IMPACT VALIDATION AND SIMULATION OF COMPOSITE AEROFOIL STRUCTURES

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Keywords: Delamination, cohesive zone, soft body impact.

Abstract

This paper presents impact simulation results and validation of a composite aerofoil structure against crushing and soft impact threats at this intermediate scale using a simulation approach that is appropriate for the full component. This simulation approach involves the use of Continuum Damage Models to capture the stiffness degradation and (possible) fracture of the aerofoil component and Cohesive Zone Modelling in the form of contact interfaces to simulate energy absorption originating from delaminations occurring through the thickness of the aerofoil. In the case of soft body threats, the results are validated against experiments. Having validated the simulation against more complex behaviour than simple crushing, conclusions are then drawn against the overall impact behaviour of the structure. Finally, gaps are identified in the current Commercial Off The Shelf (COTS) tools available for composite impact simulation.

1. Introduction

Although composites have been considered for aerospace turbofan applications for many decades it has not found widespread application across the sector until more recently. Composite fan blades have been in operation for around 15 years, but it has only been in the last decade that the application of such technology has spread throughout the aircraft propulsion industry. The latest announcement has come from Rolls-Royce on 26th February 2014 with the declaration of a composite fan system being targeted for the next wide-chord fan blade application.

Figure 1 Image of the recently publicised Rolls-Royce composite fan set.

One key reason for this slow uptake in contrast perhaps to the airframe community has been the difficulty to account for very damaging events such as bird strike on to the fan blades or the release of a fan blade into the surrounding containment structure. Both events drive the composite fan blades into realms where delamination can no longer be avoided and must therefore be accounted for in their analysis.

Accounting for delamination during the analysis of such events, at a component scale can be challenging as the length scale of the component is in conflict with the length scales typically required for modelling such events. To manage the analysis of a full component the element count needs to be kept as low and the time step as long as reasonably possible. In contrast, to model delamination in a reliable fashion the element edge lengths need to remain ideally below 0.5mm [1, 2], which would result in impractically large analysis models.

Some attempts have been made to find a solution to this problem [2, 3, 4]. In such cases, using the cohesive zone modelling approach the constituent properties are altered, typically changing the separation force and the final displacement in favour of maintaining the strain energy release rate. It is crucial to appreciate the limitations of such solution [5] as well, especially where delaminations grow under limited face separation. In such cases these simplifications can lead to under-predictions of the delamination as not all the energy can be released from the interface or element.

When considering high energy events such as bird strike or fan blade containment it may again be feasible to apply such simplifications and achieve reasonable results that in turn could result in a practicable method for its purpose. This paper seeks to demonstrate the viability of such an approach through the analysis of a representative, but much simplified specimen. Results of the simulations will be compared and critiqued against previously published test results on the same specimen [6].

1.1. Specimen Description

The specimen discussed in this paper, is a composite aerofoil-like structure with chord-wise and span-wise taper, although with no twist. A metal wrap is also bonded on to the edge that interacts with the gelatine impactor [6]. The validation cases used in this paper were conducted at the ILK, Dresden and involved gelatine to simulate soft body impacts. Figure 2 shows the geometry of the specimen.

Figure 2. Photo of the specimen (a) and ILK, Dresden spinning rig with a specimen installed (b)

2. Analysis Method Selection

2.1. Overview of Commercial off the Shelf Software options

Whilst a significant amount of research has been conducted into composite mechanics and damage modelling, only a small portion of it has been transferred into Commercial Off the Shelf Software (COTS). Table 1 presents an overview of the material models available in LS-DYNA3D 971 R4.2 [7] along with a small critique for their applicability.

