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Structural analysis and optimisation of an all-composite damage tolerant wingbox

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Summary

Carbon fibre reinforced plastics (CFRP) are widely used in aerospace structures because they offer excellent properties, such as resistance against fatigue and corrosion, with significant weight savings. However, when in service, they are subject to impact threats such as dropped tools, runway debris or hail and the induced damage which may not be visible, can lead to significant strength reductions.

Currently, individual methods for design, inspection, damage assessment and repair of composite structures are available, used albeit at various levels of confidence. Since a cost-effective, through life, service performance is a primary requirement, a need exists for a comprehensive methodology to allow the damage management of composite aircraft structures, based on an integrated approach towards design, inspection, assessment and repair. This paper describes this process with respect to a representative CFRP wingbox structure. This programme of work has been conducted under the WEAG THALES Joint European Programme JP 3.29 DAmage Management Of Composite Structures for Cost Effective Life Extensive Service (DAMOCLES) collaborative agreement between the UK, Italy and The Netherlands.

The results presented consider alternative manufacturing methods and through-thickness enhancement (stitching and Z-pins) to optimise a monolithic stiffened structure in terms of weight, performance and damage tolerance. Conclusions to date are presented, that show the limitations and structural advantages of through-thickness reinforcement in suppressing delamination growth.

Contents

(15 pages in total)

1 Introduction

The focus of the DAMOCLES programme was to evaluate new materials and structural concepts at the level of a wing box structure. The aim of this programme was to evaluate the benefits of new materials and structural concepts and to develop capabilities for damage tolerant design and accurate damage assessment, while taking into account inspection and repair considerations.

To allow a significant number of damage tolerance concepts to be assessed, the programme was split into three phases. In the first phase concepts based on an intermediate scale were assessed. Four panels were developed, based on optimised damage tolerance and low cost manufacturing and tested in a modular wingbox which simulated in-service loading. In the second phase the most promising concepts from phase 1 were investigated on a full-scale all-composite structure. The final phase will focus on the evaluation of merits and benefits of the programme, and on the dissemination of the methodology to industry.
This paper provides an overview of the technical work performed in phases 1 and 2 of the programme, highlighting the key technical achievements and summarising the main conclusions.

The programme of work considers the optimisation of stiffened CFRP panels to that of impacts typically seen in service. This type of design can be broken down into damage resistance and damage tolerance. In the interests of clarity, for the purposes of this study, the damage resistance of a panel is defined as the resistance of that panel to initial failure following a localised low velocity (typically up to 5 m/s) impact. The damage tolerance of a panel is defined as the resistance of that panel to the growth of damage once it has initiated. Ideally, a composite structure should be both damage resistant and damage tolerant. The focus of this study was therefore to design a panel that was initially resistant to an impact threat typical of those likely to be seen in service and then to be resistant to damage growth, once damage had initiated following an increase in the threat level.

2 The numerical design and optimisation of the skin-stringer panels

Work was conducted at NLR to examine the stacking sequence of the laminates, the panel geometry (stringer height and flange width), and the panel topology (type and number of stringers). Two different panel configurations were designed and of each configuration two panels were manufactured. The first two panels were made using a traditional tape lay-up procedure (DAM1 panels). The other two panels utilised a resin infusion, low cost,

manufacturing route (DAM2 panels). One of each of the DAM1 and DAM2 panels incorporated a through thickness reinforcement; z-pinning in the case of DAM1 and stitching in DAM2.
Both panel configurations were designed using Finite Element Analyses on a panel 710 mm wide by 500 mm in length, as defined by the test section of the modular wingbox. In the analyses, the panels were loaded by uni-axial compression with the sides simply supported. The design of the DAM1 panels was based on several linear analyses, investigating different panel geometries and topologies and the lowest weight was found for a four-stringer design. The damage resistance for a bay, stringer foot, and stringer centre impact was predicted to be 11.6J, 8.2J, and 3.8J, respectively.
The DAM2 panels were designed for increased damage resistance, using optimisation routines developed under the DAMOCLES programme [1]. Again a four-stringer design performed best, now giving a damage resistance of 20.7J, 26.9J and 19.2J for the bay, stringer foot, and stringer centre. The large increase in damage resistance was gained with only a minor increase in weight compared to the DAM1 panels. The main feature of the damage resistant panels is that material was shifted from the stringers to the skin, see table 1.

