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PROGRESSIVE FAILURE OF IMPACT-DAMAGED COMPOSITE OMEGA STIFFENERS

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Summary: *Although fibre-reinforced composite materials have been successfully applied to aircraft structures providing increased flexibility in engineering and design through improved laminate design and material selection, the optimization process is unfortunately still time consuming and costly. This is partly due to the fact that numerous and extensive coupon and component level testing are routinely required in the assessment of the possible designs. However, recent advances in computational techniques and improved understanding of the mechanics of failure in composites may be exploited to reduce the design cycle and cost. In this study, progressive damage finite element models are developed to predict the behaviour of composite omega frames under low-velocity impact load and four-point bending test. The results of this study are presented and show how these tools may complement experimental testing with improved understanding of the underlying progressive failure mechanisms leading to final failure.*

1 INTRODUCTION

Many parts of aircraft structures are made of stiffened panels in which thin sheets of metallic or composite panels are stiffened by beam profiles called stringers, frames, etc. These beam profiles maintain the shape of the panels and increase its resistance to bending, tensile, and compressive loads. These loads are mainly unidirectional in the longitudinal direction; therefore employment of anisotropic materials such as fiber reinforced composites in these profiles could give significant weight savings compared to the traditional profiles made of isotropic materials such as aluminium.

The application of fiber reinforced composite materials to these stiffener profiles creates flexibility in design in terms of laminate design and material selection. Engineers are able to choose various layup sequences of the composite profiles and use combination of materials in the layup. These design parameters should be tailored such that the stiffeners can achieve its design purpose while having the lowest possible weight or cost. Unfortunately the process of design iterations can be costly and time consuming due to numerous coupon tests in assessing each possible design. Robust, accurate analytical and numerical methods can expedite and reduce the cost of this iteration process.

In this study, omega frames under successive load of impact and 4 point bend shown in Figure 1 are tested and simulated. These test cases are important in designing frames for aircraft fuselage because the composite frames are expected to be able to withstand the design load despite the presence of accidental damage within the frames. A finite element progressive damage tool was developed to predict the behaviour of this omega frame under these successive loads. The progressive damage modelling method employed follows a previous study by Ridha et al. [1] and Su et al. [2] in which each composite layers are modelled by using three dimensional shell elements while the interface between layers are modelled using cohesive elements. The predicted impact damage size and subsequent failure under four-point bend were compared to scanned images of the damage and recorded strength of actual specimens in both types of experiments. The finite element tool is the used to analyse various omega frame layup design to find a better design solution.

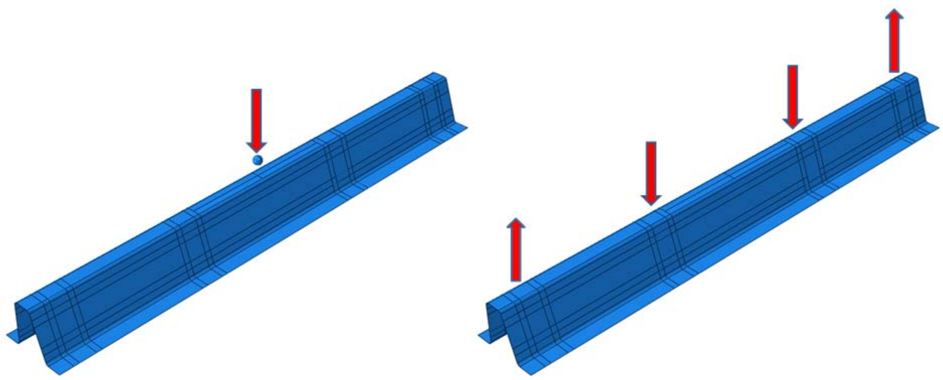

Figure 1 Impact and four point bending simulations

2 EXPERIMENTAL TESTS

Omega frames made of IMA-M21E carbon fiber reinforced epoxy were autoclave-cured and cut to 1 m length each. Figure 2 shows the schematic cross-section of the omega frames. The web and outer flange part of this omega frame have the layup $[-30, 90,30,-30,30,-30,30]_s$ while the inner flange part has two additional 0 degree plies, resulting in the layup $[-30, 0,90,30,0,-30,30,-30,30]_s$.

