IMPROVED DESIGN METHODS FOR CRASHWORTHY COMPOSITE HELICOPTER STRUCTURES

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Abstract

The development and validation of new methods to simulate the crash response and energy absorption of composite airframe structures are described in this paper. The simulation methods were developed and demonstrated on representative crush element tests, then larger sub-elements. Final validation, as reported in this paper, was conducted using a structure representative of a helicopter fuselage frame complete with an energy absorbing sub-floor. Scaled instrumented structures were tested quasi-statically and dynamically. The numerical model developed in PAM-CRASH was capable of predicting the deformation modes and provided excellent agreement with the steady state crushing loads and energy absorption. The ability to predict the dynamic response of a composite frame section gives confidence that numerical models can be used to design the next generation of crashworthy helicopter structures using 'virtual' crash tests resulting in lighter, stronger, safer helicopters.

1 Introduction

The crashworthiness of advanced composite materials in the aerospace industry has generated considerable interest resulting from the increased application in fuselage and other structures. Well designed composite structures absorb crash loads in a controlled and progressive manner through crushing. By tailoring the fibre type, matrix type, fibre-matrix interface, fibre stacking sequence and fibre orientation, composite crashworthy structures have been shown to have outstanding energy absorption performance characteristics [1-3]. Modern military helicopters now incorporate light-weight composite energy absorbers in the subfloor structures to meet crashworthiness requirements.

Traditionally, crashworthy composite structures have been designed using semi-empirical techniques which rely heavily on a large database of experimental test data. Improved design methods are needed to offer improved crashworthiness in the next generation of aircraft. This has focused on the use of explicit FE software commonly employed in the crashworthy design of cars and other land transport vehicles. The continual improvement in computational power means that large and complex crash problems can now be solved in a practical period of time.

To predict the crushing characteristics of composite structures, the physically observed complex failure modes and the associated energy absorption need to be accurately represented. A solution is to model the energy absorbing structure with a layered or stacked-shell approach, successfully used recently by several researchers [2-8]. The stacked-shell approach has the capability of predicting the splaying (or petalling) mode associated with the controlled collapse of composite energy absorbing structures. A deficiency in the publicly available research efforts are the limited range of structures that have been analysed using the stacked-shell modelling approach.

In this paper, the outcomes of a collaborative research project between the Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) and the German Aerospace Center (DLR) are reported. The aim of the project was to develop improved design methods and innovative designs of crashworthy helicopter structures, validated through experimental testing [9]. A building block approach was adopted for this purpose comprising of experimental tests ranging from material characterisation through to large scale crash testing [9]. This paper describes the experimental methodology for large scale crash testing, coupled with an analysis method developed in the explicit finite element code PAM-CRASH to predict the crush behaviour and energy absorption.

2 Design of Energy Absorbing Composite Structures

Composite structures can be designed to absorb significant energy through crushing type failures. However, poorly designed composite structures can fail in a brittle global buckling mode with little or no energy absorption. A sudden catastrophic structural failure could result in the transfer of large injurious accelerations to the occupants, or worse, breach the integrity of the cabin space.

Prevention of a brittle global buckling mode is typically achieved through the incorporation of a well designed triggering mechanism. The function of the trigger is to limit the peak load and ensure a progressive crushing mode is achieved. A lower peak load reduces the likelihood of the structure buckling. There are several types of triggering mechanisms including plug triggers, steeple triggers, chamfered tips, saw tooth triggers, ply-drops and offset ply-drops. A schematic representation of several trigger configurations is shown in Fig. 1.

Selection of a suitable trigger configuration is dependent on the structural configuration. Due to weight restrictions, helicopters do not have a stand alone crashworthy structure. Instead, the energy absorbing elements are integrated into the load carrying structure. Of the trigger mechanisms shown in Fig. 1, the offset ply-drop trigger is most easily integrated into structural elements and capable of carrying the required loads. For this reason offset ply-drop triggers are typically incorporated into energy absorbing keel beams and frames. An example of a corrugated beam with an offset ply-drop trigger is shown in Fig. 2.

