Abstract

The present numerical work intents to contribute to the investigation of a crushing simulation tool for two thin-walled case studies, the first is a quasi-static crushing of a corrugated coupon and the second consists on a dynamic crushing of two impact energy absorber tubes used as lateral crash energy absorbers. Two Finite Element programs, Abaqus® (using Abaqus/Explicit and CZone application) and HyperWorks® (HyperMesh® and HyperCrash® preprocessors and RADIOSS® solver) are used in this work. Abaqus/Explicit showed to provide the best results, when the finer meshes were used, but the computational time required was inappropriate for structural early design projects. CZone proved to be an easy and acceptable composite crushing simulation tool. However attention must be paid to the fact that CZone’s simulation results are highly dependent on the input variables, that are not directly related to the material properties and require previous physical tests crushes.

Keywords: Composite material, Finite Element simulation, Quasi-static crushing, Dynamic impact.

1. Introduction

In the current stage of development, numerical models are still too simplistic to simulate all the mechanical processes relative to the crushing of composite structures. Delamination, for example, is rarely modeled due to the intrinsic numerical difficulties, even though the behavior of a component is considerably different when delaminated. Some studies concerning composite fuselage sections for light aircraft or blade or wing bird impacts can be found in literature [1, 2, 3] and composite helicopter [4] or automotive structures [5, 6, 7, 8, 9] but they are still few and do not cover all the composite structure modeling. Numerical composite crushing simulations can be very useful for early structure’s design, however, they require a lot of experience and knowledge from the designing engineer.

This work’s theme was proposed by Optimal Structural Solutions, this company differentiates itself by being specialist in composite materials. It is divided in two parts: The first part, consists on the recreation of a quasi-static crushing simulation of a sinusoidal composite plate, described in a set of published articles. The second part consists on the modeling a dynamic crush of two composite tubes used as lateral impact energy absorbers in F1 cars. The softwares used in this work are the Altair products of HyperWorks® and Abaqus® (Abaqus/Explicit and CZone).

2. Background

The Specific Energy Absorption, SEA, is defined as the energy absorbed per unit mass of crushed material, and can be written as, \( SEA = \frac{W}{\rho A \delta} = \frac{\int F \, d\delta}{\rho A \delta} \), where the total energy absorbed, \( W \), is equal to the integral of the load, \( F \), over the total crush displacement \( \delta \), or the area underneath the load versus displacement curve, \( \rho \) is the material density, and \( A \) is the cross-sectional area of the specimen. SEA is widely believed to be dependent on the strain rate in the composite material during crushing, and thus SEA results obtained from quasi-static compression testing may not be the same as those obtained from dynamic crush experiments that produce higher strain rates in the material. The sustained crush stress, \( \bar{\sigma} \), defined as the average crush load \( \bar{F} \) divided by the cross sectional area, \( A \), is also a critical design parameter that must be known when designing an energy absorbing structure using CZone. However, the crush stress is dependent on a number of material and geometric parameters.

Damage is characterized by the degradation of material stiffness. Many fiber reinforced materials exhibit elastic-brittle behavior, where damage is initiated without significant plastic deformation. Consequently, plasticity can be neglected when modeling behavior of such materials. The constitutive stress-strain relations (\( \sigma = H \epsilon \)) of each ply are formulated in a local orthotropic cartesian coordinate system with the base vectors aligned with the fibers directions. The damage parameters are included in
the compliance tensor in the constitutive law, thus reducing the material parameters and affecting global material properties, in \( \sigma = H \epsilon \).

\[
H = \frac{1}{D} \begin{bmatrix}
    E_1 & 0 & 0 \\
    \nu_{12} E_2 & E_2 & 0 \\
    0 & 0 & D(1-d_{12})G_{12}
\end{bmatrix}
\]

(1)

where \( H \) is the elasticity compliance matrix; \( \epsilon \) is the elastic strain vector; \( \sigma \) is the stress vector; \( D = \frac{1}{(1-d_{11})(1-d_{12})} \); \( E_1 \) and \( E_2 \) are the Young's Moduli in the principal orthotropic directions; \( G_{12} \) is the in-plane shear modulus; \( \nu_{12} \) and \( \nu_{21} \) are the principal Poisson's ratios; \( d_{1} \) and \( d_{2} \) reflect the principal orthotropic directions state of damage, that evolve between 0 (undamaged) and 1 (fully damaged); and \( d_{12} \) is the damage parameter associated with the matrix micro-cracking due to the in-plane shear deformation. If the fully damaged state is reached for one of the failure modes the integration point is removed for that ply. The Hashin criterion is the damage criterion used in this work Abaqus® and HyperWorks® simulations [10, 11].

