. The successful development of a composite crush structure requires the right combination of material characteristics, geometry, thickness of laminate, fiber orientation, etc. Simulating the crush characteristics of composite structures is challenging, as the conventional failure mechanisms cannot describe the crushing response of the composites really well. It is difficult to accurately represent each failure mechanism involved, such as, buckling, delamination, matrix cracking and fiber breakage including crushing. Enabling a cost-effective simulation solution that achieves the desired performance parameters and represents the crushing response of composite structures is inevitable. Many composites, but not all, crush in a continuous way that provide an ongoing resistive force at the crush front defined as ‘crush zone’. Elements start to compress in the crush zone, following to stiffness degradation, damage and failure. Crush itself encompasses a number of failure mechanisms within the composite, that brings challenges for a simulation tool to distinguish between these failure modes. It might be an efficient approximation to combine the effects of all these failure modes within the crush zone.

CZone is an Abaqus-based application providing advanced crush simulation for energy-absorbing structures made from laminated composites. Based on the technology from Engenuity Ltd. [6], this add-on capability is a direct implementation of crush-based element force generation in the failure crush zone. It combines material crushing and other modes of composite failures available already in Abaqus material model [7] “Damage for Fiber Reinforced Composites”. Crush zone is typically located at the forward edges of the structure in direct contact with the impactor, although the behavior of the composite structure outside the crush zone is simulated utilizing the existing capabilities of in-plane lamina failure along with the possible intra-laminar delamination. In this study, a novel approach is adopted to study the energy-absorbing capacity of the composite C-channel. This provides a reference to the adopted method to validate the predictive modeling capability and establish a reliable computational framework for crushing of composites.

II. Material Systems

The C-shaped panel specimen is composed of carbon fiber/epoxy braided fabric; fabricated by hand lay-up of the T700S/TC275-1 and cured using an autoclave following the vendor recommended manufacturing process [5]. The lay-up consists of a quasi-isotropic $[0/+60/-60]_s$ braid with 24K and 12K tows in the axial and bias directions respectively. The composite specimen is made with six plies with the average thickness of 0.135 inch and 5 inch long. Each ply is assumed as a transversely isotropic material, with its properties obtained experimentally from ASTM standard tests. All the input material properties including the elastic stiffness, strength and the fracture properties are summarized in Table 1.

Model parameter	Tension	Compression
Longitudinal Young’s modulus, E_{11} , Msi	6.55	6.26
Transverse Young’s modulus, E_{22} , Msi	6.34	6.06
Longitudinal Poisson’s ratio, ν_{12}	0.24	0.24
Longitudinal Shear modulus, G_{12} , Msi	2.38	2.38
Transverse Poisson’s ratio, ν_{21}	0.21	0.21
Longitudinal Strength, X, Ksi	134.9	82.5
Transverse Strength, Y, Ksi	127.7	52
Shear Strength, S, Ksi	34.3	27
Transverse Fracture toughness, in.*lb/in. ²	3.8	3.8
Axial Fracture toughness, in.*lb/in. ²	24	24

Table 1. Lamina material properties used.

III. Geometry and finite element modeling

The C-channel has an open rectangular profile with different radii defined for the two corners, as shown in Figure 1. One side of the specimen was chamfered to create a zone of crushing trigger and to initiate crushing in a stable manner. The crushing test was conducted at a compressive crosshead velocity of 0.5 inch/min and the load-displacement response of the structure was measured from each test [5]. The test results were consistent and a good

repeatability was obtained as reported in the literature. The impact scenario is created by applying fixed boundary conditions at the bottom of the composite plate and prescribing an initial velocity to the rigid plate at top. In this case, a stationary C-channel is impacted by a moving rigid plate with a constant velocity. The geometries of the solid impactor and the composite shell are created in Abaqus and a snapshot is shown schematically in Figure 2.



Figure 1. Cured part of C-shaped composite panel [5] (Courtesy: NASA/TM-2019-220350).