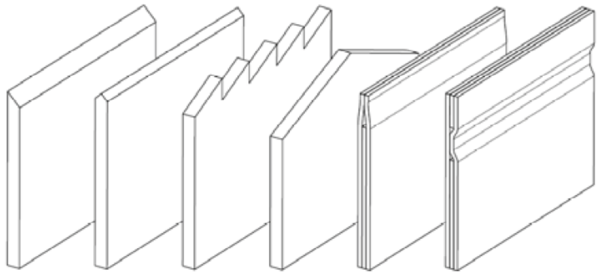

Fig. 1. Various trigger configurations (left to right) chamfer, double chamfer, saw-tooth, steeple, ply-drop and offset ply-drop [4]

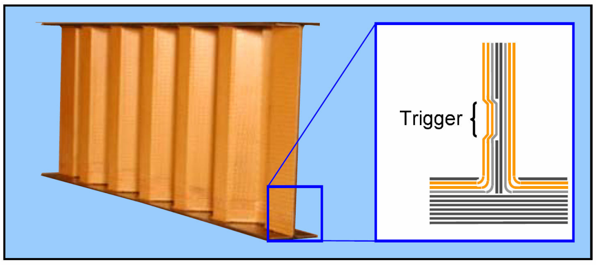

Fig. 2. Example of a corrugated beam with an offset ply-drop trigger [11]

3 Test Program

3.1 Overview

A test program based on the building block approach was designed to evaluate crashworthy composite structures and produce experimental data to validate numerical design methods. The width of the pyramid, shown in Fig. 3, relates to the number of specimens tested and the height relates to the structural complexity. The lower level experimental tests produced design data and allowables while the higher level tests provided insight into the failure of structures of increasing complexity.

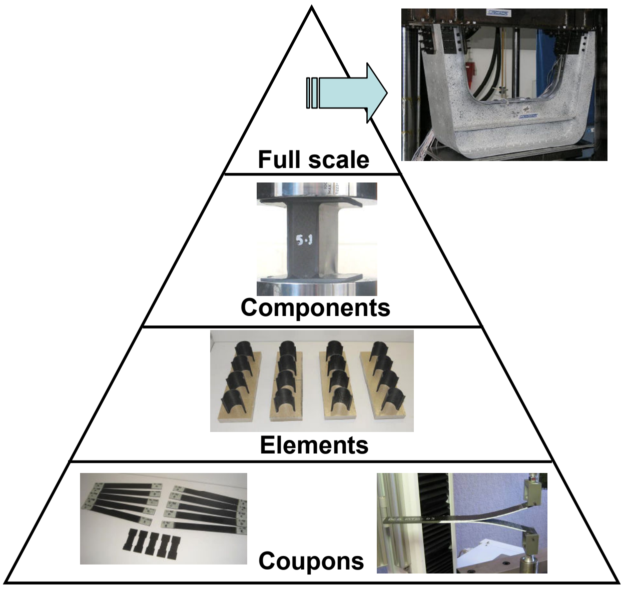

Fig. 3. Building block approach [9]

Coupon tests were conducted to obtain material constants that could be entered into the numerical material models. Element level tests were conducted to assess the crushing response of various design parameters including thickness, layup, loading rate and geometric configuration. The experimental test data was used to develop and validate FE models described in Section 3 [1-5,9-11].

Component tests were used to assess the performance of components that included the additional complexity of structural interaction and bonding. The component specimens were representative of a portion of the energy absorbing section of the Large Test Article (LTA). Component testing allowed a robust energy absorbing configuration to be matured through an evolutionary test program, thereby validating the structural configuration and the trigger design. The final configuration consisted to a corrugated web with a ply-drop trigger, with the corrugated web sandwiched between two C-sections. The flanges of the C-sections were two plies thicker than the web and the transition of thickness between the web and the flange was a weak point that functioned as a triggering mechanism. This configuration was used to design the energy absorbing section of the LTA.

3.2 Large Test Article (LTA)

The LTA is representative of the lower half of a helicopter frame. The structure consists of three main components:

- Semi-rigid upper frame (survival space)
- Sacrificial energy absorbing subfloor
- Skin

The overall dimensions of the LTA were 450 mm (height) x 700 mm (width) x 200 mm (depth). A completed LTA is shown in Fig. 4. A photograph of the energy absorbing section was taken prior to final assembly of the LTA (right hand image of Fig. 4). The detailed image shows the detail of the corrugated core sandwiched between the two 'C-sections' webs. The LTA's were manufactured from a carbon fibre epoxy woven pre-preg fabric, with the sub-components bonded together. The skin was mechanically fastened and bonded to the energy absorbing structure and upper frame.

