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Composite Helicopter Structural Crashworthiness

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Helicopter structure design technologies include more and more composite materials. Their high mechanical characteristics and mass specific energy absorption capability motivate their use in subfloor structural and crashworthy components in preference to metals. Today, the increased performance of computers and new explicit finite element (FE) software developments is leading industry to consider the opportunity of using them for design of composite structures and to study crashworthiness. In order to address the crash analysis of composite structures a German/French research cooperation was set up between ONERA* and DLR and the paper summarises results from the first 3 years collaboration. In the first part of the paper, ONERA presents its contribution to the characterisation of composite materials from 10^{-5} s^{-1} up to 100 s^{-1} on hydraulic machines. Simulations have been undertaken to model the tests and evaluate the FE codes. In the second part DLR studies are presented on the application of a commercial explicit FE code to simulate the behaviour of composite helicopter sub-floor elements under low velocity crash conditions (up to 15 m/s). This includes some comparisons between predicted structural response and failure modes with observed test results.**

1. INTRODUCTION

Helicopter structure design technologies include more and more organic composite materials. Their high mechanical characteristics and mass specific energy absorption capability motivate their use in subfloor structural and crashworthy components in preference to metals. This technology has already been validated and integrated into several rotorcraft structures. Nevertheless, the constant evolution of materials and the certification requirements is restricting technology advancement. To comply with official crash requirements, helicopter manufacturers have either to repeat extensive certification test programs each time for each new material, or prove that the change does not modify the crash performance of the rotorcraft. The consequences for design costs are then significant for the commercial viability of the projects.

Today, the increased performance of computers and new explicit finite element software developments is leading industry to consider the opportunity of using them to address the design issue and the crashworthiness problem. Several studies have shown that the development of FE techniques for composite structures was an ambitious but achievable goal which would require basic research activities.

Within a German/French research cooperation, ONERA* and DLR** have been cooperating for 3 years in order to investigate and improve the general understanding and knowhow in FE modeling of crashworthy composite components. ONERA has placed more emphasis on the materials point of view and DLR on the structural one. Part of the work has been dedicated to the mechanical static and dynamic characterisation of polymer composite ply materials and laminates used by the industrial partners in subfloor components such as sinewave beams or cruciforms. Once completed, the database has been used as input data for numerical models. ONERA-Lille began by investigating the potential of 3D FE models using a self-developed and self-implemented composite materials law, while DLR-Stuttgart started by evaluating the relevance of 2D FE shell models use for industrial problems. ONERA-Lille has thus placed more emphasis on the materials point of view and DLR-Stuttgart on carrying out structural simulations. Results have been exchanged and discussed to meet a common validation target for composite structures.

The paper is divided in two parts. In the first part, ONERA-Lille presents its contribution to composite material law developments. Three thermoset composite materials have been statically and dynamically tested by ONERA-Lille for strain rates between 10^{-5} s^{-1} and 100 s^{-1} on hydraulic machines: unidirectional (UD) carbon, carbon fabric, and aramid fabric reinforced epoxy resins. Results have been used first to analyze the dynamic behaviour of those composites in terms of strength and energy absorption, and then to define parameters for the ONERA-Lille materials model. Basic numerical validations have been performed which proved that complex orthotropic behaviour of composites can be accurately modeled within a single set of materials parameters. More complex simulations have also been undertaken to model the test programme. Problems such as the computing costs of such 3D models, the intrinsic quality of the materials parameters values or the influence of the test procedures are addressed.

