DISCRETE FE MODELING TO SIMULATE MICRO-FRACTURE MODES IN PROGRESSIVE CRUSHING OF FIBER REINFORCED COMPOSITE TUBES

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Abstract
Progressive crushing failure in which a stable zone of micro-fracture, such as fiber breakage, fiber kinking, and matrix cracking, propagates down is generally preferred for better energy absorption in fiber reinforced composite tubes subjected to axial compression. There are two extremes of crushing modes, splaying and fragmentation. The crushing mode largely determines the reaction force and the energy absorption. In many finite element (FE) models for the fracture simulation of composites, the continuum damage mechanics (CDM) model is introduced and largely deformed or distorted elements are deleted to represent material failure. However, this approach cannot properly account for the effect of load transmission after the fracture due to the contact of debris during the progressive crushing. In this study, we propose a discrete FE modeling scheme where cohesive zone elements (CZEs) are inserted at all possible crack locations (i.e., axial splitting, transverse shearing, and circumferential delamination). Since there is no loss of mass due to element deletion, it is possible to accurately simulate the effect of load transmission. Numerical studies with different laminate configurations reveal that the proposed model can capture the crushing mode in different circumstances.

1. Introduction

Crash simulation is especially important in automotive design because of the strict regulations which specify passive safety requirements. The numerical prediction of axial crush deformation of a composite structure is of great interest with increasing applications of advanced materials in car design. Stable progressive crushing processes at crush zones are often observed in fiber reinforced composite tubes subjected to axial compression. They are classified into two major modes: splaying and fragmentation [1, 2]. These modes significantly influence the reaction force the composite tube can bear during the crushing process. The real crush mode of a composite tube, either one of or a combination of these two modes, depends on tube geometry, laminate configuration, material properties and other variables.

Therefore, a numerical model which can predict the progressive crushing process is valuable for designing composite products. Even though the continuum damage mechanics (CDM) [3] model is introduced in many finite element (FE) models for the fracture simulation of composites [4-11], this approach is not appropriate to represent the crushing mode of a composite tube. To represent material failure, FE models delete largely deformed or distorted elements. However these deleted materials, which are debris in real cases, play an important role in transferring contact force to the undamaged structure. Some recent advanced approaches, such as the extended finite element method (XFEM) [12], the phantom node method (PNM) [13] and the floating node method (FNM) [14], can express cracks more explicitly, but are still difficult to use for designing composite products because of their high computational cost.

To overcome this dilemma, this paper proposes a discrete FE modeling approach which can capture the micro-fracture process in a composite that is the crucial feature leading to the ultimate crushing mode. This approach simulates the anisotropic material behavior before the maximum stress with conventional solid elements. Meanwhile, cohesive zone elements (CZEs) are initially inserted at all possible crack locations. Since there is no loss of mass due to element deletion, it is possible to accurately reproduce the effect of load transmission after the fracture due to the contact of debris. Numerical studies with different laminate configurations reveal that the proposed model can capture the crushing mode in different circumstances with practical computational cost and the simulated results are in good agreement with the experimental results reported in the literature [1].

2. Typical Failure Modes in Progressive Crushing

A crush zone progresses in a steady form during the crushing in fiber reinforced composite tubes when subjected to axial compression (Fig. 1 (a)). Hull [1] and Farley [2] classified the progressive failure mode into two extremes of crushing modes based on crushing morphology. These are called splaying (Fig. 1 (b)) and fragmentation (Fig. 1 (c)). During progressive crushing deformation of composites, complex failure phenomena such as fiber breakage, fiber kinking, and matrix cracking are observed at crush zones. Failure may also involve inter-laminar delamination in Mode I and Mode II. These micro-fracture events at crush zones determine whether the resulting crushing mode is splaying mode, fragmentation mode, or a combination of these modes.

