12th HSTAM International Congress on Mechanics
Thessaloniki, Greece, 22 – 25 September 2019

Parametric analysis of Cohesive Zone Model Method for CFRP Stiffened Panel CAI behaviour

Dimitrios G Gaitanelis[1], Ioannis K Giannopoulos[1*], Efstathios E Theotokoglou[2]

[1]*Centre of Excellence for Aeronautics, School of Aerospace, Transport and Manufacturing, Cranfield University, Cranfield, MK43 0AL, UK*

[2] *Department of Mechanics, Laboratory of Testing and Materials, School of Applied Mathematical and Physical Sciences, National Technical University of Athens, GR-157 73, Greece*

Keywords: Finite Element Analysis, Damage Mechanics, Cohesive Zone Model (CZM), Delamination

Abstract. This paper examined the effect of the stiffness of the cohesive elements on the accuracy and the computational efficiency of Carbon Fibre Reinforced Polymer (CFRP) stiffened panels under Compression After Impact (CAI). Abaqus® software was used and the Cohesive Zone Model (CZM) method was applied to capture the damage initiation and propagation of the panels. Various case studies were examined and the effect of the stiffness parameters of the cohesive elements was critically assessed. Moreover, the required number of cohesive zones to fully capture the damage mechanisms of the impacted and pristine panels under compressive loading was examined. The results showed that a wrong set of parameters can even lead to neglecting the induced damage and can cause severe convergence problems in the numerical model.

1 INTRODUCTION

The beneficial mechanical properties of composite materials have increased their applicability in several industries. However, when composite structures and specifically composite stiffened panels are damaged from impact events, they have a much lower residual strength from their pristine conditioning. Predicting the behavior of composite stiffened panels under the presence of structural damage is an important topic that has received great attention from researchers. In general, the presence of a pre and/or post-service damage or manufacturing inherited damage can highly affect the structural performance of the panels. So far, to prove the structural capability of a panel, physical testing is required. Considering the high cost and complexity of this procedure, finite element modelling is widely used to reduce the size and scope of physical testing, especially in the early design stages. One of the main damage mechanisms of CFRP stiffened panels caused by an impact event is delamination. To predict delamination initiation and growth, the cohesive zone model (CZM) is a widely used method. However, within the public domain literature, the need for further investigation in the modelling parameters of CZM application for increasing the accuracy and computational efficiency was evidenced. This paper aimed at contributing to this investigation and a parametric analysis was conducted with several models being examined and compared aiming at faster, more robust and more accurate simulations.

2 METHODS

To investigate an efficient modelling approach for CAI loading scenario, a stiffened panel with 4 I-type stiffeners was examined (figure 1). The experimental results in the study of Feng et al [1] were used. In this study, a CAI loading scenario was investigated, where 12 CFRP panels were tested (nine impacted with 50 *J* impact energy and three pristine). The applied materials were UD carbon fiber/epoxy resin BA9916-II/HF10A-3K prepreg and plain woven BA9916-II/HFW220TA with a nominal thickness of 0.125 *mm* and 0.23 *mm* respectively. The material properties can be found in

Copyright © The Authors. Published by The Hellenic Society of Theoretical & Applied Mechanics . This is the Author Accepted Manuscript. Please refer to any applicable publisher terms of use.

table 1 and the ply sequence in table 2. The panels were modelled in Abaqus software and the effect of the impact damage on the damage initiation and propagation and overall CAI panel strength was examined. Dynamic implicit analysis was chosen as the optimal simulation scheme. Continuum shell elements were used for the skin and the stiffeners. (linear hexahedral elements of SC8R type). The cohesive zones were modelled with cohesive elements COH3D8 with a finite thickness equal to 0.01 *mm* and were connected to the three-dimensional shell elements with TIE constraints. Quasistatic loading was applied with a displacement of 10 *mm*. To improve convergence behaviour, viscous regularization scheme was used, with a viscosity parameter equal to 10^{-3} [2]. In all the panels, a preliminary linear buckling analysis was conducted for incorporating imperfections in the form of panel shape distortions [3]. Twenty eigenvalues were extracted from the analysis and an initial imperfection was set for the non-linear models as 10% of the first eigenvalue. The experimental impact results of Feng et al. [1] were implemented in the numerical model by removing a rectangular cohesion zone. For positions A, B and C the dimensions of the rectangle shape were 30 *mm x* 15 *mm*, 56 *mm x* 22 *mm* and 12 *mm x* 8 *mm*. Finally, the values of the damage evolution in the composite material (G_{CIc}, G_{TIc}, G_{CIIc}, G_{TIIc}) were the following: $G_{CIc} = G_{TIc} = 12.5$ *N*/*mm* and $G_{CIIc} = G_{TIIc} = 1.0$ *N*/*mm*. [4]