Table 1   Mass components of the skin-stringer panels

Panel	**Skin [kg]**	**Stringer [kg]**	**Total [kg]**
DAM1	2.7	1.3	4.0
DAM2	3.7	0.5	4.2

The actual panel geometry for all the test specimens is a panel 710 mm wide by 600 mm in length, figure 1 (DAM1 configuration). The extra length is only used for assembly in modular wingbox testing facility at QinetiQ, figure 2. This uses a metal frame to support the composite test panels and permits novel materials and structural elements to be tested within a structural context, [2].

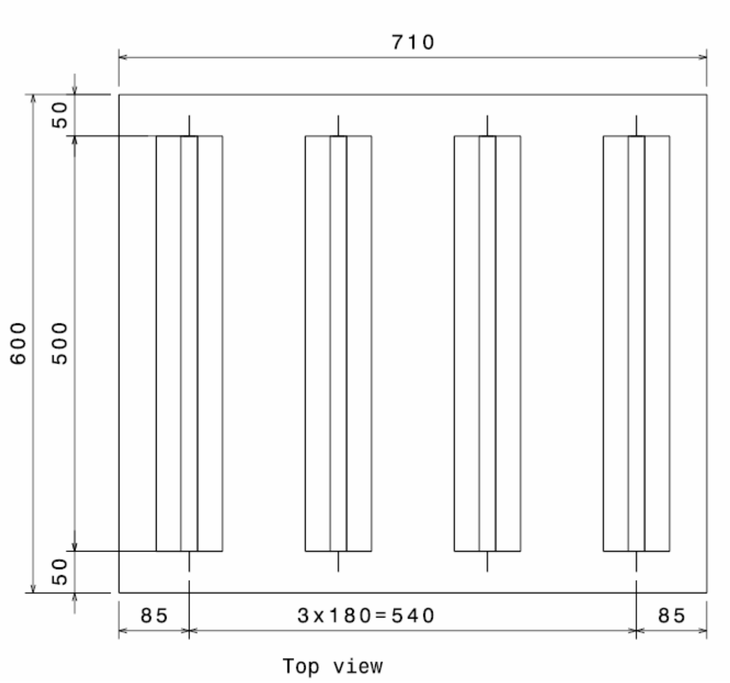

Fig. 1   A schematic illustrating the geometry of the panels tested

Fig. 2   Modular wingbox under test at QinetiQ

Initially, the performance of the structure was characterised and compared with a prior non-linear analysis conducted at NLR and CIRA, [3] figure 3. Further, in order to evaluate the buckling behaviour and to simulate damage growth, the feasibility of a global-local approach was investigated, including, 2D-3D mesh coupling. The contact friction forces calculation between the two sub-laminates at the delaminated area and the determination of the Energy Release Rate (ERR) along the delamination front were performed by adopting, respectively, the

Penalty Method and the ‘Virtual crack closure technique’. To determine the delamination size an existing empirical approach was adopted assuming circular delamination. Three different delamination locations in the panel were investigated.

