Modeling Delamination Growth in Composites using MSC.Dytran

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ABSTRACT

Composite structures present difficult challenges for crash modeling. A variety of failure mechanisms not commonly associated with ductile materials are active in composite crushing, including various matrix and fiber failure mechanisms, separation between fiber matrix materials and delamination. In this paper, various techniques for model delamination growth are compared using MSC.Dytran. Researchers have utilized several techniques to model delamination growth in composite structures using finite element crash codes. Among these are using spotweld elements to represent an interface, a cohesive failure model and the fracture mechanics-based virtual crack closure technique (VCCT). These three methods of predicting delamination growth are compared for an illustrative fracture mechanics problem. While relatively easy to implement, the spotweld method does not have a strong physical basis, and *a priori* selection of failure forces is difficult. The cohesive failure model avoids some of the deficiencies of the spotweld method, for example by allowing energy to be absorbed by the delamination growth process, and by reducing problems associated with abrupt, finite crack extension. This method is relatively easy to implement, though some unconventional property data are required. The virtual crack closure technique allows accurate predictions of delamination growth to be achieved. However, the computational demands of this method for crash analysis are great. A sample structural problem of a scaled aircraft fuselage structure containing foam-cored sandwich structures is reviewed. Separation of facesheets from the core material was a significant factor in the crushing response of the test article. Facesheet delamination is modeled using the spotweld method. Results illustrate some of the difficulties in accurately modeling the response of a composite structure exhibiting delamination. The paper concludes by presenting the author's perspective on the role of delamination modeling in crash analysis.

INTRODUCTION

Composite structures present many challenges for crash modeling. Some of these difficulties are illustrated by a photograph of a composite structure being crushed under laboratory conditions (Figure 1). Several failure mechanisms not commonly associated with the crushing of ductile materials are active, including various matrix and fiber failure mechanisms and separation between fibers and the matrix material. Although not visible externally in Figure 1, internal cracks form between layers of different fiber architecture. The size and patterns of these internal cracks are strongly correlated to the overall energy absorbency of the structure [1]. There is a large variety in the global crushing behavior that may be exhibited by composite structures [1,2]. In addition to the "splaying" failure mode seen in Figure 1, in which the largely unidirectional composite separates into two primary sublayers, one of which moves toward the interior of the tube, while the other spreads toward the outside in a mushroom shape, other failure modes are possible. For lay-ups with fibers predominantly perpendicular to the loading direction, a "transverse shearing" failure mode may occur in which progressive shear failures near a surface of crushing initiation dominate the crushing behavior of the laminate without the formation of large fronds. Particularly for Kevlar-reinforced composites, or hybrid laminates containing Kevlar, a local buckling mode similar to the accordion buckling behavior typical of metallic tubes may occur. For each of these failure modes, a complex interaction of small-scale behaviors governs the overall crushing behavior. The three composite crushing modes, as identified by Farley [2], are illustrated in Figure 2.

It is clear that delamination behavior is fundamental to the crushing response of composites. Even if the detailed crush morphology of a composite structure is not considered, delamination can have a significant influence on the crushing performance of composite structure. Bonded joints, the use of sandwich structures, and internal discontinuities such as ply drop-offs are all instances in which macro-scale delaminations can initiate. Whether or not a delamination forms or propagates from such a location could significantly alter the crash behavior of a structure.

In this paper, the author reviews the literature on modeling composite crushing behavior with an emphasis on the role of delamination. Various techniques to model delamination growth are

FIGURE 1 QUASISTATIC CRUSHING OF A SQUARE PULTRUDED GLASS/POLYESTER TUBE

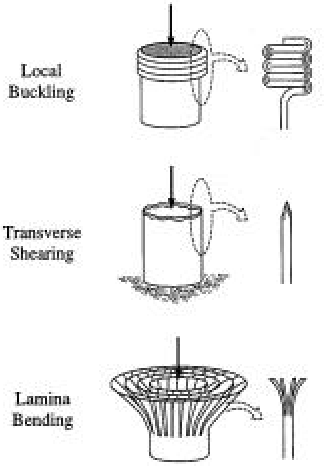


FIGURE 2 COMPOSITE CRUSHING MODES IDENTIFIED BY FARLEY [2]

compared using MSC.Dytran. Results from a sample problem illustrating the role of delamination growth in crash modeling are presented.

LITERATURE SURVEY

For weight efficiency, a composite energy absorbing element should exhibit a crushing mode in which wholesale destruction of the composite results from an impact event rather than one in which global collapse of the structure results. Thus, the complexity of the composite crushing phenomena described above must be addressed in some way if a crash model of an efficient composite structure is needed. Various authors have attempted to address this problem. Finite element models of simple composite specimens such as tubes or cones are made and modeled under simulated quasistatic or dynamic crushing loads. Despite the simplicity of the geometry and loading conditions of the modeled cases, such modeling problems are extremely difficult. It is a testament to the complexity of the crushing phenomenology that despite numerous efforts and years of study, no completely successful predictive model of composite crushing has been achieved, to the best of the author's knowledge. The following paragraphs describe some of the efforts that have been made by previous researchers to model the crushing of simple composite specimens.