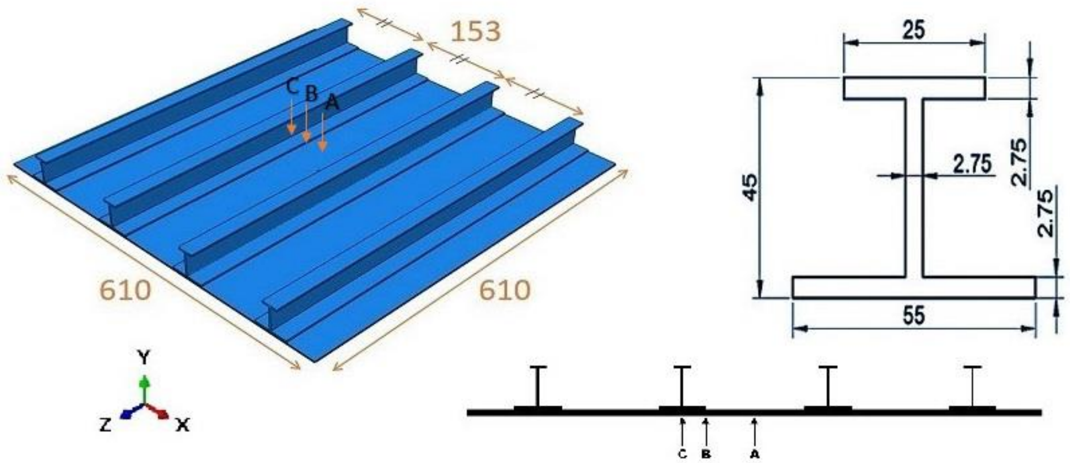

Figure 1. Panel Geometry and Impact Positions A, B & C

UD BA9916-II/HF10A-3K							
E_{11}/MPa	124.000	E_{22}/MPa	10.000	E_{33}/MPa	10.000	G_{12}/MPa	4510
G_{13}/MPa	45.100	G_{23}/MPa	3260	ν_{12}	0.16	ν_{13}	0.16
ν_{23}	0.2	X_t/MPa	1448	Y_t/MPa	55	X_C/MPa	1172
Y_C/MPa	172	S_{12}/MPa	90	S_{13}/MPa	161	S_{23}/MPa	161
Plain Woven BA9916-II/HFW220TA							
E_{11}/MPa	55.000	E_{22}/MPa	52.000	E_{33}/MPa	56.000	G_{12}/MPa	4140
G_{13}/MPa	4140	G_{23}/MPa	3760	ν_{12}	0.28	ν_{13}	0.28
ν_{23}	0.30	X_t/MPa	600	Y_t/MPa	540	X_C/MPa	631
Y_C/MPa	584	S_{12}/MPa	60	S_{13}/MPa	60	S_{23}/MPa	116

Table 1. Material Properties of UD & Woven materials

	Ply Sequence	Total No. Of Plies	Total thickness (mm)
Skin	$[45(woven)/45/0/0/0/-45/90/0/90]_s$	18	2.46
Stiffener	$[-45/0/0/45/0/0/-45/0/0//90]_s$	22	2.75

Table 2. Ply sequence and total thickness of the examined skin and stiffener.

3 FINDINGS

To investigate an accurate and computationally efficient numerical model for CAI behaviour of CFRP panels, the stiffness of the cohesive elements and the number of the required cohesive zones were examined. To begin with, a sensitivity analysis was conducted to investigate the optimum overall meshing factor (OMF). OMF is the ratio between the mesh size of the shell elements and the mesh size of the cohesive elements. An OMF equal to four was used, since it provided the optimum results, while a greater refinement increased the computational cost without providing more realistic results. To examine the effect of the stiffness of the cohesive elements, eight models were investigated. Different values for the cohesive elements were applied in the initial four models, and those values were derived from existing studies from other researchers. It must be mentioned that in the initial four models the same values were used for the evolution of the existing damage under the compressive loading. In table 3 the initial four models are presented and the results are presented in figure 2.