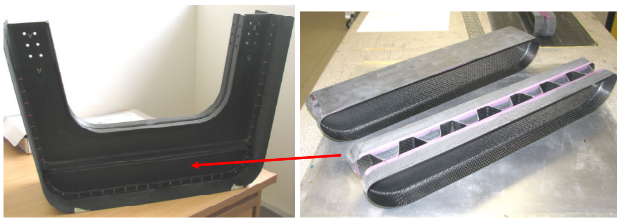

Fig. 4. LTA and detail view of EA section

Three LTA's were evaluated and a summary of the test conditions and experimental results is shown in Table. 1. The objective of the quasi-static test was to establish the baseline performance of the structure to estimate the crushing loads and energy absorption. The dynamic tests successively increased the impact energy equating to 50% and 80% of the total energy absorbing capacity of the sacrificial structure. Dynamic testing was conducted with a vertical impact velocity of 8.0 m/s, in accordance with DEF STAN 00-970 [12] and MIL-STD-1290A [13].

Table. 1. Test summary of the LTA's

Quantity	Test		
	Quasi-Static	Dynamic 1	Dynamic 2
Mass (kg)	N/A	98	159
Impact Velocity (m/s)	N/A	8.05	7.99
Impact Energy (kJ)	N/A	3.2	5.1
Absorbed Energy (kJ)	6.3	2.9	5.1
Crush Distance (mm)	62	32	56
Maximum Load (kN)	123	126	120
Steady Crush Load (kN)	113	104	101

4 Composite Modelling in PAM-CRASH

The fabric composite global ply material model available with the explicit solver PAM-CRASH [14] allows the user to represent each ply as a homogenous orthotropic elastic-plastic damaging material. There is zero damage provided the elemental strain remains below a threshold level. After the threshold strain has been exceeded, the degradation of the mechanical properties is governed by several damage evolution equations (longitudinal, transverse and shear). Degradation of the mechanical properties correspond to physical failure modes including fibre fracture, compressive failure (kink banding) and matrix microcracking.

4.1 Stacked-shell Modelling Approach

Energy absorbing composite structures typically exhibit a splaying mode during progressive crushing. The numerical model must be capable of simulating this phenomenon in order to accurately represent the physical failure mode. A stacked-shell model has the ability to predict a splaying mode through failure of the interface tying the layers of elements together. Stacked-shell models have been shown to be capable of predicting the failure mode and energy absorption of composite structures of varying thicknesses and geometries [4],[6].

A stacked-shell modelling approach involves discretising a physical model into two or more layers of shell elements with cohesive elements (or a cohesive contact) embedded between adjoining shell layers. Contact between elements is achieved through utilisation of an appropriate contact algorithm, which is applied to each shell layer. For the models investigated in this work, a multi-layered material model was assigned to each shell layer and numerical plies stacked within this material model. The composite global-ply material model (Type 7) was used exclusively to represent the mechanical behaviour of the plies.

The dissection of the laminate into shell layers is dependent on the loading conditions the model will be subjected to. For example, if a laminate was subjected to a low velocity (through the thickness) impact, the laminate would be discretised to allow cohesive elements to be embedded between two plies of differing orientations. This is because the stress concentration induced by the differing mechanical properties of the two plies is an area where delamination is likely to occur. When using the stacked-shell approach to simulate a crushing failure, the discretisation process is somewhat simplified. The orientation of the plies becomes less relevant, and the model is ideally discretised to produce an even number of shell layers with a constant distance between each shell layer (where possible). The LTA model used three layers of shell elements to model the corrugated core to capture the energy absorption through crushing. A single layer of shell elements was used to model the C-sections bonded to the corrugated core as these were not designed to crush.

4.2 Model Validation

The material models and modelling methodology was validated at each stage of the test program. A building block approach was used to validate the numerical models and incrementally increase the size and complexity of the models. The building block approach used in the simulation development is shown in Fig. 5. Material constants and damage parameters for the composite fabric global ply material model were calibrated against coupon tests. A comparison of the experimental and numerical cyclic shear response of the carbon-epoxy fabric is shown in Fig. 6. The composite global ply material model is capable of representing the evolution of irreversible plasticity due to the presence of micro-cracks in the epoxy matrix. Upon unloading, the numerical shear strain does not return to zero, rather, the model retains a residual strain corresponding to that measured in coupon testing. The PAM-CRASH cohesive fracture interface model material constants were derived from the fracture toughness tests and validated by simulation.