IN-PLANE FAILURE AND DAMAGE MECHANICS

For efficient modeling, composite structures are often represented by shell elements. The properties of the shell elements allow for arbitrary composite lay-ups and may allow failure and property degradation of each individual ply to be predicted using either conventional in-plane failure predictions or other damage mechanics models. Because such failure models do not typically allow treatment of out-of-plane failures, particularly delamination, the general crushing behavior of composites cannot be modeled. Such approaches are therefore more likely to be effective for material and structural configurations that result in failure modes such as local buckling, or are dominated by global effects such as tearing of a wall, than for failure modes that result in wholesale destruction of the material. As a result, the success of these approaches is more likely for material/structural configurations that have suboptimal energy absorbing performance. Some of the efforts reported in the literature for modeling composite crushing using these methods are reviewed in the following paragraphs.

Haug et al. [3] describe a composites damaging model implemented in PAM-CRASH. This model treats the fiber and matrix in a filamentary composite as distinct phases from which the overall properties of the ply are derived. Damage parameters are introduced for the fiber and matrix phases. The values of these parameters are determined based on volumetric and deviatoric strain components in each of the phases. Elastic properties of the phases are reduced according to the calculated damage parameters. Reference 3 describes some initial investigations using this method to predict the crushing of composite tube structures, such as might be used in automotive applications. The model appears to be successful for modeling columns that fail in a local buckling failure mode or by progressive folding from one of the ends. For a structure with a more brittle failure mechanism, the results appear less encouraging. Other researchers have used and advanced this method. Kermanidis et al [4] used this approach to model the crushing of a sinewave beam element. Comparison with experimental results is not clear, but the crushing load appears to have been underpredicted. Kohlgrüber and Kamoulakos

[5] used the PAM-CRASH bi-phase model, enhanced to handle fabric composites, to model the crushing of carbon/Kevlar hybrid composite tube segments (roughly semicircular) as well as simulated elements of helicopter subfloor structures. For the tube segment models, it was noted that behavior such as delamination in the crashfront could not be modeled, and a more detailed model using solid elements and breakable constraints at ply interfaces was attempted to produce better results. For the larger structural models, a reasonable agreement between finite element and experimental results is shown. However, photographs of the deformed specimens show that failure is dominated by large-scale failures such as tearing at structural intersections and buckling of walls, and that relatively little wholesale crushing behavior is evident. Johnson and his collaborators [6,7] show additional models based on this approach.

Other damage mechanics models have been proposed. Faruque and Wang [8] present a model in which elastic properties of a ply are degraded by two damage parameters controlled by tensile strains in the shell element. The properties are related to the fiber principle directions, and do not utilize a micromechanics approach as in the bi-phase model above. A modification of the model to account for inelastic behavior typical of braided composites is also shown. Results for a braided glass/vinylester tube are shown and compared with experimental results. Lee and Simunovic [9] present a constitutive model for random fiber composites based on an elastoplastic model. Progressive fiber/matrix debonding is predicted based on a statistical model. The model is implemented in DYNA3D, and demonstrated for a problem involving the crushing of a square tube. Failure is dominated by tearing of the composites at the corners. Tabei and Chen [10] present a micromechanical model for composites. Various failure criteria are applied to predict behaviors such as fiber fracture, matrix cracking, and fiber microbuckling. A model of a square graphite/epoxy tube is shown, but no comparison with experimental results is made. The failure mode in the finite element model appears to be a folding mode.

A different approach from the damaging models described above, based on classical laminated plate theory, is presented by Matzenmiller and Schweizerhof [11]. Failure of plies is predicted based on ply stresses and conventional strength properties. However, some features are added to address the crushing response of composite structures, albeit in an empirical fashion. An erosion feature is used to eliminate elements if the time step becomes too small compared to the original time step (roughly equivalent to a maximum compressive strain criterion). A “crashfront” is then defined from elements sharing nodes with deleted elements. All strength values for elements in the crashfront are reduced by a softening factor, which is empirically determined as the ratio between the crushing stress in a tube crushing test, and the stress corresponding to first-ply failure under axial compression based on the in-plane failure theory. If effective, this should provide an empirical factor forcing the stress in the crashfront to correspond to the tested value. Considering ply degradation rules, however, it is not clear that softening each of the strength criteria will correspond exactly to limiting the stress in this way. Furthermore, localized buckling of material in the crashfront can derail the effectiveness of this method. Matzenmiller and Schweizerhof [11] show correlations between experimental and finite element results for a 13-ply glass/vinylester tube using LS-DYNA. A remarkable agreement is shown. The authors note, however, that agreement was due to the ability of the model to capture the “local folding” failure mechanism seen in the experiment. It is not clear how effective the approach would be for splaying type failure mechanisms, in which delamination plays a larger role in the response and the deformed shape may play a role in stabilizing the material in the crashfront. Results of a similar model, this time of a tube triggered by an internal plug triggering mechanism, are presented by Kerth and Maier in Reference 12. While the agreement with experimental results is shown to be good, the authors note that a reason for the discrepancies that exist is that, "the material model implemented …cannot explicitly take into account delamination." An apparently similar model is shown by Castejón et al [13]. However, almost no details about the modeling techniques are given.