Parameters	K_{NN} (N/mm^3)	$K_{SS} = K_{TT}$ (N/mm^3)	N_{MAX} (N/mm^2)	$S_{MAX} = T_{MAX}$ (N/mm^2)
Model 1, [5]	3,250	24,920	54	80
Model 2, [6]	240,000	86,000	64	121
Model 3, [7]	1,000,000	1,000,000	60	90
Model 4, [4]	1,150,000	600,000	54	80
G_{Ic} = 0.325 N/mm, $G_{IIc} = G_{IIIc}$ = 2.492 N/mm, η = 2,193				

Table 3. Initial four examined models – Properties of the cohesive elements

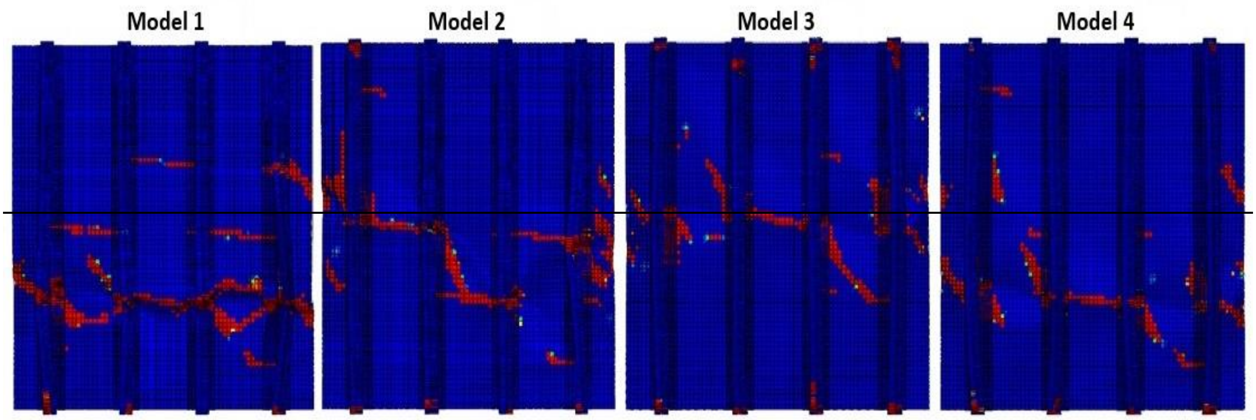

Figure 2. Matrix Compression Damage in the four initial models

All the models had the same induced damage in position C (figure 1). According to the conducted compression test [1], the damage was expected to initiate and develop from the impacted position. However, as it can be seen in figure 2, a wrong combination of CZM properties can even sideline the existing delamination within a model. For instance, in models 1 & 4 the damage was neglected. After comparing those numerical results with the existing experimental results, a further investigation was applied in two of the four initial models to define the optimum numerical recipe. Even though model 1 was not accurate it showed the optimum convergence behaviour. For the reason stated above, models 1 and 2 were further examined to improve the accuracy of model 1 and the computational efficiency of model 2. The 4 new models are presented in table 4. Models 5, 6, 7 are variations of model 1 and model 8 is a variation of model 2. In greater detail, even though in model 1 the damage initiated from the impact point, the damage propagation was stable after a specific point of the simulation. For the reason stated above and the effective computational behaviour this model was further examined.

In all, three versions of model 1 were examined with the already applied elastic properties. Damage initiation criteria of models 2 and 3 (table 3) were implemented in the first two new versions and in the third model, different properties for the damage evolution were applied. [3] A version of model 2 with those damage evolution properties [4] was examined as well to improve its convergence behaviour. The exact properties of the four new models are presented in table 4.

Models	Elastic Parameters		Damage Initiation		Damage Evolution		
	K_{NN} (N/mm^3)	$K_{SS} = K_{TT}$ (N/mm^3)	N_{MAX} (N/mm^2)	$S_{MAX} = T_{MAX}$ (N/mm^2)	G_{Ic} (N/mm)	$G_{IIc} = G_{IIIc}$ (N/mm)	η
Model 5	3,250	24,920	60	90	0.325	2.492	2.193
Model 6	3,250	24,920	64	121	0.325	2.492	2.193
Model 7	3,250	24,920	54	80	0.243	0.514	4.6
Model 8	240,000	86,000	64	121	0.243	0.514	4.6

Table 4. Properties of the cohesive elements of the new examined models

To analyse the damage initiation and propagation of the models the quadratic nominal stress criterion was applied, and the results can be seen in the figures below.

