Tire debris impact modeling on a composite wing structure

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Abstract: This paper presents the implementation of an industrial FE methodology to predict delamination and debonding for a composite wing box subjected to tire impact. This numerical approach has been developed in Abaqus/Explicit v6.10 and is calibrated and validated using a building block strategy, where analysis has been correlated to test at each level. Ply-to-ply interface and bondline properties have been determined by an exhaustive test campaign to calibrate the cohesive element material cards. Intra-laminar damage model based on the Hashin model has been used together with cohesive elements to model the ply interface and bondlines. The methodology, successfully validated using the aforementioned building block approach, was then applied to tire impact on a composite wingbox structure. Of particular interest is the effect of including modeling of delamination on the prediction of stringer disbonding. For this large structural application a number of limitations were encountered, such as complex interaction of interfaces which created difficulties for run completion, for which a work-around was successfully applied.

Keywords: Aircraft, Composites, Damage, Delamination, Impact, Rubber, Tires.

1. Introduction

This paper presents the implementation of an industrial FE methodology to predict delamination and debonding for a composite wingbox subjected to tire impact. This will enable the effect of such tire impact to be determined numerically without the recourse to very expensive tire impact testing of a whole wing structure.

First the building block strategy is presented, whereby the Non-Linear Finite Element Analysis (NLFEA) methodology is calibrated and validated at each level. The application of the validated methodology to tire impact on composite wingbox structure is then briefly presented. Of particular interest is the effect of incorporating modeling of skin delamination on the extent of skin-stringer debonding. However, there are still a number of limitations such as number of elements required plus the complexity of the interaction of various interfaces, which required a work-around to enable the analyses to complete successfully.

2. Derivation of Methodology

As the methodology is required for large industrial models, only a macro-scale approach is appropriate in order to limit model size and runtime. It is therefore rather challenging to predict delamination and debonding as this usually requires a high level of mesh refinement.

The development of the methodology adopts a newly developed engineering approach to meet vulnerability requirements in terms of delamination and debonding modeling. Based on a cohesive element approach using a ‘knockdown strategy’, this method was first calibrated at coupon level (Level 6) and validated at panel level (Level 5-4). The panel levels include small tire debris impact on generic flat composite panels (Level 5-for details see section 2.1), small tire debris impact on generic skin/stringer panels (Level 4S-see section 2.2) and large tire impact on generic skin/stringer/rib panels (Level 4C-see section 2.3). The material data has been produced from qualification tests plus additional tests such as MMB, to generate parameters used in the model. Intralaminar damage based on the Hashin model has been used together with cohesive elements to model the ply interface and bondlines. This building block approach, Figure 1, aims at monitoring the quality of prediction at every scale so that when it is applied to an A/C sub-component, such as a composite wing box, there is a good level of confidence in the analysis prediction.

Abaqus/CAE has been used to construct the models, and the analyses have been performed in Abaqus/Explicit v6.10-1.

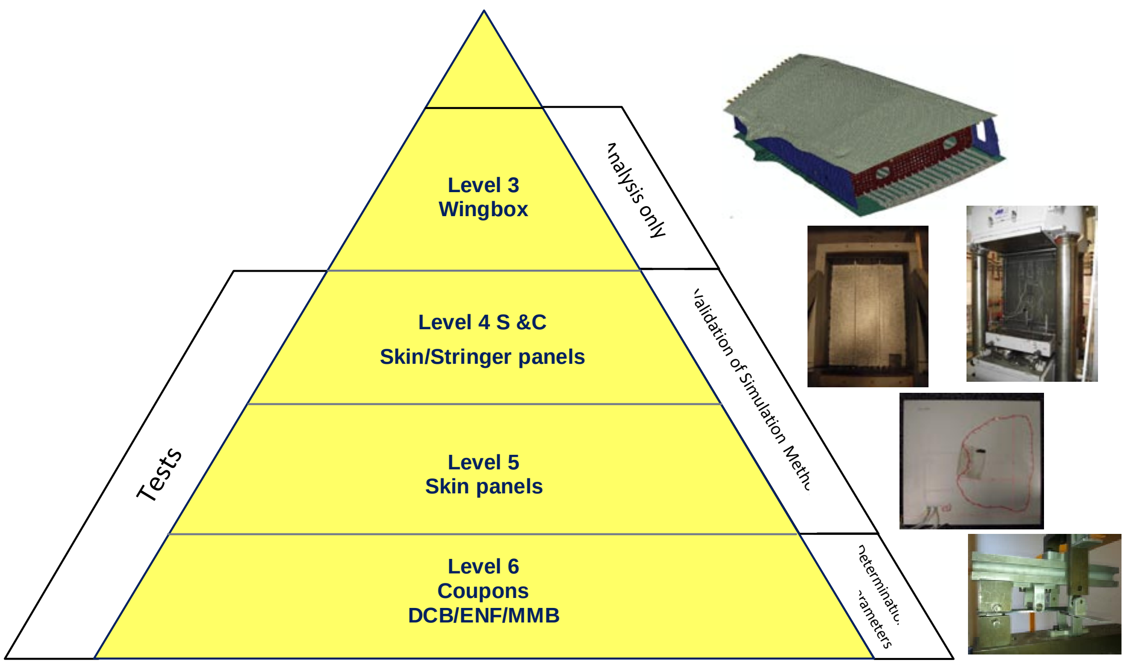


Figure 1: Building block approach applied for method calibration and validation

2.1 Lower Level Testing

Specific material characterization has been conducted on composite materials and bonded joints appropriate for the composite wingbox study. These are then calibrated at coupon level to produce a calibrated material card.