2.1. Simulations

The simulations of the quasi-static and dynamic crushings of this work, can be divided into three parts, which include the boundary conditions, contact interface definition, the composite modeling.

2.1.1 boundary and initial conditions

The movement of the 780Kg impactor plate is defined with a prescribed constant velocity of 200 mm/s (for the quasi-tatic model) and initial velocity of 10m/s (for the dynamic model), applied to the impactor rigid body set that include all its nodes. The displacement, velocity, acceleration and crushing force of the impactor plate are monitored for post processing analysis. The geometries’ base nodes are also restrained in an encastred rigid body set.

2.1.2 Contact interface definition

A friction coefficient of 0.12 was used between the impactor plate and the crushed geometry [12]. In the case of 3-D continuum shell elements simulations, a 0.3 friction coefficient was used between the composite plies.

2.1.3 Composite modeling

Modeling of the composite material was done by using sandwich shell properties, where multiple layers of composite material can be modeled, specifying their thicknesses, their position relative to the reference surface, each layer's material and the fibers orientations [11, 10].

In the HyperWorks® simulations, in compression, the yield limits are set to occur at approximately half the maximum stress levels. In shear, the yield limit is set to occur at approximately a third of the maximum stress, due to the fact that FRPs tend to yield much in shear [13].

The crushing simulations were modeled using both 2-D conventional shell elements (in Abaqus/Explicit, CZone and HyperWorks®) and 3-D continuum shell elements [10] (for the quasi-static simulation in Abaqus/Explicit). In the 2-D conventional shell elements simulations, only intralaminar (in-plane) failure is modeled, i.e. no delamination is considered. On the other hand interlaminar delamination/decohesion is considered in the quasi-static simulation in Abaqus/Explicit.

A CZone simulation is run through the modification of the input file of Abaqus/Explicit, introducing the CZone commands in it [14]. The sustained crush stress is a critical design parameter that must be known when designing an energy absorbing structure in CZone.

In this work, the VUMAT approach was not contemplated in the 3-D continuum shell elements quasi-static crushing simulations [15], only the built-in options of Abaqus® were implemented. This factor may be the reason why the simulations did not replicate the experimental results. The available cohesive traction-separation model in Abaqus® assumes initially linear elastic behavior followed by the initiation and evolution of damage. The elastic behavior is written in terms of an elastic constitutive matrix, \( K = 10^6 \), that relates the normal and shear stresses, to the normal and shear separations across the interface. Damage initiation at the interfaces was defined using the quadratic nominal stress criterion (QUADS) according to which damage is assumed to initiate when the quadratic interaction function involving the stress ratios reaches a value of one. Damage evolution can be defined based on the fracture energy that is dissipated as a result of the damage process, modeled using the critical mixed mode energy behavior based on the Benegzegagh–Kenane (BK) law.

3. Quasi-static crushing simulation

A quasi-static crushing of a carbon fiber corrugated coupon is here simulated, using and comparing three FE simulation tools previously presented, to replicate experimental crushings and numerical simulations of this specimen, described in a set of published articles [12, 13, 15, 16]. The material here modulated is a bidirectional “pre-impregnated” (pre-preg) carbon fiber fabric with T700 carbon fibers and 2510 epoxy resin. It is a 2mm thick 8 plies \([0/90]_{2\times4}\) stack-up. On one end, where crushing is desired to start, a trigger is created on the edge with a 45° chamfer. It is modeled as a single element row with reduced thickness from
2 \, \text{mm} \text{ to } 1 \, \text{mm}. \text{ This helps to initiate crushing and avoid initial pikes in crush loads. The height of the plate is 76.2 \, \text{mm} \text{ and the width is 50.8 \, \text{mm}. The friction coefficient is set to be } \mu = 0.12} \text{ [12].}

In this work’s 3-D continuum shell elements quasi-static crushing simulation, each of the eight fabric plies was individually meshed with 1 \, \text{mm} by 0.5 \, \text{mm} 3-D continuum shell elements (SC8R). The 2-D conventional shell elements simulations were modeled using 0.5 \times 0.5 \, \text{mm} \text{ and } 1 \times 1 \, \text{mm} \text{ distorted quadrangular meshes and a triangular elements mesh with } L_c = 1.5 \, \text{mm} \text{ characteristic length. The material properties used are presented in Table 1.}

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
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<tr>
<td>E_2</td>
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<td>Y_+</td>
<td>770.1 , \text{MPa}</td>
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<tr>
<td>G_{12}</td>
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</table>

Table 1: Material properties to be used in simulations - Carbon fiber fabric prepreg T700/2510.

