NUMERICAL ENERGY ABSORPTION STUDY OF COMPOSITE TUBES FOR AXIAL IMPACT LOADINGS

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SUMMARY

This paper focuses on the numerical energy absorption behaviour of pultruded composite tubes under an axial impact loading case. The circular and square cross sectional glass-polyester composite tubes are considered for the study. In order to capture the typical failure modes such as delaminations, lamina bending, axial cracks and fibre fracturing, a new innovative approach was used using multiple shell elements, cohesive elements and pre-defined seams. To predict the correct peak crush load and the corresponding energy absorption, the importance of the numerical modelling of multiple delaminations and triggering are discussed. Two types of triggering were chosen for the study (45° deg chamfering around the edges and a tulip pattern with an included angle between the edges of 60°). Finally, the results of this numerical investigation are compared with experimental data. The commercially available finite element code ABAQUS V6.7-3 Explicit was used for this study.

Keywords: Composite tubes, energy absorption, triggering, delamination, cohesive elements

1. INTRODUCTION

A wide spectrum of high speed engineering applications needs to satisfy certain safety regulations. The modern civil and military aviation, ship industry and the automobile industry are the prime examples. On the other hand, the entire world faces the problem of security for the civil engineering structures due to terrorist activities. A preventive solution is needed to safeguard the civil engineering structures and to avoid human casualties due to explosion. In connection with the above applications, a numerical investigation was carried out to study the energy absorbing characteristics and progressive deformation behaviour of uni-directional pultruded composite tubes. In order to capture the typical failure modes (delaminations, lamina bending, axial cracks and fibre fracturing) of the composite tube [1], a new innovative approach was used using multiple shell elements, cohesive elements and pre-defined seams. To predict the correct peak crushing load and the energy absorption, the importance of the numerical modelling of multiple delaminations and triggering are discussed. Finally, the results of this numerical investigation were compared with experimental data.

It is a well-known fact that one can achieve higher energy absorption with composite materials compared to metal alloys with proper construction and architecture. Moreover, composites have a relative advantage in terms of the specific energy absorption, ease of manufacture and maintenance. The effect of composite specimen dimensions and its geometry on the energy absorption were studied in [1, 2]. However, the energy absorption characteristics are not only depending on the shape of the specimens and its dimensions [3]. Various variables control the energy absorption of the composite structures. The progressive crushing process which yields higher energy absorption depends on the mechanical properties of the fibre and the resin, fibre and resin volume fractions, laminate stacking sequence, fibre orientation and the geometry of the tube. To produce a significant deceleration during the crash event, the failed tubes exhibit delamination, bending, axial cracking and fibre fracturing modes [4].

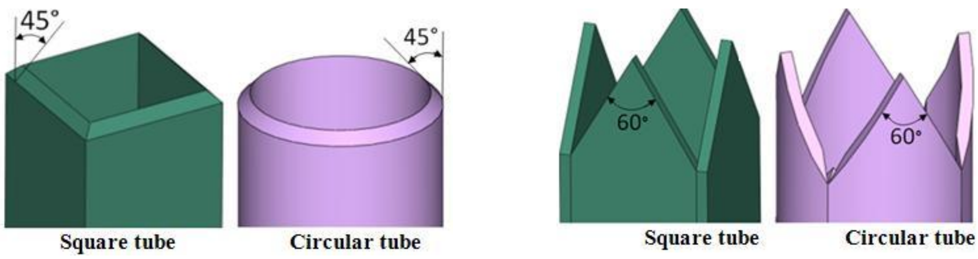
Often conducting a full scale experiment is an expensive affair. Hence an alternative predictive technique to assess the energy absorption of a composite material is very important. The numerical simulation using the finite element technique can be adopted for this case. Few static and dynamic numerical studies have been conducted to assess the energy absorption characteristics of composite tubes [5, 6]. In these studies the numerical modelling of the composite tubes was done with a single layer of shell elements. However, the numerical modelling of triggering especially 45^{o} chamfering cannot be modelled with a single layer of shell elements. Furthermore, the numerical modelling of the multiple delaminations which cause the split of outer and inner plies of the composite tubes cannot be modelled with a single layer of shell elements. The consideration of the multiple delaminations approach is important to predict the correct energy absorption because it causes the separation of plies and loss in bending stiffness of each sub-laminate.