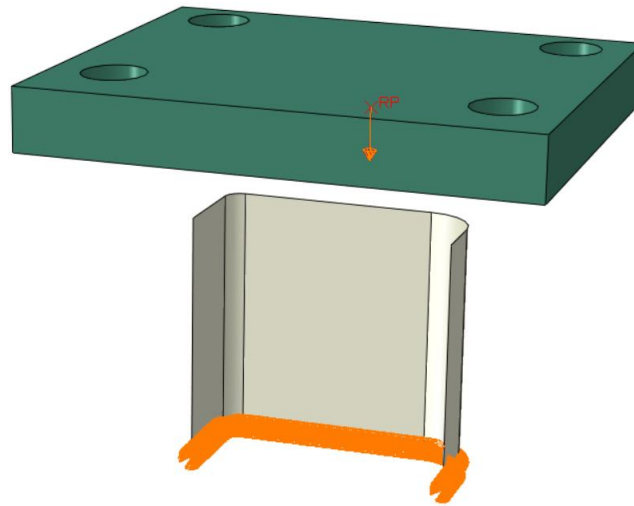


Figure 2. Schematic loading and boundary conditions.

A mesh convergence study was conducted [5] to determine the adequate mesh density needed for computational efficiency and the accuracy. The same optimized mesh density is used here for the C-channel specimen to be consistent with the predicted results without the CZone. The FE modeling approach uses quadrilateral conventional shell elements S4R for ply modeling, utilizing homogenized composite-layup in Abaqus. The shell element is chosen over solid element for capturing out-of-plane plate bending as observed in impact simulations. The plies are assumed to be homogenized and the input material parameters are obtained from experimental measurements available in the literature. The crushing load is applied using a smooth step definition and the general contact algorithm is applied at the interface of impactor and the composite plate. In CZone modeling approach, individual zones can be defined as “Trigger”, “No Trigger” or “No Crush”. As the crush zone evolves during the progressive damage of composite plate, the elements underlying the “No Trigger” zone switch to “Trigger” zone, based on the calculation of contact force and meet the criterion for crush stress input. No mass scaling was used in this analysis. This whole modeling set up is simulated to capture the crushing behavior and the progressive damage of the composite. A snapshot of the FE model for both the geometries is shown in Figure 3.

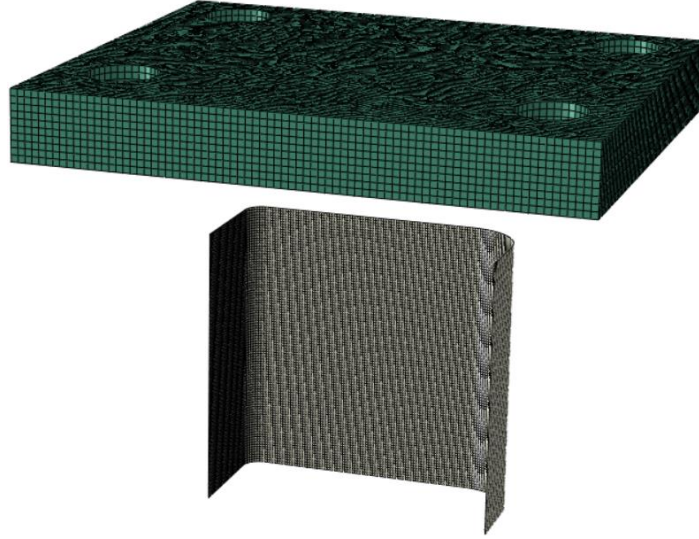


Figure 3. Finite element mesh of the impactor and the C-channel.

While conducting the crush test [5], the specimens were machined with a single-sided 45° chamfer to favor the initiation of stable crushing at one end of the specimen and to avoid undesirable initial spikes in crush loads, which may lead to a specimen instability. This chamfer is known as the trigger, or crush initiator. As shown in Figure 4, the trigger zone is modeled by assigning the single top layer of elements at the crush front of the specimen. The rest of the elements are assigned as ‘no trigger’ zone at the beginning of analysis, but eventually turn into crushable elements as the impactor progresses.