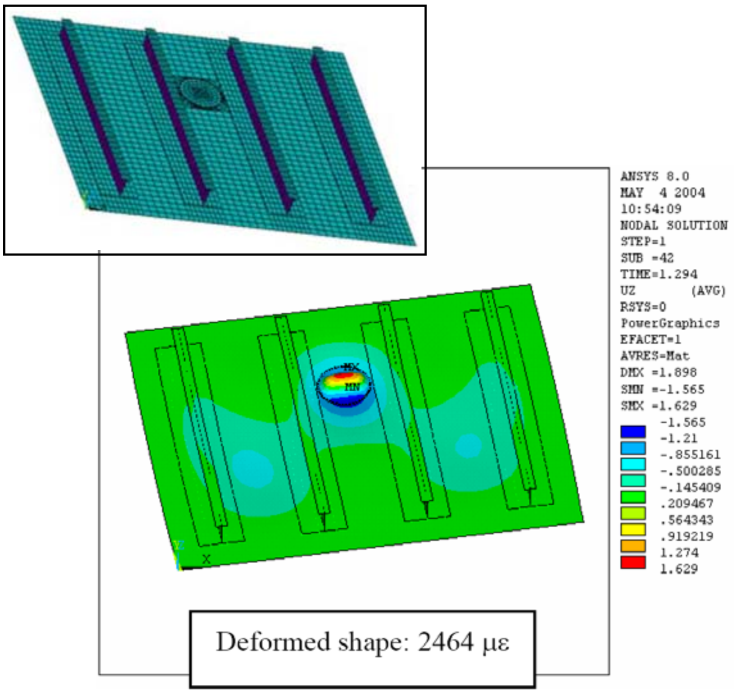

Fig. 3 Non-linear analysis on the DAM1 panels

Non-linear buckling analyses were able to detect a change in global buckling mode and load when compared to a panel without delamination. This behaviour was not captured by the linear buckling analyses and demonstrates the limitations of this type of analyses. The numerical results for the stiffened composite panels with three different delamination locations, do not show any appreciable differences in terms of delamination growth initiation load whereas some changes in the ERR distribution along the delamination front can be detected. However in all cases the direction of propagation is the same and mode I (interlaminar tension) is the dominant fracture mode.

3 Testing the panels in the modular wingbox

Following the characterisation tests conducted to establish the buckling modes, the damage resistance test was started with a series of low velocity, large mass, impacts on the panels at locations within the bay or over the stringer. This mode of impact was chosen as it tends to promote delamination within composite structures. (Typically mass = 2.5 kg, velocity = 3 m/s).

Ultrasonic inspection, i.e. ANDSCAN, was used to identify the formation of damage. For the purposes of this study, the panel was assumed to have been damaged when an impact resulted in a damage that was quantified as being of 10 mm or greater diameter when detected using a hand held ANDSCAN probe. Further, that such damage indicated is identified as being at least two plies in depth. It should be noted that this is not necessarily the same as BVID; the damage detected by the ANDSCAN probe might not be visible from either of the two sides of the panel.

Following the application of impact threats the panels were loaded through tip deflection to generate first a tension and then a compression field in the panel. The panels were then unloaded and the extent of damage growth was ascertained.

4 Discussion of the test results for the panels

The predicted levels of impact for the bay and foot for the DAM1 panel were 11.7J and 8.2J respectively. This was in fairly good agreement with the energy levels associated to the onset of delamination as estimated from the test results (approximately 13-14J for a bay impact and 10-11J for a stringer foot impact). The predicted levels of impact for the bay and foot for the DAM2 panel were 21J and 27J respectively. However, the impact tests were performed whilst the structure was under compressive load. Exploratory non-linear analyses showed that (compressive) loading on the panel can strongly influence the damage resistance (both positively and negatively, depending on the location), especially if the panel is in its post-buckling regime. Therefore the energy levels found by test could not readily be compared to the predicted levels.

The two panel designs investigated in this study responded to the combined compression and localised impact loading regimes very differently. The increased skin thickness of the DAM2 design compared to the DAM1 design appears to have significantly influenced the response of the structure. There is evidence of a stiffer response, with less difference between the response of the bays and the response of the stringers.
The DAM2 panel demonstrated considerably more damage resistance. Even if the results for energy absorption are normalised with respect to the change in panel thickness, the panel has demonstrated an ability to absorb considerably more energy. It is interesting that the damage tolerance of the bay in the DAM1 panel appears to be better than that in the DAM2 panel. Despite the maximum compressive load being limited to –2200 $\mu\varepsilon$, a 20% increase in damage area was identified. In contrast, the damage on the stringers exhibited little growth for the DAM2 panel, whilst significant growth was observed in the DAM1 panel when z-pins were not incorporated.