Many studies [7, 8] demonstrated that fibre orientation along the axis of the tube absorbed more energy than other orientations. Hence, square and circular cross sectional pultruded tubes (uni-directional) made up of glass polyester were considered for the study. To address the importance of correct numerical modelling of triggering two different types of triggering (45° deg chamfering around the edges and a tulip pattern with an included angle between the edges of 60°) were chosen. Strength based failure criteria are commonly used to predict the failures in a composite material. Generally, for the impact and the crash analysis of a composite material, the approach of the continuum damage mechanics is preferred in which the failure is first identified and consequently, the degradation of the elastic properties is computed till final fracture. A good example of the above approach can be found in [9], in which a user material model was implemented in explicit finite element code (LS-DYNA) to capture the tensile and compressive response of a braided composite material. However, there have been several studies proving that the well established and existing models available in commercial finite element codes can be adopted to predict the energy absorption behaviour of a composite tube. Han et al. [6] and Zarei et al. [10] used Material model 54 of LS-DYNA to predict the failure patterns and the energy absorption of the circular and square cross-sectional tubes respectively. Material model 54 [11] has the option of using either the Tsai-Wu failure or the Chang-Chang failure criteria for the individual lamina. The Chang-Chang failure criterion is the modified theory of the Hashin's failure criterion which accounts for the non-linear stress-strain behaviour. Although many failure criteria are used, the failure criterion proposed by Hashin [12] is extensively employed in many applications. Hence in this work the same failure criterion was adopted to assess the energy absorption behaviour of the composite tubes. All numerical axial impact analysis of circular and square tubes was carried out for an initial impact velocity of 9.3 m/s. Finally the results (deformation patterns and the corresponding energy absorption) of this approach were compared with the experimental results.

2. NUMERICAL STUDY

2.1 Geometry and material data

Pultruded glass-polyester composite tubes with circular (outer diameter =50 mm; thickness =3 mm and length = 220 mm) and square (outer width = 60 mm; thickness = 4.5 mm and length=220 mm) cross sections were used for this study. Two types of triggering, 45° edge chamfering (Type 1) and tulip pattern (Type 2) were adopted for circular and square tubes. The details of triggering patterns are shown in Figure 1 (a) and (b). The mechanical properties of the glass-polyester pultruded tube in principal directions are given in Table 1. For the interface modelling (delamination) between plies, the properties of the polyester resin were considered. The mechanical properties of the polyester resin were adopted from [13].



(a) Triggering type 1 (b) Triggering type 2

Figure 1: Triggering types of pultruded composite tubes.

Table 1: Material properties of pultruded glass-polyester composite tubes in principal directions.

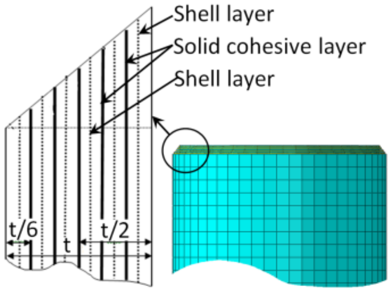
Parameters	Symbol	Values
Material and elastic data		
Density (kg/m^3)	ρ	1850
Longitudinal modulus (GPa)	E_{11}	33.5
Transverse modulus (GPa)	E_{22}	8.0
In-plane shear modulus (GPa)	G_{12}	5.0
Out-of-plane shear modulus (GPa)	G_{23}	5.5
Poisson's ratio	ν_{12}	0.29
	ν_{23}	0.32
Glass polyester composite Strength		
Longitudinal tensile strength (MPa)	X^T	400
Longitudinal compressive strength (MPa)	X^C	200

Transverse tensile strength (MPa)	Y^T	30
Transverse compressive strength (MPa)	Y^C	50
In-plane shear strength (MPa)	S^L	30
Out of plane shear strength (MPa)	S^T	30

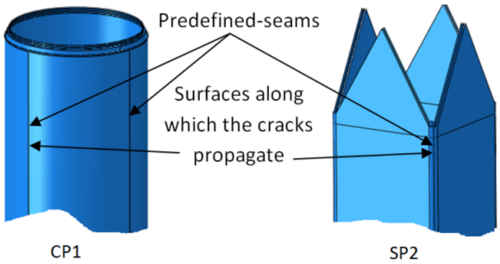
2.2 Salient features of numerical modelling