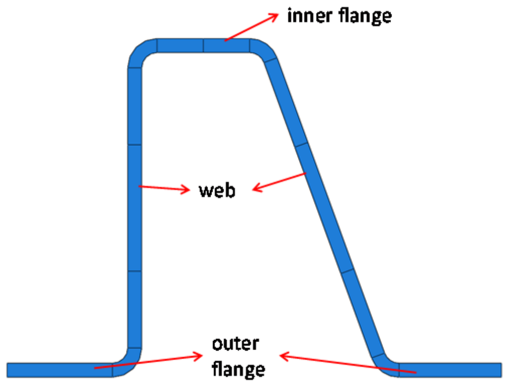

Figure 2 Omega frame cross section

The omega frames were then impacted in the middle of the inner flange using a round tip impactor of 16 mm in diameter with 30 kJ impact energy. The frames were ultrasonically scanned to obtain the damage map. The damage area is marked on the specimen, as shown in Figure 3.

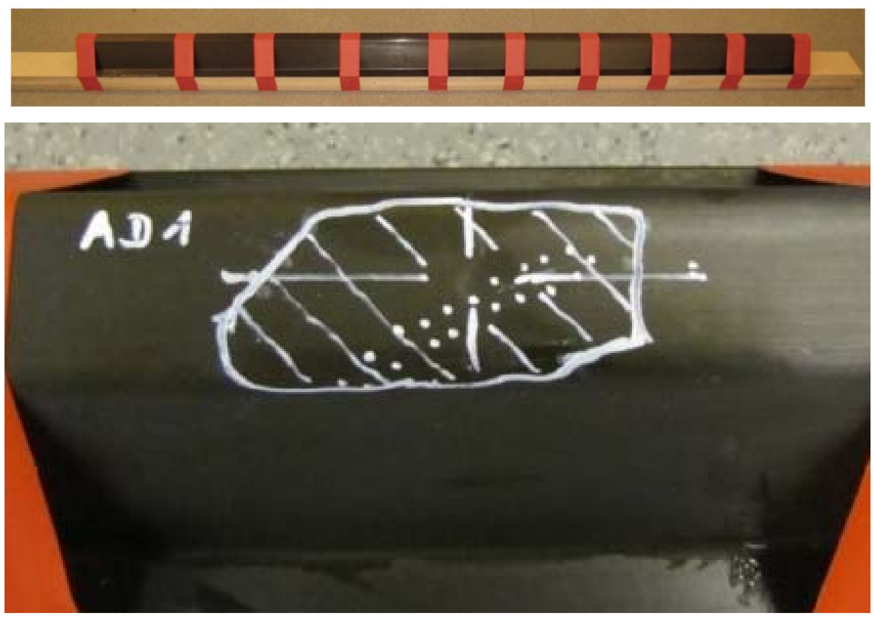

Figure 3 Impacted omega frame

Impacted specimens were then loaded via four-point bend jig; Figure 4 shows the schematic of the test. Three specimens were tested and the average recorded strength is 27.17 KN with a standard deviation of 3.44 KN.