Whilst it is clear that the presence of z-pins had a significant effect on the response of the DAM1 panel, the presence of the stitching in the DAM2 panel appears to have affected only the stringers, suggesting a highly localised effect. This suggests that through thickness reinforcement can be used to influence the damage resistance and damage tolerance of a primary aircraft structure.

5 The numerical design and optimisation of an all-composite wing

Phase 2 of the DAMOCLES programme took the design concepts explored in phase 1 and developed these to manufacture an all composite wingbox.

The finite element analysis results on the entire wing structure showed that the assumption of uniform axial compression in the upper skin was not valid. Rather the analysis results found that the panel was in a state of combined compression-bending as noted in the testing of the modular panels in phase 1. As a result the linear analysis was found to be inadequate for predicting displacements, stresses and strains, at high load levels. The non-linear analysis on the final configuration of the wingbox structure (with a total of four rib bays and integrally stiffened skin panels) shows that the individual upper panels tend to bend inward at low load levels. At higher load levels bay 2 (counting from the root) still bends inward, but bay 3 starts to bend outward, forced by the large inward displacements of the more heavily loaded bay 2, with the rib in between the two bays acting as a fulcrum point. An investigation of the bending strains in the upper panels shows a strong increase of bending, which could be associated with buckling, at approximately 80% of ultimate load. The non-linear buckling analysis finds a 20% lower buckling load than the eigenvalue (or linear buckling) analysis. Strains and stresses may differ even more.

Although it has been shown that a linear analysis cannot predict the wingbox behaviour accurately, it is not possible to simply apply the non-linear analyses in the design and optimisation of the current wing structure. The amount of CPU-time involved with a non-linear analysis is too large to be used efficiently in a design environment. A solution is not readily available, certainly with the current gradient based optimisation routine. One possibility is to constrain the linear buckling load in the optimisation beyond the ultimate load. (e.g. no buckling below 1.25 U.L), so the strong non-linear behaviour falls outside the actual loading regime, thereby extending the validity of the linear analyses to higher loads as well. However, this may unnecessarily increase the weight of the structure.

6 Testing the all-composite wingbox

The wingbox was placed in the loading frame used to load the modular wingbox in phase 1. The load applied to the wingbox was introduced by a load saddle that spread the load along the entire width of the structure, see figure 4.

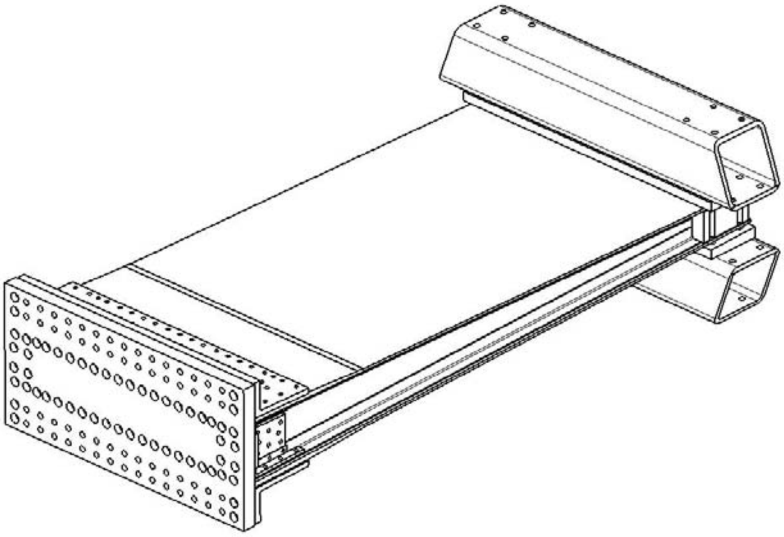

Fig. 4 Wingbox in test rig showing loading saddle

The performance of the structure was characterised and the buckling modes obtained through the use of Moiré analysis, figure 5. These compared favourably with the predictions of the model generated at NLR and CIRA.