The material cards are then validated by Level 5 tests, in which a small tire debris impacts simple composite plates. From these tests the delaminated area of the plate and strain gauge readings are available for various angles of impact and thickness of plate. An FE model of the test was created, whereby the composite plate is split into two continuum shell layers with a tied cohesive layer at mid-thickness. To capture the failure modes occurring within the composite uni-directional plies, the onset of damage is predicted using Hashin's initiation criteria and a damage evolution law controls the progression of damage. The evolution law is based on fracture energy dissipation during the damage process and the increase in damage is controlled by equivalent displacements. Cohesive elements are used in the tied cohesive layer and are based on a traction-separation law, which predicts elastic, failure and energy absorption of ply/ply interface during loading.

The overall correlation between the FE results and the Level 5 tests were satisfactory, with the FE tending to overestimate the delaminated area.

2.2 Level 4 Simple: Tire impact onto skin/stringer panel.

A test campaign has been conducted on composite skin/stinger panels under tire impact loading. The panels comprise either 1 or 2 stringers with two different skin thicknesses; a 200g tire debris is used at 45° and 90° impact angle with suitable range of velocities required to generate different level of damage within panel.

The panel is located in a rig, Figure 2, where skin and stringer ends are clamped with sides simply supported in out-of-plane directions. A DIC system at the back of the panel is used to monitor panel displacement and additional strain gauges are used to obtain accurate local strain measurements.

Figure 2: Test set-up used for Level 4 Simple test

2.2.1 Finite element model definition

The material card and methodology derived using the lower level tests described in section 2.1 was used to model skin/stringer panel from the Level 4 simple test campaign. Model boundary conditions are similar as applied by test rig; top and bottom panel are clamped using rigid bodies, and sides are simply supported to limit out-of-plane displacement using rigid bodies, as shown in Figure 3.

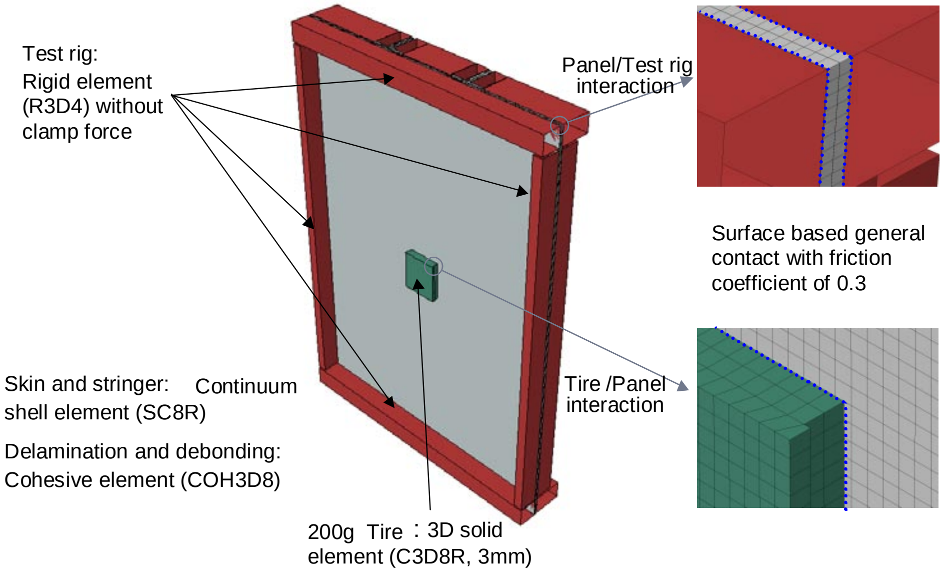


Figure 3: Level 4 Simple finite element model definition

Cohesive layers are introduced in skin, stringer web and skin stinger interface, as shown in Figure 4, to predict delamination in skin and stringer web but also debonding at skin/stringer interface.

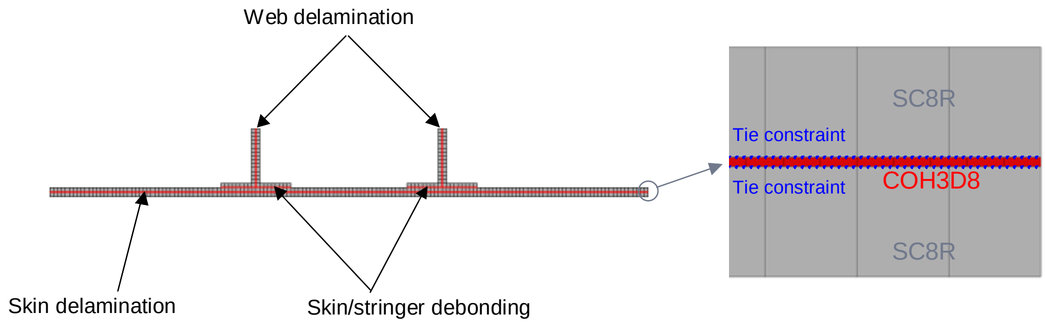
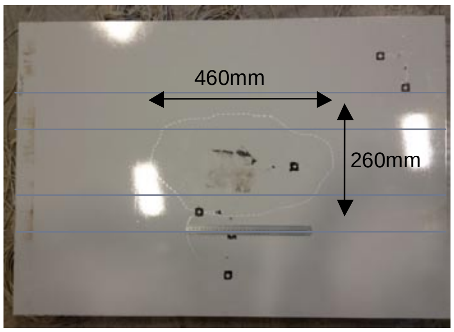