Some recent efforts have attempted to introduce strain rate effects into the modeling of composite structures. Feillard [14] modeled foam-filled e-glass/vinylester composites using a modified Johnson-Cook mechanical law, with properties based on high rate tensile tests of the glass mat material. Good correlations between experimental and finite element results are shown for tubes specimens. However, the author notes that modeling problems remain relative to accurate modeling of the bonding between the composite and the foam. Furthermore, it is not clear how applicable this approach would be to composite systems other than the glass mat used in the study. Philipps et al [15] present work on characterizing the response of composites to high strain rates for application to crash models.

PHENOMENOLOGICAL MODELING OF COMPOSITE CRUSHING

The failure and damaging models described above appear to be effective for structures whose failure modes are governed by large-scale laminate failure or local instability. However, these models (or perhaps any modeling approach based on modeling a laminate by a single shell) may be limited in their ability capture the full range of behavior present in the crushing of a composite specimen. If delamination is a significant part of the crushing behavior, specialized procedures must be introduced into the model to account for it. Various authors have attempted to produce more detailed models of the crush zone in composite structures. These efforts are reviewed in the following paragraphs.

Perhaps the earliest attempt to model the crushing behavior of composites was reported by Farley and Jones [16]. They used a static finite element model to predict the crushing performance of composite tubes. The laminate was modeled as an assembly of plate elements representing the plies joined by springs representing the ply interfaces. Delamination was predicted using a virtual crack extension technique. Correlation with experimental results was reasonable given the limited phenomenology modeled. Similar models featuring progressive delamination growth were developed by several researchers for more detailed application to crushing analysis. Kindervater [17] describes a quasistatic finite element model used to study the initiation of crushing damage in a composite laminate under quasistatic crushing loads. Initiation and propagation of delamination damage was modeled by predicting failure in resin layers modeled between plies in the finite element mesh. The author, with Vizzini, [18] developed a 2-D, quasistatic finite element model applicable to the crushing of composite plates. Delamination between plies was modeled based on strain energy release rates computed using the virtual crack closure technique. The model qualitatively captured some of the physical behavior of plate crushing, but due to the limited failure phenomenology included in the model did not yield accurate predictions of crushing stress. Hamada and Ramakrishna [19] developed a finite element model for the crushing of composite tubes that exhibit a splaying failure mode, in which a single primary delamination divides the laminate into two fronds that are forced away from each other by a wedge of compacted debris. The initial finite element mesh included a representation of a pre-existing debris wedge and delamination crack. Extension of the central crack separating the fronds was predicted by calculating a stress intensity factor, K, at the crack tip. This approach is limited by its reliance on a predefined crush zone morphology and linear computation as well as by limitations in the fracture mechanics used in the model.

More recently, finite element crash codes have been used to make detailed models of laminate crushing. Bolukbasi and Laananen [20] modeled the crushing of a graphite/epoxy plate using an enhanced version of the implicit code NIKE3D. Their model was essentially a rectangular mesh of solid elements. An initial crack was assumed at the midplane of the laminate, and due to the assumption that the resulting deformation would occur in a splaying mode only one half of the laminate thickness was modeled. Strain energy release rates were calculated and used to predict delamination at various ply interfaces. Boundary conditions near the outer supports were released following failure of the material near the sides of the elements to mimic the physical supports in the plate crushing test that was being modeled. The authors show a good correlation between the computed and experimental crushing stresses, while noting that their results were sensitive to the friction coefficient used for contact between the composite plies and the steel crushing surface. Kohlgrüber and Kamoulakos [5] modeled the crushing of a composite semi-circular laminate using the finite element crash code PAM-CRASH. The laminate was modeled by discretizing each ply separately. Plies were held together by multipoint constraints. Delamination growth was predicted based on the forces resulting from the constraints. The model showed qualitative agreement with experiments in terms of the deformation shape, though the crushing force was underpredicted. Boonsuan [21] made some preliminary attempts to model the initiation behavior of graphite/epoxy composite plates under crushing loads using MSC.Dytran. The results showed a strong relationship between assumed initial delamination geometries and subsequent deformation shapes in the crush zone. Tay et al [22] present some of the most detailed models of the crush phenomenology of composite laminates to date. They modeled a detail of the crushing zone for a carbon-peek composite. The models are phenomenologically based, and use an initial mesh that is designed to trigger a splaying type deformation mode. Because solid elements are used, there is a practical limitation to the number of ply delaminations that can be modeled. The authors permitted delaminations at a smaller number of interfaces than existed in the physical structure (20 plies). Axisymmetric and 3-D models of a portion of the ring of a tube structure were made using ABAQUS. Delamination growth was predicted based on the tensile and shear forces generated by tied connections connecting nodes on opposite sides of a laminate interface. Reasonable agreement with experiments is achieved. However, the authors note that the goal of accurately modeling the crushing behavior of a composite “does not yet appear to have been achieved.”

The models described above demonstrate the potential for modeling composite crushing behavior by using finite element models based on simplified crushing phenomenology. Good correlations are obtained in many cases using models that do not fully capture all aspects of crushing damage observed experimentally, provided sufficient attention is given to the aspects of crushing that most directly control the response. In most of the previous studies, delamination is identified as a critical component of crushing behavior. Experiments on the crushing of composite laminates under axial crushing loads have shown that the appearance and growth of delaminations can significantly influence the energy absorbency of the laminate [1,2]. Large delaminations may result in reduced amounts of fiber and matrix damage in a laminate if crushing displacement can be accommodated by bending of the sublaminates. Therefore, delamination modeling is critical for accurate modeling of the crushing behavior of composite laminates.

