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Numerical Modelling Strategies for Composite Structures Crashworthiness: A Review

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ABSTRACT

The crashworthiness test programs used to validate the design variants through experimental works has caused the design costs increase drastically. In the meantime, the growth in computer performance resources and new explicit finite element codes has given the opportunity to use such tools to address the design issue and the crashworthiness problem by developing numerical modelling to minimize the experimental tests costs. As a result, extensive crushing simulations for composite structures had been conducted and reported in the open literature. In this paper, it distinguished the state of the art in composite crashworthiness numerical modelling studies. Different approaches and methodologies such as modelling scales, failure modelling and architecture of crushing simulation have been studied where these factors could affected the outcomes of the simulations result for the crash analysis significantly.

Keywords:
Crashworthiness, composite, modelling, crushing, finite element method

1. Introduction

Parallel to the development in the experimental works, numerical simulation has been proposed to model the composite crushing as a part of the design process for the development of crashworthy components. In fact, the interest in the recent studies of composite crashworthiness [1-6] has focused more on the simulation of the crushing behaviour using finite element analysis as a solution to substitute the expensive experimental programs [7]. Different approaches and methodologies have been introduced to improve the numerical modelling of composite crashworthiness with varying degrees of success. The extensive development of numerical models is motivated by the advances in computer resources and finite element software. Nevertheless, the composite crashworthiness modelling is particularly complex to develop compared to other composite modelling problems, such as impact. The damage mechanisms involved are the same

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(delamination, fibre rupture etc.) but it needs to be modelled till the complete rupture (or crushing of all the material) that is the real big difference, and what leads to more complexity.

Literary wise, the numerical modelling of composite crashworthiness was initiated in 1989 by Farley and Jones [8] concerning the prediction of the crushing response of circular composite tubes. The developed model was a quasi-static numerical model and it was based on a virtual crack extension technique as the main feature of the model was the ply separation. Their model was able to simulate the failure modes observed in the experiment with ply separation but the laminate crushing stress was not well-predicted. Since then, many efforts have been made by researchers to improve the numerical modelling of composite crashworthiness in various aspects such as the choice of constitutive models [2,9], delamination techniques [7,9] and triggering mechanisms [1,10] in order to properly predict the crushing morphologies, specific energy absorption (SEA) and force-displacement curve, as observed in the experimental works.

To adequately describe the crushing morphology in the numerical simulation which involves large deformation and non-linear behaviour, the use of non-linear analyses via an explicit code seems to be more appropriate in describing the initiation and progression of a crushing mode failure [3,7,11]. Besides the integration scheme, the development of composite crashworthiness simulations is also depends on the choice of modelling scales, damage models and the architecture of the crash modelling. Nevertheless, these factors have not been discussed and reviewed comprehensively in the open literature. Therefore, an extensive review on these factors will be presented in this paper.

2. Modelling Scale

Crushing phenomenon in composite structures mostly involves failure modes that different to those observed in the conventional metallic structures such as fibre fracture, intra- and inter-laminar matrix cracking, fibre–matrix debonding, delamination and debris accumulation which take place at different length of scales [8,12]. Therefore, it is necessary to define a scale on which the material could be described properly without going into excessive details. Three main modelling scales classically classified are macro-, micro- and meso-scale.

2.1 Macro-scale (structure scale)

Some of the models developed in the past [2,4-6] were based on global test characterizations that take place at macro-scale (structure scale) making the model strongly dependent on the global laminate behaviour, as an example in Figure 1a [13]. Even though this methodology makes modelling simpler and reduces the computational time, any precise failure modes or interface damages, for example delamination cannot be well predicted. Moreover, the SEA and the mean force cannot also be predicted as the inputs are usually come from the tests on the global structures and not from elementary mechanical characteristic. Normally, the macro-scale is used for larger scale structure as the main motivation of the modelling is to predict the energy absorption capability with roughly prediction on the global damage of structure in the crushing zone. Therefore, this scale is more favourable for the structure-level modelling.

2.2 Micro-scale (fibre scale)

Concerning the models using micro-scale approach, physical representation of such a complex phenomenon is difficult. Even if it is possible, detailed physical parameters and internal variables concerning each kind of damage involved [14] are required which are very difficult to obtain. The modelling motivation is concerns more on the comprehensive study of the physical mechanism at fibre or matrix level such as fibre-matrix debonding [15] and fibre friction effect [16] rather than designing a composite part or structure as an example in Figure 1b. Furthermore, it requires high computational time that would restrain the study cases only to the small structures.

2.3 Meso-scale (ply scale)

Between macro- and micro-scale, the meso-scale (ply-scale) approach that commonly used in the composite modelling [17-19] seems to be the most appropriate one. This is an intermediate scale between the micro-and macro-scale associated with the thickness of the layer and the different inter-laminar interfaces [18]. Although it requires more detailed laws as compared to macro-scale models, it has the potential to capture most of the physical phenomena that present at the crushing front [20-22]. An illustration of a meso-scale model is shown in Figure 1(c) [20].