Figure 4: Cohesive layer locations in Level 4 Simple panel model

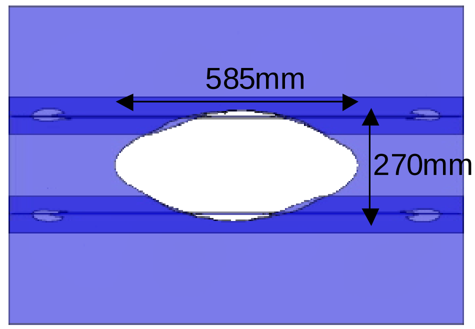
2.2.2 Prediction results

A number of tests were carried out but only one typical simulation result will be presented.

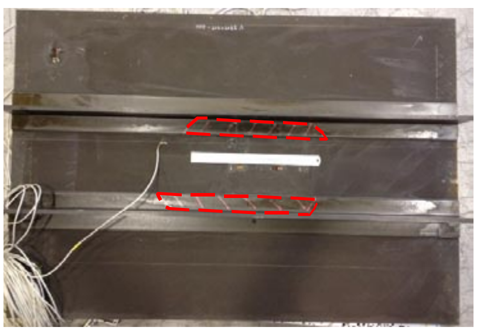
It was found that the analysis predicts satisfactorily the extent of delamination and debonding as shown in Figure 5. In terms of overall structural behavior, the prediction also shows good agreement to test. For instance, strain gauge readings between test and prediction, at impact location, exhibit similar behavior, see Figure 6.



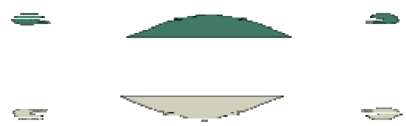
Delaminated area



Predicted Delaminated area



Debonded area



Predicted Debonded area

Figure 5: Correlation to test for Level 4 Simple panel

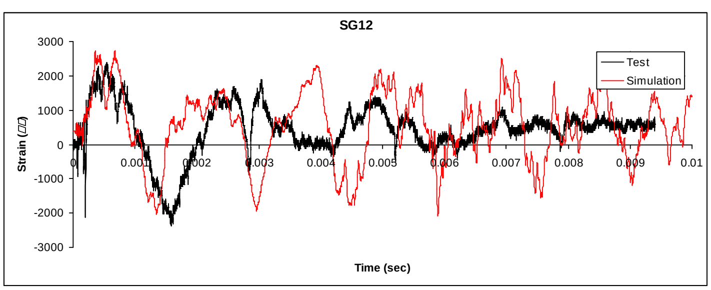


Figure 6: Level 4 Simple panel strain gauge correlation

2.3 Level 4 Complex: Tire impact onto skin/string/rib panel

2.3.1 Testing campaign

A test campaign has been performed on composite panels representative of a wing box lower covers structure; this type of structure is categorized as Level 4 Complex (L4C), Figure 1. Two different panel skin thicknesses were investigated using a 1260g tire and impact angles 90°, 60°, 45° to the panel. Every L4C panel comprises 5 bonded stringers with two bolted ribs as shown in Figure 7.