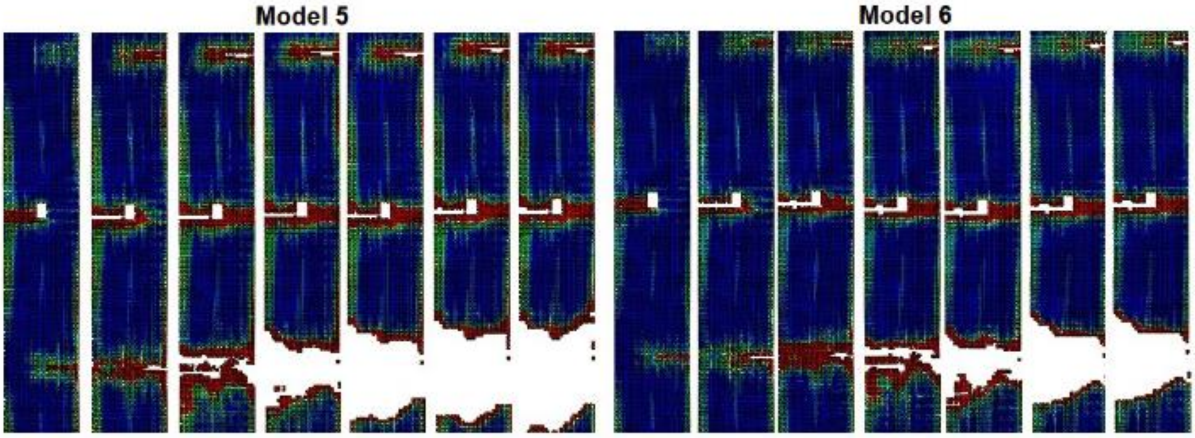

Figure 3. QUADS Criterion in models 5 & 6

As it can be seen from figure 3, the damage initiates from the impact point but does not propagate throughout the whole simulation. By applying different damage evolution properties this issue is overcome. In model 7 the damage initiates from the impact point and propagates through the whole simulation. However, the damage propagates in a more severe way in the quarter length of the panel as it does in the pristine panel (figure 4). As a result, a definite answer whether the model is accurate or not, cannot be given and further physical experiments should take place. It must be mentioned that the implemented impact damage within the model in position C is 12 x 8 mm. It must be mentioned that in the experimental research of Feng et al, this damage caused by the applied 50J impact did not affect the damage mechanics of several of the examined panels under compression. Those panels followed the same damage pattern as the pristine panel. [1]