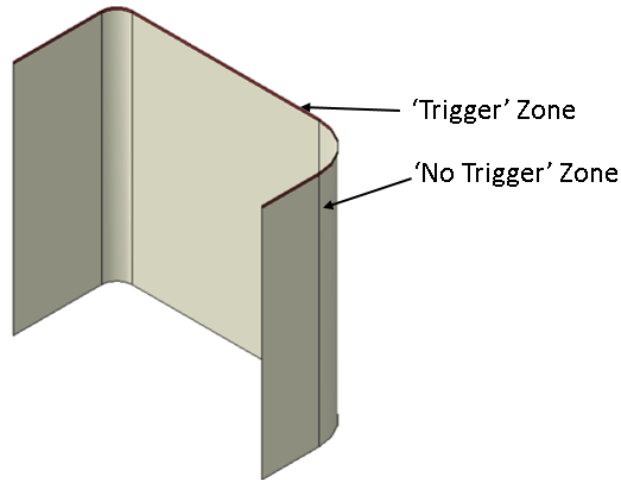


Figure 4. ‘Trigger’ vs ‘No Trigger’ zones of the C-channel.

IV. CZone Analysis procedure

The crushing modeling is characterized by output quantities like energy absorption, peak crush force and mean crush force. For thin-walled energy absorption composite structures, it is crucial to evaluate the predictive capability of the numerical tool in terms of these output parameters. CZone allows analyzing the crushing behavior of carbon composite structures in a very cost-effective way so that one achieves the desired performance parameters. This method is applicable to materials that crush in a continuous way and provide an ongoing resistive force at the crush front. The tool uses conventional Abaqus material models and adds the CZone crushing material definition. A number of failure mechanisms like fiber breaking, matrix cracking and delamination can be included in the model build up.

These failure mechanisms occur in a zone of damage at the crush front, but the model does not distinguish among these failure modes. Crush stress, as determined from the experimental tests, is used to represent the combined effects of these failure modes. Crush stress, as defined by the contact pressure calculations at the crushing interface, is considered as a material property, although it does not interfere with the constitutive relations of the materials under the crush zone.

IV.A. CZone Plug-in interface to Abaqus

CZone is a state-of-the-art methodology for simulating the crushing response of composite materials and allows to analyze crushable carbon composite structures that absorb energy during impact. Crushing zone is the area where the composite material may crush against an impacting object and CZone is the acronym for ‘crushing zone’. It is a design tool to enable engineers to develop crashworthy structures and uses empirical data to determine the crushing forces acting on a structure, based on crush tests of coupons or components. This modelling approach is used to develop crash structures on a predictive basis and uses tested material properties as an input. The tool is available as a plug-in in the interaction module of Abaqus, as shown in Figure 5 and provides an interface to define the CZone interactions and crush strength along with the damage models for fiber-reinforced composites, predefined in Abaqus material library. This tool is an add-on capability for Abaqus/Explicit and combined with the powerful impact modeling capabilities included in Abaqus/Explicit. It is implemented through a crushing material definition, which describes the material crushing response, along with a contact definition, which models localized loads occurring in the crushing zone. The technology provides direct implementation of crush-based element failure in defined crush zones at the leading edges of the impacted structure. To summarize, CZone needs specific element type, material properties, composite shell section definition, and contact definitions as modeling requirements. Few specific field output variables are available for both general contact and contact pairs definitions along with history output variables, as documented in [7].

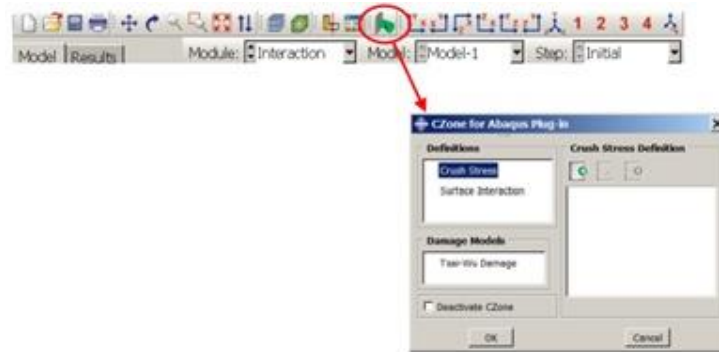


Figure 5. A snapshot of the CZone plug-in tool to Abaqus.