The commercially available finite element code ABAQUS V6.7-3 Explicit was used to study the energy absorption characteristics of pultruded composite tubes. In order to model the multiple delaminations and the correct geometry of triggering, the thickness of the composite tubes was modelled with six layers of shell elements (S4R elements: 4-node, quadrilateral, stress/displacement shell element with reduced integration and with finite membrane strain formulation). Accordingly the thickness of each shell layer was divided equally. The integration points representing all the layers of the 0° laminate were located evenly through the thickness of the tubes using Simpson integration rule. A minimum of 3 integration points was located at each layer of the shell elements. To model the delaminations the solid cohesive elements (COH3D8: cohesive, three dimensional element with 8 nodes) were placed in between the shell layers. A pure master-slave *"tied"* constraint was established between the shell layers and the solid cohesive layers. It can be noticed in Figure 2(a) that this approach formed a correct representation of the geometry of triggering type 1. To simulate the axial impact load only in vertical direction, apart from the vertical translation, all degrees of freedom of the top analytical rigid body were arrested. To represent the fixed crushing plate at the bottom, all the degrees of freedom of the bottom rigid body were also arrested. The "*surface-to-surface*" master-slave contact algorithm was established between the bottom rigid analytical surface and the composite tube with the friction coefficient equal to 0.2.

During the experimental crushing of a composite tube, the inner and outer petals were subjected to bending inside and outside of the tube followed by the central delamination. The material splaying outwards flared into petals due to the phenomena of axial cracks and the material splaying inwards showed bending without any petalling [12]. As a result, a considerable amount of energy was dissipated due to the axial cracks of the outer petals and significant amount of deceleration of the impactor was provided by the inner plies. To model the axial cracks on the outer shell layers, the predefined seams (16 for circular and 4 for square tubes) were introduced only at three outer shell layers for a length of 70 mm (Figure 2(b)). During meshing, ABAQUS [14] creates duplicate overlapping nodes on the seam; these coincident nodes are free to move apart as the seam separates. The material properties of the shell sections in principal directions were defined by introducing a local Cartesian coordinate system for the square tubes and a local cylindrical coordinate system for the circular tubes. The impactor and bottom crushing plate were modelled as analytical rigid surfaces. An impactor mass of 68.85 kg was assigned to the centre of the top analytical rigid surface. The element size of 3 mm was used for all the studies.



(a) Finite element modelling of circular tube with triggering type 1



(b) Finite element modelling of circular and square tube with seams.

Figure 2: Finite element modelling of composite tubes.

2.3 **Damage model for composite laminates**

The undamaged orthotropic plane stress material response was specified directly by the elastic stiffness matrix which is given in Table 1. In ABAQUS Explicit V6.7-3, the anisotropic damage model considers the following four failure modes given by Hashin and the damage initiation criteria have the following forms [14];

Fibre tension $(\hat{\sigma}_{11} \geq 0)$: $$F_f^t = \left(\frac{\hat{\sigma}_{11}}{X^T}\right)^2 + \alpha\left(\frac{\hat{\tau}_{12}}{S^L}\right)^2 \quad (1)$$

Fibre compression $(\hat{\sigma}_{11} \leq 0)$: $$F_f^c = \left(\frac{\hat{\sigma}_{11}}{X^C}\right)^2 \quad (2)$$

Matrix tension $(\hat{\sigma}_{22} \geq 0)$: $$F_m^t = \left(\frac{\hat{\sigma}_{22}}{Y^T}\right)^2 + \left(\frac{\hat{\tau}_{12}}{S^L}\right)^2 \quad (3)$$

Matrix compression $(\hat{\sigma}_{22} \leq 0)$: $$F_m^c = \left(\frac{\hat{\sigma}_{22}}{2S^T}\right)^2 + \left[\left(\frac{Y^C}{2S^T}\right)^2 - 1\right]\left(\frac{\hat{\sigma}_{22}}{Y^C}\right) + \left(\frac{\hat{\tau}_{12}}{S^L}\right)^2 \quad (4)$$