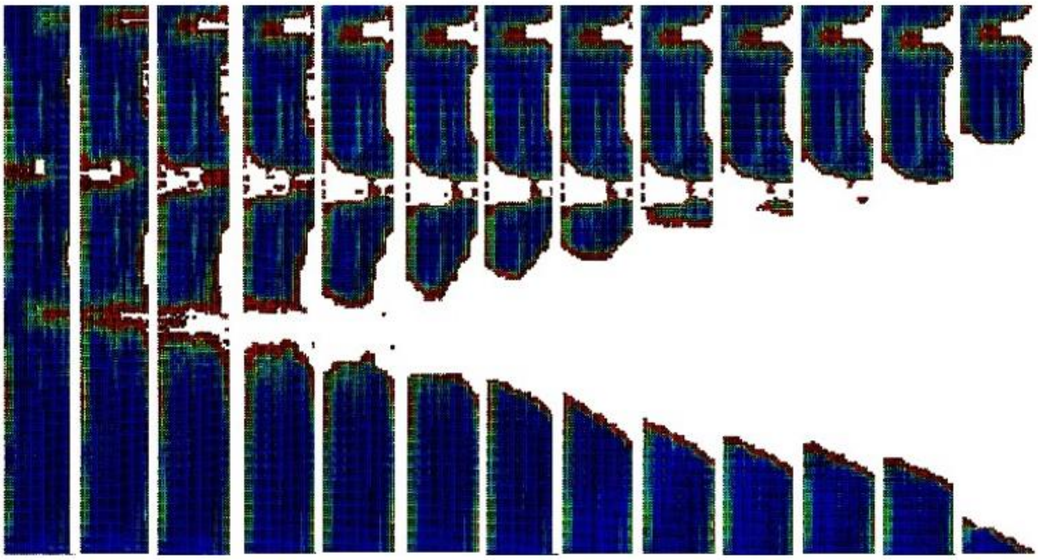

Figure 4. QUADS Criterion in model 7

Model 8 with higher elastic properties showed a different behaviour. The damage initiated from the impact point, but the damage initiation criterion was reached within the model more globally. This was the reason that the model showed inefficient computational behaviour. (figure 5)

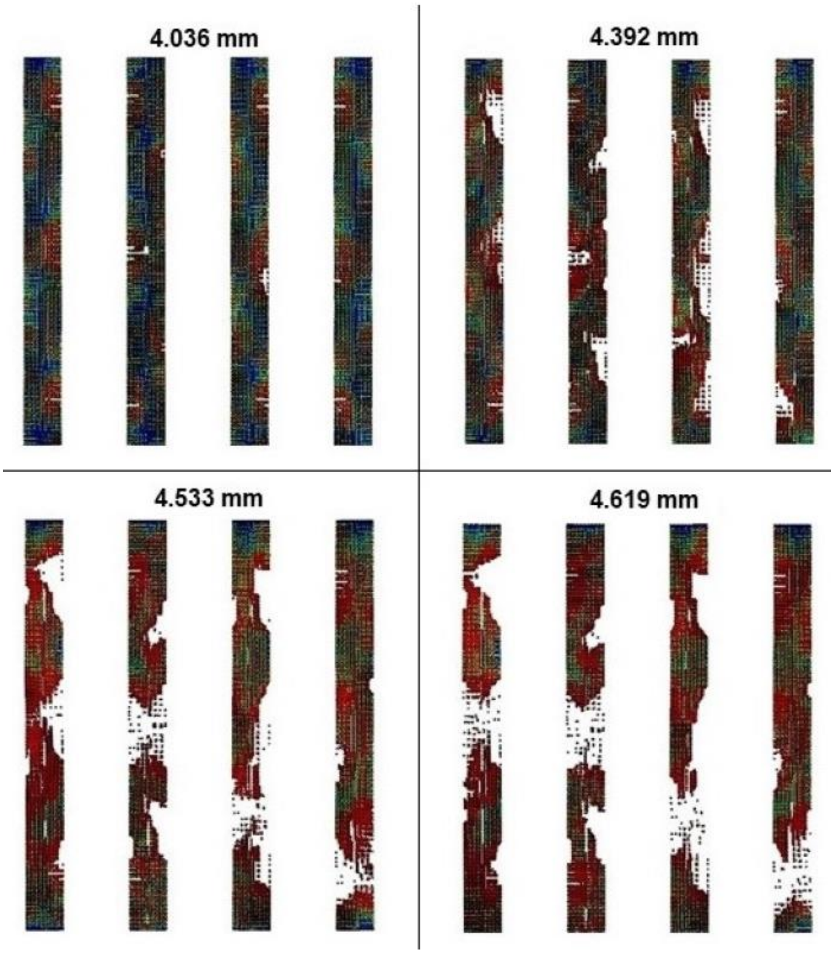

Figure 5. QUADS Criterion in model 8

In general, it was observed from the study that higher elastic properties of the cohesive elements do not favour the convergence behaviour of the models. The reason for this is that a greater number of elements reaches the peak values for the damage initiation criterion in the CZM method and the model gets computationally inefficient. A comparison of several models with increasing elastic properties is shown in table 5.

Parameters	Model 5	Model 8	Model 3	Model 4
K_{NN}	3,250	240,000	1,000,000	1,150,000
K_{SS}, K_{TT}	24,920	86,000	1,000,000	600,000
Increment	2450	1140	1430	1270
Applied displacement (mm)	6,802	4,737	4,563	4,555
Increment 1050	5,256	4,677	4,518	4,531

Table 5. Convergence behaviour of examined models with increasing elastic properties

Each time step refers to ten increments. From table 5, model 4 with the highest elastic properties developed in 2200 increments only 0,024 mm. On the other hand, model 1 had surpassed the 5,25 mm applied displacement in increment 1050. This phenomenon is due to a greater number of elements reaching the damage initiation criterion simultaneously when higher elastic parameters are applied.