IV.B. Damage models for crushable composites

The composite laminate properties can be defined for both crush and non-crush zones combined. The plug-in can be used to add Tsai-Wu Damage properties [7] to an existing Abaqus material model, but the alternative Hashin damage model [8] is also supported using the keywords editor option in the input file. CZone crushing is the primary failure mechanism, although can be combined with the Hashin or Tsai-Wu damage initiation criteria available with Abaqus built-in constitutive material models. Both require linearly elastic behavior of the undamaged material and the damage evolution is characterized by progressive degradation of material stiffness, leading to material failure. The anisotropic elasticity is combined with strength in different failure modes of composite materials along with the associated fracture energy for the individual modes. A snapshot of the Tsai-Wu failure criterion and its interface to CZone plug-in is shown in Figure 6. The Tsai-Wu failure criterion defines the onset of damage and the damage evolution must be defined as the rate of degradation of the material stiffness once the initiation criterion is satisfied. Linear material softening is assumed for damage evolution, as the softening is controlled by field variable dependence of the material properties. The fracture energy value dictates the maximum element size and smaller elements are recommended for CZone applications. The energy release rate can have a big influence of the behavior of a component subjected to crushing forces which cause a failure behind the crush front.

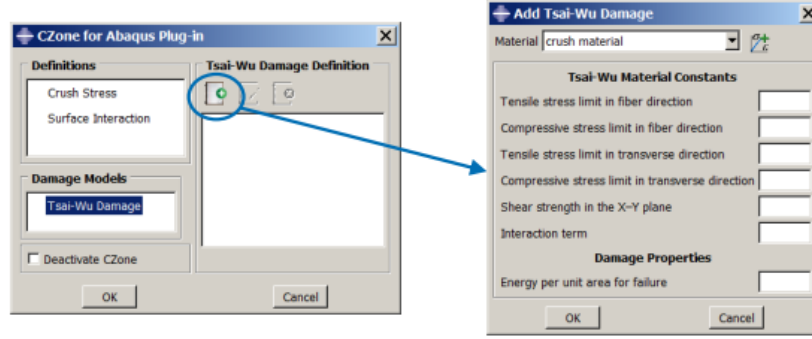


Figure 6. A snapshot of the ‘Tsai-Wu Damage’ definition - CZone plug-in interface.

IV.C. Crushing strength and parametric variability

The ‘Crush Stress’ definition, as shown in Figure 7, is used to specify crush stress and optionally, the crush stress velocity factor. The plug-in interface allows users to define the crush stress as a constant value or as tabular input as a function of material angle. The crush stress velocity factor is optional and can be used to specify the variation in the crush stress with respect to the velocity of the impactor. The scaling factors are specified to scale the crush stress w.r.t. the relative velocity. Crush stress is defined as the ongoing resistive force per unit area of a material in crush and measured from either component or coupon level testing. The crushing behavior itself encompasses a number of failure mechanisms within the composite, those occur in a zone of damage at the crushing interface, or crush front. It does not distinguish between these failure modes, rather uses the crush stress definition to represent the combined effect of these failure modes. Crush stress depends on various factors, such as the component geometry, loading rate and the ply orientation angles of the laminate. The corrugated or curved specimens can affect the crush stress, as give rise to a higher crush strength compared to a flat specimen. Thermoplastic composites are likely to exhibit greater velocity dependence, as higher crush stress values are measured at slower speeds approaching quasi-static. It is very crucial to define a velocity-dependent crush stress property definition, as allowed in CZone modeling. However, the rate-dependency behavior or the dynamic loading behavior of this specimen using CZone is a scope of future research.

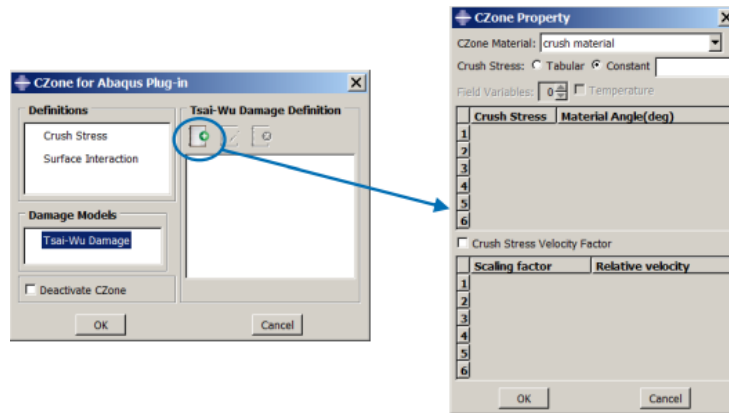


Figure 7. A snapshot of the ‘Crush Stress’ definition - CZone plug-in interface.