In Equation 1, α is a coefficient that determines the contribution of the shear stress to the fibre tensile initiation criterion. The shear stress contribution was taken into account for the tensile failure, so the value of α was taken as 1. The $\hat{\sigma}_{11}$, $\hat{\sigma}_{22}$, $\hat{\tau}_{12}$ are the components of the effective stress tensor. Then $\hat{\sigma}$ can be written as

$$\hat{\sigma} = M\sigma \quad (5)$$

where σ is the nominal stress and M is the damage operator, which can be written as

$$M = \begin{bmatrix} \frac{1}{(1-d_f)} & 0 & 0 \\ 0 & \frac{1}{(1-d_m)} & 0 \\ 0 & 0 & \frac{1}{(1-d_s)} \end{bmatrix} \quad (6)$$

d_f , d_m and d_s are the damage variables that characterize the fibre, matrix and shear damage respectively. Prior to any damage initiation the damage operator, M, is equal to the identity matrix. Once the damage occurs at any material point for at least one mode, the damage operator becomes significant in the criteria for damage initiation of other modes.

2.4 Damage model for cohesive elements

The constitutive response of cohesive elements is based on the fracture mechanics approach. The traction-separation constitutive response was used which ensures that nominal strains are equal to the relative separation displacement of the cohesive layer. The nominal traction stress vector," *t*", consists of three components t_n (normal component), t_s and t_t (shear components). The corresponding separations are denoted by δ_n, δ_s and δ_t. Considering "T_0" the original thickness of the cohesive element, the nominal strains and the elastic behaviour can be written as Equation (7) and (8).

$$\epsilon_n = \frac{\delta_n}{T_0}, \epsilon_s = \frac{\delta_s}{T_0}, \epsilon_t = \frac{\delta_t}{T_0} \tag{7}$$

$$t = \begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix} = \begin{bmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{ns} & K_{ss} & K_{st} \\ K_{nt} & K_{st} & K_{tt} \end{bmatrix} \begin{Bmatrix} \epsilon_n \\ \epsilon_s \\ \epsilon_t \end{Bmatrix} = K\varepsilon \tag{8}$$

The process of degradation was assumed to occur when a quadratic function involving the nominal stress ratios reaches the value of one (Equation (9)).

$$\left\{\frac{\langle t_n \rangle}{t_n^0}\right\}^2 + \left\{\frac{t_s}{t_s^0}\right\}^2 + \left\{\frac{t_t}{t_t^0}\right\}^2 = 1 \tag{9}$$

A typical mode-independent traction-separation with linear softening response was used for this study. A scalar damage variable "D" captures the overall damage in the material. During the damage process the stress components can be calculated from the following relations,

$$t_n = \begin{cases} (1-D)\bar{t}_n, & \bar{t}_n \geq 0 \\ \bar{t}_n & otherwise \end{cases} \tag{10}$$

$$t_s = (1-D)\bar{t}_s \tag{11}$$

$$t_t = (1 \quad D)\bar{t}_t \tag{12}$$

where $\bar{t}_n$, $\bar{t}_s$ and $\bar{t}_t$ are the stress components calculated by the elastic traction-separation behaviour for the current strains without damage.

3. RESULTS AND DISCUSSIONS

The analysis was carried out for circular and square composite tubes with triggering type 1 and 2 for an initial impact velocity of 9.3 m/s. The deformation of the tube was obtained from the displacement of the top analytical rigid surface and the reaction force was extracted from the interface force between the composite tube and the bottom analytical rigid surface. The successive stages of deformation patterns of the circular tube with triggering type 1 and square tube with triggering type 2 are shown in Figure 3 and 4. It can be noticed that the typical failure modes such as delaminations, lamina bending and axial cracks are clearly evident. Due to the predefined seams the results of the initial time increments showed the complete splitting of the outer shell layers at the seams assigned locations, while the inner plies continued to fold inside. The later stages of the analyses gave a clear evidence of the bending of elements which belong to the outer shell layers. For all tube series the numerical modelling approach with multiple layers of shell elements with cohesive elements and predefined seams showed a very good correlation of the deformation patterns with the experimental results (Figure 3 and 4).There was no significant difference in the deformation pattern was noticed between the triggering type 1 and 2 for circular composite tubes. Hence the circular tube with triggering type 1 and square tube with triggering type 1 and 2 are considered for the comparison of failure patterns. The experimental failure pattern of these three tube series for the impact velocity of 9.3 m/s are shown in Figure 5. Similarly the final numerical deformation patterns of these tubes are shown in Figure 6. It can be noticed that similar to experimental results the numerical models captured all the micro and macro failure modes of composite tubes.