Material Number	Suitable Elements	CDM	Failure Criteria	NL Shear	Book Keeping	Comments
2	ALL	No	None	No	No	Elastic-only card; inaccurate for large strains
22	ALL	No	Chang-Chang	Yes	No	No treatment of compression in XX direction
54/55	Shells	No	Chang-Chang or Tsai Wu	Yes	No	Includes post-failure softening
58/158	Shells / Thick Shells	Yes	Hashin, or Max Stress	Yes	Yes (ERODS)	158 has a non-linear viscoelastic term used for rate dependency
59	Shells/Solids SPH	No	Max Stress or Proprietary Interactive	Yes	No for solids	Exhibits stability issues during crush
219	ALL	Yes	Proprietary	No	Yes	Non-physical input
221	Solids,	Yes	Proprietary	No	Yes	Non-physical input

Table 1. Overview of LS-DYNA composite models up to version R4.2 [7]

For modelling delamination in LS-DYNA, three distinct methods exist:

1. MAT_132 (Orthotropic Smeared crack) [7] – this is in itself a material card that provides behaviour comparable with cohesive modelling.
2. Cohesive elements - although these can provide the means of representing the traction-separation present in delamination, once the element is failed they also require further means to prevent the separated faces from interpenetrating and thus increasing the complexity of their modelling.
3. Cohesive contacts – these provide a robust means of modelling the delamination from the continuum through the traction-separation to the subsequent contacting surfaces.

Using *MAT_132 (the orthotropic smear crack model) would mean that a delamination would amount to the erosion of a part of the actual in-plane load carrying material. This would lead to erroneous results in terms of stiffness/strength of a component. Trying to minimise that amount would additionally lead to very small elements through the thickness and would subsequently unacceptably limit the time step.

For the purposes of this study the combination of *MAT_58 [7] together with cohesive contacts was selected. The particular choice of cohesive contacts has been guided by [8].

2.2. Material card calibration process

The *MAT_058 allowables for the laminate were generated using a bottom up process, where ply properties were calibrated with test data and equivalent laminate properties were extracted from respective finite element models. Calibration of the ply properties included consideration for the non-linear shear effects observed from shear tests.

The DYCOSS cohesive model [7] was used to model the delamination. As already established in the literature [2], tractions used for interface failure are element size dependent. For this reason, a set of traction allowables were generated based on different mesh sizes and calibrated against mode I and mode II fracture tests.

3. Test Cases and Model Setup

To investigate the validity of the above material card and delamination modelling approach on the selected test vehicle two representative test cases were selected:

- Impact by a soft body onto the specimen whilst it was rotating and
- Impact of the specimen onto an inclined steel target.

3.1. Model Description

Figure 3 shows an exploded view of the specimen and its constraints. The composite part was made up of seven sublaminates through its thickness with six interfaces between the sublaminates. Each interface was populated with the DYCOSS tiebreak definition and each sublaminate with the *MAT_058 material card. The metal wrap was modelled with a Johnson-Cook material model.

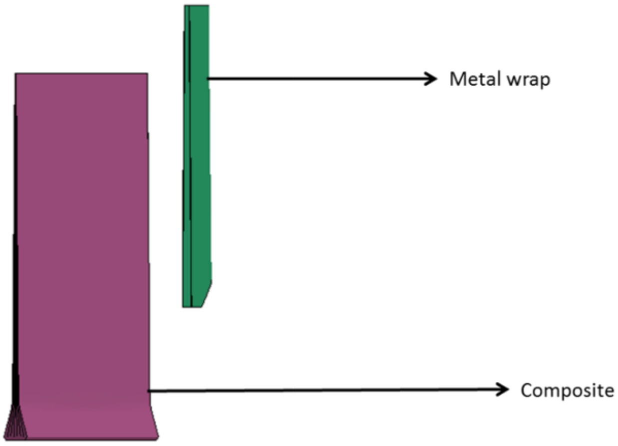


Figure 3. Exploded view of the finite element model of the specimen and holder.

For the soft body impact cases, a cylindrical impactor was used, whilst for the case of the aerofoil crush, an inclined steel target was used. It should be noted here that for reasons of computational efficiency, the run time of the soft body impact event was limited to 20 msec. The rundown time of the actual aerofoil in test (before the aerofoil has stopped rotating) was around 1 sec.