DELAMINATION MODELING

Researchers have used several techniques to model delamination growth in composite structures using finite element crash codes. Among these are using spotweld elements to represent an interface [5,23,24], a cohesive failure model [25] and the fracture mechanics-based virtual crack closure technique (VCCT) [20,26]. These three methods of predicting delamination growth are compared using MSC.Dytran for an illustrative fracture mechanics problem. A dynamically loaded, adhesively bonded graphite/epoxy double cantilever beam (DCB) specimen is modeled. Finite element crack propagation results are compared with experimental data from the literature [27]. References 26 and 28 describe the finite element modeling efforts. All models of the DCB structure were made using solid elements to represent composite sublaminates on opposite sides of the delamination interface. The interface between the sublaminates is modeled using either spotweld elements or using EXELAS user-defined springs for the cohesive failure and VCCT approaches. Sample results using each of these methods are presented below.

SPOTWELD METHOD (TIED CONNECTIONS WITH FORCE-BASED FAILURE)

By this method, as described by previous researchers in References 5, 23 and 24, nodes on opposite sides of an interface where delamination is expected are tied together using spring elements, rigid rods, or other constraints. If the constraint forces exceed some criterion, the constraint is released and the delamination grows. Spotweld elements in MSC.Dytran may be used for this purpose in a straightforward fashion. The primary disadvantages of this method are that the failure forces alone are not an accurate predictor of fracture phenomena, and there is consequently no strong physical basis for determining the failure forces. However, some previous researchers have shown good correlations with experimental results using this method [23]. Recent results by the author with Fasanella [24] on modeling a scaled fuselage concept exhibiting debonding of composite facesheets from foam cores using the spotweld technique are described below.

To model the DCB specimen, rod elements (CROD) referencing MSC.Dytran's spotweld (PWELD) failure property are used to represent the adhesive interface. This property calculates the forces generated in the rod element as it ties two nodes together, and predicts failure if the magnitude of the total force or its components exceeds specified strength values. For the case of the pure Mode I DCB problem under study, no shear forces are expected and the failure criteria reduces to a simple maximum force criterion. To model delamination, an appropriate tensile failure load F_{Nc} (FAILTENS) must be determined. This load was estimated from typical properties of epoxy according to $F_{N_c} \approx \sigma_{ult} A_e$, where σ_{ult} is the strength of the adhesive and A_e is the interface area modeled by a spring element. Because strength properties for the epoxy used in Reference 27 were not available, a typical value of σ_{ult} of 80 MPa was used. This yielded a value of 0.08 kN for F_{Nc}. Crack growth histories were produced using this value and using values of the failure force spanning approximately an order of magnitude around this value. Figure 3 shows delamination length versus time curves for DCB specimens loaded by an opening displacement rate of 23 m/s. MSC.Dytran results using a variety of failure forces are compared with experimental data from Reference 27. Although a reasonable agreement with experimental results is obtained using the estimated failure force, these results illustrate the sensitivity of the delamination propagation response to the choice of spotweld failure force.

COHESIVE FRACTURE MODEL

An improvement to the spotweld method was developed by Reedy et al [25]. They used a cohesive failure model to represent the properties of the interfacial material. The force-displacement response of interfacial elements is based on classical cohesive failure behavior, as shown in Figure 4. Properties defining the force-displacement response are obtained from the conventional critical energy release rates, and from harder-to-obtain cohesive zone length or maximum force. The use of the cohesive model avoids some of the deficiencies of the spotweld method. For example, the cohesive model allows energy to be absorbed by the delamination growth process, and reduces spurious dynamic effects associated with abrupt, finite crack extension. Reedy et al [25] implemented this model in PRONTO3D using a special hex element.

For the present evaluation, this model was implement in MSC.Dytran using EXELAS user-defined spring elements to provide stress-separation response according to Figure 4. CELAS1 spring elements referencing the cohesive model EXELAS subroutine are used to model the interface. Due to the simple geometry and loading of the DCB specimen, only springs in the Mode I orientation were included. As can be seen from Figure 4, the cohesive failure model requires two parameters to define the curve. Reedy et al [25] define the area under the curve for $u_c \le \delta \le u_{\max}$ as the critical energy release rate. The second parameter must be either u_c, $u_{\max}$, or some relationship between these two quantities. Figure 5 shows results from the MSC.Dytran model of dynamic DCB behavior based on the cohesive failure model for two loading rates. For these cases, G_c was taken from experimental results in Reference 8. $u_{\max}/u_c$ was taken to be 10. Results show that in an average sense the crack growth is well modeled for the slower displacement rate, though details of the dynamic response are not captured. At the higher opening displacement rate the experimental response is well captured initially, but the finite element result diverge from the experiment after some initial displacement.