The crush stress is also dependent upon the relative quantities of different fiber orientations in the laminate and the direction in which the laminate strikes the barrier. Compared to unidirectional (UD) laminate, multi-directional fiber-matrix laminates have anisotropic crush properties. To account for this CZone materials can be assigned crush stresses, which are dependent upon the relative angle between the barrier and the local fiber direction. The element crush property is the average of all the ply properties making up the laminate.

IV.D. Contact definitions

The ‘Surface interaction’ definition, as shown in Figure 8, can be used to define CZone-specific contact

interactions. The plug-in automatically creates a new surface interaction with a user specified friction coefficient and available as contact pair definitions in Abaqus framework. The CZone specific interaction definition can be deactivated as wanted, with only the material definition data written out to the input file with damage and failure properties. The crush initialization is triggered at one end and the crush state evolves to the adjacent elements in a continuous manner. The CZone capability integrates material modelling, element deletion and contact algorithms to simulate continuous crushing behaviour. Only node-to-surface contact is supported as a part of general contact interactions and limits the contact stress based on the consideration of the underlying material. The methodology triggers element deletion due to crushing, based on crush stress.

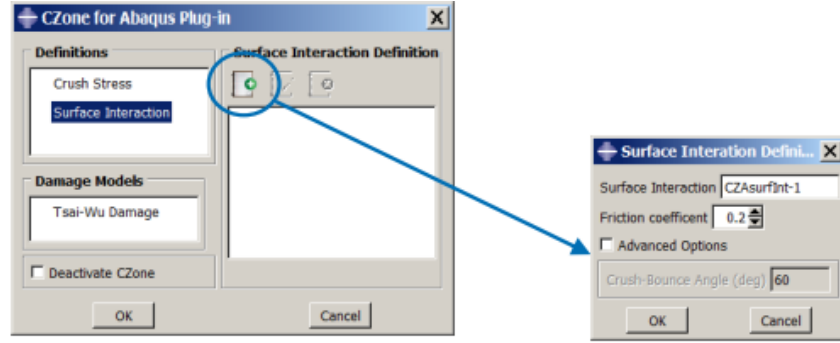


Figure 8. A snapshot of the ‘Surface Interaction’ definition - CZone plug-in interface.

Elements of C-channel composite structure start to compress and degrade at the impactor end according to prescribed damage criteria and eventually leads to element deletion according to element failure criteria. With the element deletion, a gap is created between the impactor wall and the composite front end. The contact algorithm available in CZone fills this gap and the impactor reattaches with the structure after crossing gap, which deleted the element occupied earlier. Without CZone, contact force is calculated based on the structure's stiffness and applied until element completely fails and is removed. But with CZone, contact force is applied based on crush stress input until contact interfaces passes completely through an element. This key differentiator makes the CZone technology more efficient and suited for impact applications of crushable composite structures.

V. Results and Discussion

Considering the mesh-convergence results from literature [5], an optimized and computationally efficient 0.04 by 0.04 in. mesh density was used to carry out CZone analysis. The sensitivity of material variations on the load-displacement response was also investigated in the literature [5] and an optimized set of model parameters were compiled from the quasi-static simulations. The influence of physical and nonphysical model parameters on the load-displacement response of the C-channel composite specimen was studied and compared to the experimental results. Taking advantage of these optimized model parameters, CZone analysis here used the same set of lamina material properties (in terms of elastic stiffness, strength and fracture toughness) to study the crush behavior of the composite structure. As found in the four experimental results [5], the load-displacement curves show considerable variability in the crush strength and the overall response throughout the loading range. The CZone model studied here try to address the experimental variability in terms of its own physical model parameters (crush strength, material angle, velocity scaling factor and trigger strength). This study aims to calibrate the CZone model parameters to match the experiments, along with studying the parametric variations and its effect on the crushing response. Hence, the same Hashin model is considered here as the composite damage material model to be consistent from the literature. Retaining the same mesh density and the optimized Hashin damage model parameters, the goal here is to shed more light on CZone specific model parameters and its variability study on the crush response. Experimentally measured crush force is an input to the CZone model as the trigger zone strength (12000 lbf), as we find in the next section, the influence of the trigger strength (2000-12000 lbf) on the crushing response of the composite. Using the CZone plug-in interface and the ‘crush stress’ definition, crush stress is specified in the range of 19000-25000 lbf, as a function of material angle. Additionally, the functionality of crush stress velocity factor is used to specify the scaling in the crush stress with respect to the relative velocity of the impactor. The ‘trigger’ and ‘no trigger’ zones are built into the model definition, along with the specified trigger zone strength and the scaled crush strength variations with respect to material angle