In the splaying crushing (Fig. 1 (b)), the composite laminate axially splits and circumferentially delaminates. The delamination is located at nearly half the thickness of the laminate. In both sides of this delamination, the lamina bundles exhibit significant bending deformation, while the main delamination progresses in an opening mode, Mode I. In this mode, broken and compressed pieces of material, which are the result of material kinking, buckling and cracking, form a debris wedge. According to the authors' previous numerical study [11], the debris formation, which means not only the size, but also the location, can decide successive damage progression and deformation mode of the material which directly relates to the capability of energy absorption of the structure. Therefore, reproducing the effects caused by the debris wedge is important for numerical simulations.

The fragmentation crushing mode (Fig. 1 (c)) is characterized by a wedge shaped laminate cross section with transverse shearing. The lengths of the circumferential delamination and axial splitting are typically less than the thickness of the laminate in this mode.

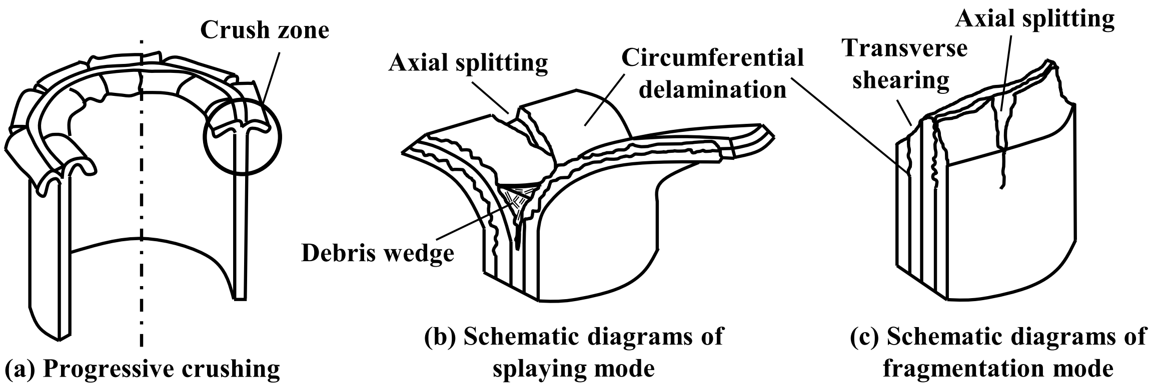

Figure 1. Progressive crushing in composite tube [2, 4].

Comparison of the splaying and fragmentation modes indicates that the competition between different micro-fracture mechanisms at a crush zone determines the eventual crush mode. In order to predict the progressive crushing mode at each crush zone and the energy absorption of the composite structure, it is necessary to accurately simulate the micro-fracture phenomena.

3. Numerical Method

This section discusses a scheme for discrete FE modeling which can capture the micro-fracture process in composites, which is the crucial feature leading to the ultimate crushing mode. The modeling schematic is shown in Fig. 2. In the proposed model, CZEs with zero thickness are pre-inserted into solid elements at all the positions where cracks are expected to occur (Fig. 2 (a)). These CZEs represent axial splitting, transverse shearing, and circumferential delamination during the progressive crushing as mentioned in Section 2.

In this approach, the surfaces of conventional solid elements are tied by CZEs. The relative displacement between the surfaces is negligibly small compared to the deformation of the solid up to the maximum stress because the stiffness of the CZE is large enough compared to the Young's modulus (physical elastic properties) of the solid element. Once the stress state reaches the failure criterion defined as the maximum traction in CZEs, the cohesive separation starts to increase and stress drops linearly from the peak stress to zero. In this study, the material behaviors, except for longitudinal shear deformation, are treated as linear (Fig. 2 (b)). The energy absorbed is equal to the damage variables of the CZEs driven by fracture toughness. To account for the characteristic non-linear longitudinal shear behavior of unidirectional fiber reinforced composites, a 1D elasto-plastic formulation is introduced to the solid elements (Fig. 2 (c)).