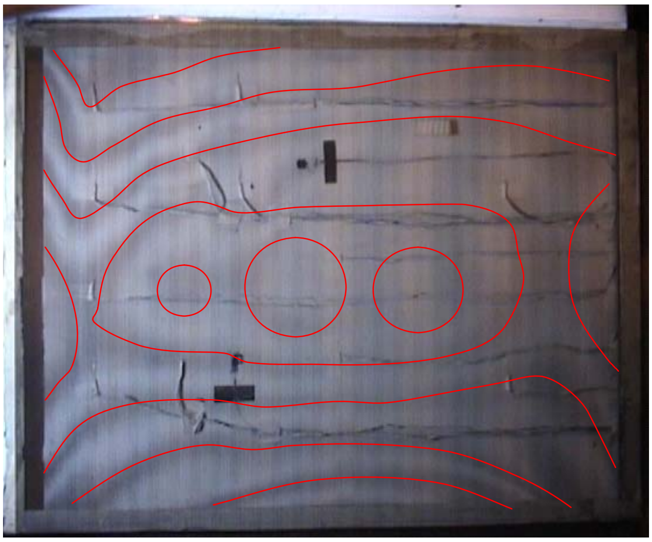

Fig. 5 Results from the shadow moiré analysis (bay 2), illustrating the buckling modes