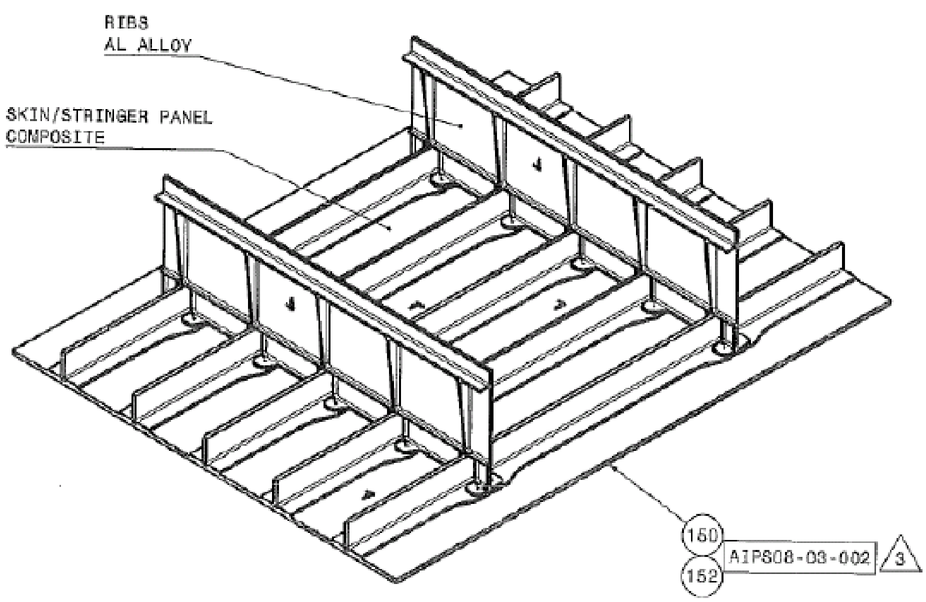
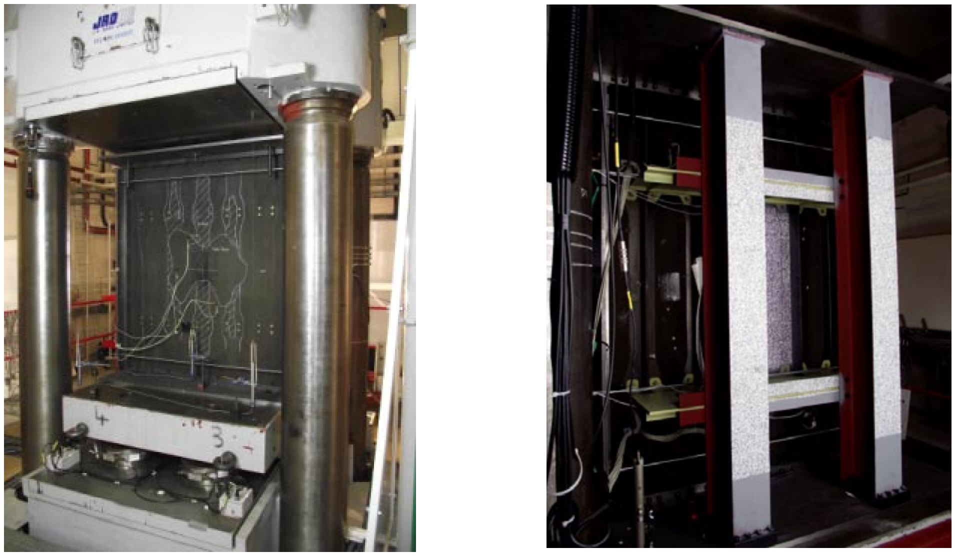


Figure 7: WTF Level 4 Complex test panel and rig set up

The panel is located into a rig, Figure 8a), where clamping is applied at top and bottom ends of panel; the panel sides are simply supported to avoid out-of-plane displacement. To avoid rig movement, the rig is located into a press, which applies a compressive pre-loading. A Digital Image Correlation (DIC) system is used at the back of the panel, Figure 8b), to measure out-of-plane displacement during impact loading. Also strain gauges, located on skin, stringer and ribs, were used at various locations in order to capture panel overall behavior.



a b

Figure 8: Test set-up; a) compressive rig used to support panel; b) DIC system used to monitored out-of-plane displacement

2.3.2 Finite element model definition

The material cards and methodology described in section 2.1 were used to model the composite parts of the Level 4 Complex structure. The created finite element model is as representative as possible to the actual structure, Figure 9. In order to limit model size, only parts of the test rig that clamp to the panel were modeled.

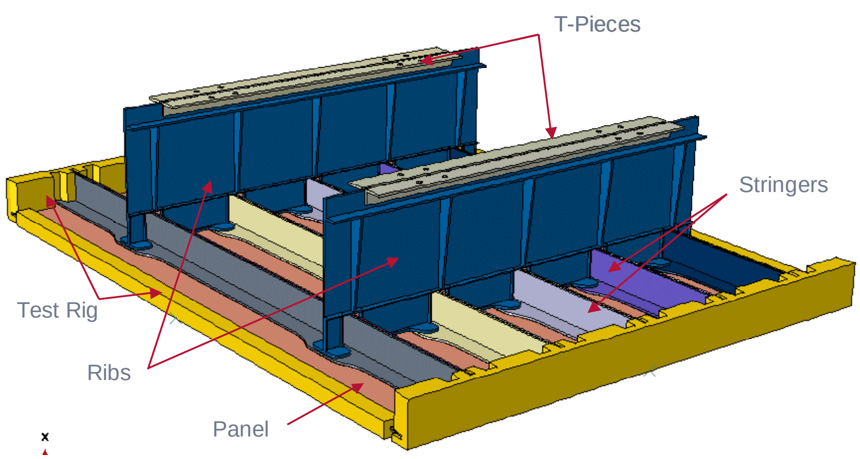


Figure 9: Level 4 Complex panel finite element model definition

Cohesive layers are introduced in skin, stringer web and skin stinger interface in a similar fashion to that shown in Figure 4, in order to be able to predict delamination in skin and stringer web but also debonding at skin/stringer interface.

Mesh independent fasteners were used to represent the bolts between the rib feet, stringer flange and panel. Encastre boundary conditions are used to fix the test rig parts and the ends of the dummy ribs.

In order to ensure correct loading of the panel, the tire location and spatial orientation obtained from test is reproduced as accurately as possible in the model.

2.3.3 Prediction results

A number of tests were carried out but only one typical simulation result is presented here. It can be seen that good correlation is obtained between analysis and test for delamination and debonding as shown in Figure 10. However, the prediction shows small debonding in stringer 1 and 5; this confirms that proposed methodology is conservative in terms of predicting damage initiation.