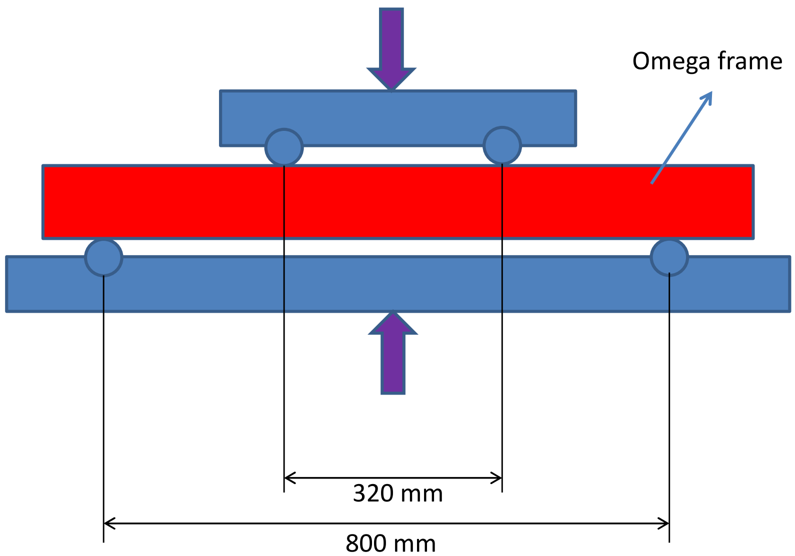

Figure 4 Schematic of four-point bend test

3 PROGRESSIVE DAMAGE SIMULATION OF IMPACT TEST

Progressive damage models of composite stiffeners under impact tests and the corresponding 4 point bend after impact test were developed based on the recent study by Ridha et. al.al. [1] . In this progressive damage model, composite plies are modelled using the continuum shell element in Abaqus [3] while interfacial delamination is modelled using cohesive elements. Failure initiation in composite plies are determined using the Tsai-Wu [4] failure criterion for the matrix dominated damage and the maximum stress criterion for the fiber dominated damage. Initiation of delamination is determined using a quadratic stress criterion and its progression is based on a fracture energy criterion.

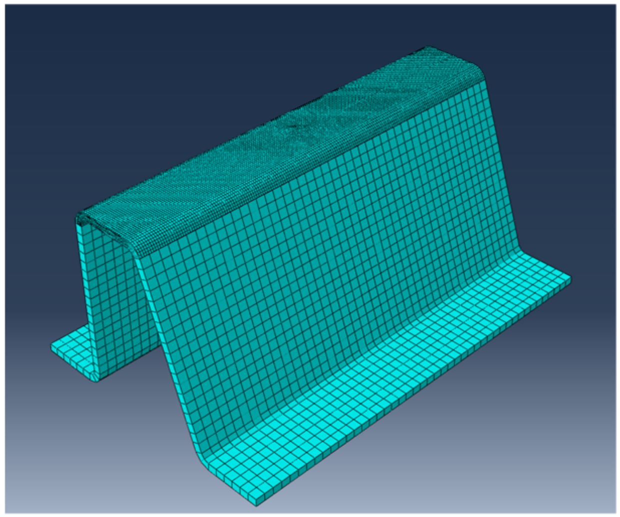

Figure 5 Finite element model of composite stiffener

Figure 5 shows the finite element model used to model the impact load on the omega frame. Since impact damage is expected to occur only in the top part of the stiffener, progressive damage model algorithm and fine mesh are only applied to this part of the model. In order to decrease computational time, the web and outer flange of the omega frame is modelled using coarse continuum shell elements. The length of the model is 180 mm. As shown in Figure 6 the load and boundary conditions of the impact test are idealized as concentrated pressure at the impact point and pin-roll boundary conditions at the base respectively.