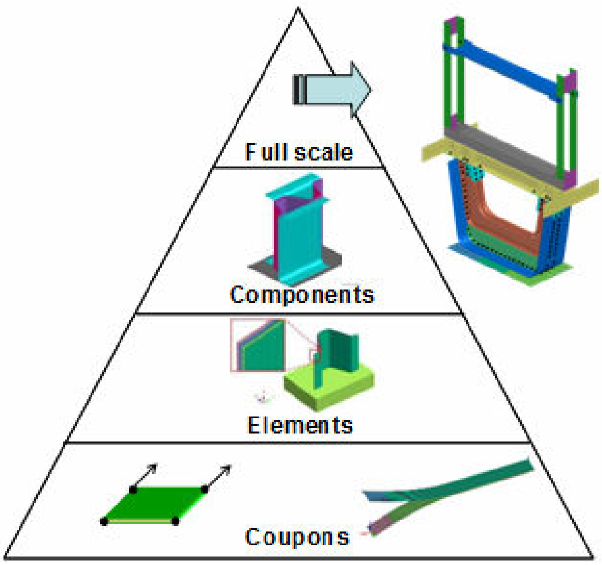

Fig. 5. Building block approach for simulation validation

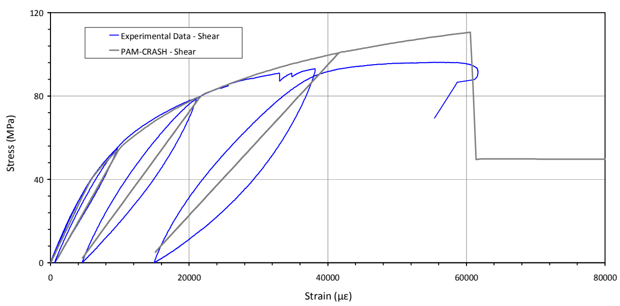

Fig. 6. Validation of the material model (cyclic-shear response)

Once the composite global ply material model and cohesive failure models were validated, the crushing response of element level structures was predicted. The element level models consisted of multiple shell layers, contact definitions, rigid walls, friction, boundary conditions and element elimination criterion. Parametric studies were performed to identify a robust set of modelling parameters to enable the models to predict the failure mode, crushing loads and energy absorption of structures of varying geometry and thickness. A comparison of the experimental and numerical crushing responses of hat-shaped crush elements of varying thicknesses is shown in Fig. 7. The numerical models were capable of predicting the steady state crushing load over a range of specimen thicknesses using an identical set of material constants. Similar correlation was achieved for different element geometries showing that the modelling methodology can accurately predict the crushing response of a range of energy absorbers.

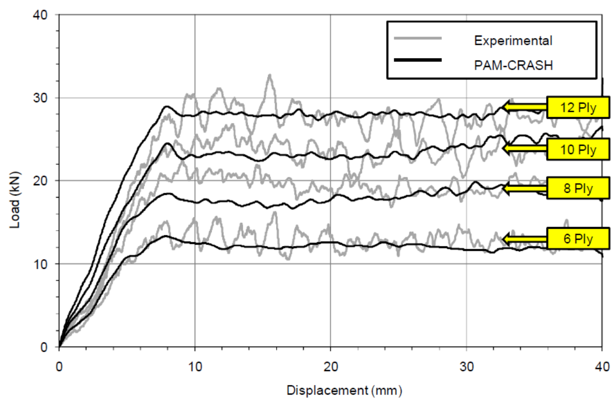

Fig. 7. Validation of the stacked-shell modelling approach (element level specimens) [4]

4.3 Evolution of the Explicit FE LTA Model

The experimental test setup and FE model of the LTA are shown in Fig. 8. The grey arrows indicate the labelling convention for the impact platform which includes three load cells (Left, Middle and Right). The local coordinate frame of the outer plies was aligned with the direction of the strain gauge(s).

The configuration and boundary conditions of the numerical model were identical to the experimental test. A gravitational acceleration field of 9.81 m/s^2 and an initial velocity of 8.05 m/s were applied to the entire model.

The FE model shown in Fig. 8 has been developed to better represent the transfer of inertia during the crash simulation. Initially, a half model of the LTA was created with symmetrical boundary conditions applied to the plane of symmetry, as previously reported [9]. The first iteration FE model did not include the I-beam or the two-rail sled and the mass of these