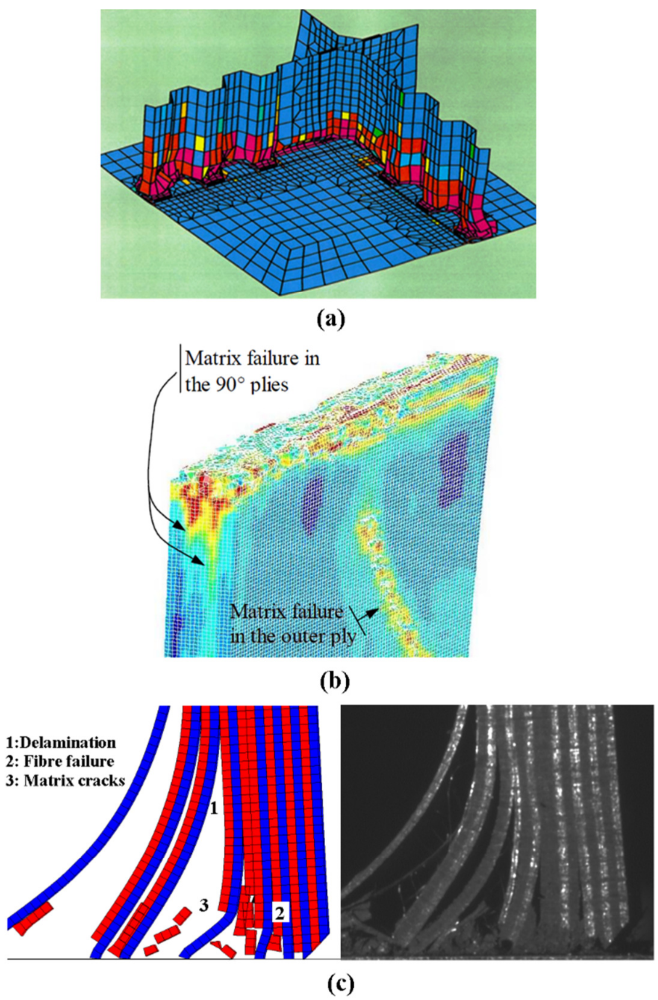

Fig. 1. Examples of crushing modelling (a) macro-scale: Dynamic-crash simulation on corrugated sub-floor box [13], (b) micro-scale: Quasi-static crushing of composite column with (45/0/90/45)s [29] and (c) meso-scale: Plate crushing of (0/90) laminate [20]

3. Failure Modelling

Failure criteria are used to represent the sudden failure of the ply or to introduce a progressive failure through the damage evolution. Various approaches have been used in the open literature to predict the damage mechanisms. Most of the failure models used in crushing modelling are based on conventional failure criteria (Tsai-wu [23], Hashin [24], Chang-chang [25] and Matzenmiller [26]) with varying degrees of success in simulating the crushing behaviours of composite structures. In general, most of them are strength-based failure criteria and have been proposed since 1971 [23] with the aim to accurately predict the onset of the composite material damages. Recent works in composite crashworthiness modelling have focused less on the role of delamination and put more attention on improving the intra-laminar failures [4,6]. Nevertheless, there are also several researchers that recognized the importance of delamination in simulating the crash behaviour and keep enhancing the modelling of delamination [7,9,27]. The review of failure modelling is classified into two categories, intra-laminar failure and delamination modelling.

3.1 Intra-laminar Failure
3.1.1 Damage initiation prediction

Predicting the intra-laminar failures of composite is complex as it involves fibre failure and matrix cracking either under tension, compression, shear or combination of these loads. For the damage initiation or sudden failure of the ply, there are two types of failure models reported in the literature called non-physically [23] and physically-based failure criteria [28-29].

3.1.1.1 Non physically-based failure criterion

A non-physically based failure criteria is defined as a dependent function of all components of the stress tensor from which it determines the global state of the material. It is relatively simple to use but it does not specifically consider the failure modes observed in composite materials or non-phenomenological. For example, the Tsai-Wu criterion [23] used quadratic stress-based equation to predict the global failure of composite as expressed in Eq. (1) for three dimensions case.