The interface damage initiation QUADS properties, as well as the damage evolution critical fracture energies (BK law), used in the quasi-static 3-D continuum shell elements’ analysis, are listed in Table 2. \eta is the power coefficient taken to be 2.284.

<table>
<thead>
<tr>
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<tr>
<td>\tau_9</td>
<td>70 , \text{MPa}</td>
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<tr>
<td>\tau_8</td>
<td>70 , \text{MPa}</td>
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</tr>
<tr>
<td>G_{11C}</td>
<td>1.566 , \text{KJ/m}^2</td>
</tr>
</tbody>
</table>

Table 2: Interface damage initiation and evolution properties.

3.1. Crush stress influence in CZone’s simulations

As the average crush force of the simulation of the article is \bar{F} = 16900 \, \text{N} \text{ and the corrugated coupon cross-sectional area is } A = 125.2 \, \text{mm}^2, \text{ the crush stress used in this simulation is } \bar{\sigma} = \frac{\bar{F}}{A} \approx 135 \, \text{MPa} \text{. The crush stress influence on the CZone simulations results is here briefly studied. Two more values of } \bar{\sigma} \text{ are used, respectively } \bar{\sigma} = 135 \, \text{MPa} - 25\% \approx 101.25 \, \text{MPa} \text{ and } \bar{\sigma} = 135 \, \text{MPa} + 25\% \approx 168.75 \, \text{MPa}.}

4. Results and discussion

4.1. Results of simulations using HyperWorks®

The crushing progressions of the quadrangular 1 \times 1 \, \text{mm} \text{ elements mesh and the triangular } L_c = 1.5 \, \text{mm} \text{ elements mesh simulations, are presented in Figures 1 and 2. The respective results, are presented in Figure 3.}

Figure 1: HyperWorks® quasi-static crushing simulation evolution using a 1 \times 1 \, \text{mm} \text{ quadrilateral mesh.}

Figure 2: HyperWorks® quasi-static crushing simulation evolution using a 1.5 \, \text{mm} \text{ characteristic length triangular mesh.}

Figure 3: Reaction force versus displacement graphic of the corrugated coupon quasi-static crushings using HyperWorks®.

All simulations in HyperWorks® present an initial peak force, followed by a zero reaction force section, that corresponds to the destruction of the trigger row of the corrugated coupons’ top end, that, when deleted, creates a gap between the impactor plate and the remaining corrugated coupon. The quadrangular 0.5 \times 0.5 \, \text{mm} \text{ mesh crushing simulation suffers a longitudinal failure in fronds that bend over themselves and absorb, then, less energy. In the case of the distorted quadrangular 1 \times 1 \, \text{mm} \text{ mesh, there is only an initial peak reaction force, before a buiking failure is verified at the coupon’s base. The reduction of the stiffness interface factor (which is the elastic energy loss during the interface spring-like nodes}
contact behavior) may be one of the reasons why the mean crushing force observed in the graphics is underestimated, when compared to the experimental results [12].

4.2. Results of simulations using Abaqus/Explicit with 3-D continuum shell elements

The crushing progressions of the corrugated coupon simulations using 3-D continuum shell elements in Abaqus/Explicit, for different numbers of elements in the thickness of each layer, presented similar crushing behaviors, such as the 3 elements through the thickness simulation, in Figure 4. Its results are presented in Figures 5.

![Figure 4: Abaqus/Explicit quasi-static crushing simulation evolution using 3-D continuum shell elements and 3 elements per layer.](image)

Figure 4: Abaqus/Explicit quasi-static crushing simulation evolution using 3-D continuum shell elements and 3 elements per layer.

The main reason to explain the difference between the simulation and the expected experimental results, might be the fact that in this work, only the built-in capabilities of Abaqus/CAE were used, and no subroutine was implemented to characterize the composite interlaminar and material intralaminar damage behavior [15]. This made the layers less stiff than expected and to bend over themselves without being damaged. Further investigation on composite models crushing using 3-D continuum shell elements and the built-in Abaqus/CAE capabilities should be done. The increasing number of elements in the thickness of each layer, did not change the excessive bending behavior described previously, however, the average crushing load, \( \bar{F} \), augmented with the the increase of elements in the thickness of each layer.