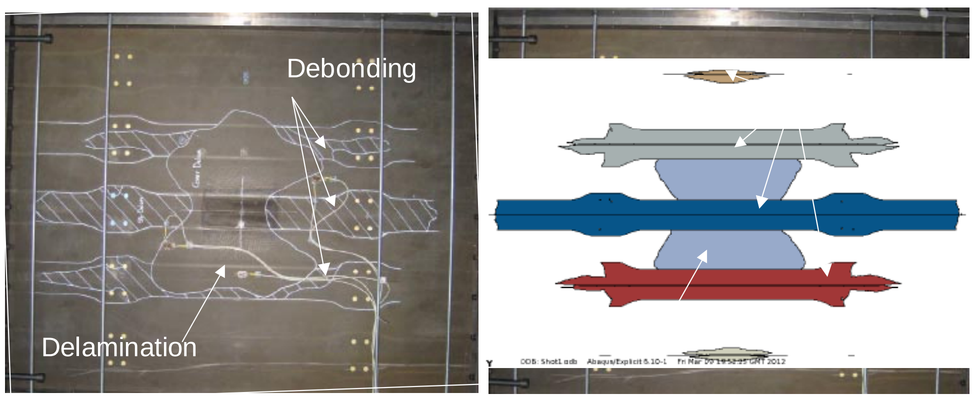


Figure 10: Level 4 Complex impact correlation between test and prediction

From the Digital Image Correlation (DIC) on the back of the panel, out-of-plane displacement curves were extracted at different locations. In terms of overall structural behavior, the FE prediction shows a good agreement to test. This is shown in Figure 11, where the out-of-plane displacement at various locations within the impact vicinity correlate closely with test results.

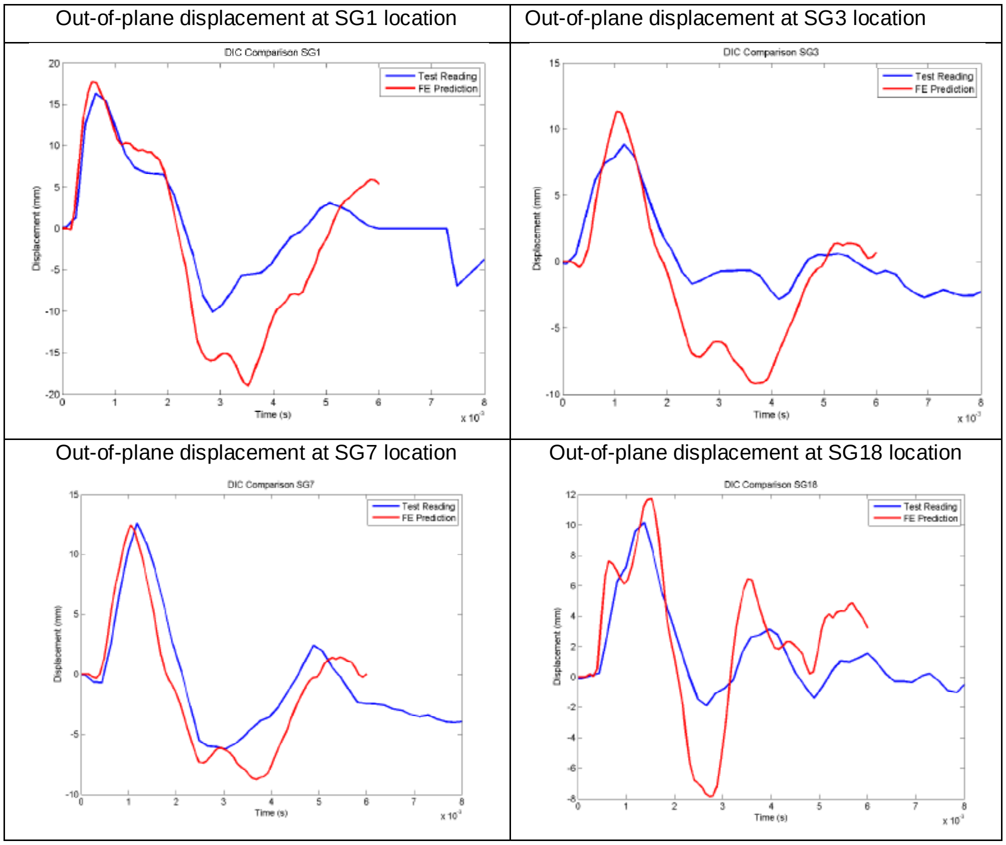


Figure 11: Out-of-plane displacement comparison between test and prediction at various locations

3. Application of Validated Methodology to Composite Wingbox

The building block approach outlined in section 2 resulted in the following methodology:

- For the composite uni-directional plies, the onset of damage is predicted using Hashin's initiation criteria and a damage evolution law controls the progression of damage.
- Ply-to-ply interfaces and bondline interfaces are modeled using cohesive elements based on the traction separation law. Not all ply-to-ply interfaces are considered and so only a few are selected for modeling.
- The knock-down approach is adopted whereby larger cohesive elements can be used, by manipulating material parameters following the method of Turon (Turon, 2007).
- Material data for UD composite is obtained from Qualification Test Report (QTR).