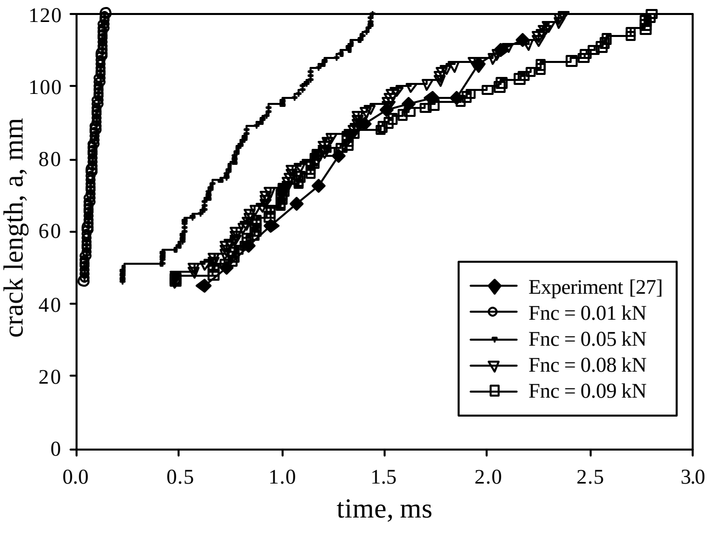


FIGURE 3 DELAMINATION PROPAGATION RESPONSE FOR A DCB SPECIMEN MODELED USING SPOTWELD ELEMENTS TO REPRESENT THE INTERFACE SHOWING THE INFLUENCE OF THE FAILURE PROPERTY F_{NC}

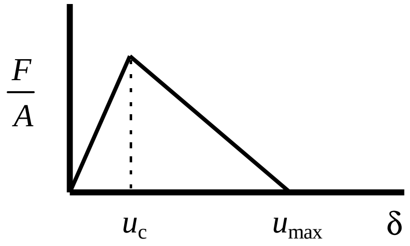


FIGURE 4 STRESS-SEPARATION RELATIONSHIP FOR THE COHESIVE FRACTURE MODEL [25]

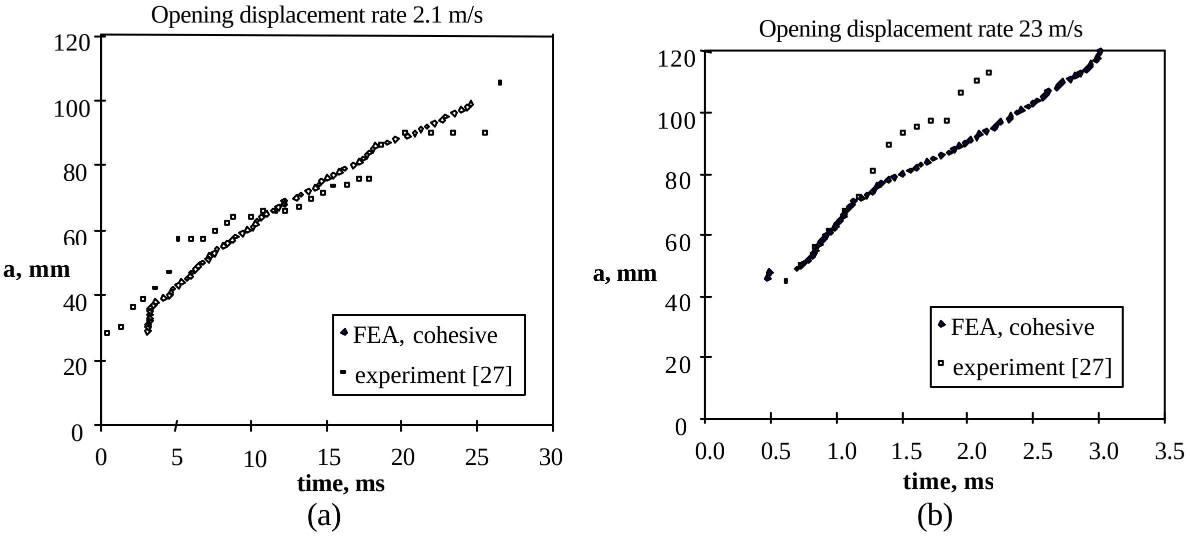


FIGURE 5 DELAMINATION GROWTH VERSUS TIME FOR DCB MODELED USING COHESIVE MODEL [25] FOR TWO OPENING DISPLACEMENT RATES

VIRTUAL CRACK CLOSURE TECHNIQUE (VCCT)

The virtual crack closure technique (after Rybicki and Kanninen [29]) is often used by researchers in the area of fracture mechanics. Energy release rates are calculated from nodal forces and displacements in the vicinity of a crack front and compared to critical property data to predict crack growth. For mode I, the strain energy release rate is computed as follows:

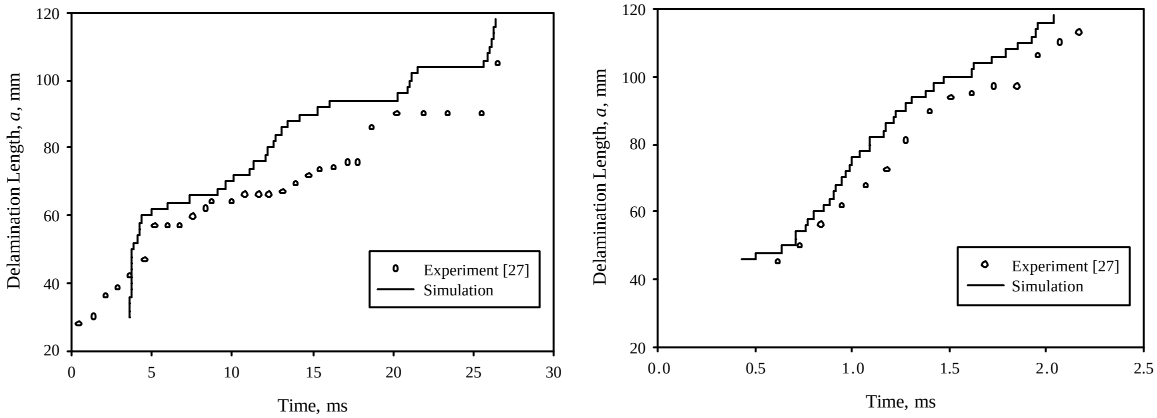
$$G_I \approx \frac{1}{2\Delta A} F_I (u^+ - u^-) \,,$$

where F_I is the force in the spring aligned with the mode I direction, and u^+ and u^- are the nodal displacements in the mode I direction at the nodes immediately ahead of the crack front. These displacements are computed relative to a rotating coordinate frame defined relative to the bond surface. ΔA is the increment in interfacial area associated with failure of the spring elements. Mode II and Mode III energy release rates are computed in a similar fashion. Like other fracture mechanics techniques, the VCCT is sensitive to mesh refinement. However, it is less so than other fracture modeling techniques that require accurate calculation of stresses in the singular region near a crack front. Further, the use of conventional force and displacement variables obviates the need for special element types sometimes used for fracture modeling that are not available in crash codes. Among the methods studied, the VCCT has the strongest physical basis, and the greatest research history. However, it must be recognized that the accuracy of this method carries a substantial computational burden due to the relatively small mesh sizes required.

To employ the VCCT using MSC.Dytran, spring elements are used to effectively model an interlaminar region. Failure of spring elements in the model represents crack growth. Calculation of energy release rates and failure prediction was carried out using user-defined EXELAS spring properties. The stiffness of the interfacial springs is selected based on a simple elastic foundation model. Tests showed little sensitivity of the results to the choice of spring stiffness. For simplicity of computation, it was assumed that nodes located on opposite sides of the bond fall upon the same normal vector. No offset in the plane of the bond is permitted between the endpoints of the springs. To permit general loading, three springs are co-located at each nodal location on the bond surface, acting in mutually perpendicular directions corresponding to the three fracture modes. The EXELAS subroutine determines whether each spring is located at a crack front, and if so it computes the energy release rate components at that point. Once all components of the energy release rate are calculated, a mixed mode fracture criterion is checked. If crack growth is detected, the forces in the springs at the site are set to zero, and are ignored in future time steps. The EXELAS procedure was written to predict crack growth according to a linear fracture law. For the DCB models, however, results are dominated by Mode I, and the choice of fracture law is not significant. Critical values for strain energy release rates are obtained from dynamic tests reported in the literature [27] for use in the following examples. The procedure as used in this study does not permit different values of the critical strain energy release rates to be used for initiation and propagation, though in principle such effects may be readily added.

Figure 6 compares finite element results using VCCT with experimental results reported by Blackman et al [27] for opening displacement rates of 2.1 m/s and 23 m/s. No strong loading rate dependence on the critical strain energy release rates was observed in the experiments modeled, although the strain energy release rate upon crack arrest was somewhat different from the initiation value [27]. Constant values of the critical strain energy release rate, obtained from the initiation values given in Reference 27, were used in the finite element model.

For the opening displacement rate of 2.1 m/s, both the computation shown in Figure 6(a) and the experimental results from Reference 27 show a decrease in average crack velocity near a time of 5 ms and a crack length of 60 mm, though the delamination initiation is more abrupt in the finite element model than in the experiment. Such changes in crack velocity are characterized in Reference 27 as a "stick-slip" behavior resulting from alternate periods of crack growth and crack arrest and occurs several times in the experiment at this opening rate. This behavior is also evident in the finite element results shown in Figure 6(a). At higher loading rates, the prominence of this stick-slip behavior diminished in the experimental behavior, resulting in a single plateau in the crack length versus time curve, beginning at about 1.5 ms. A similar, though shorter, plateau occurs in the finite element results shown in Figure 6(b). For each of these cases, the time to final failure of the DCB specimens computed by the finite



(a) (b)

FIGURE 6 DELAMINATION GROWTH VERSUS TIME FOR DCB MODELED USING VCCT FOR TWO OPENING DISPLACEMENT RATES: (A) 2.1 m/s, (B) 23 m/s element model is within about 10% of the experimentally measured values. These results demonstrate the ability of the current approach to accurately capture significant aspects of dynamic fracture behavior.

SANDWICH TRUSS FUSELAGE MODEL

The author with Fasanella [24] used MSC.Dytran to model the crushing of a composite aircraft fuselage concept that utilizes foam-core composite sandwich structures arranged in a truss-like pattern as a subfloor energy absorbing system. The sandwich truss subfloor, described by Fasanella and Jackson in Reference 30, is shown in Figure 7(a) from Reference 30. The subfloor truss members are contained between a stiff structural floor, which carries flight and pressure loads, and a thin outer skin. The skin is designed to readily deform in a fashion that promotes the engagement of the subfloor energy absorbing members. This subfloor concept has been subsequently refined to improve the energy absorbing characteristics of the structure [31]. However, modeling the original sandwich truss concept allows the effectiveness of modeling delamination as part of a crash model to be evaluated. The finite element model of the structure is shown in Figure 7(b). The experimental article and the finite element model in Figure 7 are shown in an upside-down configuration with the floor at the bottom of the figure and the impacting surface at the top.