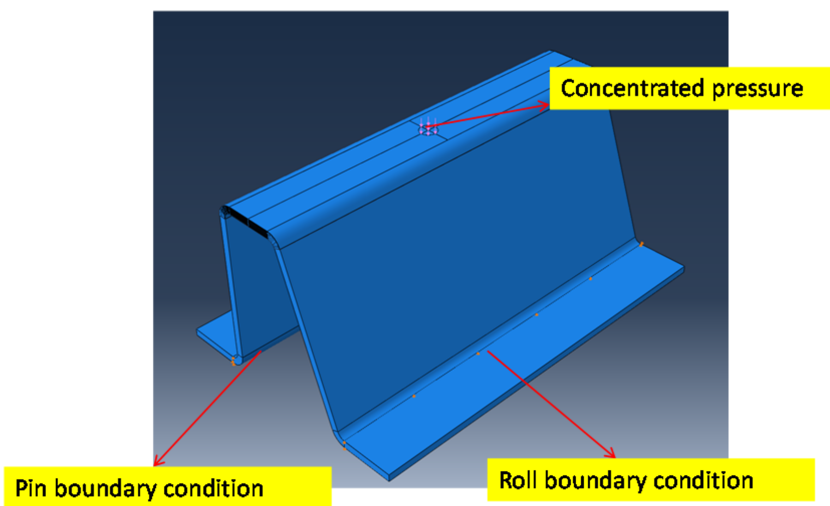

Figure 6 Load and boundary condition

The damage map predicted by the model is shown in Figure 7 and compared to the actual damage map obtained from experiment. The predicted area is smaller and damage more concentrated than the actual damage map in the test specimens. This is probably due to some uncertainty in the assumed delamination strength and toughness used in the model. The analysis also did not consider geometric nonlinearity, which could result in more locally concentrated damage.

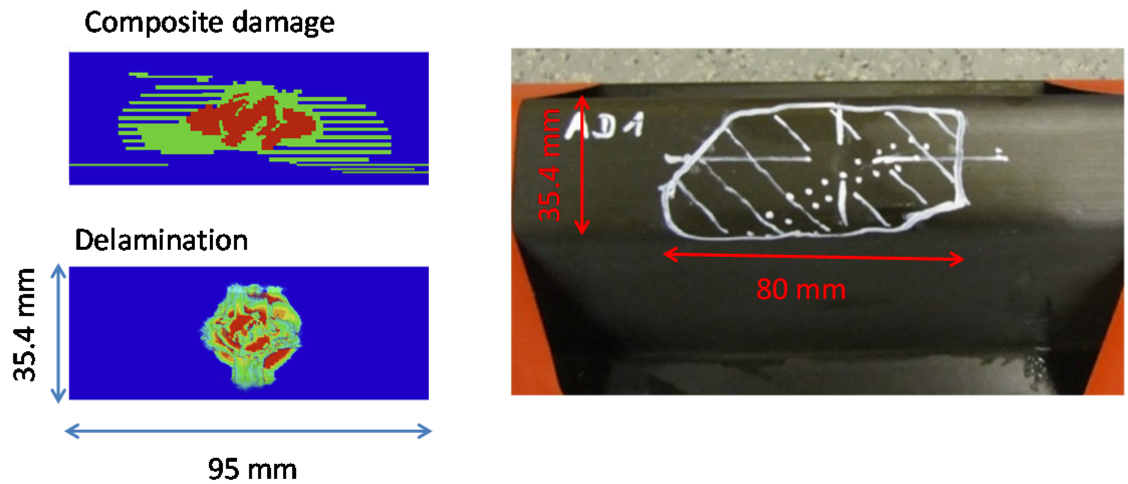

Figure 7 Damage prediction of impacted composite stiffener

4 PROGRESSIVE DAMAGE SIMULATION OF FOUR-POINT BEND TEST

Modelling of the subsequent four-point bend tests was also performed. Each layer of the composite lamina was modelled using three dimensional shell elements while the interfaces between layers are modelled using cohesive elements (Figure 8). To save computational time, only the midsection of this model uses finer mesh with damage modelling algorithm. As shown in Figure 9, the impact damage was idealised as elliptical in shape based on the predicted damage map shown in Figure 7.