Since the contact for the surface of the solid which is tied to the CZE becomes active after the failure of the CZE, it is possible to accurately reproduce the effect of load transmission by contact of the debris.

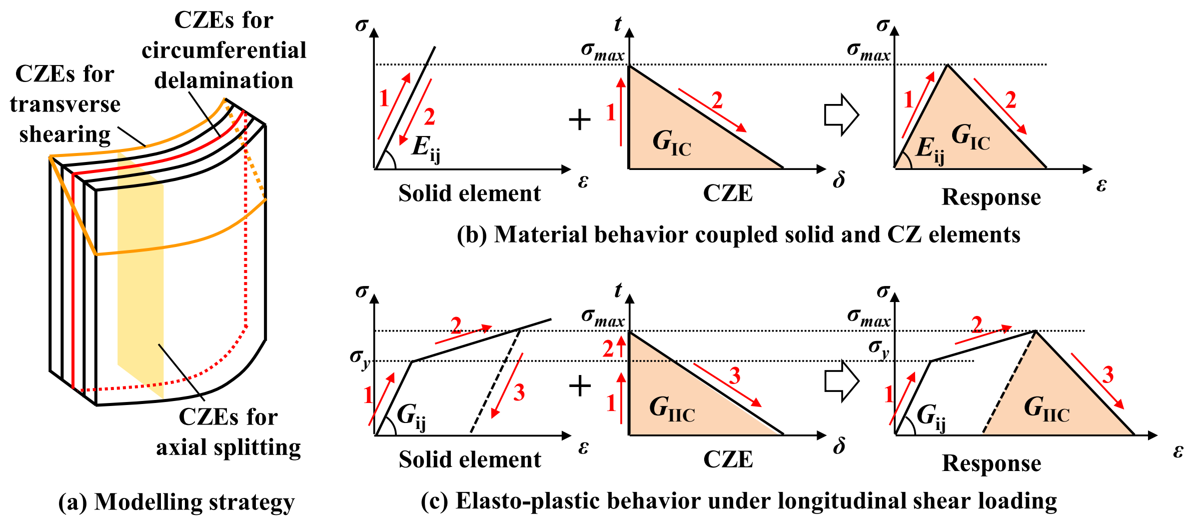

Figure 2. Schematic of proposed model.

4. Numerical Case Study

This section presents an axial crushing simulation by the commercial finite element code LS-DYNA [15].

4.1. Model Setup for Crushing Simulation

The material properties of the unidirectional (UD) tape of CFRP (T700S/2592, Toray) used in this study are listed in Table 1 [8, 16].

Table 1. Material properties of T700S/2592 for solid elements [8, 16].

Elastic properties [16]	
Longitudinal Young's modulus E_{11}	135 GPa
Transverse Young's modulus E_{22}, E_{33}	8.5 GPa
Longitudinal shear modulus G_{12}, G_{31}	4.8 GPa
Transverse shear modulus G_{23}	2.7 GPa
Longitudinal Poisson's ratio v_{12}, v_{13}	0.34
Transverse Poisson's ratio v_{23}	0.49
Longitudinal shear elasto-plastic properties [8]	
Yield stress σ_y	95 MPa
Tangent modulus for plasticity E_t	90 MPa

The geometry of a chamfered cylindrical CFRP tube is referred to in the literature [1]. The diameter of the tube is 50 mm and the wall thickness is 1.95 mm. Three tubes with different hoop (90°) to axial (0°) ratios (H:A), 3:1, 7:5 and 1:3, are simulated as shown in Fig. 3. All tubes have a 30° outside chamfer. Using these configurations, it is possible to investigate the effects relating to H:A. In order to reduce the size of the model and save computational cost, only a 1/48th section of the tube, 12mm in height from the top, is modeled. Bottom nodes of the tube are fixed in all directions, and appropriate cylindrical symmetry conditions are applied. The mesh size is about 0.08 mm. A rigid platen is placed on top of the tube and moves down quasi-statically, considering contact with the tube.