3.2. Cases Considered

Figure 4 presents the overall summary of results taken from the aerofoil test campaign [6]. It was from these that the soft body impact cases were selected. One of the selected cases has been highlighted with the dashed rectangle. The other test case involves a fully delaminated specimen. In terms of specimen crushing, an incident velocity of 20 m/sec was considered, with a total initial kinetic energy of around 30kJ.

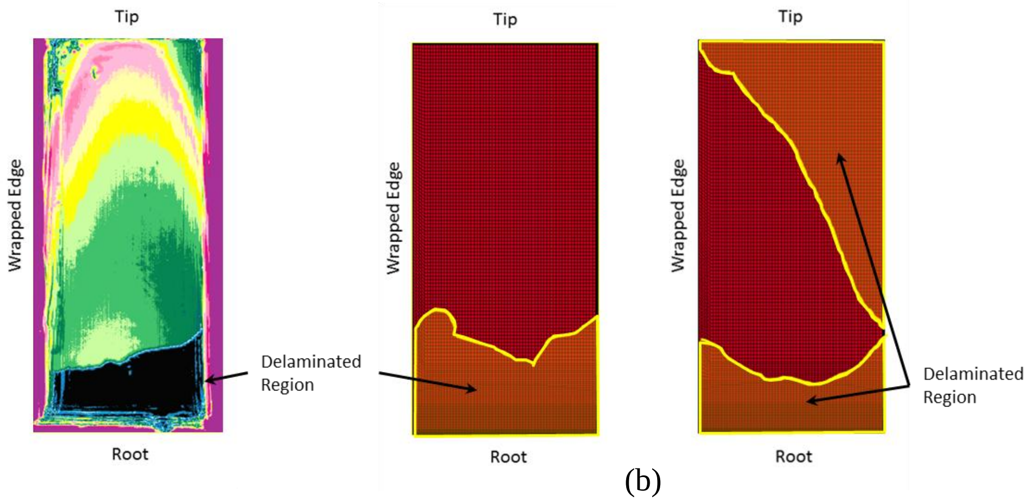
4. Analysis Results

4.1. Soft body impact behaviour

In order to be able to compare the results previously presented [6], the analysis results have been presented in such a way as to represent ultrasonic C-scan and optical photography images.

4.2. Delamination progress with increasing Impact Energy

Figure 6 shows the plan view of the delamination extents for the two soft body impact cases, where (a) represents the limited delamination case including a comparison with the test result and (b) the fully delaminated case. Figure 7 further shows the comparison of the predicted delamination case against that observed in test.



(a) (b)

Figure 6. Specimen delaminations for partial (a) and full (b) delamination cases

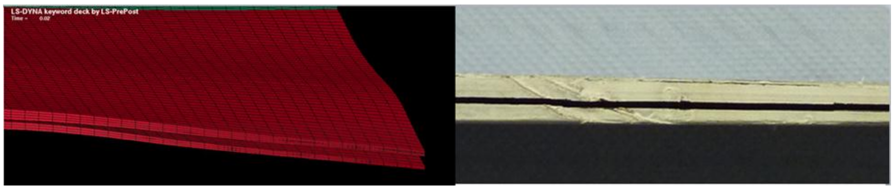


Figure 7. Comparison of separation plane between experiment and simulation.

With regards the first case (Partial delamination) the following observations can be made:

- The model has the same behaviour as the actual experiment. Delaminations tend to propagate around the edges of the aerofoil, while being reduced towards the centre.
- Delamination extents are within 10-15% of the test

In the fully delaminated case, one can see two different delamination planes originating from the tip and the root propagating. Again this is consistent with the experimental behaviour. It is also apparent that the extent of the root delamination is reduced in comparison to the partially delaminated case due to the root being offloaded through the delamination emanating from the tip. This is also consistent with experimental evidence. The position of the delamination through the thickness of the laminate has also been captured well (figure 7).