Testing of the experimental article is described in Reference 30. Details of the finite element model and comparison with experimental results are given in Reference 24. The subfloor was fabricated using sandwich elements comprised of single-layer E-glass/epoxy facesheets and a PVC foam core. The structure was crushed between flat surfaces under a uniform loading rate of 20 in/min. Photographs of the experimental damage sequence from Reference 30, shown in Figure 8(i) below, illustrate the significance of facesheet-core debonding on the crushing behavior. To model this behavior requires an explicit treatment of delamination. After reviewing various methods, as described above, it was determined that the spotweld method would be most appropriate. Energy release rate property data are not available for the skin/core interface used in the experiment. In the absence of reliable material property data, the use of more rigorous fracture mechanics method is not justified. Solid elements were used for the core material, and shell elements for the facesheets and skins. Facesheet/core interfaces were modeled using rod elements with spotweld (PWELD) failure properties to join the composite facesheets to the cores. The reference surface of the shell elements on the interface was offset to coincide with the interface.

Material properties for the E-glass/epoxy skin and facesheet materials are those used in Reference 30. Skin and facesheet elements were modeled using PSHELL elements with elastic-plastic DMATEP properties. The only available properties of the core were generated from crush tests conducted at NASA Langley Research Center. The foam was modeled using solid elements with the PSOLID material property data referencing the FOAM1 crushable foam


(a) (b)

FIGURE 7 SANDWICH TRUSS FUSELAGE SECTION, (a) EXPERIMENTAL ARTICLE [7], AND (b) FINITE ELEMENT MODEL

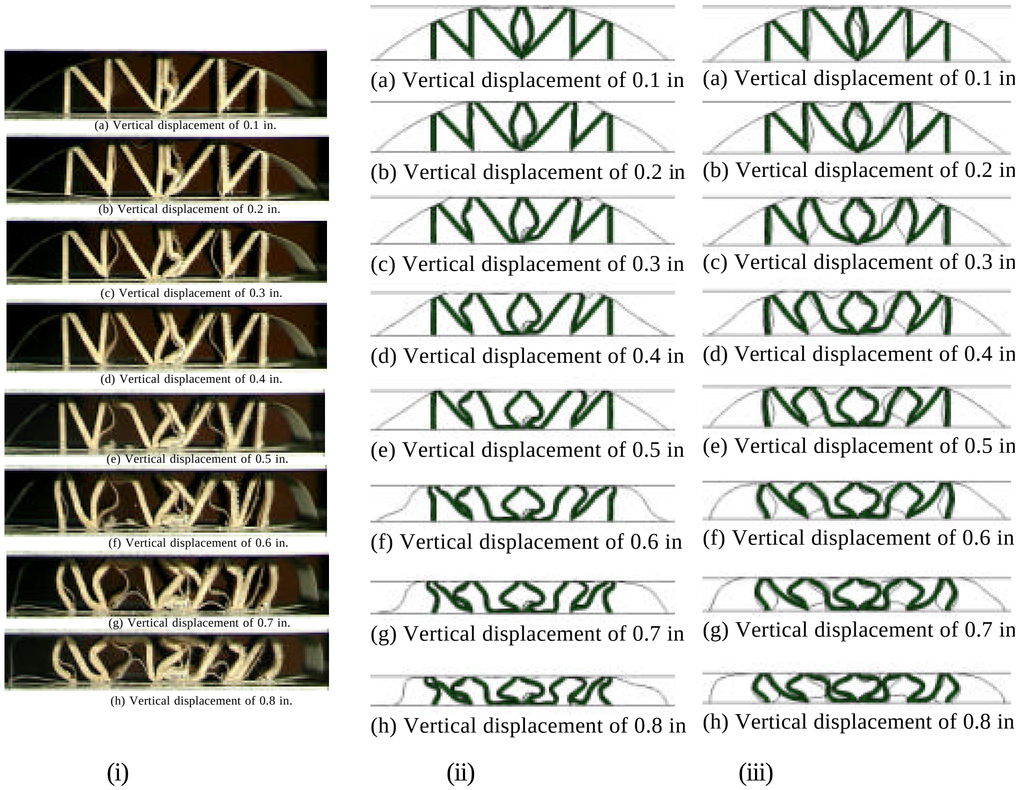


FIGURE 8 DEFORMATION SEQUENCES FOR (i) EXPERIMENTAL ARTICLE [30], (ii) FINITE ELEMENT MODEL WITH NORMAL AND SHEAR FAILURE PROPERTIES OF 2.0, 1.0, AND (iii) FINITE ELEMENT MODEL WITH NORMAL AND SHEAR FAILURE PROPERTIES OF 0.4, 0.15

material property. Data from two separate crush tests were combined to generate the input property data: a large displacement uniaxial test up to 90% strain, and a separate test up to 1% strain which showed a greater initial modulus of the foam than was apparent from the large strain test. The use of the FOAM1 property in this application is not ideal in some respects. The foam initially acts as a core material, and its bending properties may not be well modeled by the FOAM1 property. Also, the FOAM1 property assumes a zero Poisson’s ratio, which may not be accurate for the PVC foam used in the structure. However, given the input data available, and the mixed use of the foam (core material at relatively small displacements, crushable material at large displacements), the use of this property seemed to be a good compromise.