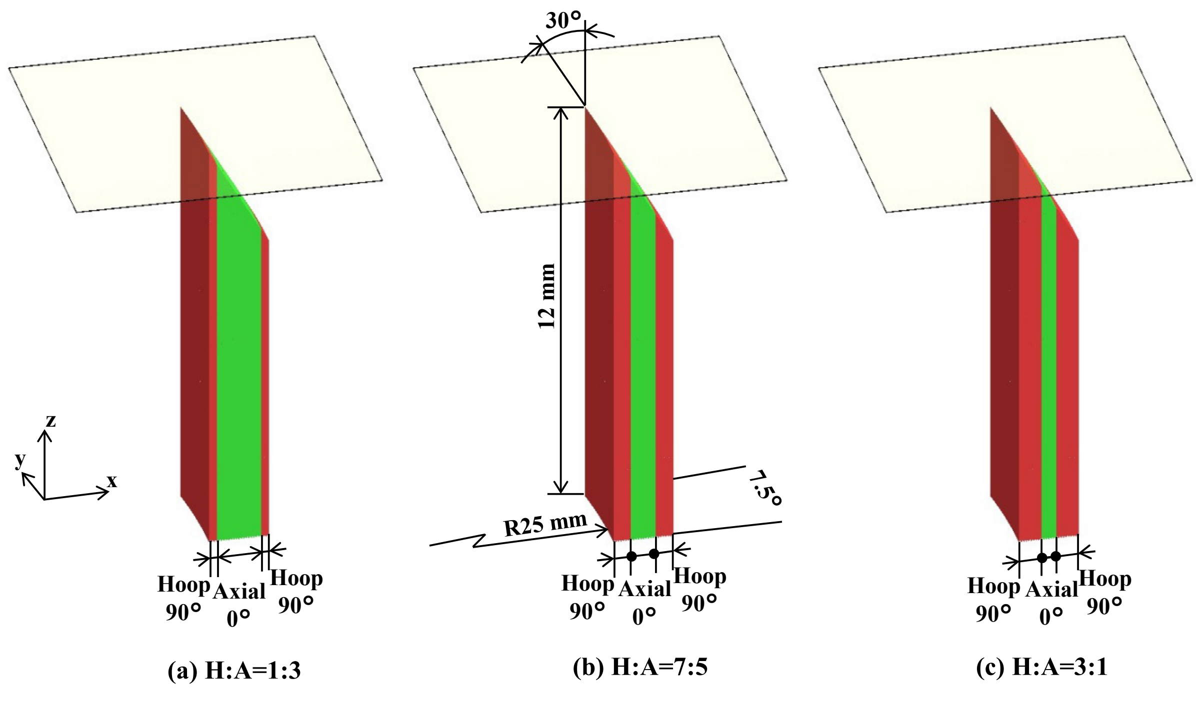

Figure 3. Crushing simulation model for different lay-up configuration.

CZEs are pre-inserted into each of the 0° and 90° layers, for expressing transverse shearing and axial splitting within lamina, and between each layer for circumferential delamination. Because the transverse shearing is often observed at 30° in the experiments [1], CZEs for this fracture are inserted at 30° to the axis of the tube. The patterns of these CZEs are summarized in Fig 4.