This methodology has been applied to the lower wing skin of a composite wing box structure. Non-Linear Finite element Analysis (NLFEA) has been carried out using Abaqus/Explicit v6.10-1. The purpose of the analysis is to predict the behavior of the wingbox lower cover subjected to tire impact, particularly in the prediction of composite damage including disbond of stringers and delamination of the cover.

3.1 Modeling approach

The majority of the structure was meshed using conventional shell (S4R) elements, but the lower cover and stringers were modeled using continuum shell (SC8R) elements. Cohesive (COH3D8) elements were also used where appropriate.

In the region of interest the model typically had a mesh density of 5mm x 5mm elements. This fine meshing ensured that the behavior (and in particular failure) of critical components could be captured. To keep the overall number of elements in the model as low as possible the mesh density was coarsened further away from the impact zone. Figure 12 shows the mesh density used.

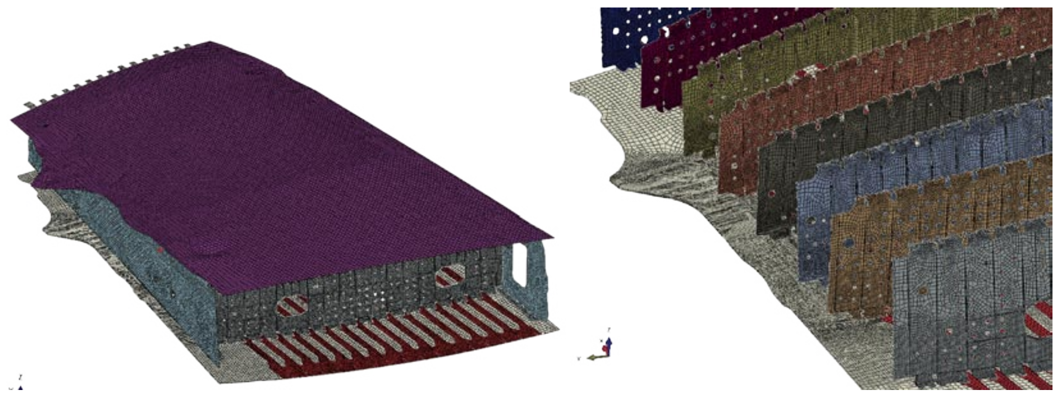


Figure 12: Overall mesh of wingbox model (l), and mesh density used in and around the region of interest (r).

The model of the wingbox contained approximately 2.8 million elements.

3.2 Tire Debris Impactor

The tire debris weighed 1.26kg, was 181.66mm square and had a thickness of 18mm.

The tire debris was constructed using 3D continuum elements (C3D8R), approximately 3mm x 3mm x 3mm, and has material regions appropriate for external rubber tread and a reinforcement layer. The material for the upper tread and reinforcement used a hyperelastic formulation. Densities were modified to ensure the overall mass was correct.

3.3 Wingbox Materials

A number of different materials are used to construct the inboard wingbox. The distribution of these materials in the wingbox is shown in Figure 13.

The majority of the wingbox (covers, spars and stringers) is manufactured from uni-directional composite laminate. The ribs were modeled with aluminium alloys.

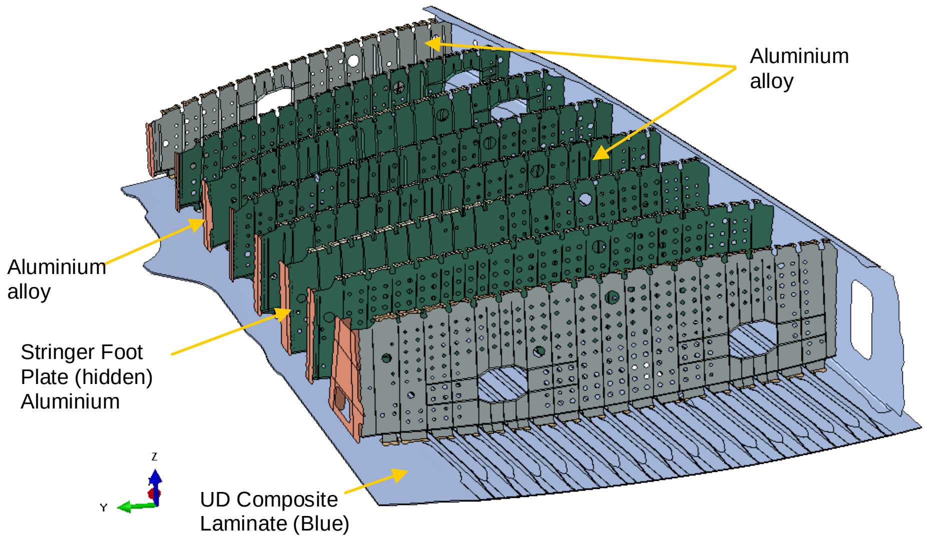


Figure 13: Wingbox materials

3.4 Bolted Joints

The bolts connecting the rib feet through the stringer flange to the lower cover are of interest. Mesh independent fasteners were used to represent the bolts. Bi-linear bolt flexibility curves were used for bolt shear and tension. Bolt failure was allowed in tension and shear; however a coupled shear-tension criterion was not used.