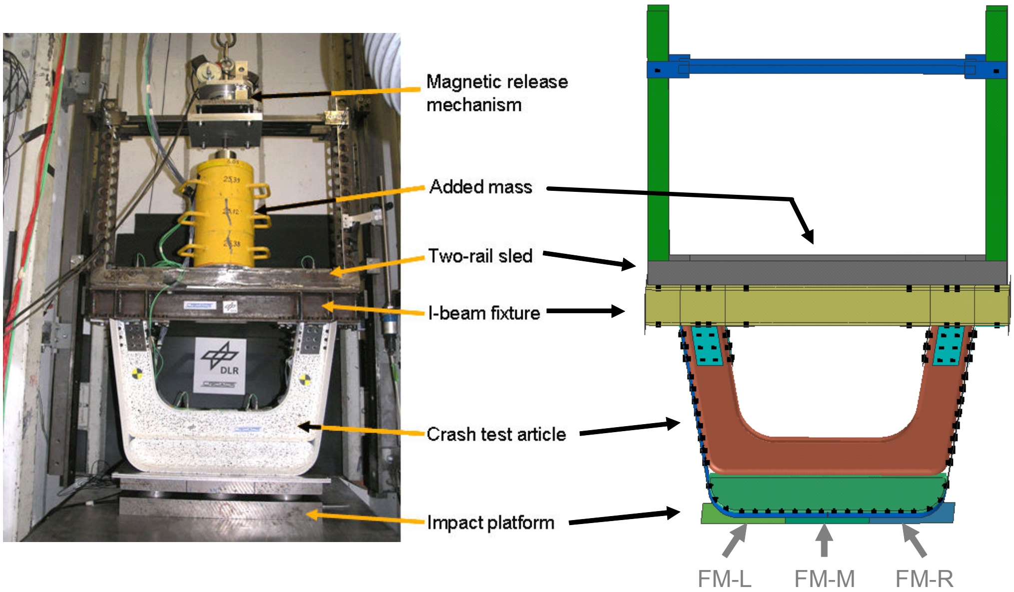

Fig. 8. Comparison of the experimental test setup (left) and numerical model (right)

structures was applied directly to the frame as a lumped nodal mass.

To reflect the mass distribution, centre of gravity and inertia of the entire system more precisely, the I-beam and two-rail sled were included in the revised FE model. The I-beam (yellow) was fastened to the sled (grey, green and blue) using point link (PLINK) elements (black). Eight metallic brackets (light blue) were used to secure the frame to the I-beam and were connected using PLINK elements. The half model was mirrored to create a full FE model. There were several minor changes to the LTA model following detailed analysis of the numerical failure modes and experimental observations from the high speed video:

- The mass was added to the upper sled to reflect the test configuration (the increased bending stiffness of the I-beam and two-rail sled were effective in reducing any significant flexural deformation of the I-beam during the impact).
- The rivet tails between the C-sections and the skin were meshed and included as rigid bodies. The fastened connection between the C-sections and the skin was modelled with PLINK's as shown in Fig. 9. The rivet tails were included in the simulation as they prevented the webs splaying outwards during crushing and contained the failed material. It was important to capture this phenomenon in the model as this containment role of the webs contributed to the overall crushing response as observed in the experimental tests.
- The impact platform was split into three sections, which allowed the contact force for the left, middle and right contacts. The loads obtained from these contacts were directly compared to the experimental load cell data.
- Slight off-axis loading conditions (0.11° for DY1 and 0.27° for DY2.) was included to reflect the experimental impact conditions.

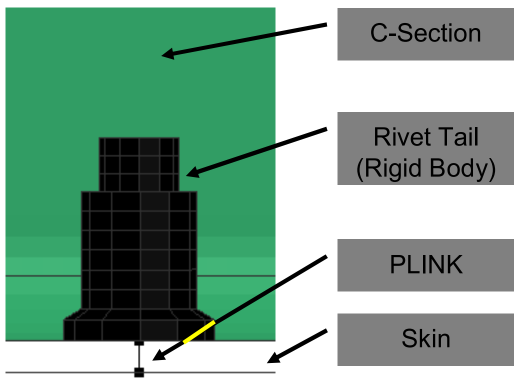

Fig. 9. Detail view of rivet tail representation

These changes added detail to the model to more accurately simulate the experimental impact conditions and allow a more accurate comparison between the experimental and numerical results.

5 LTA: Comparison of Experimental Results and FE Predictions

The progressive failure of the FE model was validated against experimental test data. The accuracy of the model was assessed qualitatively and quantitatively. The predicted load-displacement response, failure behaviour and strain response were compared. Overall the FE model correlated very well with the experimental test data.

5.1 Experimental Response

Comparisons of the predicted, and experimental load-displacement response for the dynamic impact case (DY1) are shown Fig. 10. It should be noted that no filtering was applied to the numerical curves.