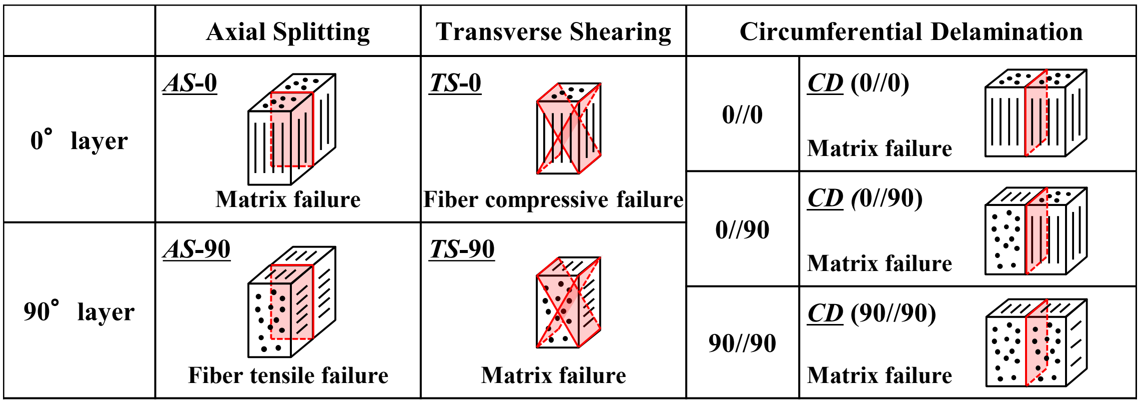

Figure 4. CZEs for representing cracks during progressive crushing.

Table 2. Material parameters of T700S/2592 in CZEs [16-18].

	Matrix failure ***AS*-0, *TS*-90, *CD***	Fiber tensile failure ***AS*-90**	Fiber compressive failure ***TS*-00**
Elastic stiffness			
Normal stiffness E_N [N/mm^3]	1.0e+6	1.0e+8	1.0e+8
Tangential stiffness E_T [N/mm^3]	1.0e+6	1.0e+8	1.0e+8
Mode I			
Maximum traction σ_{Imax} [MPa]	69 [16]	2550 [16]	1.0e+5 (not fail)
Fracture toughness G_{IC} [N/mm]	0.277 [18]	60 [17]	1.0e+3 (not fail)
Mode II			
Maximum traction σ_{IImax} [MPa]	100 [16]	1.0e+5 (not fail)	1273 *
Fracture toughness G_{IIC} [N/mm]	0.788 [18]	1.0e+3 (not fail)	0.75 (adjusted)

* estimated from fiber compressive strength, 1470 MPa [16]

The properties including elastic stiffness, strength and fracture toughness of each CZE used in this study are listed in Table 2 [16-18]. The high values of elastic stiffness are necessary to not affect material behavior as mentioned in Section 3. The values for the stiffness of CZE are 1.0e+6 N/mm^3 and 1.0e+8 N/mm^3 in fiber and matrix directions respectively. The fracture toughness of CZEs to express the transverse shearing in the 0° layer (*TS-0*) was adjusted by numerical trial and error.

4.2. Simulation Results and Discussion

Fig. 5 shows the simulated result with H:A=1:3. The development of a splaying mode crush zone can be observed. The first stage of crushing involves shear failure in the 90° layer due to the compression (Fig. 5 (a)). The movement inward also induces the fiber kinking and buckling in the 0° layer (Fig. 5 (b)). A wedge of crushed material develops at the platen and cracks form in the middle of the 0° layers (Fig. 5 (c)). Eventually the wedge of crushed material pushes the axial material to the inside and outside of the tube and forms the splaying mode (Fig. 5 (d)).