In the second part DLR studies are presented on the application of a commercial explicit FE code to simulate the behaviour of composite helicopter subfloor elements under low velocity crash conditions (up to 15 m/s). This includes some comparisons between predicted structural response and failure modes with observed test results. An energy absorbing (EA) composite subfloor design and fabrication concept consisting of a framework of longitudinal beams and lateral bulkheads, connected by cruciform intersection elements is presented in [1],[2]. To understand subfloor crash response and EA characteristics, a versatile FE model has been developed which allows different beam (sinewave, trapezoidal or rib-stiffened) and cruciform elements to be used within the box model so that both the static structural integrity and the dynamic crush response of a range of different boxes could be simulated. In order to validate this concept impact simulations are presented on the key composite elements and results compared with impact test data. As an example FE simulations are shown in the paper on the crash response of hybrid carbon/aramid fabric reinforced epoxy cruciform intersection elements, and of four such cruciforms integrated into a sub-floor box structure. The results demonstrated how the FE simulation tool can be used to aid the designer in evaluating the crashworthiness of different structural concepts with composite materials.

2. MATERIAL CHARACTERISATION

2.1 Tests

Three servo-hydraulic test machines can be used at ONERA-Lille* to characterise composite materials. The first one is a static machine the capacity of which is 10 tons. The second machine is a static tri-axial machine the capacity of which is 40 tons. It is used for combined compression/ tension/ shear tests on materials. It has been especially used for several years to measure the damage sensitivity of composites under multi-axial loads and to identify the Tsaï Wu coefficient F_{12}. The last machine is a dynamic servo-hydraulic one the capacity of which is 5 tons and 10 m/s. It is used to characterise the dynamic behaviour of materials [3].

A lot of work is being done with the latter to define specific specimen geometries and methods in order to reach intrinsic material characteristics. Various materials have been tested, which includes both thermosets: UD carbon/epoxy, carbon and aramid fabric/epoxy, and thermoplastics: carbon and aramid fabric/PEI. The usual tests that ONERA-Lille* performs with its dynamic facility are tension and compression tests on 0°, 90° and +/-45° specimens. Some assumptions are made to reduce the number of tests, thus the behaviour of fabrics in the warp and weft directions are assumed to be the same. Static compression/tension tests have been performed for each material and direction before testing them dynamically. Force vs displacement curves are obtained from tests. Conventional stresses are calculated, and strains are measured to reach the material stress vs strain behavioural law.

The strain rates are measured in the linear domain. Maximum strains are given when the limit of the strain gauges has not been reached. Yield stresses are defined when the behaviour appears to be nonlinear enough to define a 0.2% strain limit value.

The behaviour of UD carbon/epoxy is elastic brittle in tension and compression along the fibre directions. If standard specimens are used for compression, the maximum stress falls down to less than half the tension value. Once specimens with anti-buckling guides are used to prevent buckling instabilities, the difference of behaviour between tension and compression almost disappears. In the transverse direction, the maximum stress and strain are much higher in compression than in tension (more than 450%). This is due to the fact that the failure mechanism is very sensitive to the direction of loading (fibre/matrix debonding in tension). The tension behaviour looks elastic brittle, and the compression one elastic-plastic. For +/-45° laminates, the static behaviour is elastic-plastic in both tension and compression.