4.3. Results of simulations using CZone

The crushing progressions of the corrugated coupon simulations in CZone, for different meshes, showed to have similar crushing evolutions, such as the one presented in Figure 6. The reaction force of the impactor rigid wall is presented in Figure 7, for different meshes and crushing speeds.

![Figure 6: CZone quasi-static crushing simulation evolution using a 1 × 1mm quadrilateral mesh.](image)

Figure 6: CZone quasi-static crushing simulation evolution using a 1 × 1mm quadrilateral mesh.

The mesh size and shape have no influence in the quasi-static crushing simulation behavior using CZone. It was assumed that the crushing velocity would not influence the crushing force of the composite component in CZone. There is a 14% difference between the article's crushing force result [16] and the crushing forces here obtained. The major factor that defines the CZone simulations is, as can be observed in Figure 8, the crush stress.

![Figure 7: Crushing force versus displacement graphic of the corrugated coupon quasi-static crushings using CZone.](image)

Figure 7: Crushing force versus displacement graphic of the corrugated coupon quasi-static crushings using CZone.

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![Figure 8: Crush stress influence in CZone quasi-static crushing simulations Reaction force versus displacement.](image)

Figure 8: Crush stress influence in CZone quasi-static crushing simulations Reaction force versus displacement.
5. Dynamic crushing simulations

The second part of this work consists on the dynamic crushing simulation of two carbon tubes used as lateral impact energy absorbers in F1 cars. The simulations are validated against experimental data provided by Optimal Structural Solutions. The impactor’s kinetic energy must be dissipated by the composite tube’s destruction and the negative acceleration felt by the rigid wall must remain under 30 g’s. The crushing evolution of the experimental crush can be observed, for different time steps on Fig. 9.

![Figure 9: Experimental crush test performed by OPTIMAL Structural Solutions.](image)

The composite tubes layup is $[9_6, 45, 0_1]_t$. The tubes are, respectively, 30.8cm and 39.6cm long, approximately. Each tube has a cross-sectional area, $A = 852.47mm^2$. They are made out of two carbon fibers, denominated as “Material A”, for layers 1, 7, 14 and 20, and “Material B”, for the remaining layers. Material properties are presented in Table 3 (from supplier (Delta-Tech) and [17, 18]):

- **Material A:** GG380T – DT121H – 40% Toray T700 (12K);
- **Material B:** MTM/22S/CF0300L – HS (3K) 200gsm 2x2 Twill.

<table>
<thead>
<tr>
<th>Property symbol</th>
<th>Material A</th>
<th>Material B</th>
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<tbody>
<tr>
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<tr>
<td>$S_{21}$ [MPa]</td>
<td>105.1</td>
<td>114.9</td>
</tr>
</tbody>
</table>

Table 3: Material A and Material B properties used in the dynamic crushing simulations

The laminate’s density, $\rho$, that includes the 4 layers of Material A and the 16 layers of Material B, is assumed to have the following value:

$$\rho = \left(\frac{14}{20}\right) \rho_{Mat A} + \left(\frac{16}{20}\right) \rho_{Mat B} = 1.562 \text{ Kg/m}^3.$$  

Due to the absence of information, the same values of the fracture energies in the principal and transverse fiber directions ($G_{12}^C$, $G_{23}^C$, $G_{13}^C$, $G_{23}^C$), used in the quasi-static simulations, were assumed in this part’s Abaqus/Explicit and CZone simulations.

**Mesh size influence** Four mesh sizes were created using quadrilateral 2-D conventional shell elements, and were compared with each other: $3 \times 3mm$; $5 \times 5mm$; $7.5 \times 7.5mm$; and $10 \times 10mm$. The two finer meshes required extremely large computational time to complete the simulations. A mesh size influence study was firstly done to understand the mesh influence on the results. Due to computational time and accuracy of the results, only the $7.5 \times 7.5mm$ mesh size was used to create the other studies explained below.

**Friction coefficient influence** The friction coefficient between the impactor plate and the carbon tubes, of the experimental crush made by Optimal Structural Solutions was unknown, therefore the assumed value used for the dynamic crush simulations of this part is $\mu = 0.12$, which is the same value used in the quasi-static crushing simulation previously presented. However, the influence of the friction coefficient between the impactor plate and the composite tubes is here briefly studied, using two more values: $\mu = 0$, corresponding to an ideal frictionless crushing and, $\mu = 0.4$ [9].

