ANALYSIS OF OMEGA STIFFENER UNDER BENDING AFTER IMPACT TESTS

M. Ridha[1], T. E. Tay[1], S. Werner[2], P. Joern[2], V.B.C. Tan[1]

[1]Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576
Email: mridha@nus.edu.sg, Web Page: http://www.nus.edu.sg/
[2]Airbus Operations GmbH, Department: ESCRBY Airframe Composite Fuselage R&T, Kreetslag 10, 21129 Hamburg, Germany

Keywords: modelling, progressive failure, impact damage, bending, residual strength

Abstract

In addition to the intrinsic high specific strength, high specific stiffness, and high fatigue resistance, fiber-reinforced composite materials also provide higher flexibility in engineering and design because of the unlimited variations in laminate designs and material selections. Unfortunately the current design optimization process practiced in aircraft industries requires numerous coupon and component level testing for every considered design. This study is aimed at developing progressive damage simulation tools for composite stiffeners under bending in the presence of damage due to impact load. The combined experimental and simulation studies shows that a proper progressive damage tools can give a better understanding of the underlying progressive failure mechanisms during impact and how it influences the residual four point bend strength. It was found first in simulation and then also in experiment that changing the orientation of a few longitudinal plies to the transverse direction can reduce the extent of impact damage and increase residual bending strength. This proves that the simulations can be used to complement experimental testing by guiding engineers to find the correct path of finding better design solutions and therefore can potentially reduce the design cycle and cost.

1. Introduction

Fiber reinforced plastic composites are increasingly being used in aircraft structures because of their intrinsic high specific strength, high specific stiffness, and high fatigue resistance. Furthermore, fiber reinforced plastic composites are typically anisotropic an hence they are very ideal to be used in structures that are mainly loaded in one direction such as frames, stringers, ribs, etc. The loads in these structures are mainly bending, tension, or compression in its longitudinal direction and thus engineers can design a composite laminates that has high stiffness and strength in this direction to save weights.

In addition to the potential weight saving due to the superior intrinsic properties, employment of fiber reinforced plastic composites also significantly enlarge the design space because engineers are not only able to choose geometric parameters such as shape and thickness but also materials and layup design. These parameters can be tailored to obtain a design that can fulfill its function as load bearing structures while having the lowest possible weight and costs. Finding the most optimum combination of those design parameters is however not an easy task as the current design optimization process requires numerous tests for each design iteration. A better understanding of failure mechanisms may lead to a more systematic method for searching a better design. Robust and accurate numerical model may be used to study the failure mechanism and perform virtual tests. This will expedite and reduce the cost of design iterations.

Excerpt from ISBN 978-3-00-053387-7

Numerical studies such as Ridha et al. [1] and Su et al. [2] have shown that finite element based progressive damage model can be used to predict the behavior of fiber reinforced composite laminate under coupon level open hole tension and compression tests. They modeled composite each composite layer using three dimensional shell elements while the interface between layers are modelled using cohesive elements. In this study, the same modelling approach is used to model composite frames under successive impact and bending load shown in Figure 1. The actual frames are expected to be able to withstand the design load despite the presence of accidental impact damage caused by tool drops during manufacturing process. Comparisons were made between the experimental and simulation results. The simulations are then used to analyze the failure mechanism and find better design solution.

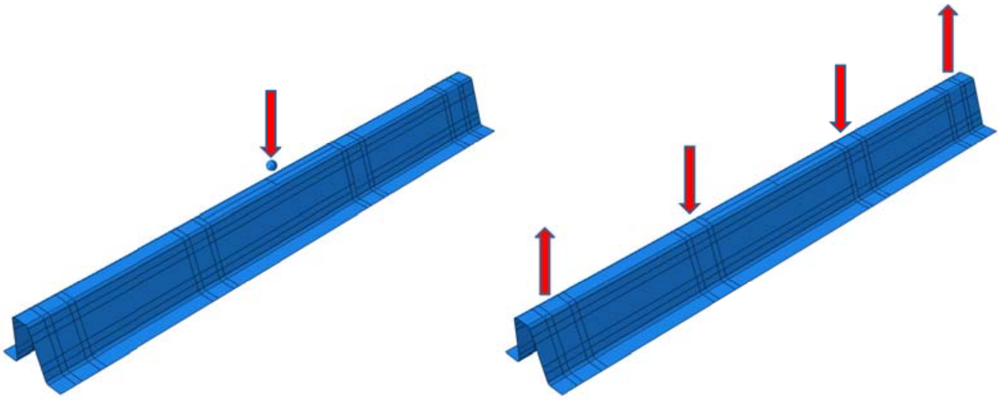

Figure 1. Impact and four point bending simulations

2. Impact and bending tests

Beam profiles made of fiber reinforced composites with omega cross section shown in Figure 2 is considered to be used for fuselage frames. The current design uses IMA-M21E carbon epoxy system with [-30, 90,30,-30,30,-30,30]s layup sequence for the webs and outer flanges. Four additional 0° plies were added to the inner flanges, resulting in the layup [-30, 0,90,30,0,-30,30,-30,30]s.