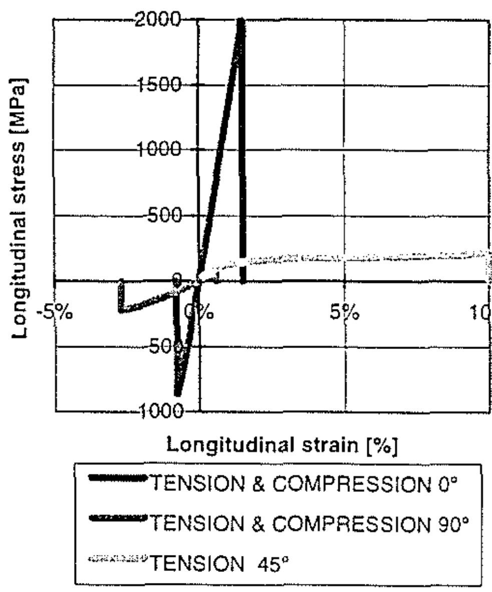

Figure 1 - Material behaviour of UD carbon/epoxy

Figure 1 summarises standard carbon UDs static behaviour. In dynamics, for the transverse (in compression) and shear directions, the material characteristics are very sensitive to the strain rates (the dynamic range is studied between 10^{-3} s^{-1} up to 50 s^{-1}). The static behaviour for carbon fabrics/epoxy looks elastic brittle in tension and compression along the fibres direction (both warp and weft). The difference between tension and compression is noticeable but not fundamental. According to the +/-45° direction, the static behaviour is elastic-plastic in both tension and compression. Figure 2 summarises standard carbon fabrics static behaviour. This kind of material seems to be the most sensitive one to shear strain rates between 10^{-3} s^{-1} and 50 s^{-1}.

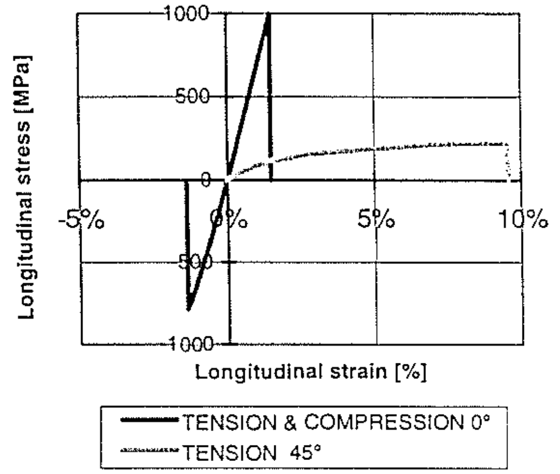

Figure 2 - Material behaviour of carbon fabric/epoxy

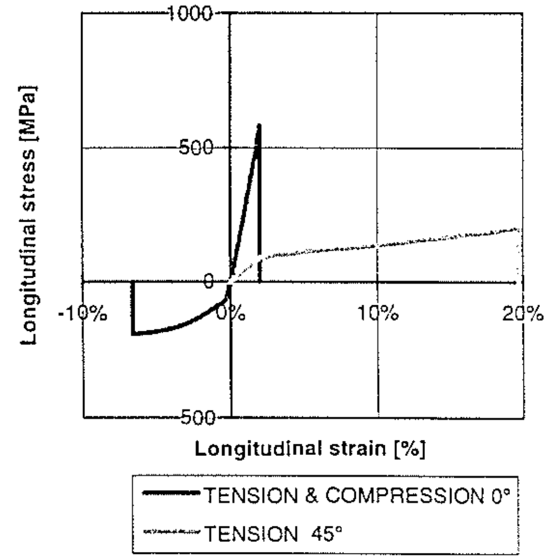

Figure 3 - Material behaviour of aramid fabric/epoxy

Compared to the carbon fabric/epoxy, the behaviour of the aramid fabric/epoxy is different in tension and compression along the fibre directions. It looks elastic brittle in tension and elastic-plastic in compression. In shear, the maximum strain level is also higher (more than 20%). Figure 3 summarises standard aramid fabrics static behaviour. For compression, the material characteristics are highly sensitive to the strain rate between 10^{-3} s^{-1} and 50 s^{-1}.

Figure 4 presents an example of the strain rate dependency of the maximum shear stress of the 3 tested materials. Similar dynamic influence could be observed on shear moduli and shear yield stresses.