$$\begin{aligned}&\frac{\sigma_{11}^2}{X_T X_C}+\frac{\sigma_{22}^2+\sigma_{33}^2}{Y_T Y_C}+\frac{\left(\sigma_{12}^2+\sigma_{13}^2+\sigma_{23}^2\right)}{{S_L}^2}-\frac{\left(\sigma_{11}\sigma_{22}+\sigma_{11}\sigma_{22}\right)}{\sqrt{X_T X_C Y_T Y_C}}-\frac{\sigma_{22}\sigma_{33}}{Y_T Y_C}\\&+\sigma_{11}\left(\frac{1}{X_T}-\frac{1}{X_C}\right)+\left(\sigma_{22}+\sigma_{33}\right)\left(\frac{1}{Y_T}-\frac{1}{Y_C}\right)\geq 1\end{aligned} \tag{1}$$

with X_T and X_C: longitudinal tensile and compressive strength
Y_T and Y_C: transverse tensile and compressive strength
S_L: longitudinal shear strength
σ_{ij}: stress tensor

3.1.1.2 Physically-based failure criterion

Physically-based failure criteria on the other hand distinguish between failure modes, aiming at describing the physics of the failure process. The maximum stress and maximum strain criteria can be considered the simplest physically-based failure criterion that have been used not only in crashworthiness modelling [28] but also in impact modelling [30] for predicting the fibre tensile failure.

$$\sigma_l \leq X_T \quad / \quad \varepsilon_l \leq \varepsilon_l^0 \tag{2}$$

with: σ_l: current longitudinal stress

ε_l: current longitudinal strain

ε_l^0: tensile failure strain in fibre direction

Among the physical based failure criteria exist in the literature are Hashin failure criteria [24]. It has been widely used to predict the failures in composite laminate [5,10,21] as this criteria able to distinguish the damage initiation in various failure modes at each constituent (fibre and matrix) separately. This criterion used quadratic interaction equation to propose four failure modes that are separately considered between tension and compression failures:

Tensile fibre failure

$$\left(\frac{\sigma_{11}}{X_T}\right)^2 + \frac{\left(\sigma_{12}{}^2 + \sigma_{13}{}^2\right)}{S_L{}^2} \geq 1 \tag{3}$$

Compressive fibre failure:

$$\frac{\sigma_{11}^2}{X_C^2} \geq 1 \tag{4}$$

Tensile matrix failure

$$\frac{1}{Y_T{}^2}(\sigma_{22} + \sigma_{33}) + \frac{1}{S_T{}^2}(\sigma_{23}{}^2 - \sigma_{22}\sigma_{33}) + \frac{\left(\sigma_{12}{}^2 + \sigma_{13}{}^2\right)}{S_L{}^2} \geq 1 \tag{5}$$

Compressive matrix failure

$$\frac{1}{Y_C}\left[\left(\frac{Y_C}{2S_T}\right)^2 - 1\right](\sigma_{22} + \sigma_{33}) + \frac{1}{4S_T{}^2}(\sigma_{22} + \sigma_{33})^2 + \frac{1}{S_T{}^2}(\sigma_{23}{}^2 - \sigma_{22}\sigma_{33}) + \frac{\left(\sigma_{12}{}^2 + \sigma_{13}{}^2\right)}{S_L{}^2} \geq 1 \tag{6}$$

with: S_T: transverse shear strength and the rests are the same notations as for Tsai-Wu criterion in Eq. (1).

Nevertheless, some studies have reported that the stress interactions in this failure model does not always fit the experimental results, especially in the case of compressive failure of fibre or matrix [28,31]. Furthermore, it does not consider the effects of in-plane shear in the compressive fibre failure that reduces significantly the effective compressive strength of a ply [31].

Besides Hashin failure criterion, several other failure models have been proposed in the literature for general prediction of the failures in composite laminate. Chang–Chang failure criterion [25] for example has been proposed in 1987 that was a modified version of the Hashin failure criterion [24] which includes the non-linear shear stress-strain behaviour in the tensile fibre mode equation. This failure model has been established in LS-DYNA commercial code and has been used in many composite crashworthiness modelling studies [9, 32-33].

In general, as reported in World Wide Failure Exercise [31] most of these conventional damage models were unable to capture some failures with regard to compressive loading on the fibre and matrix which is important in the crashworthiness modelling. For example, the simulation of the fibre and matrix under compressive crushing mode. Based on this report, various efforts have been made by several researchers to enhance the existing failure criteria. Among them are Dàvila and Camanho [31], and Pinho [28-29] who have proposed failure criteria for matrix and fibre compression based on Mohr-Coulomb criterion (Eq.(7)) presented in [31] and Eq.(8) presented in [28-29]. The idea of their works was to take into account the interaction between the stresses and the angle of the fracture plane that was found oriented at 0° and 53°±2° (Figure 2a). Furthermore, they have also proposed the formulation of fibre kinking in compression (Figure 2b) based on a micro-mechanical model and coupled with the failure criterion matrix.