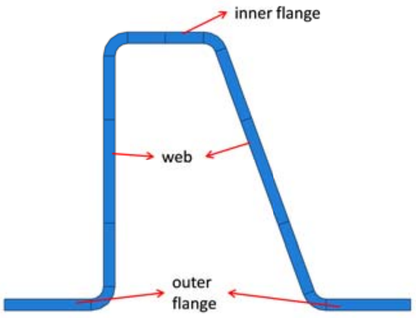

Figure 2. Omega frame cross section

1 meter length specimens were manufactured for this study. The omega frames were then attached to a wooden base using plastic tape and then a 35 J impact load were applied to the middle of inner flange using a 16 mm diameter round tip impactor. Ultrasonic scanner was used to identify the damage area which was then marked on the specimen shown in Figure 3.

Excerpt from ISBN 978-3-00-053387-7

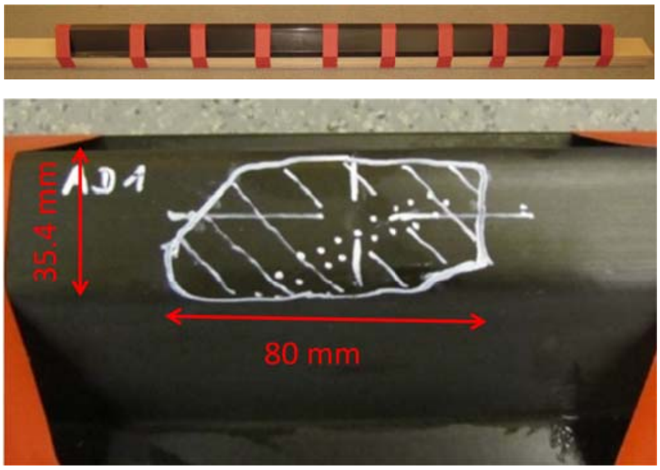

Figure 3. Impacted omega frame

The specimens are then bent using a universal testing machine and a four point bend test jig shown in Figure 4. The distance between the loading points on the top jig is 320 mm while the distance between the loading points in the bottom jig is 800 mm. Three specimens were tested and the resulting average bending strength is 3503 Nm with 13 % coefficient of variance. The final failure started when the inner flange cripples and failure progresses to the webs and outer flanges.

Figure 4. Four-point bend test using Shimadzu Autograph-25 TG universal testing machine

3. Simulations

Consecutive impact and bending simulations were made using the same progressive damage method used by Ridha et. al [1]. Each layer of composite lamina were modelled using continuum shell element in Abaqus [3]. Cohesive elements were inserted between the composite layers to model delamination. Matrix dominated damage in the composite lamina is assumed to start when the Tsai-Wu [4] failure criterion is satisfied while the fiber damage is determined by the maximum stress criterion. Quadratic stress criterion is used to determine the start of delamination. Damage progression in each elements are effected through degrading the stiffness constants following energy based criterions. The progressive damage model algorithm are written into user subroutine UMAT in Abaqus.