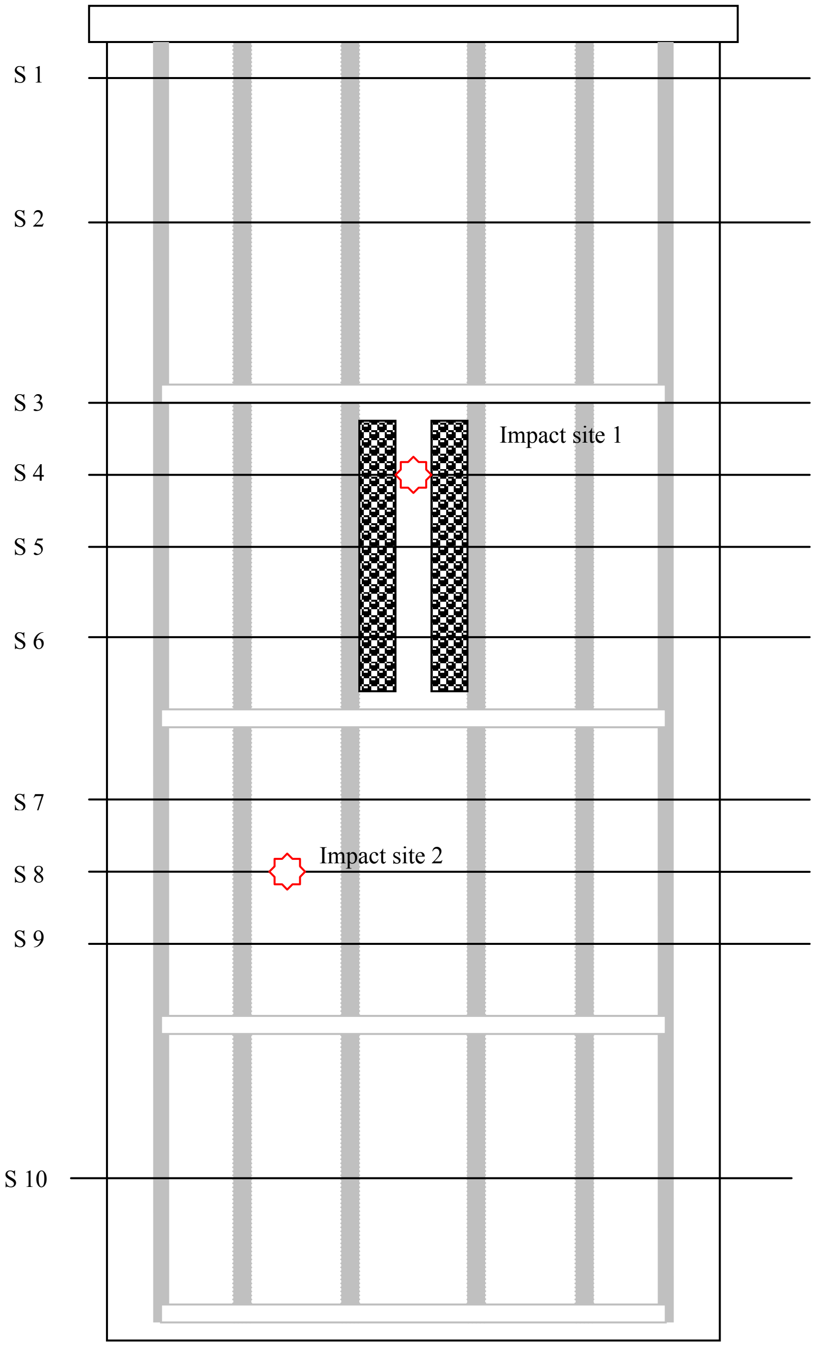

Fig. 6 Wingbox top view showing z-pin areas and impact locations

The wingbox was then subjected to localised low velocity impact. See figure 6 for the impact locations. An impact energy threat level of 22.8J, was applied to the wing skin. The threat level used was the maximum that the structure was predicted to withstand before damage was caused, which is called the damage resistance of the structure at the particular location. The size of damage caused at this threat level of 22.8J was estimated by ANDSCAN to be 3.8 mm across.

This damage is associated with a surface chip and can be considered as no damage or the limit of damage resistance, figure 7.