$$\left(\frac{\langle|\tau_T| + \mu_T\sigma_n\rangle}{S_T}\right)^2 + \left(\frac{\langle|\tau_T| + \mu_L\sigma_n\rangle}{S_L}\right) \geq 1 \tag{7}$$

$$\left(\frac{\tau_T}{S_T - \mu_T\sigma_n}\right)^2 + \left(\frac{\tau_L}{S_L - \mu_L\sigma_n}\right)^2 \geq 1 \tag{8}$$

with: τ_L and τ_T : longitudinal and transverse shear stresses acting on the fracture plane
μ_L and μ_T : internal material friction in longitudinal and transverse directions
S_L and S_T: longitudinal and transverse shear strengths
σ_n : Stress normal to the fracture plane

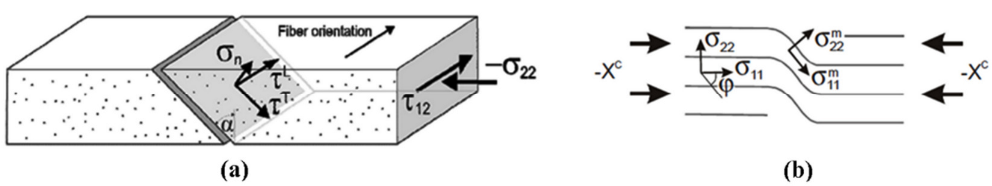

Fig. 2. (a) Angle of fracture plane of a UD lamina subjected to transverse compression and in-plane shear (b) Fibre kinking in UD lamina subjected to longitudinal compression [31]

3.1.2 Damage evolution prediction

Some of the numerical models in the literature were only consider the damage initiation by using one of the failure criteria explained before to account the failure mechanisms at crush front. Once failure is detected, the relevant elastic properties are reduced to zero over a fixed number of time steps. This approach is unrealistic as the post-failure behaviour is completely disregarded as reported in [28-29]. In order to model the damage propagation, damage variables are defined to degrade linearly the relevant stress components (which could be either normal or shear) to zero as indicated in Figure 3a. The positive slope of the stress-displacement curve prior to damage initiation corresponds to linear elastic material behaviour while the negative slope after damage initiation is achieved by evolution of the respective damage variables according to the damage evolution of different failure modes [34-36]. The onset equivalent displacement, δ^{o}_{eq} refers to the corresponding relative displacement at damage initiation, while the final equivalent displacement, δ^{f}_{eq} indicates the relative displacement where the material point is not able to further carry any loads. In addition, as shown at point B in Figure 3a, it is assumed that unloading after damage initiation brings the material point back to the origin, and the subsequent reloading will follow the same unloading curve. In general, final degradation of material is depending on the energy dissipated G^c which is corresponds to the area under the curve (0AC).

Nevertheless, in some studies of crashworthiness modelling [37-38] a constant crushing phase as example shown in Figure 3b has been added into damage evolution of fibre compression failure, particularly to have better representation of fragmentation crushing mode and force-displacement curve. Generally, the constant plateau is characterized from the laminate mean crushing stress, σ_c. Therefore, this type of damage model is dependent on the global behaviour of laminate which does not permit to have a predictive model.

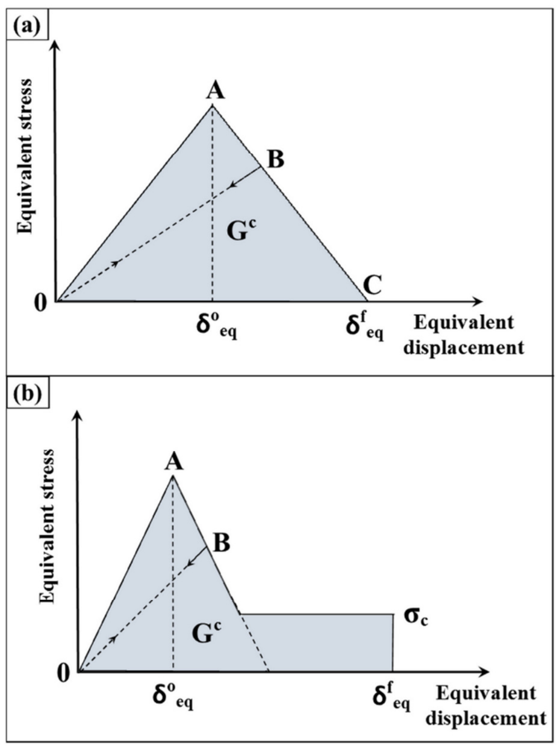

Fig. 3. Damage evolution (a) linear degradation after initiation [28, 34-35] (b) Additional constant crushing phase [35-37]

There are also failures models specifically innovated for the composite crashworthiness studies. In particular, continuum damage mechanics-based model for composite materials (CODAM) which initially proposed by William and Vaziri [39] to analyze tensile dominated failure. Then, it has been further developed by McGregor *et al.*, [38] to include compressive predictive capabilities in order to use in composite crushing of braided tubes [2,40]. It generally includes both damage initiation and evolution. This model has delivered better results than Matzenmiller failure criterion [26]. However, the compressive stress-strain response in this model depends on the estimated plateau stress (laminate mean crushing stress) measured in coupon specimens under compression. Thus, this stress is not an intrinsic parameter that makes it dependent on the global parameters of the coupon specimens. Moreover, this model is specifically proposed for the braided type composite. There is no study reported using CODAM criterion on other types of fibre architectures such as unidirectional (UD) and woven.