Excerpt from ISBN 978-3-00-053387-7

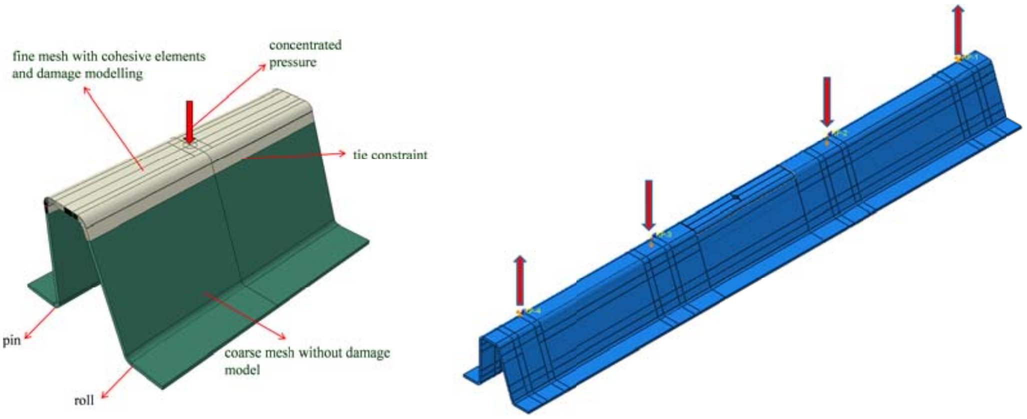

Figure 5. Finite element model of composite stiffener

Figure 5 shows the finite element model for impact and bending simulations. Since major impact damage are expected only to occur in the top part of the test specimen, only the inner flange area and part of the web area are modelled in details using layer by layer fine continuum shell and cohesive elements which are allowed to fail. The other parts of the model are modelled using a single layer of continuum shell elements which are not allowed to fail. Only 180 mm length of the omega frame was modeled in the impact simulation to decrease the computational cost. Impact load is simplified as concentrated pressure over a circular area of 8 mm in diameter on the middle of the inner flange. Pin boundary conditions were applied to the edge of the outer flanges. The full length of the test specimen was modeled in the bending simulation in which the middle part of the model uses the same mesh as the impact model but with additional progressive damage modeling in the web and outer flange area.

Figure 6 shows the damage map and deformation predicted by the impact simulation. The size of the delamination is very similar to the actual damage detected by the ultrasonic scan. The inner flange bends in the transverse direction during the impact and causing the interfaces to delaminate. Almost all of the interfaces suffers from delamination with the largest delamination occur between the −30° and 30° layer nearest to the middle of the composite layer. Bending, mainly in the transverse direction, causes this delamination. Compressive fiber failures are observed mostly on the three upper layers of the composite laminate while the lower layers suffer from minor tensile failures.

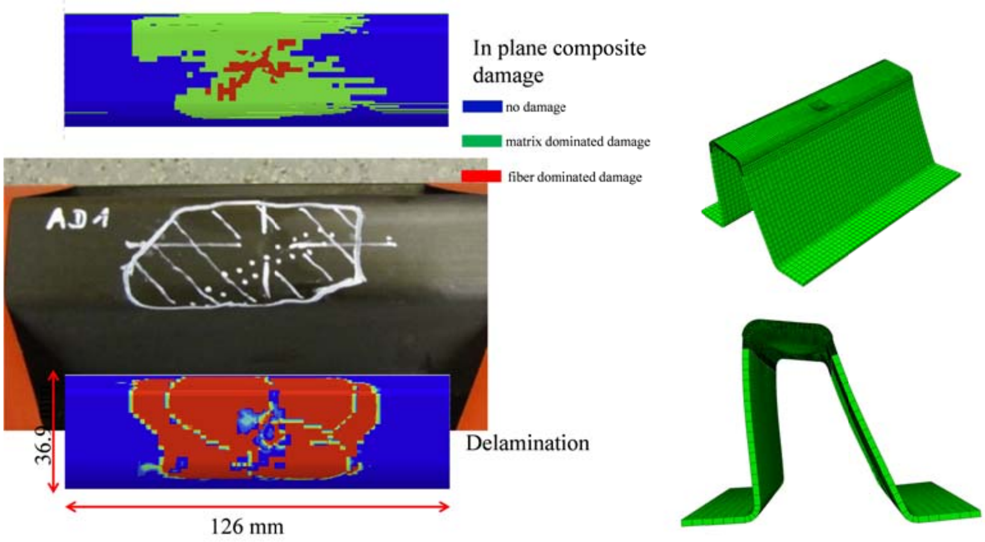

Figure 6. Predicted damage map and deformation during impact load

Excerpt from ISBN 978-3-00-053387-7

Excerpt from ISBN 978-3-00-053387-7

The damage information shown in Figure 6 are then carried over to the bending model by giving low strength values to the elements that has suffered any damage in the impact model. The four point bending load was then applied through the points where pins are inserted in the actual specimen to transfer the load from the four point bending jig. The model collapses at 3665 Nm of bending load or about 12 % higher than the average experimental value. Final failure occurs due to crippling or out of plane displacement starting from the impacted area. Fiber damage then quickly progresses cutting across the inner flange and dropping the load bearing capacity of the whole structure. Very limited progression of delamination occurs prior to this final collapse.