Moreover, the required number of cohesive zones was critically assessed to obtain accurate and computationally efficient models. For this scope, impact position A was examined (figure 1). In general, in the examined studies most of the researchers examine the CAI behaviour of CFRP panels applying cohesive elements in the area between the skin and the stiffeners. On the other hand, in impact studies, a greater number of cohesive zones is applied to capture the damage mechanics in impact events. [6]

This parametric study aims at defining the sufficient number of cohesive zones to accurately predict the CAI behaviour with efficient numerical models. The examined case-studies are presented in figure 6 and the results can be seen in figures 7 and 8.

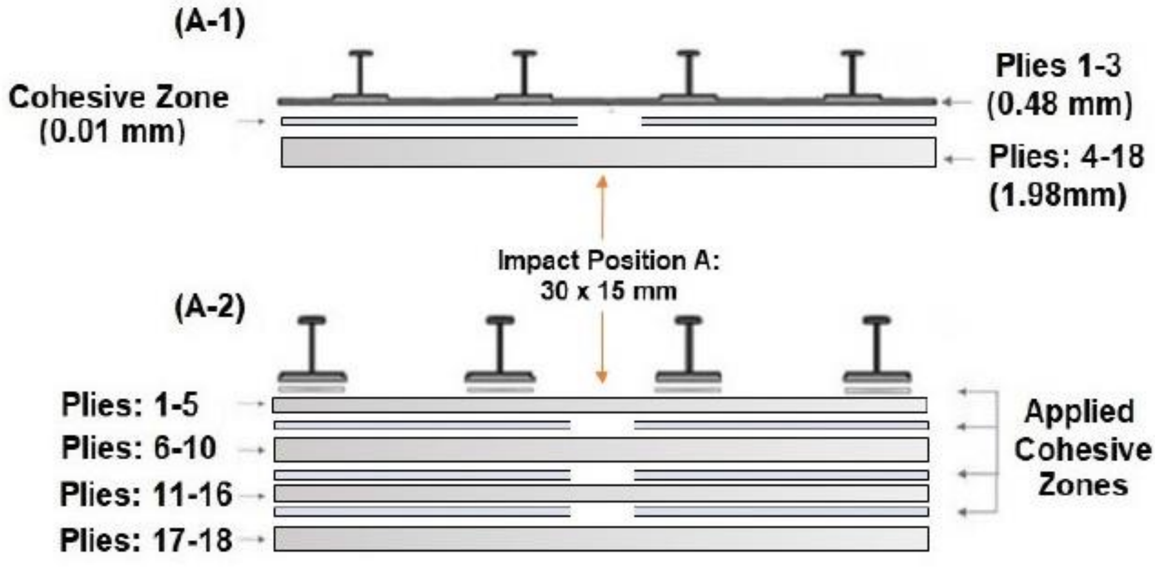

Figure 6. Examined models of impact position A – 1 to 4 applied cohesive zones

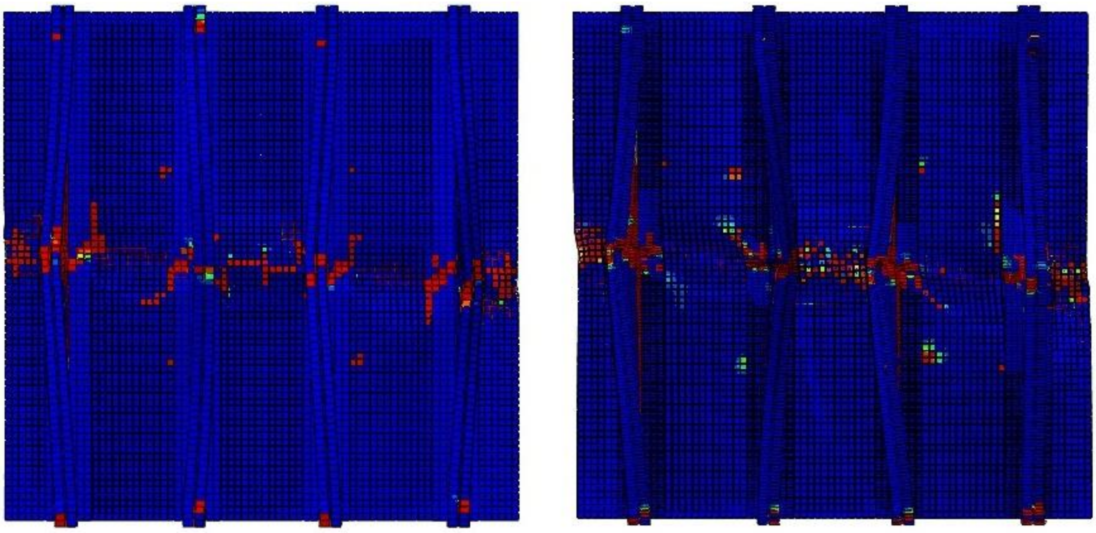

Figure 7. Tensile Matrix damage in models A-1, A-2.

Figure 7 shows that increasing the number of cohesive zones increases the detail in which the damage is captured. Also, an important finding is that to fully capture the stiffener’s