and relative velocity. This whole modeling set up is simulated with built-in Hashin damage model in Abaqus, including four damage failure criteria, namely, fiber rupture in tension, fiber kinking in compression, matrix cracking in transverse tension and matrix crushing in transverse compression. The global load-displacement response from the simulation result is shown in Figure 9, as compared to the experimental results. As observed, the simulation curve provides a reasonably good representation of the crushing scenario, considering experimental variability. The most dominant failure mechanisms are caused by fiber compression and matrix crushing, as reported in the literature [5]. Figure 10 shows the progressive damage contours of the composite plate along with the element deletion and deformed shapes. To identify regions that crushed, field variable CRUSHSTATE for general contact is plotted in Figure 11, on the undeformed model shape.

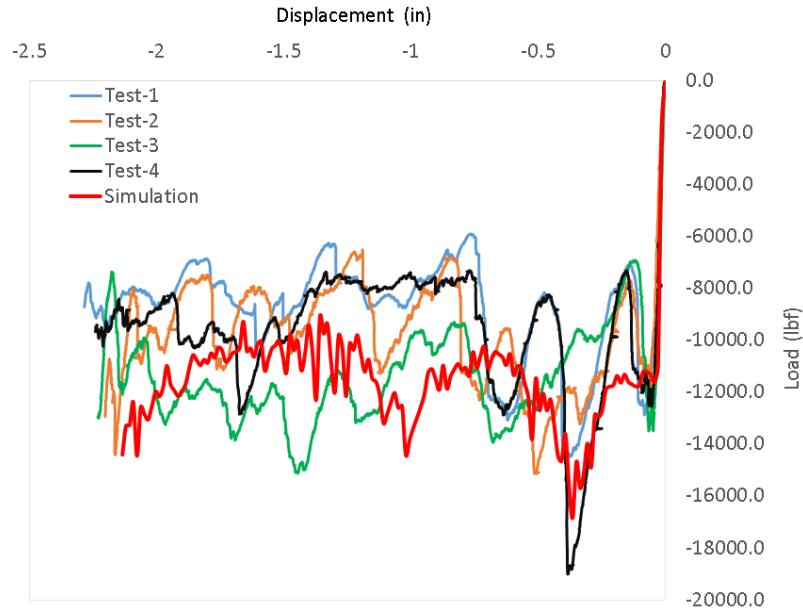


Figure 9. Comparison of load-displacement response of the C-channel with experiments.

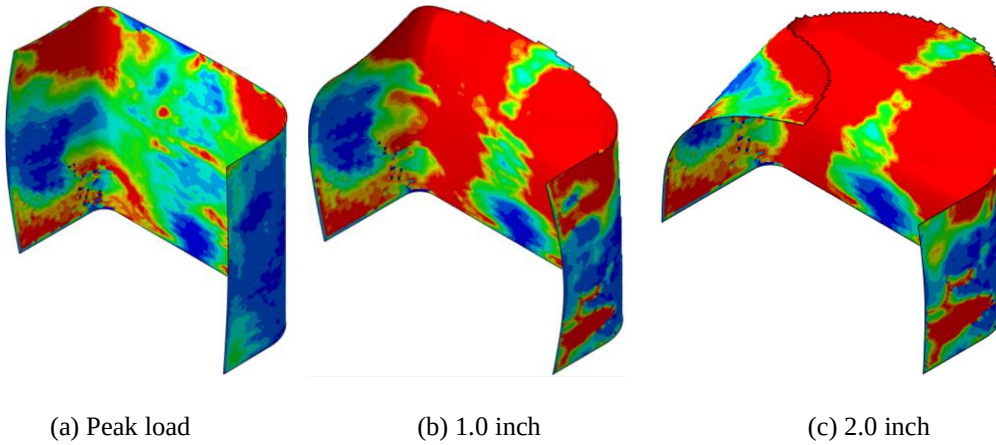


Figure 10. Damage contours of the C-channel – Matrix compression - (a) peak load, (b) 1.0 inch, and (c) 2.0 inch displacement points.