4. Analysis and design modification

Both simulation and experimental results suggests that the main failure mechanism during bending test is crippling or out of plane displacement of composite lamina around the impacted area. Crippling can easily occur in the impacted area because of the low local bending stiffness due to the presence of large delamination between the composite lamina. The simulation suggests that this delamination were mainly created during the impact test when large transverse bending displacement occurs at the inner flange; delamination progresses very little during the bending test.

Based on this observation, a new design with higher bending stiffness on the inner flange area was proposed. Instead of adding four layers of 0° for the inner flange area as were done in the original design, the new design uses two additional 0° plies and two additional 90° resulting in $[-30,90,30,90,-30,30,0,-30,30]_s$ configuration for the inner flange area while maintaining the $[-30, 90,30,-30,30,-30,30]_s$ configuration for the webs and outer flanges. This will effectively increase the bending stiffness of the inner flange in the transverse direction and at the same time decrease the overall longitudinal stiffness of the frame.

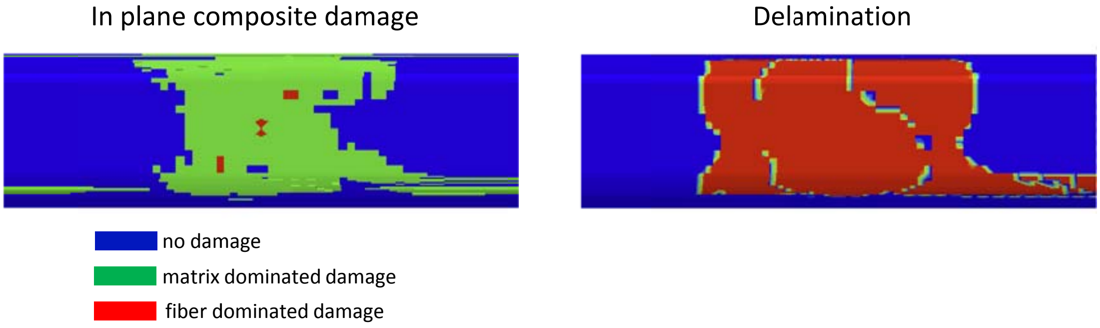

Figure 7. Impact damage of frame with new design

Figure 7 shows the impact damage predicted for the new design. The new design suffers less impact damage compared to the original design with 10 of the interfaces remains almost intact at the impact point. The original design on the other hand delaminated in all interfaces except for the two outer most interfaces. The subsequent bending simulation shows that this new design is able to withstand bending load up to 3960 Nm after the impact load, higher than the predicted 3665 Nm for the original design. Experiment data shows a similar trend with the simulation; the average residual bending strength increases from 3260 Nm for the original design to 3732 (7 % standard deviation) for the new design.

5. Conclusions

This study shows that the current progressive damage simulation technique available for modelling fiber reinforced materials is sophisticated enough to be used in analyzing the behavior of structure components made of composite materials under successive loadings. The impact and bending model for omega frames shown in this study are able to provide a better understanding of the failure mechanism under both loading conditions. Despite some minor discrepancies between the predicted residual strength and the actual residual strength obtained from test, the knowledge gained from the simulation is shown to be very useful for finding better frame design that has higher residual bending strength after impact. It should be noted that the minor discrepancies may be caused by the assumptions made for some of the material properties in the absence of experimental data.

The analysis shows that increasing the number of 0° plies in the frame is not necesarilly a good solution for composite frames or other stiffeners although the main loads in these stiffeners are in the longitudinal direction such as compression, tension, or bending. Transverse direction stiffness is also important in this structure because of the requirement for tolerance to accidental impact load. Additional 90° or other high angled plies are needed to increase the transverse direction stiffness and strength to reduce the severity of damage upon accidental impact which in turn can increase the overall residual strength of the stiffener especially under bending load.

Acknowledgments

Supports from AIRBUS Operations GmbH through grant number R-265-000-503-597 and from the National University of Singapore through grant number R-265-000-523-646 for this work are gratefully acknowledged by the authors.

References

[1] Ridha, M., et al., Modelling complex progressive failure in notched composite laminates with varying sizes and stacking sequences. *Composites Part A: Applied Science and Manufacturing*, 2014. **58**(0): p. 16-23.

[2] Su, Z.C., et al., Progressive damage modeling of open-hole composite laminates under compression. *Composite Structures*, 2015. **122**(0): p. 507-517.

[3] Abaqus Analysis User's Manual, Version 6.11, 2012.

[4] Tsai, S.W. and E.M. Wu, A General Theory of Strength for Anisotropic Materials. *Journal of Composite Materials*, 1971. **5**(1): p. 58-80.

Excerpt from ISBN 978-3-00-053387-7