**Material properties influence** The material properties influence is here briefly studied, using Abaqus/Explicit and CZone, increasing and decreasing, respectively, by 25%, the material strength properties, i.e. $X_+$, $X_-$, $Y_+$, $Y_-$, $S_{12}$ and $S_{21}$, specified as part of the damage initiation definition.

**Impactor plate mass influence** The impactor plate mass influence is here studied for two cases, using a 78Kg and a 390Kg impactor rigid wall mass, respectively. These simulations were performed with Abaqus/Explicit and CZone, with a $7.5 \times 7.5mm$ mesh size due to computational time.

**Tubes’ length influence** The influence of the tubes’ lengths is here briefly studied, simulating a second set of composite tubes. In this new set of tubes, the length of the longer tube is reduced approximately 2cm. Because the impactor reaches the shorter tube earlier than in the longer geometry set, more energy is absorbed in a shorter distance, imposing a greater deceleration felt by the Rigid Wall impactor.

**CZone Crush stress influence** The crush stress obtained from the tubes dynamic experimental crushing results performed by Optimal Structural Solutions was defined as $\bar{\sigma} = \frac{Kn}{A} = 210.6 \text{MPa}$,
where \( m \) represents the 780Kg impactor mass, and \( \bar{a} \approx 230.14m/s^2 \) is the average deceleration during the crush test until the maximum impactor’s displacement was reached. Two more values of the crush stress value are here briefly studied: one is the quasi-static CZone simulations crush stress, \( \bar{\sigma} = 135MPa \), and the second one is an intermediate \( \bar{\sigma} = 179MPa \) crush stress.

5.1. Results and discussion

Mesh size influence

The crushing progressions of the tubes simulations are here presented for the 3 \times 3 mm mesh size (see Figures 10, 11 and 12). The correspondent crushing progressions of mesh size influence results are presented in Figures 13, 14, 15, 16, 17 and 18, for each FE program.

![Figure 10: HyperWorks® dynamic crushing simulation evolution using a 3 \times 3 mm mesh size.](image)

![Figure 11: Abaqus/Explicit dynamic crushing simulation evolution using a 3 \times 3 mm mesh size.](image)

![Figure 12: CZone dynamic crushing simulation evolution using a 3 \times 3 mm mesh size.](image)

All crush progressions have similar initial behaviors as the experimental one (see Figure 9). In all CZone simulations the impactor’s kinetic energy has been absorbed by the composite material’s destruction, as expected. This behavior was not verified in the larger meshes of HyperWorks® and Abaqus/Explicit. In these last two cases, the material models were unable to absorb all the impactor’s kinetic energy. However, the finer meshes of the HyperWorks® and Abaqus/Explicit simulations followed, in the initial section, the experimental crushing behavior, as expected. A clear mesh size influence on the crushing behavior can be observed in the Abaqus/Explicit and HyperWorks® simulations.

![Figure 13: Velocity - Mesh influence in the dynamic crushing simulation of two composite tubes using HyperWorks®.](image)

![Figure 14: Acceleration - Mesh influence in the dynamic crushing simulation of two composite tubes using HyperWorks®.](image)

![Figure 15: Velocity - Mesh influence in the dynamic crushing simulation of two composite tubes using Abaqus/Explicit.](image)

![Figure 16: Acceleration - Mesh influence in the dynamic crushing simulation of two composite tubes using Abaqus/Explicit.](image)

In CZone, all simulations seem to be less dependent on mesh refinement than in Abaqus/Explicit and HyperWorks® simulations.
Figure 17: Velocity - Mesh influence in the dynamic crushing simulation of two composite tubes using CZone.

Figure 18: Acceleration - Mesh influence in the dynamic crushing simulation of two composite tubes using CZone.

HyperWorks®. However, the CZone simulations tend to overestimate the material stiffness, forcing the impactor’s velocity to decrease faster which increases the deceleration (up to 77% greater than the 30 g/s allowed by FIA for this kind of lateral crash energy absorbers). Due to computational time consumption and availability, the 7.5 × 7.5mm mesh size is used for the analysis of the remaining parameters’ influence, for all FE programs.

Friction coefficient influence

The friction coefficient influence is here briefly studied using two more values, one is $\mu = 0$ (frictionless), and $\mu = 0.4$ [9], with Abaqus/Explicit and CZone. The results are presented in Figures 19 and 20.