3.5 Cohesive elements

Cohesive elements were used to model the bond interface between the stringers and the lower cover. To model delamination, the lower cover is split into 4 layers, each separated by a cohesive interface. From inspection of the ply stacks used across the region of interest of the lower cover, it was decided to locate the three cohesive layers through the depth of the panel which were symmetric about the cover centreline. The stacking of the four layers of continuum shell elements with the three layers of cohesive can be seen in Figure 14.

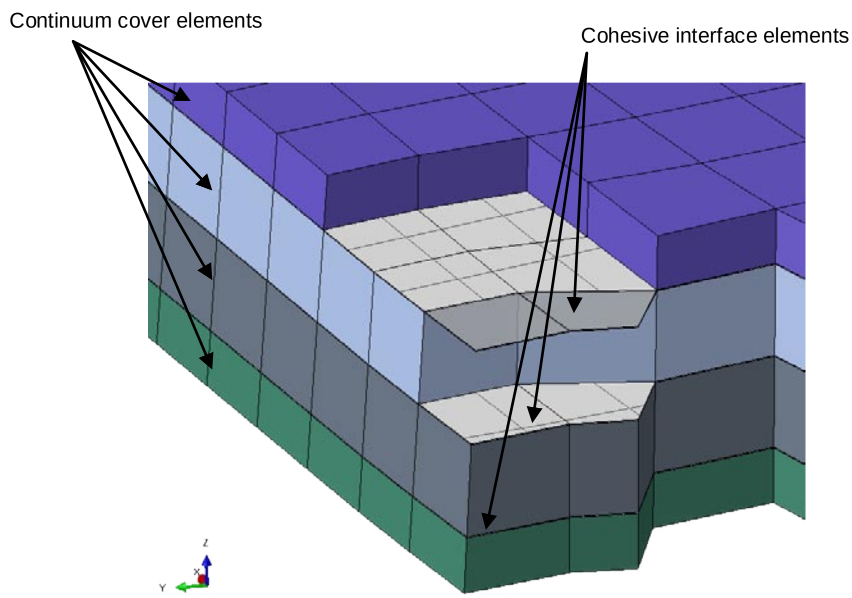


Figure 14: Thin cohesive layer inserted between 4 layers of stacked continuum shells

This split-panel method was only applied in the region of interest, since the extra number of elements it required was significant. The region of interest meshed in this way can be seen in Figure 15. The edges of this region are not smooth because the boundary of the stacked-shell region follows the thickness changes in the cover; it therefore tracks along the edge of existing different section definitions.

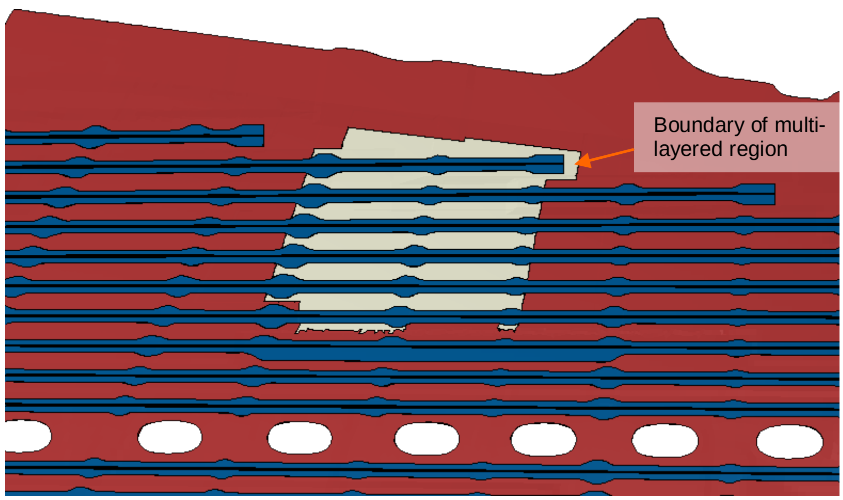


Figure 15: Region of interest (white) with cohesive elements within the cover.

3.6 Limitations

The method of splitting up the lower cover introduced a significant number of additional elements, taking the element count to 2.8 million. As well as the large number of elements the solver also had to cope with very difficult contact regime created by the multiple thin cohesive layers, and element failure. This high degree of complexity meant that it was difficult to get the model to run to completion.

When all parts of the model were set up as desired, spurious cohesive failure was often observed at the extremities of the model. A work-around to these unrealistic results was found by removing the tie constraint between the stringers and the cover outside of the region of interest. This means that outside the region of interest the lower cover will be more flexible in the model than in reality. It was judged that this would not significantly affect the results since the damage in the panel is a local effect.

4. Results

4.1 Impact Scenarios

A study was performed to determine the likely worst case scenarios for tire debris impact, taking into account trajectory of impact and cover thickness. The results of this investigation resulted in a total of ten impacts on the lower cover being analyzed.

One of these results is briefly presented here. The results are presented both for an analysis which include modeling of lower cover delamination, as well as an analysis where no cohesive elements have been used in the lower cover.