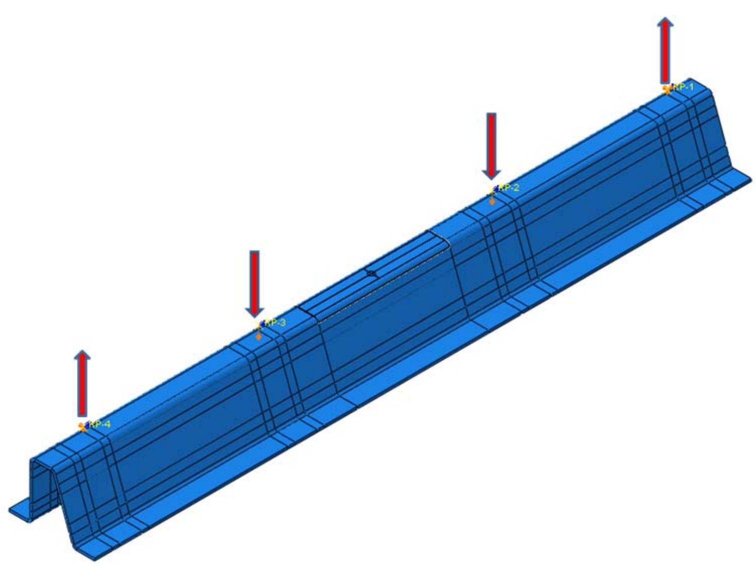

Figure 8 Four-point bend test model

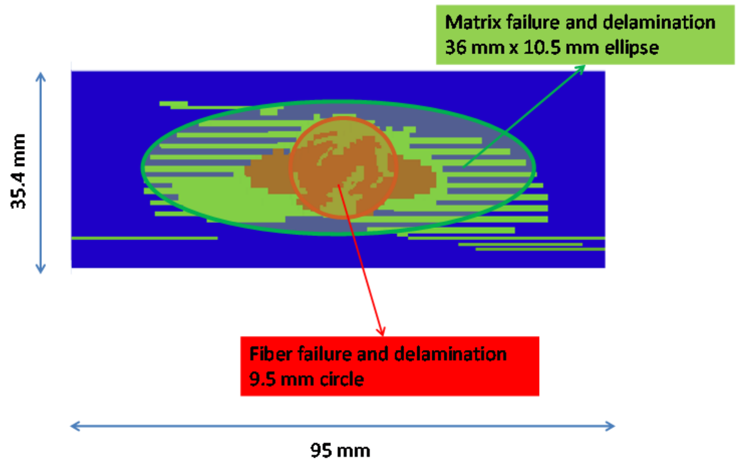

Figure 9 Impact damage idealization

Figure 10 shows the specimen deformation predicted by the model for the omega frame with $[-30/0/90/30/0/-30/30/-30/30]_s$ layup in the middle flange area. Damage in the four-point bend test specimen is predicted to start at the impacted middle flange area marked by buckling or out of plane deformation of composite layers. The damage then spread towards the web where the composite layers in this area deform outwards and buckles. The same failure pattern was observed in the experiments.