In the fully delaminated case, however, full delamination had not occurred within the 20ms of the analysis. This could be attributed to one (or both) of the following factors:

- Delamination propagation continues to occur even after the first 20ms. It should be noted that during the experiment, the aerofoil continued to rotate until at least 1 sec after impact.
- The inherent and accepted drawback of cohesive modelling which causes delaminations not to propagate as extensively under limited face separations [5].

When considering the second statement above it must be observed that during the delamination events prevalent under soft body impacts as presented here the relative displacements of the delaminated faces would indeed be notably lower than one might obtain during the more traditional mode I and mode II delamination tests. This may well be an issue when considering the appropriate material properties for analysis and will need further consideration. This is indeed an issue that both the simulation and testing communities should first sentence, coordinate and then act on.

4.3. Specimen Crush

Figure 8 presents different phases of the specimen crush event. One can see that at around 7.5ms part of the aerofoil has been distorted to almost a right angle with no issues of numerical stability. Additionally, no un-zipping of the interfaces, or element deletions have taken place and the timestep remains virtually constant (figure 9).

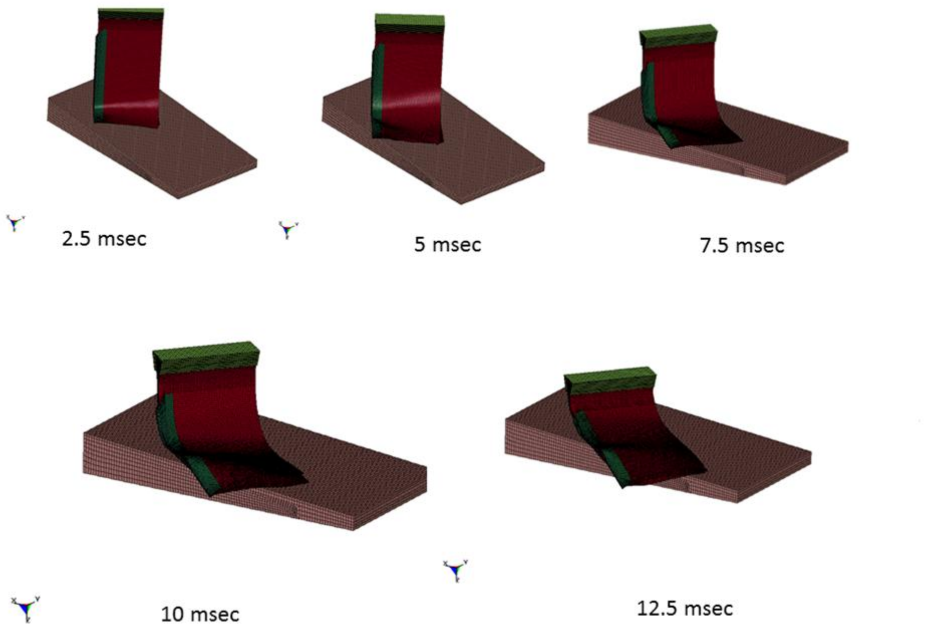


Figure 8. Different specimen crush phases.