The coupling model between viscoplasticity and damage has also been introduced to improve the composite structure response when subjected to the high strain rate loadings such as impact and crushing [41]. This coupling is realized through the introduction of the effective shear stress which is stands for the stress that should be applied to the undamaged material to obtain the same state of deformation as the one obtained with shear stress on the damaged material. However, in the case of tube crushing simulation, the prediction of crushing response is focusing more on the brittle failure at the middle of the tube structure instead of the damage at the crushing front.

3.2 Delamination Modelling

Delamination response is also a complex behaviour to simulate. Several techniques and criteria have been introduced to improve the delamination behaviour during crushing. An absence of delamination model in composite crashworthiness modelling could cause the prediction of SEA and deformation pattern to be different from the experimental results [10]. An extensive review on delamination modelling for the composite crash application has been provided by Fleming [27]. In general, interface modelling technique (discrete model) has been widely used in predicting the delamination failure in composite crashworthiness modelling since early 1990's [42].

In the context of crash analysis, three methods of delamination modelling are reported in the literature, which are stress-based failure models, virtual crack closure technique (VCCT) and cohesive zone model (CZM). As reported in [27], the stress-based criterion is the easiest to implement by using the equation as follow

$$\left(\frac{\sigma_N}{\sigma_{Nc}}\right)^{a_n} + \left(\frac{\sigma_S}{\sigma_{Sc}}\right)^{a_s} \geq 1 \tag{9}$$

with: σ_N: normal stress acting on the interface surface
σ_S: shear stress acting on the interface surface
σ_{Nc}: normal failure stress
σ_{Sc}: shear failure stress
a_n/a_s: parameter governing the interaction between the failure modes

Normally, it is assigned with tiebreak contact interface that has been widely used in composite tubes crash modelling [2,33,40]. Nevertheless, the failure properties are hard to define and basically it can be obtained through experimental correlation. Furthermore, it is often reported that the results are likely to be mesh-dependent. Thus, a fracture mechanics based criterion is recommended which depends on the critical energy release rate such as virtual crack closure technique (VCCT) and cohesive zone model [27,42].

Virtual Crack Closure Technique (VCCT) is commonly used to calculate the strain energy release rates in the model and to predict delamination growth. This method is based on the assumption that the energy required for an infinitesimal amount of crack extension is equivalent to the work that would be required to close the crack to its original length [27]. Thus, the accuracy of this model is also strongly dependent on the mesh size and may require mesh refinement that are incompatible with a crash modelling. Wisnom [42] also reported that VCCT method may present limitation to the simulations which involve multiple failures and interact to each other. This limitation can be seen in the modelling of composite plate crushing done in [27].

The cohesive zone model (CZM) on the other hand has received more attention lately to be used to simulate the delamination failure in composite laminate. Pinho et al. [7] is one of the first authors that has demonstrated its potential application for crashworthiness modelling based on the procedures presented by Camanho *et al*. [43]. They simulated composite tubes crushing based on the experimental tests of Hamada et al. [44] with good correlations results were obtained. Following to this achievement, it has been widely used in composite crash modelling works as reported recently in [5,10,11,22,45].

Cohesive zone model controls the delamination at the interface based on bilinear traction-separation laws which considers the amount of energy required to create new fracture surfaces. This model usually works with cohesive elements that are placed between the different oriented plies to represent the interface and the thickness of these elements can be either infinitely thin or have a finite thickness. It also can be assigned with tie contact interface as reported in [5,11].

In general, the traction-separation law involves three states: a damage initiation, a damage evolution and a complete separation as shown in Figure 4. The damage initiation is referring to the starting of the degradation of the response in the material when the maximum traction either in opening (mode I) (Figure 4(a)) or shear modes (Figure 4(b)) is reached. For example, the corresponding onset separations are as follow [28]

$$\delta_I^0 = \frac{t_I^0}{k} \ , \ \delta_s^0 = \frac{t_s^0}{k} \tag{10}$$

with: t_I^0 : maximum allowable traction in mode I
t_n^0 : maximum allowable traction in shear mode
k : elasticity of the element

The damage then propagates until the traction reaches zero in which the energy absorbed is equal the critical energy release rate. This leads to the definition of the final separations as follow [28]

$$\delta_I^f = \frac{2G_{Ic}}{t_I^0} \ , \ \delta_s^f = \frac{2G_{Sc}}{t_s^0} \tag{11}$$

with: G_{Ic}: mode I fracture toughness
G_{Sc}: shear mode fracture toughness

From Figure 4, it could also be noticed that the opening mode considers only the positive traction, while the shear mode takes into account both positive and negative tractions.