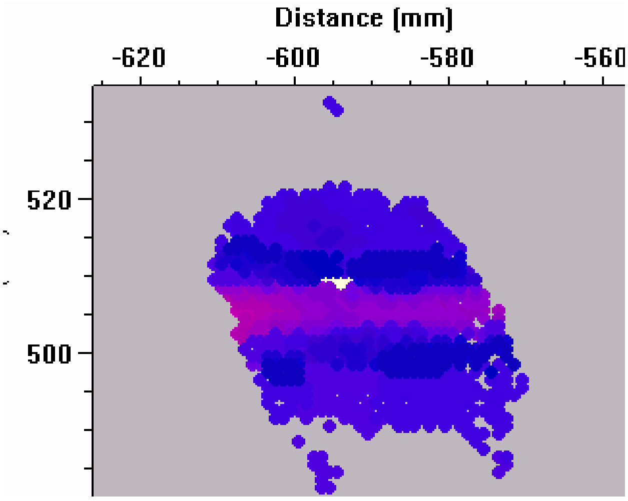

Fig. 7 ANDSCAN results after damage resistant impact level applied

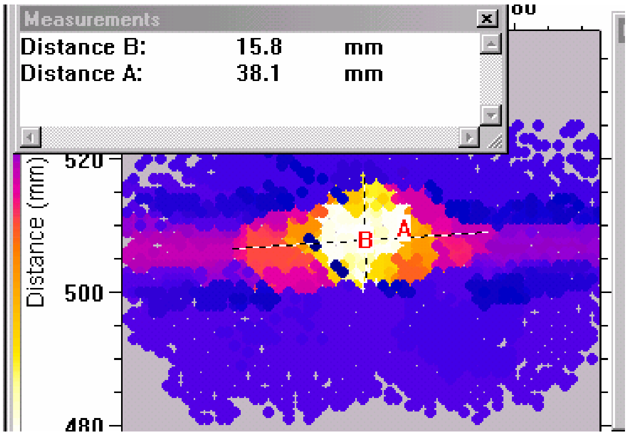

Fig. 8 ANDSCAN results after 35J impact threat applied

Subsequent impacting at the same location with a threat level of 35J resulted in the damage propagating along the centre line between the two z-pinned areas (Fig. 8). This growth was encouraged by a small change in section thickness as a result of the manufacturing process. An impact of threat level 35J was then centred within a bay which contained no z-pin reinforcements and was used as a comparison to the response of the previous impact site. The predicted damage resistance of the second impact location was 31.4J. The higher value for the damage resistance is caused by the more compliant response of the structure for an impact in the middle of a bay compared to an impact in the proximity of a rib as was the case for the previous impact site. Another contribution to the less compliant response of the first impact could be attributed to the application of z-pins in the bay; these would increase the stiffness of the skin in the z-direction and so alter the structural response due to impact, [4-5]. Subsequently, the resultant damage was much smaller than the damage caused in the bay with the z-pins. The damage size (14.2 mm in length, but a width below the measuring range of the scanning probe) suggests that the damage resistance is only slightly smaller than the 35J energy threat level. Following the application of localised impact energy, load was applied to the wingbox via the saddle across the tip such that the top skin was placed in compression. The predicted maximum load at failure was 133kN [6] and failure occurred at 129kN. This corresponded to an operational level of -3,543 με which compares favourably with the proposed limit of -3,600 με.

A fractographic assessment was conducted on the failed structure. However, this was limited to a visual inspection of the debonded surfaces. Only the debonded L-sections, and ribs were examined as there was no visual or mechanical data to suggest that any damage had occurred in the skins. The wingbox was dismantled in sections and visual inspections were carried out at each stage.
The initial inspection showed that the outer L-sections on both spars had debonded from the skin and spar over the majority of the test area but the L-sections were still bonded at the root and tip of the wingbox. The debonded area of these outer L-sections was removed by cutting through the L-section at the extent of the delamination. Figure 9 shows schematics summarising the failures observed at the debonded regions between the skins and ribs and skins and L-sections, and also between the spar and ribs and spar and L-sections. The schematics have been colour coordinated; yellow areas indicate shear cohesive failure of the resin; and green areas show where adhesive failure was observed.

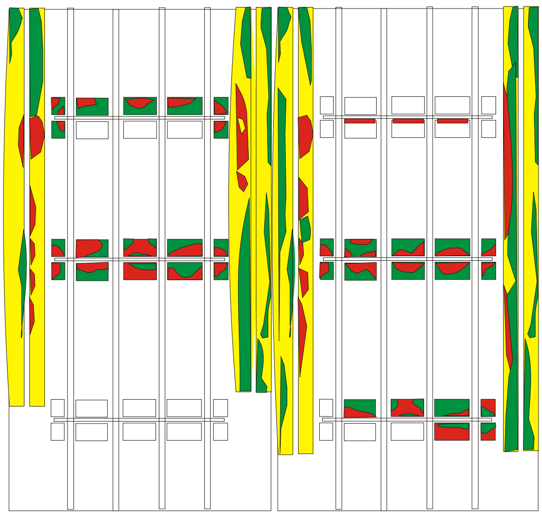

Fig. 9 Schematics showing the debonded regions within the wingbox; yellow indicates areas of cohesive shear failure; green indicates adhesive failure

The results from the fractography appear to compare well with the failure load being close to the shear strength of the adhesive.
It is interesting that no significant reduction in residual strength was observed post-impact. Despite this, there is some evidence of the presence of impact damage altering the buckling mode, possibly due to the resultant change in stiffness following the impact.
It is perhaps also interesting to note that the application of load to the wingbox following the impact events did not result in a significant growth of the damage in the panels. This suggests that the panel designs have been successfully optimised with respect to static damage tolerance. However, the growth of damage in polymer composites under high fatigue conditions is also of considerable concern. For this reason, the next phase of work will examine this aspect of the structures performance.

7 Conclusions

Numerical techniques have been developed that permit a CFRP structure to be optimised for damage tolerance whilst using low cost manufacturing techniques.

The initial buckling modes were successfully obtained using the modular wingbox. These compare favorably with the numerical results predicted by NLR and CIRA.

The energy threat levels required to cause damage to DAM1 and DAM2 panels with and without through thickness reinforcement were successfully obtained and compare well with the numerical results predicted by CIRA.

The stacking sequence directly affects the damage tolerance of the structure.

Any advantage of incorporating stitching is negated once the stitching becomes damaged.

The presence of z-pins does not appear to affect the damage resistance of a structure, although there is some evidence that the damage tolerance of the structure may be improved.

8 Acknowledgements

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