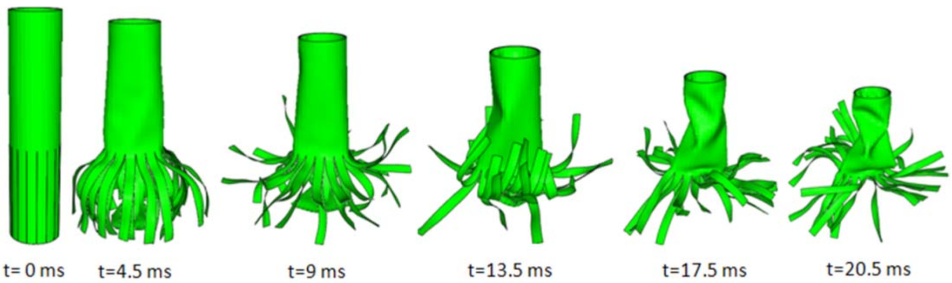


Figure 3: Deformation sequence of circular tube with triggering type 1.

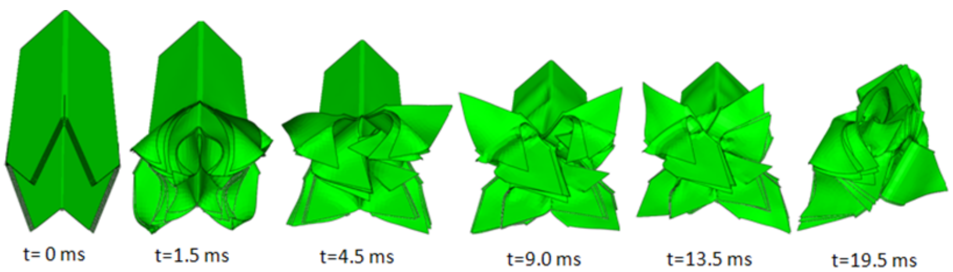


Figure 4: Deformation sequence of square tube with triggering type 2.

Figure 5: Experimental deformation patterns of composite tubes.

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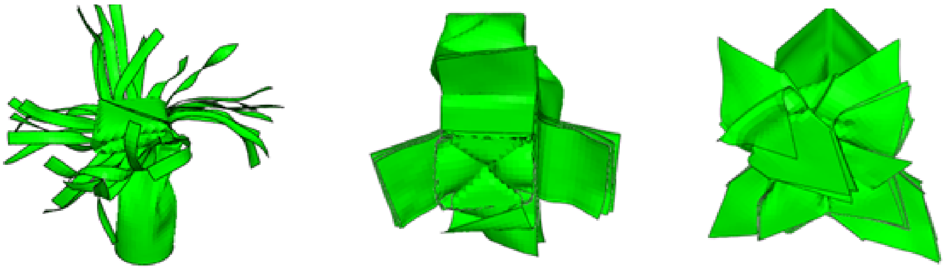

Figure 6: Numerical deformation patterns of composite tubes.

The load-deformation histories of all the tube series (circular and square tubes with triggering type 1 and 2) are given in Figure 7 to 10. The peak crush load and deformation length predictions of circular tubes with both triggering were very close to the experimental values (Figure 7 and 8). However, the square tube with triggering type 1 predicted higher peak crush load than the experimental value (Figure 9). Furthermore, it showed the increasing mean crush load with lower deformation length in the later stages. This was due to the compression of inner plies in the later stages rather than uniform progressive folding. Square tube with triggering type 2 predicted closer peak crush load compared to the experimental value (Figure 10). However, the slope to reach the peak crush load was lower compared to the experimental data. This may be due to the reduced stiffness offered by the outer shell layers at the initial time increments.