As discussed above, the PWELD tensile and shear failure forces act as empirical parameters for predicting delamination. With sufficient experimental data for comparison, values that allow reasonable correlation between the finite element and experimental results may be obtained. For this model, approximate values of these failure forces are estimated based on material strength data. The tensile strength of the foam is likely to be considerably less than that of the epoxy, and is therefore likely to largely control the tensile strength of the interface. However, no tensile strength properties are known for the PVC foam used in the experiment. Based on published properties of other types of PVC foam a tensile strength of approximately 140 psi is assumed. Using the nominal interfacial area represented by the spotweld elements in the model results in an approximate tensile failure property of 0.4 pounds. Similarly, the shear failure property is

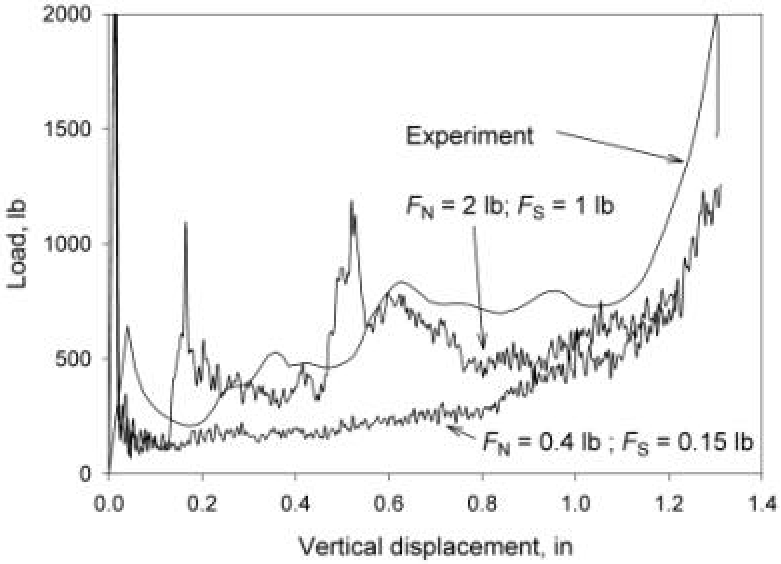


FIGURE 9 COMPARISON OF EXPERIMENTAL [30] AND FINITE ELEMENT LOAD-DISPLACEMENT RESPONSE

estimated to be 0.15 pounds. These values are used as starting points for comparison. Different values of PWELD failure properties are also considered.

Computed deformation shapes for two sets of PWELD failure strengths are compared to experimental displacements in Figure 8. Figure 8(ii) shows displacements for the finite element run that provided the best qualitative comparison with experimental load data. Figure 8(iii) shows displacements for the finite element model using the strength values estimated above. Load-displacement results, shown in Figure 9, illustrate that a reasonable agreement is made with the experimental results for the finite element model corresponding to Figure 8(ii). In this case, two plateaus in the crushing load are observed at approximately the same magnitudes as in the experiment. However, for cases in which the delamination behavior more closely captured the experimental response the crushing load was significantly underpredicted.

CONCLUDING REMARKS

The need for accurate, predictive finite element models of composite structures is increasing due to the increased use of composites in crashworthy structures in both the automotive and aerospace industries. However, modeling composite crushing behavior is a challenging problem. The small scale of the crushing damage, the complexity of the interaction between failure modes occurring on a variety of scales, the lack of reliable material characterization of significant factors (such as friction coefficients, dynamic delamination fracture toughness, etc.), and other factors all make the problem difficult. Truly predictive models of the crushing behavior of composites may not be achieved in the near term, though various researchers have made progress in this area. While currently existing phenomenological composite crush models may be used to help identify critical parameters in the crushing response of a particular material/geometry configuration, they may be impractical for engineering crash analysis. More simple damaging models present an alternative, but their predictive capability for representing the response of composite structures subject to wholesale crushing damage is questionable. Other techniques, perhaps, need to be pursued to fill the void. It seems clear that one of the key areas requiring additional attention is the role of delamination.

Various methods for modeling delamination growth as part of a crash model have been evaluated. Accurate delamination growth modeling can be achieved. However, two factors make the use of such models difficult. First, the mesh size required for accurate delamination prediction is small by the standards of engineering crash models. This may impose a prohibitive computational burden, particularly when using an explicit code, such as MSC.Dytran. Second, the dynamic property data required to predict delamination growth are not easily obtained. Critical energy release rates may vary as a function of loading rate; may have different initiation, propagation and arrest values; and are difficult to apply for mixed-mode loading conditions. Until these modeling and material characterization issues are overcome, the simple "spotweld" method of modeling an interface may present the best choice for use in a crash model. However, a substantial amount of experimental correlation may be required to provide confidence in its use for any specific material/geometry combination. This method is therefore unlikely to result in a true predictive tool for finite element crash modeling.

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