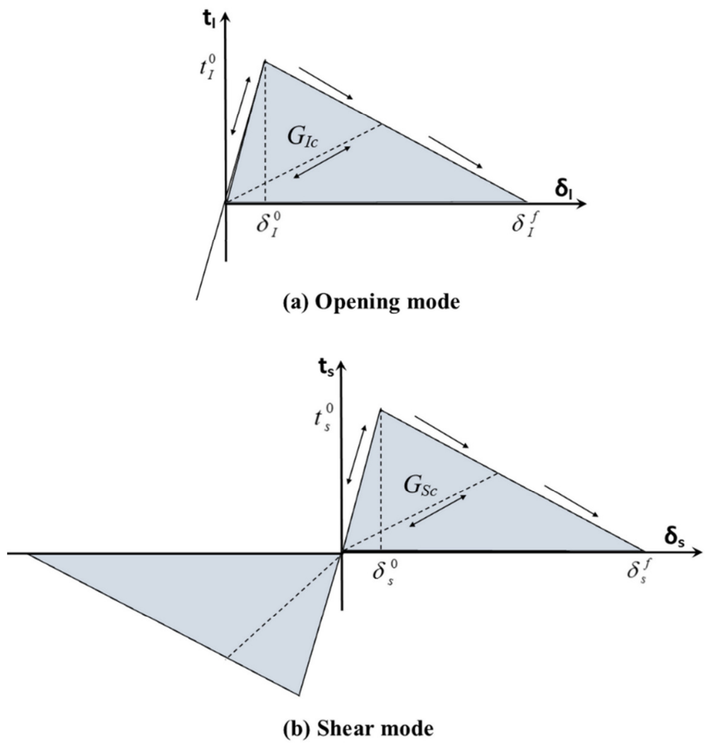

Fig. 4. Bilinear constitutive law of pure loading mode [28]

Perhaps the only drawback of cohesive element is that some of the material properties are difficult to obtain from conventional experimental data as highlighted in [7, 9]. One of the solutions often been used as reported in the literature is to simulate the delamination propagation using Double Cantilever Beam (DCB), End Notched Flexure (ENF) and Mixed-mode Bending (MMB) specimen to identify mode I, mode II and mixed-mode I/II delamination properties [46]. Generally, researchers assumed that the mode III fracture toughness is equivalent to the fracture toughness of mode II [10,20,22,30,34]. However, further works need to be done to verify this assumption [47-48].

Besides the failure criteria, several approaches have been studied in the composite crash modelling to promote the delamination in the laminate. For instance, nodes and interfaces at the edge of the model are meshed with imperfections in order to promote an initial failure as reported in [21,39,45]. Palanivelu *et al*. [45] have demonstrated the implementation of predefined seams in their models which shown an improvement by providing better deformation pattern and SEA estimation compared to the seamless models. Nevertheless, there are also some studies have proved that it is not necessary to know a priori where delamination occurs and yet delivers good prediction of crushing behaviours [11,22].

4. Architecture of Crash Modelling

The available composite crash modelling in the literature are often carried out with different methodologies and approaches that incorporated the failure criteria explained in the previous section. For the representation of composite laminates, it can be modelled either in two dimensional or three dimensional. Several methodologies of laminate modelling can be found in the literature of crash modelling. For example, a stacked-shell analysis methodology has been widely used for last few decades to simulate crushing behaviour of composite structures especially for the composite tubes [6,10,33]. In general, number of layers of shell elements may vary from single (continuum damage mechanics) to multiple layers (discrete). A single stacked-shell methodology [6] is usually handled at macro-scale level in which the prediction of SEA and global failure of laminate or structure is the main motivation. Thus, to account for both intra-laminar (in-plane) and inter-laminar (delamination) failure mechanisms in composite crushing simulation, the use of multiple layers with an insertion of interface elements seems necessary as demonstrated in [22, 45, 49].

Guillon *et al*., [21] on the other hand have developed a pseudo 2D model using 3D shell elements with the interface elements in between to simulate the elementary damages at the ply scale. Numerical simulation for the case of pure splaying mode has delivered good results compared to the experimental works. However, the use of 3D shell elements has led to problems of instability in the case of mixed-mode simulation [21]. Therefore, the use of 3D solid element becomes necessary to overcome these limitations by allowing the stress distributed through the element thickness. Recent studies have also showed 3D solid element has been used in tube crushing [3]. Nevertheless, the performance of composite crash simulation also depends upon the representation of triggering mechanisms in the model to initiate the crushing.