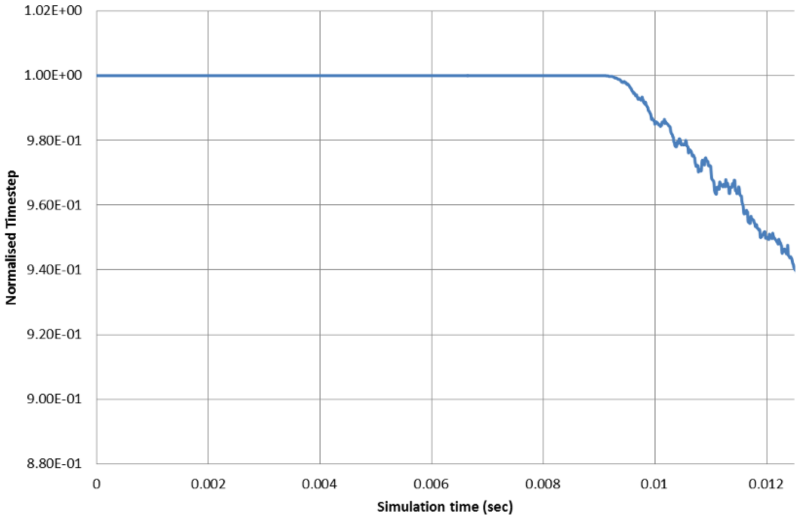


Figure 9. Timestep of the model versus simulation time

The force displacement history presented in Figure 10 is the contact force between the whole of the aerofoil and the target. As it can be seen two main peaks can be identified: the initial contact force and a peak at around 50% of normalised crush distance (against specimen length), corresponding to the specimen deforming to an almost right angle.

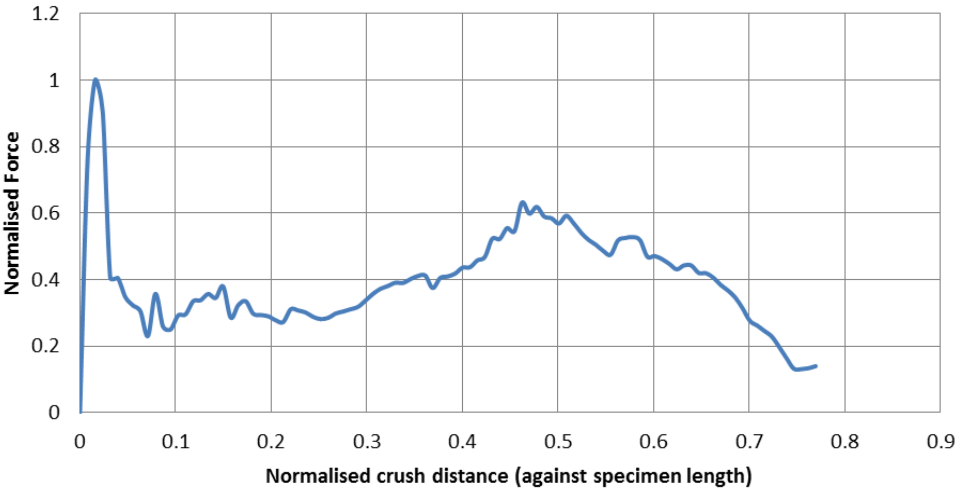


Figure 10. Force-displacement plot of the specimen crush event.

5. Conclusions

This paper presents the basic outcomes to develop a single modelling approach the events pertaining to rotating composite components, whilst retaining a level of practicality with regard to required computing resources, stability of the solution, accuracy and solution time. The methods discussed should therefore not be considered as the ultimate in accuracy for composites impact, but instead an engineering solution and a reflection of the pressures experienced in the aerospace industry.

Through the results presented in this paper it has been possible to show that the methods are accurate enough to capture the failure modes and delamination progression, correlating acceptably well with experiments whilst at the same time achieving high stability in the high energy crush simulation. Further work is still required though to understand the discrepancies for the full delamination soft body impact case, where this was not achieved in the simulation.

When surveying the available material cards in LS-DYNA it is clear that several challenges still exist for the composites modelling world when considering composites impact modelling. These challenges include the implementation of continuum damage models with inherent book-keeping capability for solid elements, the treatment of strain rate dependency both in terms of stiffness and strength and the effect of strain rate on delamination onset and propagation. The latest release of LS-DYNA (v971 R7.1) [9] may well go some way to addressing some of these for industry through the implementation of new material models such as material models 261 & 262. Nonetheless this work is far from over and research needs to continue towards these objectives.

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