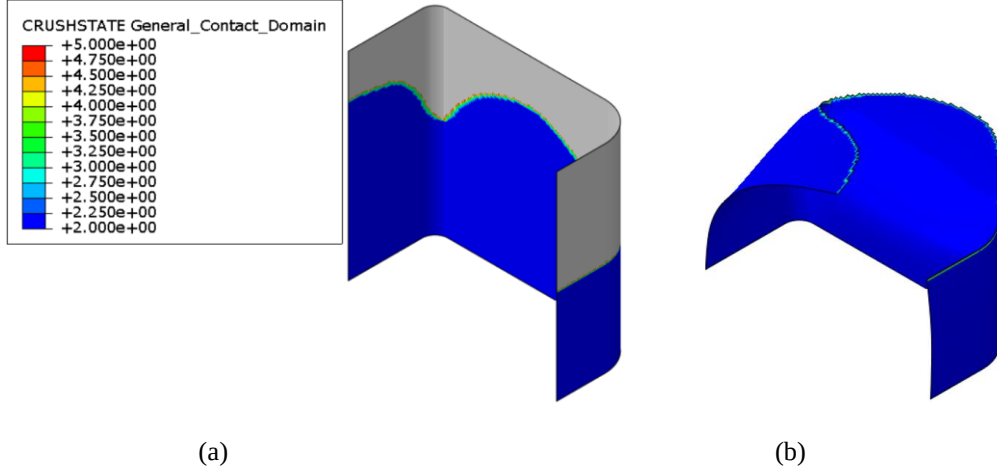


Figure 11. Failure pattern of the C-channel at the end of simulation – (a) failed region (undeformed), and (b) remaining fragments after deleting failed elements (deformed).

VI. Parametric Study

The quasi-static crush response of the C-channel composite specimen is examined here with respect to variations in CZone parameters. The proposed model offers the advantage of studying the effect of input parameters like crush stress w.r.t. the orientation of ply angle and crush stress w.r.t. the impactor velocity factor. The trigger zone crush strength is an additional input to the CZone model along with the crush stress definition. Keeping the crush stress definition and its variation with other parameters fixed, the effects of trigger zone strength and the friction coefficient in the general contact surface interaction definition are studied in details, as described in the following sections.

VI.A. Effect of Trigger Zone Strength

Experimentally measured crushing strength has an influence on the specified trigger zone strength parameter in the CZone model. The trigger zone strength is varied in the range of 2,000-12,000 lbf and a sensitivity study is carried out to understand the effect of this input parameter. The impact simulation uses the in-built Hashin material model for composite damage in no-trigger zones. Figure 12 shows the comparison of the global load-displacement responses for the range of specified trigger strengths. As observed, there is overall good agreement in peak loads with the variation in the strength parameter, however, a decrease/increase of 10-15 percent in the peak loads are notable as compared to the baseline value. An important factor in 'CZone' model is the ability to superimpose the combined effect of localized trigger zone strength and the global crush strength definitions in the same input file.

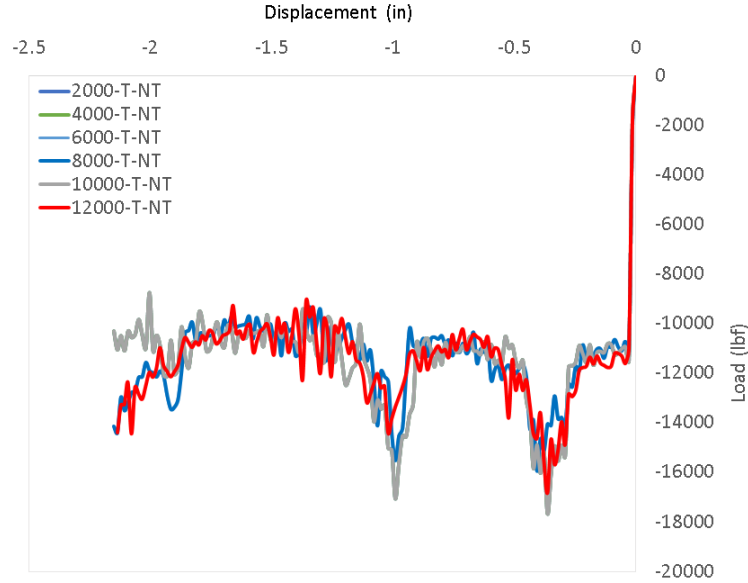


Figure 12. Influence of trigger zone strength on the load-displacement response of the C-channel.