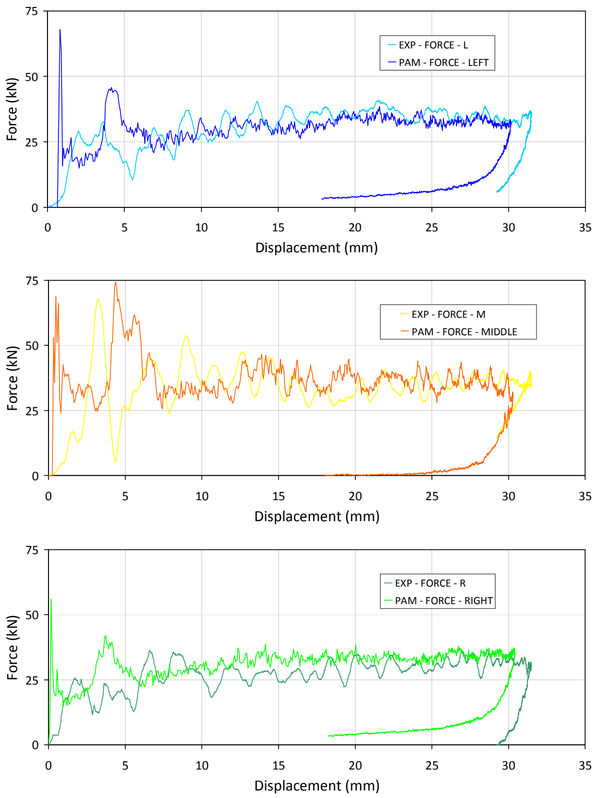

Fig. 10. Comparison of experimental and predicted load-displacement response (DY1) (top to bottom) left, middle and right load cells

The three graphs correspond to the loads measured in the left (FM-L), middle (FM-M) and right hand (FM-R) sections of the impact platform respectively. Overall, the numerical model agrees with the experimentally measured loads. Steady state crush loads for each of the three sections were well predicted. The FE model absorbed the impact energy with a slightly shorter stroke than the LTA; this was attributed to the higher peak loads in the initial stages of crushing (0.0 - 5.0 mm of displacement).

A comparison of the experimental force and energy-displacement curves (DY1) is shown in Fig. 11. The total force is the sum of the forces from the left, middle and right load cells. The results indicate that the boundary conditions of the FE model closely matched the experimental test. A comparison of the experimental results and FE predictions for both dynamic tests are presented in Table 2. The overall comparison is very good, demonstrating that the models were capable of accurately predicting the steady state crushing loads and energy absorption. The numerical models over-predicted the peak load due to the initiation of local buckling in the C-section webs coinciding with crushing in the corrugated web. Predicting the precise failure sequence with complex structural interactions and material failure remains a challenge.

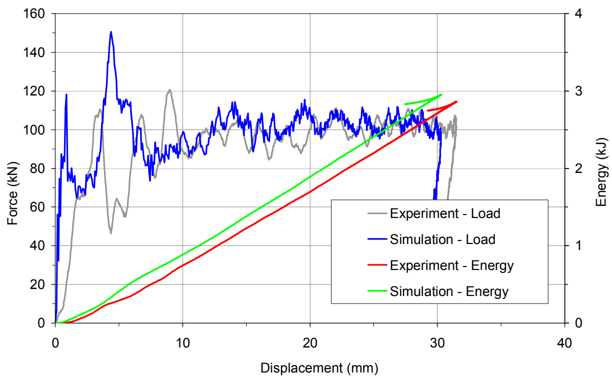

Fig. 11. Comparison of the experimental results FE predictions (DY1)

Table. 2. Summary of results from test and simulation

Quantity	DY1		DY2	
	Test	FE	Test	FE
Absorbed Energy (kJ)	2.83	2.93	5.10	5.10
Crush Distance (mm)	31.5	30.3	56.0	52.0
Peak Load (kN)	120	150	120	142
Steady Crush Load (kN)	104	105	101	99.2

5.2 Failure Modes

5.2.1 Global Failure Comparison

Sequential images of the structural responses of the LTA and the revised numerical model are shown in Fig. 12. The energy absorbing subfloor was observed to crush down progressively. As this crushing process continued, the skin portion was seen to buckle outwards. Structural failure was only limited to these portions of the LTA as desired for occupant survivability. This failure response was captured successfully in the numerical model as seen in Fig. 13.