4.2 Impact 1: Tire Debris Impact Between Two Central Stringers

The results of this impact on the model with cover cohesive elements within the lower cover skin can be seen in Figure 16. In this plot it is shown that the impact between the central stringers has caused bondline failure underneath both of these stringers. One of these is predicted to be dis-bonded completely in a rib-bay whereas the other stringer partially in the same rib-bay. In this figure, the structures are also slightly transparent so the cohesive layers within the panel can also be seen. Three rings can be seen, indicating the boundary of damage in the three cohesive layers in the lower cover. It is predicted that the total envelope of cohesive damage will be the majority of the area between the central stringers in a rib-bay, with the outermost and middle cohesive layers having a similar area of delamination and the innermost cohesive layer the smallest area.

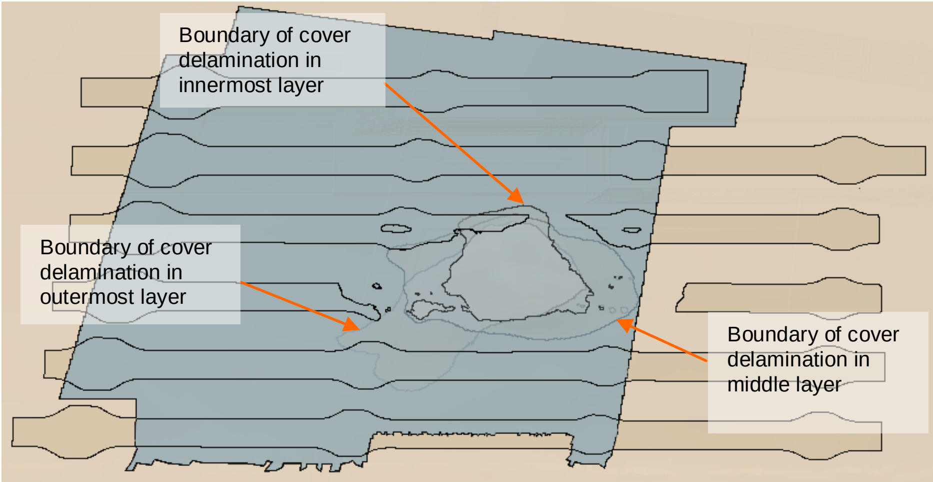


Figure 16: Impact 1 Results, With Cover Cohesive elements. Transparent Plot.

The analysis using the model without cohesive elements in the cover predicted similar levels of damage in the cohesive interface between the cover and stringers. This can be seen in Figure 17, which is contoured by displacement. It shows that the central stringer is predicted to be dis-bonded for the whole rib-bay. The other central stringer shows similar dis-bond to that shown in Figure 16, and also the lower stringer is also predicted to sustain a small amount of dis-bonding. The stringer dis-bond in the model without cohesive elements in the skin appears to be slightly less overall than the model including cover cohesive elements. There is a slightly different spread observed, with the damage in the model without cover cohesive elements not tracking so easily along stringers and spreading less readily between stringers.

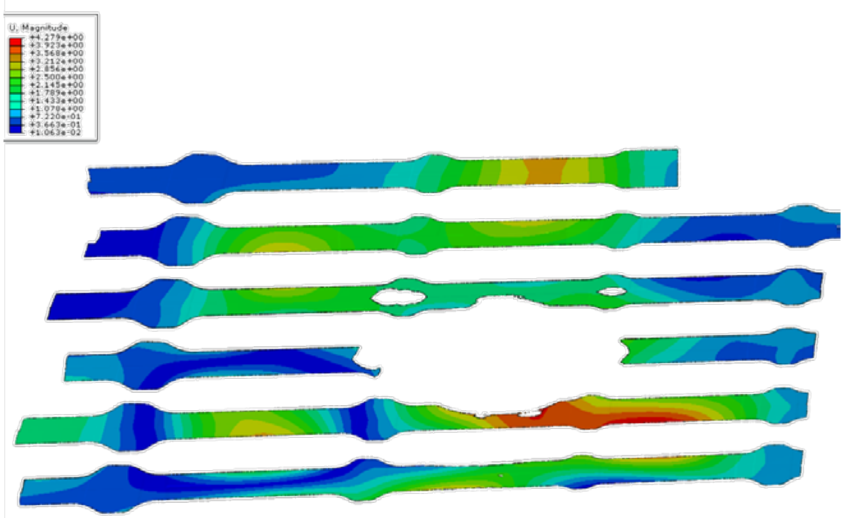


Figure 17: Impact 1 Results, Without Cover Cohesive elements.

5. Conclusions

This paper demonstrates the use of validated methodology for impact on a composite wingbox. The building block approach has been adopted whereby at each level the methodology has been correlated and validated against test.

Two different methods for modeling the composite wing box have been presented, i.e. with and without cohesive elements in the lower cover skin. For the impacts in this study, both methods give very similar damage predictions for the extent of stringer to cover dis-bonding, providing confidence in each method.

Further research is currently being carried out to enhance the delamination and debonding methodology presented herein. This includes enhanced cohesive elements and also cohesive surfaces.

6. References

1. Turon, A., "An Engineering Solution for Mesh Size Effects in the Simulation of Delamination Using Cohesive Zone Models," Engineering Fracture Mechanics 74 1665-1682, 2007.

7. Acknowledgement

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