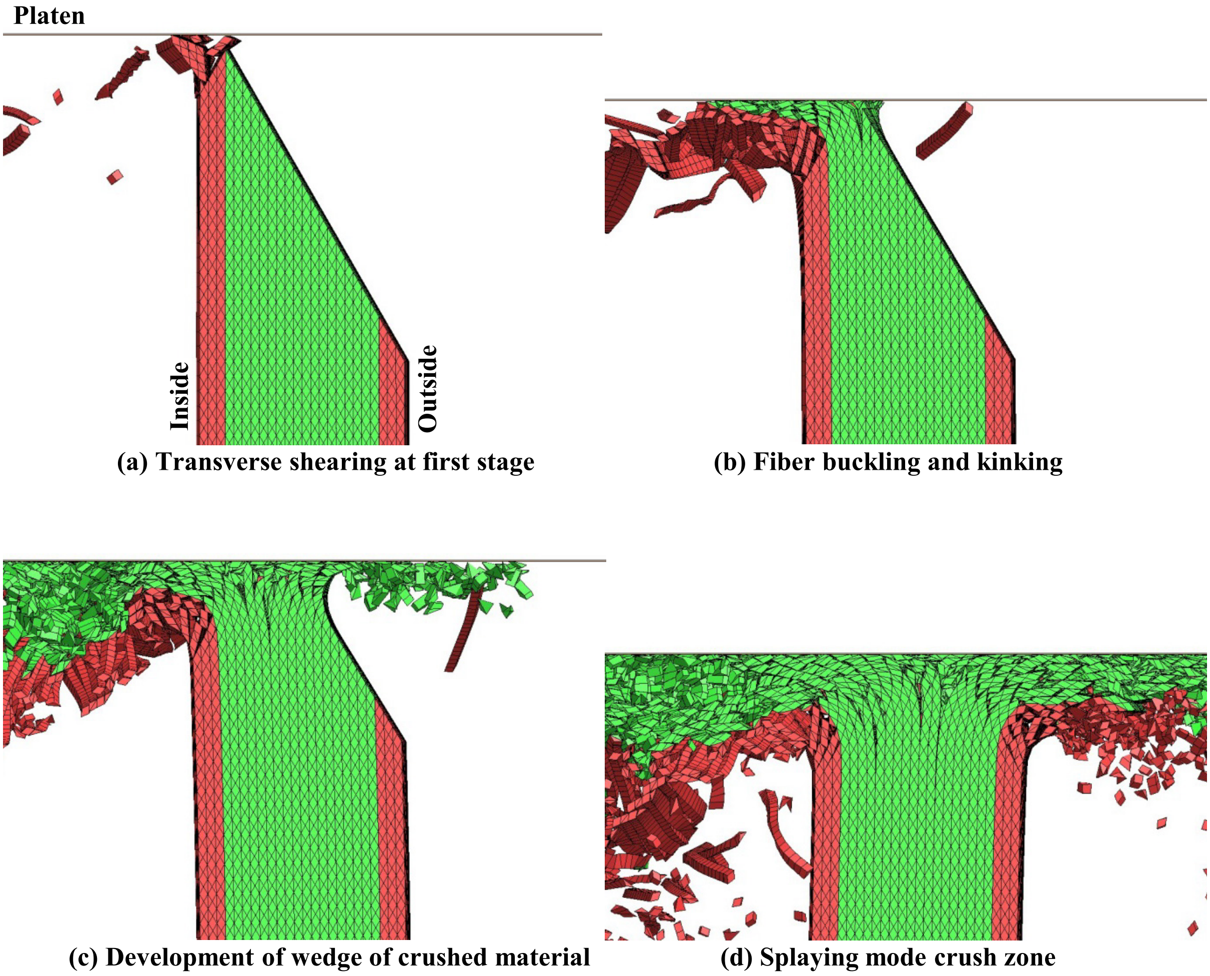

Figure 5. Simulated formation process of a splaying mode crush zone with H:A=1:3.