breakage, cohesive elements between the skin and the stiffeners are required. Model A-1 that did not have the appropriate cohesive elements in this área did not show the expected stiffener’s breakage. However, the ideal number of cohesive zones is the one that provides trustworthy results without being computationally inefficient. For this scope, model A-2 is shown in figure 8 and more precisely the quadratic nominal stress criterion in the cohesive zones of the skin is presented.

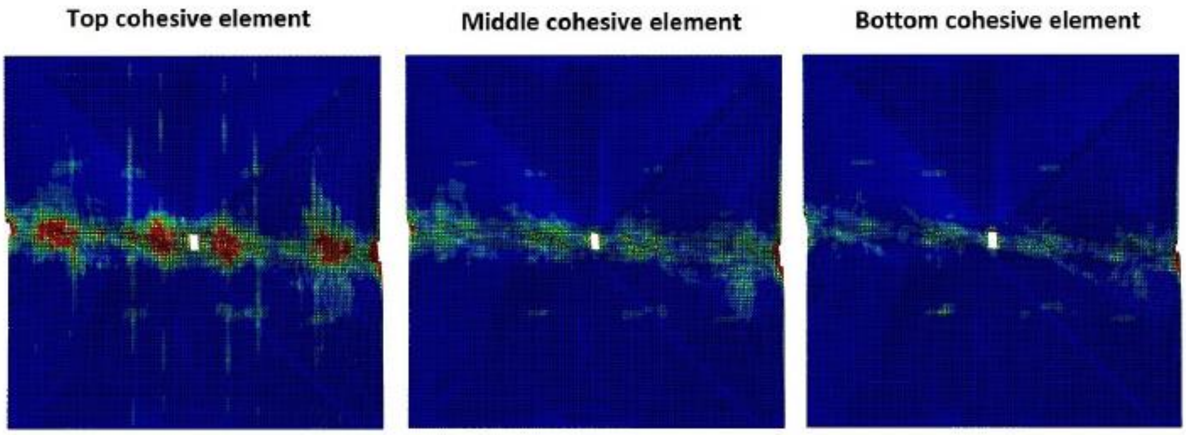

Figure 8. QUADS criterion of the cohesive zones within the skin of model A-2.

Figure 8 shows that most of the damage is captured in the cohesive zone within the top plies. The middle cohesive zone and especially the bottom cohesive zone do not reach the quadratic nominal stress criterion. As a result, those zones can be considered redundant in the model. The required zones to fully capture the damage in the model are located on the área between the skin and the stiffeners and within the top plies of the skin.

Finally, the load-bearing capability of the impacted and pristine panels was examined and the results can be seen in figure 9.