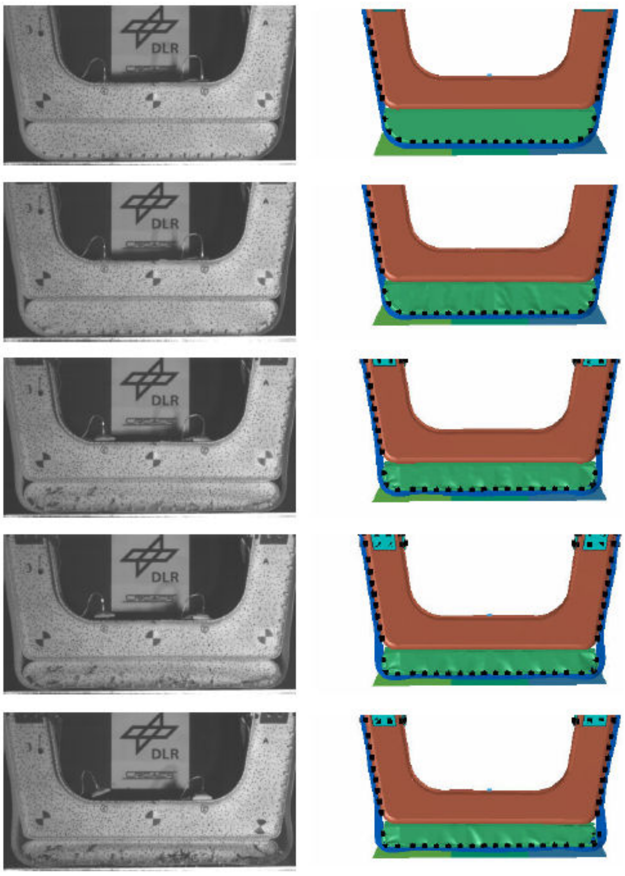

Fig. 12. Comparison of experimental and predicted failure responses (DY1)

5.2.2 Comparison with HRCT-Scan Images

A detailed analysis of the failure mechanisms of the LTA was achieved by comparing High Resolution Computed Tomography (HRCT) scans with the predictions from the FE simulations. HRCT-scanning was performed using a nanotom® CT system. The voxel resolution employed in the scanning of the LTA was 70 microns. Total time from the acquisition phase to the reconstruction of the volumetric data took approximately three hours. The HRCT-scan enables the internal failure mechanisms to be visualised non-destructively. The integrity of the composite laminates, bonded joints and fastened joints was investigated using HRCT-scan images.

A comparison of the failure morphology of the energy absorbing structure of DY1 is shown in Fig. 13. The FE model exhibited damage in the lower 35 mm of the energy absorbing section where elements were highly damaged. The FE model is capable of simulating damage that progresses ahead of the crush front. The remainder of the energy absorbing section exhibited insignificant damage and no failure of the adhesive interfaces was observed. The failure modes and extent of damage in the FE model showed excellent agreement with the HRCT-scan images. It should be noted that the HRCT-scan was conducted post-test, with the mass removed from the LTA. The numerical model of the LTA was returned to the equilibrium position to facilitate comparison with the HRCT-scan.

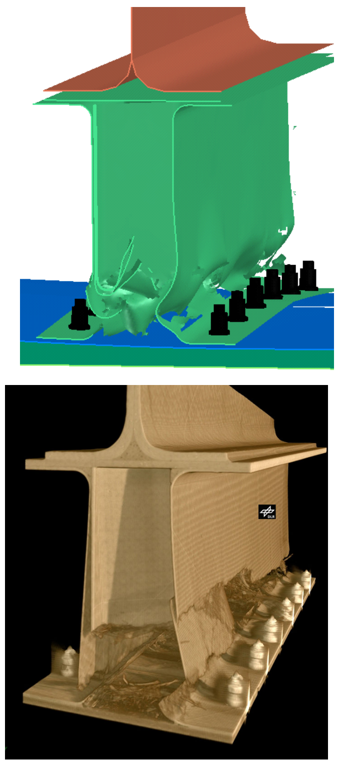

Fig. 13. Comparison of failure modes (DY1): numerical model (top) and HRCT scan (bottom)

5.3 Strain Comparison

Single element strain gauges were placed on the LTA to identify the load path and the presence or severity of any flexural deformation of horizontal and vertical members. The strain gauges were only located on the upper frame The experimental and numerical responses of the six strain gauges located on the web of the upper frame are shown in Fig. 14. The locations of these strain gauges are shown in Fig. 15.