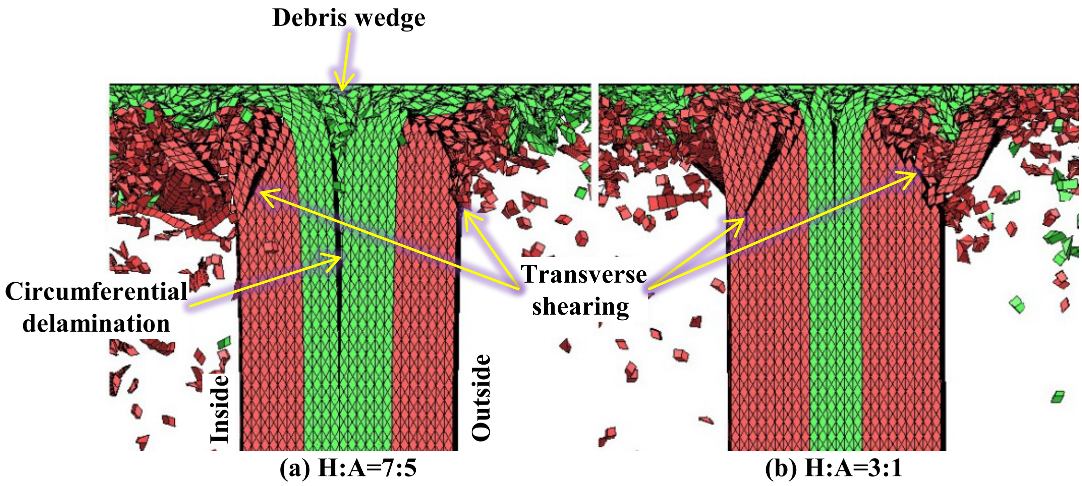

Figure 6. Comparison of simulated crushing modes for different lay-up configuration.

The comparison of the simulated results of the three different lay-ups is shown in Fig. 6. The tube with H:A=3:1 (Fig. 6 (b)) fractures into segments of varying sizes which fall away from the tube and crushes by a mode close to fragmentation described in Section 2. For the tube with H:A=7:5 (Fig. 6 (a)), the combination of splaying and fragmentation modes can be observed. Hull [1] also reported experimental results where the progressive crushing mode had changed from splaying mode to fragmentation mode as the ratio of the hoop layer increases. Calculations were done by MPP LS-DYNA with 128 cores on Intel Xeon Processor CPU E5-2640, 2.40GHz. Computing times were 19-21 hours.

Finally, the simulated energy absorptions for different H:A by the proposed model are compared to the experimental measured values from the referred literature [1]. The specific energy absorption (*SEA* or specific crushing stress (SCS_{mean})) is often selected to evaluate the energy absorption capability of composite tubes. Specific crushing stress (SCS) is defined as mean crushing load (P_{mean}) divided by the product of specimen density (ρ) and the cross-sectional area (A) of the tube. *SEA* is calculated by:

$$SEA = \frac{E_{total}}{M_c} = \frac{\int_0^{L_c} Pds}{\rho A L_c} = \frac{\int_0^{L_c} SCSds}{L_c} = SCS_{mean} = \frac{P_{mean}}{\rho A} \quad (1)$$

where E_{total}, M_c, L_c are the total energy absorbed during crush, the mass of the crushed material, and the final crushing length, respectively. *SEA*s from the simulated results and the literature are summarized in Table 3. P_{mean} in the simulation is extracted from the rigid impactor's reaction force in the stroke after the chamfered areas. Because the *SEA*s in the literature are from experiments using tubes of a different type of material, Grafil XAS surface-treated carbon fiber and Ciba-Geigy BSL 914 epoxy, the simulated *SEA* values are approximately 1.5 times larger than those in the literature. However, the tendency of *SEA*s to change when changing H:A ratio can be well reproduced.

Table 3. SEA of simulations and experiments [1] with different laminate configurations.

H:A ratio	Specific Energy Absorption (SEA) $(kN/mm^2)/(kg\ m^3)$	
	Simulation	Experiment [1]
1:3	169	109
7:5	107	65 *
3:1	82	54

* SEA referred from [1] is with H:A=7:4.7

5. Conclusions

This study proposed a discrete FE model that coupled solid elements and CZEs to predict the micro-fracture phenomena at crush zone, ultimate crushing mode and energy absorption under the axial progressive crushing of fiber reinforced composite tubes. In order to demonstrate the capability of the proposed simulation scheme, axial crushing simulations of composite tubes with varying H:A were performed. FE simulations performed show that the proposed model can capture the crushing mode in different circumstances with practical computational cost and the simulated results are in good agreement with the experimental results reported in the literature [1]. For future study, comparison to the experimental fracture modes and the reaction forces and also the possibility to apply some advanced approaches such as peridynamics [19] will be investigated.