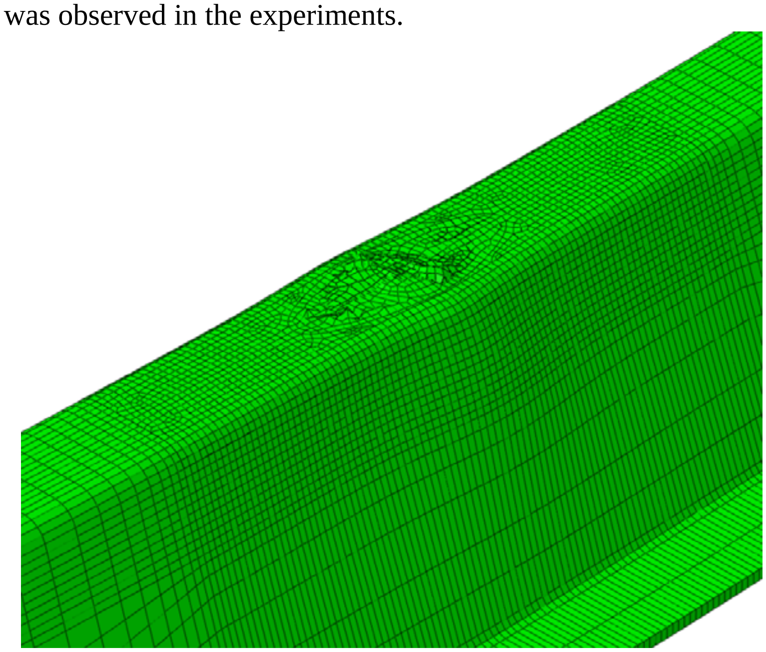

Figure 10 Predicted deformation after 4 point bend test

The model over-predicted the four-point bend strength; the predicted strength is 40 kN while the average strength of the tested specimens is 27.17 kN. At the time of the writing of this paper, preliminary results using a geometrically non-linear analysis and refined material toughness properties show better agreement between analysis and experiment, and will be reported at the conference.

5 IMPACT SIMULATION ON VARIOUS LAMINATE DESIGNS

Similar impact simulations were performed to predict the behaviour of omega frames with other alternative configurations using different laminate design and material. Figure 11 shows some of the damage map obtained from these models. Employment of more 90 degree plies and AS7/M21E carbon epoxy are considered in these models. The results show that layup configurations with more 90 degree plies in the inner flange area of the frame would likely be more tolerant to impact load because the damage area in these frames are expected to be smaller. This is because the additional 90 degree plies increases the bending stiffness in the transverse direction and in turn inhibit the damage progression under impact load.

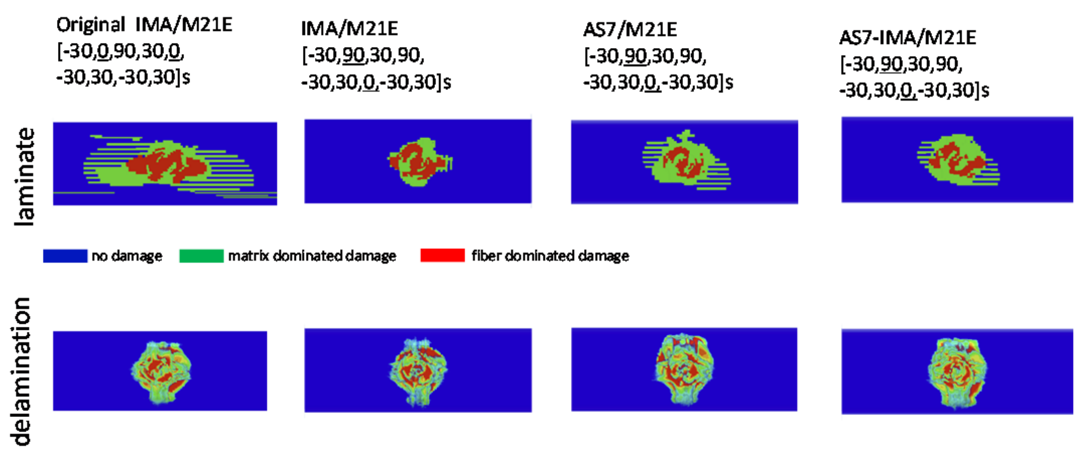

Figure 11 Comparison between impact damage in a composite frame with the original configuration and various other configurations

6 CONCLUSION AND FUTURE WORK

Progressive damage simulation models have been developed to predict the behaviour of composite omega frame under impact load and four-point bend. These models can be used to predict the damage progression and failure load, provided non-linearity of deformation and accurate material parameters are used.

Currently, the models presented here still suffer from some shortcoming; the predicted impact damage area is smaller than the damage in the actual tests and the predicted four-point bend strength is higher than the experimental values. This may be attributed to uncertainties in material toughness and strength properties assumed in the model and geometric non-linearity. The delamination strength and toughness data of IMA/M21E are currently not available and values were assumed based on other carbon/epoxy data. Therefore, experiments will be performed in the next phase of this study to obtain these data.

AKNOWLEDGEMENTS

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