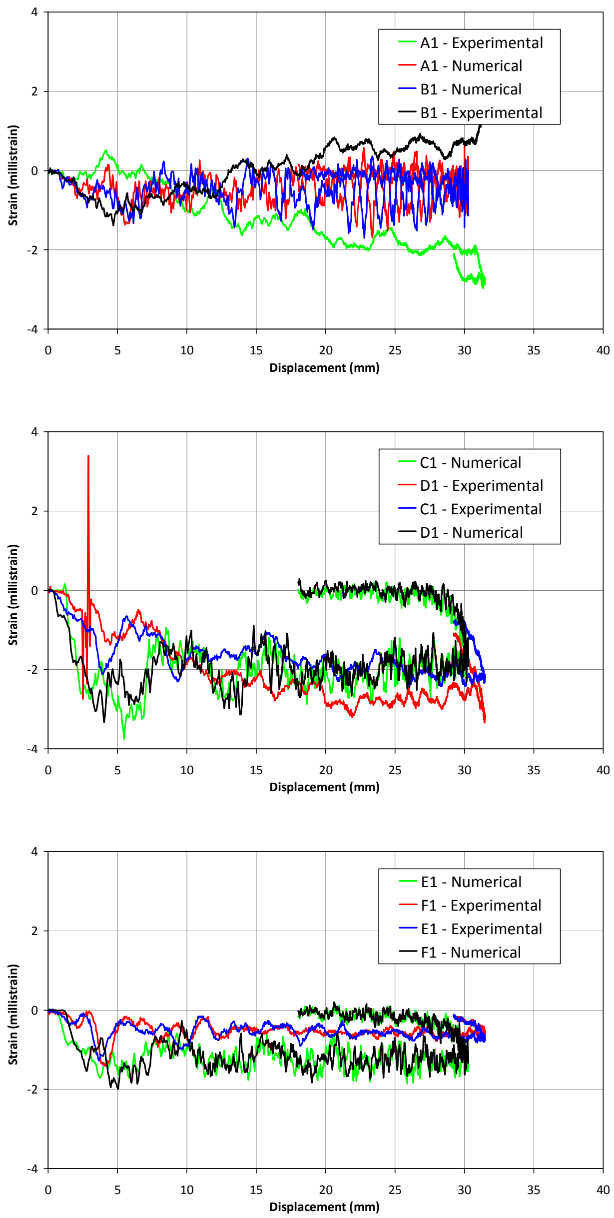

Fig. 14. Comparison of measured and predicted strains for the first dynamic test (DY1)

From the experimental strain gauge data A1 and B1, the lower end of the upper frame was observed to experience an initial positive bending about the x-axis and then a negative bending after displacement of 12.5 mm. This could be attributed to the LTA slipping on the impact platform during the crash test. Besides this ‘slipping’ behaviour, the numerical model was able to capture the characteristics (peaks and steady states) of the experimental strain-displacement curves in addition to the offset impact scenario as observed in strain gauge data C1 and D1.

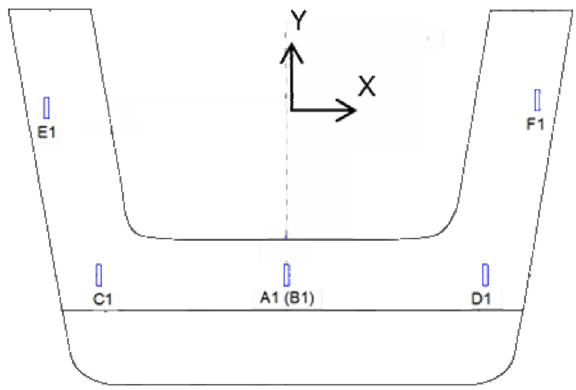

Fig. 15. Strain gauge locations on the LTA

6 Conclusion

A numerical design approach for crashworthy composite structures has been validated through testing of a representative helicopter frame section with energy absorbing sub-floor. Development of the FE approach in PAM-CRASH mirrored the experimental test 'pyramid' where structures of increasing complexity were progressively tested and the modelling methods developed. The validated FE approach was then used in the design of the large test article and to predict the response and energy absorption characteristics.

Tests were conducted quasi-statically and dynamically at two energy levels. The FE model was capable of predicting the failure modes, load-displacement, energy-displacement and strain responses. The agreement with the experimental data provides confidence that numerical models can play a key role in the design and development of future crashworthy structures. FE models can be used to efficiently predict the performance of crashworthy composite structures and optimise the design to maximise occupant safety. 'Virtual' crash testing can be used to supplement experimental crash testing allowing a wider range of crash scenarios to be investigated.

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