VI.B. Effect of Friction

CZone for Abaqus modeling requires specified friction coefficient for the surface contact definition between the impactor and the composite specimen. Unrealistic failures may occur if friction is not defined, whereas, on the other hand, real failures may be suppressed during the analysis if the friction coefficient is too high. As shown in Figure 8, the plug-in automatically creates a new surface interaction with a specified friction coefficient. The surface interaction definition in the CZone plug-in model creates the contact pair definitions by default and can be switched to general contact definition if required, by the keyword editors in Abaqus framework. Experimentally measured crushing strength has an influence on the friction parameter specified in the CZone model. The friction coefficient value is varied in the range of 0.05-0.2 and a sensitivity study is carried out to understand the effect of this input parameter in the general contact framework. The crushing responses of load-displacement plots are shown in Figure 13 for the range of friction inputs. As observed, there is a good agreement in the global response with notable ups/downs in the local peaks with the variation in this parameter. To be noted, CZone model can be defined for either the general contact or the contact pair definitions available in Abaqus.

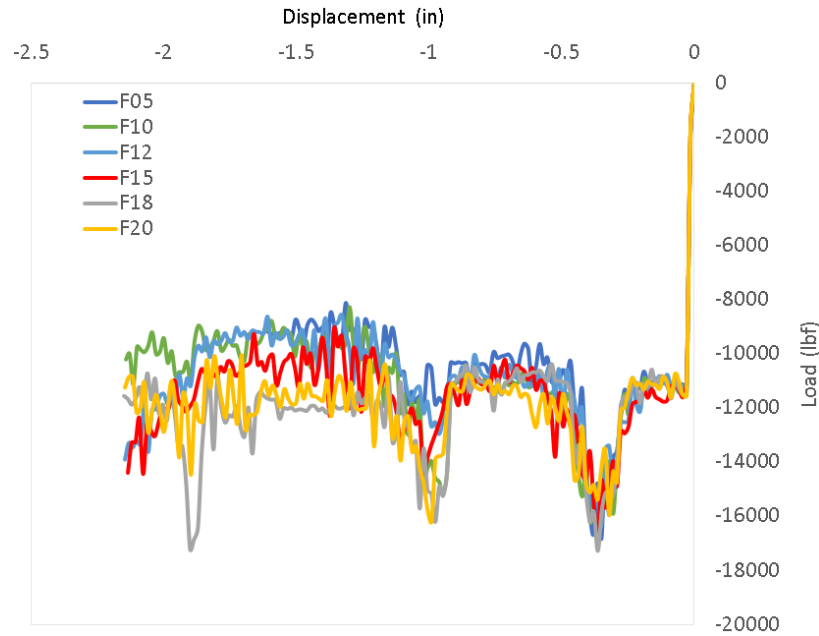


Figure 13. Influence of friction on the load-displacement response of the C-channel.

VII. Conclusion

In this work, an impact simulation is carried out for a composite C-channel to compute the crush stress and the damage parameters involved with the crushing response of the composite plate. Crush stress has a dependency on various parameters like geometry of the structure, impact velocity and the material orientation. Geometry of a specimen, flat, curved or corrugated, can affect crush stress to a greater or lesser extent. The loading rate might induce a velocity-dependent crush stress for composite materials. To carry out a crushing simulation, orientation of fiber laminates must be well defined, as the crush stress is dependent upon the stacking sequence of the laminate and the relative orientation of the local fiber direction with respect to the angle with which the laminate strikes the impactor. Effect of CZone crush stress is studied here to have a better understanding of the damage and failure mechanisms involved with the composite crushing. The predictive capability of the proposed model is assessed and a reasonably good agreement is achieved for quasi-static simulation. A material characterization method is developed for the crashworthiness study of a composite structure under quasi-static loading, but the effect of dynamic loading on crush response is a scope of future research. In addition, few parameters are studied in details to understand the effect of parametric variability on the crush response, although more parametric studies will be carried out as a future scope of work.

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