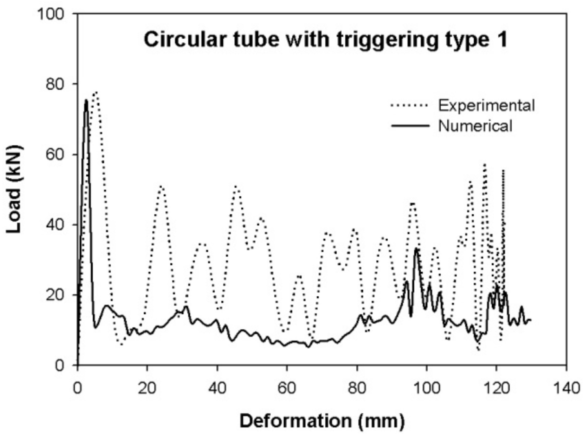

Figure 7: Comparison of load-deformation curves of circular tube with triggering type1.

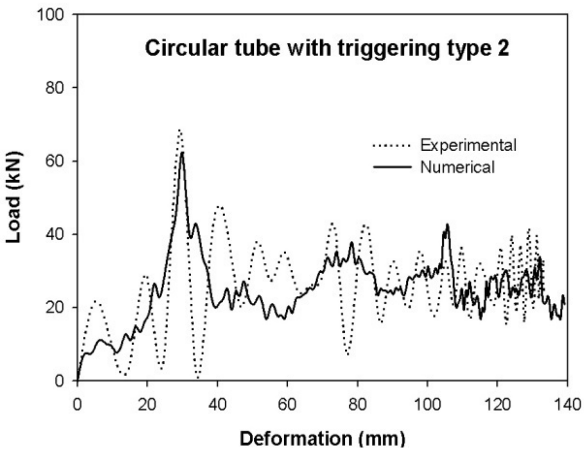

Figure 8: Comparison of load-deformation curves of circular tube with triggering type2.

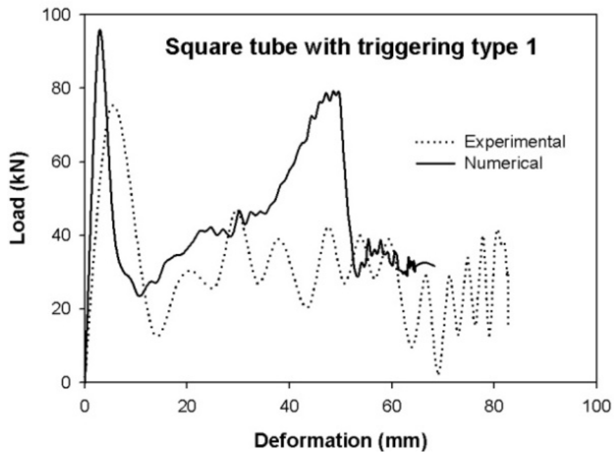

Figure 9: Comparison of load-deformation curves of square tube with triggering type1.

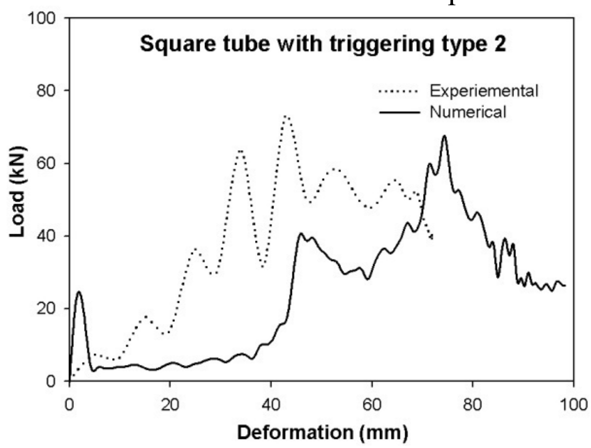

Figure 10: Comparison of load-deformation curves of square tube with triggering type2.

4. CONCLUSIONS

This paper proved the importance of considering multiple delaminations to predict the correct energy absorption of the brittle composite tubes. In order to study this effect in detail, a comprehensive numerical simulation was conducted for both circular and square cross sectional pultruded profiles made of glass-polyester with two triggering mechanisms. The effect of multiple delaminations on the peak crushing load, deformation length and the corresponding energy absorption was proved by comparison with experimental data. Furthermore, this paper demonstrated the correct modelling triggering geometry especially the triggering type 1 (45°edge chamfering). Both the above facts were proved with multiple layers of shell elements and cohesive elements and pre-defined seams. This approach provided a very good correlation of deformation patterns of pultruded circular and square glass polyester composite tubes. The corresponding energy absorption values are also close to the experimental values.

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