In the Abaqus/Explicit simulations, the increase of the friction coefficient between the impactor plate and the composite tubes, led to a buckling failure of the longest tube, and consequently to the total destruction of both tubes. The frictionless impact simulation did not diminish the impactor’s crushing velocity, because there was no reaction force to decelerate the impactor plate. These results prove that the absorbed energy is directly proportional to the friction between the geometry and the impactor plate. In CZone, the frictionless simulation gave results closer to the experimental ones, than those with a higher friction coefficient, which was coincident with the original curve (denoted as CZONE $Lc = 7.5mm$).

Material properties’ influence

The material properties were here briefly analysed varying by 25% strength properties of the two materials that constitute the tubes composite layup. The respective results can be observed in Figure 21, 22, 23 and 24.

CZone seems to be minimally influenced by material properties. The simulations using materials with more strength, increased the material resistance to the crushing movement of the impactor plate. In Abaqus/Explicit and HyperWorks®, this increase in material stiffness together with the fact that a
7.5 × 7.5mm mesh is less stiff than finer meshes, produced the closest results to the experimental ones (error under 17%).

**Impactor plate mass influence** The impactor mass influence on the crushing behavior is here briefly studied. Two new impactor plates masses, respectively 780 × 10% = 78Kg, and 780/2 = 390Kg, are tested for Abaqus/Explicit and CZone, using the 7.5 × 7.5mm mesh size. The respective velocity and acceleration graphics are presented in Figures 25 and 26.

The composite tubes crushing simulations using Abaqus/Explicit and HyperWorks® were able to absorb all the kinetic energy of the smaller impactor plate mass (78Kg). However, this was not verified with the 390Kg impactor plate mass, using these two FE programs. This last case is related to the mesh size dependence verified previously. Further studies, using finer and converged meshes, should be performed to understand the impactor mass influence.

**Tubes’ length influence** The dynamic crushing simulations in which the longest tube is approximately 2cm shorter were also performed. The simulations results are presented in Figure 27, 28, 29 and 30.

This length reduction decreased the crushing distance on a single tube (the longest tube), and
Figure 28: Acceleration - Shorter tube influence in the dynamic crushing simulation of two composite tubes using HyperWorks®.

Figure 29: Velocity - Shorter tube influence in the dynamic crushing simulation of two composite tubes using Abaqus/Explicit and CZone.

Figure 30: Acceleration - Shorter tube influence in the dynamic crushing simulation of two composite tubes using Abaqus/Explicit and CZone.

consequently augmented the deceleration level. The Abaqus/Explicit and HyperWorks® simulations underestimated the composite material kinetic energy absorption, a finer mesh would probably provide better results. In CZone, as happened in the original tubes’ set, this new shorter tubes’ set overestimated the tubes stiffness.

Crush stress influence The dynamic crushing simulations using CZone were also performed using two more values of the crush stress: \( \bar{\sigma} = 135 \text{MPa} \) and \( \bar{\sigma} = 179 \text{MPa} \). The respective results are presented in Figures 31 and 32.

As verified in the quasi-static crushing simulations of the previous chapter, a higher crush stress leads to a shorter crushing distance and consequently to a higher deceleration level. The opposite situation is also verified. The lowest crush stress value gave the best results (reduced the error from 77% to 20%). This fact proves that the crush stress value used in CZone is a key factor in CZone simulations. Its correct estimation is then essential to adequately simulate composite materials crushings. It should be noticed that this crush stress value is not a material characteristic, it is only an input parameter for this Abaqus’s application.

6. Conclusions

Mesh size and shape, friction coefficient, elastic and strength material properties and crush stress, are the major key factors for this work’s composite crushing simulations. Due to computational time and computational limitations, it was not possible to run all required simulation configurations. Further investigation is required to fully understand each factor’s real importance. The Abaqus/Explicit simulations, using the finer mesh sizes tested in this work, provided the closest results when compared to published articles simulation data and experimental crushes performed by Optimal Structural Solutions. But this finer meshes required extremely large time
computational consumption. Even if this simulation provided adequate results for finer meshes, due to its computational cost, it is not an adequate quasi-static and dynamic crushing simulation tool. On the other hand, the CZone simulation tool, required much less computational resources and provided, in some cases, reasonable results (with error around 15%). The quasi-static crushing simulations using CZone, confirmed the results presented in the published bibliography used in this work for validation. To create the CZone simulations, general assumptions had to be made: the material behavior was assumed to be independent of the crushing velocity, which is a simplification that needs further investigation, to correctly simulate composite crushings. HyperWorks® has more input possibilities, material properties that could, with further investigation, provide the best results in terms of computational cost and accuracy.

References