For that reason, different approaches to initiate crushing have been reported in the literature. For instance, plug initiator is often used in the composite tubes crushing simulation [2,40]. Different modelling techniques to model the chamfering trigger have also been reported. Huang and Wang [33] used two-layered stacked-shell model to simulate composite tube subjected to quasi-static axial crushing. Typically in the stacked-shell model, the 45° chamfer trigger is modelled with a gradual reduced of the thickness but Huang and Wang [33] have introduced a new technique to model the 45° external chamfer by translating inward the tip nodes of each shell layer from center-line. A good agreement with experimental results was obtained in term of crushing morphology but the peak load and SEA values were over estimated by the numerical model. In addition, this approach is not suitable for the other types of trigger mechanism such as steeple [11].

The presence of debris wedge in the numerical model to induce specific damages is also important to provide general behaviour of composite crushing. Such approach has been implemented in [11,40]. Both studies used stacked-shell methodology to develop the numerical model but using different techniques in presenting the debris wedge. However, the approach introduced by McGregor *et al*., [40] is not suitable for a development of predictive model as they used a pre-determined debris wedge (the geometry and location of debris wedge was fixed from the beginning of simulation) to induce splaying mode at the tip of the modeled tube. In addition, this approach is only useful for crushing case where splaying mode is the main failure mode. Joosten *et al*., [11] on the other hand, introduced a new alternative to create an internal debris wedge in composite hat-shaped model. This internal debris wedge was built up from an internal delamination produced by large stresses at the tip of specimen during initiation process. This method is capable to promote the petalling mode in the simulation but the overall failure modes are not representative of the failures in experimental test. Besides that, there is no physical proof of debris wedge presented in their model.

The formation of 90^{o} debris wedge using 3D solid elements has also been introduced in composite plate crushing simulation [20] that based on pseudo-plastic transverse deformation law. The formation of this debris is significant to enable the initiation of an eventual splaying as shown in Figure 5. However, due to the law chosen for 90° plies expansion in localized crushing has leads to the mesh dependency problem.

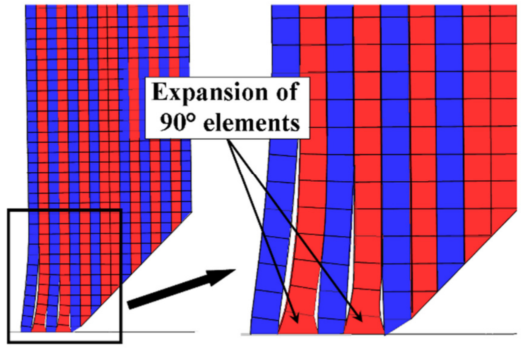

Fig. 5. 90° debris wedge formation in plate crushing simulation [20]

Finally, there are also specific techniques of crash front modelling specifically developed to account for better prediction of crushing propagation at the crash front. Not only the evolution law inside the element needs to take into account, a good damage propagation from elements to elements are also become essential to develop at the crash front modelling. For example, Matzenmiller *et al*., [50] introduced a concept of advancing crash front. This concept used a SOFT parameter (crush front reduction factor) which reduced the allowable strength of the elements in the crushing zone (only elements directly in contact with the impacted target). This parameter is used to avoid instability and to ensure the stability of crushing process during the load transitions from the crash front element to the next element. This concept has been implemented in Materials 54-55 of LS-Dyna and has used to simulate the crushing of sinusoidal composite specimens [4] and square tubes [51]. Figure 6a shows an example of crushing simulation of sinusoidal composite specimen [4]. It shows that the deletion of elements in this simulation leads to a series of unrealistic peaks in the load–displacement curve (Figure 6b) which needs to be filtered in the post-processing (Figure 6c). Besides that, the SOFT parameter is believed not to be related to any physical or measurable quantity.

To avoid such limitations, a similar free-face-crushing concept coupled with a specific behaviour law is introduced in plate crushing simulation [20]. This concept considers the element at the ply extremity (crash front) undergoes localized crushing with less strength than the inside ply elements (far from the crush front). This element deforms under constant stress (pseudo-plastic law) known as ply mean crushing stress which is an intrinsic parameter of the material [52], and it is deleted when completely crushed. The next element is then assigned the same constitutive law, and so on during the crushing of the structure. While for the inside ply elements damage (breakage plies and delamination), conventional failure criteria are used. The simulations results shown very satisfactory with the representation of the complex localized damage mechanisms that occurred at sub-ply scale and at all crushing modes (splaying and fragmentation) at the same time. Nevertheless at the moment, this concept is valid only for $(0/90)_n$ cross-ply laminates and it also experiences a mesh dependency problem.