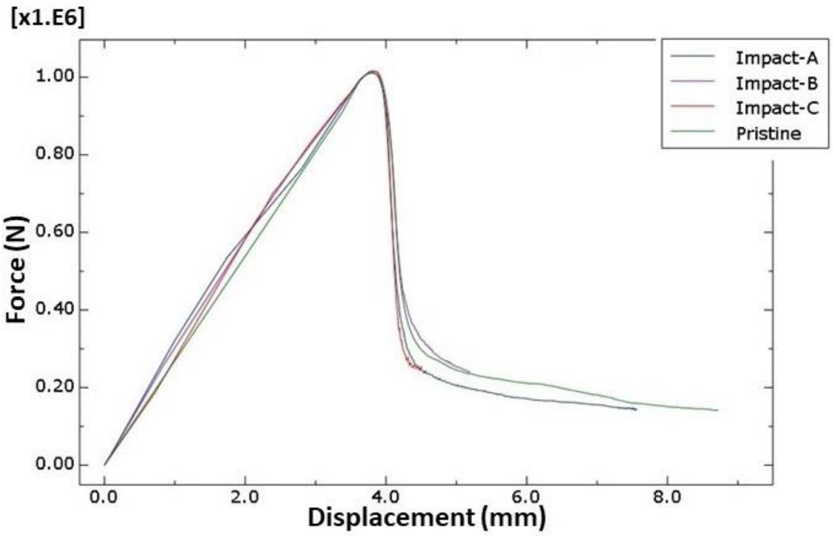

Figure 9. Force – Displacement Diagram in the impacted and pristine models.

The above diagram shows that the CZM method is not capable of capturing the decrease in the load bearing capability of an impacted panel prior to the compressive loading. It is a matter of future work to implement the required user-defined subroutine USDFLD to successfully capture this decrease.

4 CONCLUSIONS

A parametric study to produce the ideal numerical recipe for examining the CAI behavior of CFRP stiffened panels was presented in this paper. Referring to existing experimental results from Feng et al. [1], several numerical models were examined. The results showed that using higher elastic parameters increases the convergence issues of the models. Also, experimental results are necessary to provide a definite answer if a model is accurate or not. Especially, in case-studies that the impact event is not that crucial. Moreover, to successfully capture the damage initiation and propagation, cohesive zones should be applied in the area between the skin and the stiffeners and within the top plies of the skin to achieve accurate results. Applying more cohesive zones within a model was found to be redundant. Finally, it was observed that to capture the decrease in the load-bearing capability of the panels caused by the impact, CZM method is not sufficient and a user-defined subroutine should be implemented in the model.

REFERENCES

[1] Feng Y, Zhang H, Tan X, An T, Zheng J. (2016) Effect of Impact damage positions on the buckling and post-bucking behaviors of stiffened composite panel, Composite Structures; 155: 184-196.

[2] Akterskaia M, Jansen E, Hallett S.R, Weaver P, Rolfes R. (2018), Analysis of skin-stringer debonding in composite panels through a two-way global-local method, Composite Structures; 202: 1280-1294.

[3] Boni L, Fanteria D, Lanciotti A. (2012), Post-buckling behaviour of flat stiffened composite panels: Experiments vs analysis, Composite Structures; 94(12): 3421–3433.

[4] Wang XM, Cao W, Deng CH, Wang PY, Yue ZF. (2015) Experimental and numerical analysis for the postbuckling behavior of stiffened composite panels with impact damage. Composite Structures; 133: 840–846.

[5] Masood SN, Viswamurthy SR, Muthukumar M, Kumar SA, Kotresh GM. (2017), Simulation and validation of disbond growth in co-cured composite skin-stringer specimens using cohesive elements, Composite Materials; 52(6): 807-822.
[6] Zhang J, Zhang X. (2015), An efficient approach for predicting low-velocity impact force and damage in composite laminates, Composite Structures; 130: 85-94.
[7] Riccio A, Sellitto A, Saputo S, Russo A, Zarrelli M, Lopresto V. (2017) Modelling the damage evolution in notched omega stiffened composite panels under compression. Composites Part B Engineering; 126: 60-71.

Cranfield University

CERES https://dspace.lib.cranfield.ac.uk

School of Aerospace, Transport and Manufacturing (SATM) Staff publications (SATM)

2019-09-25

Parametric analysis of cohesive zone model method for CFRP stiffened panel CAI behaviour

Gaitanelis, D. G.

The Hellenic Society of Theoretical & Applied Mechanics

Gaitanelis DG, Giannopoulos IK, Theotokoglou EE. (2019) Parametric analysis of cohesive zone model method for CFRP stiffened panel CAI behaviour. In: 12HSTAM 2019 International Congress on Mechanics, Aristotle University of Thessaloniki, 22-25 September 2019.

https://dspace.lib.cranfield.ac.uk/handle/1826/14655

Downloaded from Cranfield Library Services E-Repository