References

[1] D. Hull. A unified approach to progressive crushing of fibre-reinforced composite tubes. *Composites Science and Technology*, 40:377-421, 1991.

[2] G.L. Farley. and R.M. Jones, Crushing Characteristics of Continuous Fiber-Reinforced Composite Tubes. *Journal of Composite Materials*, 26:37-50, 1992.
[3] J. Lemaitre and R. Desmorat. *Engineering damage mechanics: ductile, creep, fatigue and brittle failures*. Springer Science & Business Media, 2005.
[4] S.T. Pinho, P.P. Camanho and M.F. de Moura. Numerical Simulation of the Crushing Process of Composite Materials. *International Journal of Crashworthiness*, 9:263-276, 2004.
[5] J. Huang and X. Wang. Numerical and experimental investigations on the axial crushing response of composite tubes. *Composite Structures*, 91: 222–228, 2009.
[6] C. McGregor, R. Vaziri and X. Xiao. Finite element modelling of the progressive crushing of braided composite tubes under axial impact. *International Journal of Impact Engineering*, 37: 662-672, 2010.
[7] P. Feraboli, B. Wade, F. Deleo, M. Rassaian, M. Higgins and A. Byar. LS-DYNA MAT54 modeling of the axial crushing of a composite tape sinusoidal specimen. *Composites Part A: Applied Science and Manufacturing*, 42:1809-1825, 2011.
[8] L.N.S. Chiu, B.G. Falzon, B. Chen and W. Yan. Validation of a 3D damage model for predicting the response of composite structures under crushing loads. *Composite Structures*, 147:65–73, 2016.
[9] W. Tan and B.G. Falzon. Modelling the crush behaviour of thermoplastic composites. *Composites Science and Technology*, 134:57-71, 2016.
[10] C. Reuter, K.H. Sauerland and T. Tröster. Experimental and numerical crushing analysis of circular CFRP tubes under axial impact loading. *Composite Structures*, 174:33-44, 2017.
[11] K. Saito and M. Nishi. FE modelling to simulate the axial crushing behavior of CFRP composites. *Proceedings of the 21th International Conference on Composite Materials ICCM-21, Xi'an, China,* August 20-25 2017.
[12] N. Moës, J. Dolbow, and T. Belytschko. A finite element method for crack growth without remeshing. *International journal for numerical methods in engineering*, 46(1), 131-150, 1999.
[13] J.H. Song, P. Areias, and T. Belytschko. A method for dynamic crack and shear band propagation with phantom nodes. *International Journal for Numerical Methods in Engineering*, *67*(6), 868-893, 2006.
[14] B.Y. Chen, S.T. Pinho, N.V. De Carvalho, P.M. Baiz, and T.E. Tay. A floating node method for the modelling of discontinuities in composites. *Engineering Fracture Mechanics*, *127*, 104-134, 2014.
[15] J.O. Hallquist. *LS-DYNA Theory Manual*. Livermore Software Technology Corporation, 2006.
[16] T. Nadabe, M. Nishikawa, S. Minakuchi, T. Nakamura, J.T. Siivola and N. Takeda. Numerical analysis for damage detection in CFRP bolted joints using strain. *Journal of the Japan Society for Composite Materials*, 38:22-29, 2012.
[17] R. Higuchi, T. Okabe, A. Yoshimura and T.E. Tay. Progressive failure under high-velocity impact on composite laminates: Experiment and phenomenological mesomodeling. *Engineering Fracture Mechanics*, 178: 346–361, 2017.
[18] P.P. Camanho, P. Maimí and C.G. Dávila. Prediction of size effects in notched laminates using continuum damage mechanics. *Composites Science and Technology,* 67:2715-2727, 2007.
[19] E. Madenci and E. Oterkus. *Peridynamic theory and its applications*. Springer Science & Business Media, 2014.