CZone technology, on the other hand has been developed and incorporated as an add-on product for ABAQUS/Explicit to provide a predictive capability for composite structure in larger scale crash event [53]. The concept of CZone is the utilization of “crush stress”, a distinctive mechanical property of a composite material. This crush stress corresponds only to fibre compression stress that needs to be measured before to be implemented with numerical model. The main idea of CZone is to predict the crushing response at the crushing front as well as the prediction of damage in regions away from the crush front. It is suitable for complex structural interaction and large scale composite structures. Acceptable correlations were reached between experimental and simulation results on the global damage of the structure and the force-displacement curve as demonstrated by Nixon *et al.*, [53] using CZone technology. However, the value of crush stress can be dependent on global parameters of the tested coupons (flat plates) such as ply stack sequence and laminate thickness. Thus, it needs to be determined each time the laminate configurations changed which increases the cost and time consuming.

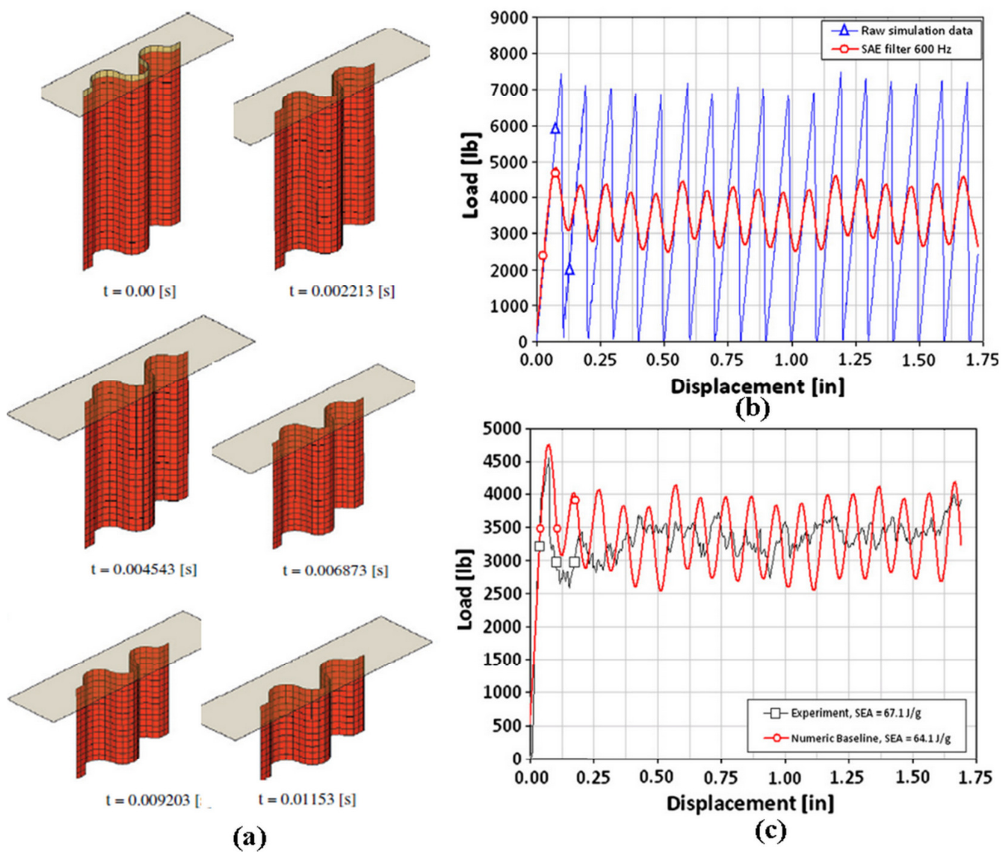

Fig. 6. Example of corrugated composite crushing simulation using SOFT parameter [4] (a) crushing morphology with row element deletion (b) Filtered versus raw data of force-displacement curve (c) Comparison of force-displacement curves between experiment and simulation

5. Conclusions

The increment of computer performance and the advancement of the explicit code have allowed rapid development of numerical models to provide good solutions for composite crashworthiness problems.

The composite crashworthiness modelling is particularly complex to develop as it involves different damage mechanisms and crushing modes that can interact with each other. Different methodologies and failure criteria have been employed with their advantages and disadvantages. However, due to complex nature of failure mechanisms in composite structures and subsequently to the lack of relevant experiments on elementary damage mechanisms, they are often too simplified or too specific to be predictive on complex structures. For example, models developed at macro-scale usually used laminate mean crushing stress and no representative of delamination. Such modelling is not predictive to represent the crushing at any structures but only allows obtaining relative representativeness.

Therefore, to adequately represent crushing morphology and the SEA, it seems necessary to develop numerical models at ply-scale to simulate physically the behaviour of plies at the crushing front and its evolution during crushing. To do so, again an improved understanding on the elementary damage mechanisms is becomes necessary to properly understand and to introduce better methodology to simulate the crushing behaviour. Only then, probably by using a multi-level strategy for development of macro-scale models could provide the overall failure mode of a structure based on a meso-scale model for the simulation of the crushing front.

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