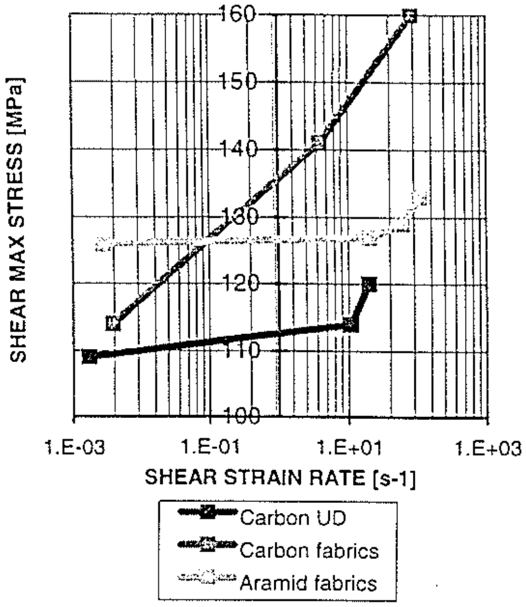

Figure 4 - Strain rate dependence on the shear behaviour for the different materials

2.2 Material models

In parallel to these experimental studies, ONERA-Lille* has been developing and implementing a 3D dynamic composite material law as a user defined material law in the RADIOSS code environment from MECALOG [4,5,6]. ONERA-Lille* 3D material law is formulated in the directions of orthotropy of the materials. Classical elastic static characteristics are defined but different Young's moduli are introduced for tension and compression. The multi-axial Tsaï-Wu criterion is used to limit the linear domain of behaviour of the material. The envelope is made strain rate dependent by C_i parameters :

$$F_{ii}/F_{Dii} = 1 + C_i \ln(\dot{\varepsilon}_i/\dot{\varepsilon}_{i0})$$

where $\dot{\varepsilon}, \dot{\varepsilon}_0$ are strain rates, F_{ii} and F_{Dii} are the initial static and current dynamic parameters in the Tsaï-Wu failure criterion.

Non linear « hardening » behaviour outside the linear envelope is introduced through the definition of tangent moduli functions of the non linear work parameters W_i:

$$E_{iiT}/E_{ii} = 1 + B_i\left[W_i\right]^{m_i}$$
$$G_{ijT}/G_{ij} = 1 + B_k\left[W_k\right]^{m_k}, \; k = 9\text{-}i\text{-}j$$

The hardening parameters B_i , m_i are characterised from the static tests, as described in more detail in [6].

The stress state is computed in an incremental way, without relaxation of the « dynamic » elastic part of it. Hardening variables are deduced from principles similar to normality and consistency rules. The modeling of rupture is based on a multi-criteria approach, with possible strain rate effects. Specific criteria are introduced in parallel to standard maximum stresses or strains. They are similar to the Tsaï-Wu formulation except that they are expressed in sub-domains with extra F_{ij} coefficients which are used to describe micro-buckling, delamination, or fibre debonding mechanisms.

Conventional stress/strain curves are extrapolated from tests, and complete sets of data are deduced, using simple hypothesis and 'on the shelf' optimising tools. Numerical and mathematical validations with single elements are done for all the directions and materials which had been tested during the experimental campaign. Eventually, the developed material law proves to be able to simulate such complex anisotropic behaviour as those shown in figures 1, 2 and 3. An example is given in Figure 5.

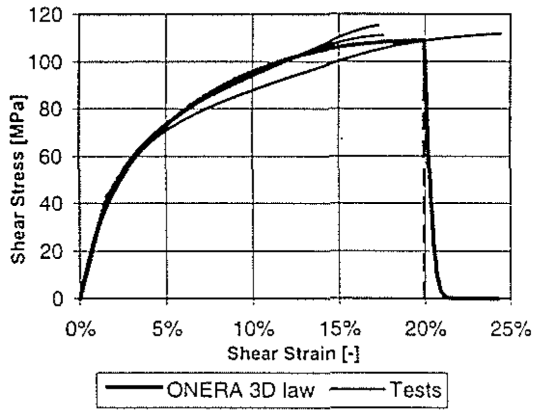

Figure 5 - Shear behaviour of the model compared with carbon fabric/epoxy tests

2.3. Simulation of the tests

Tension test specimens are modeled to apply the 3D material law developed by ONERA-Lille* on real cases, but with a limited number of elements. Great care has been taken to represent as close as possible the experimental conditions which include the geometry of the specimens, the presence of epoxy glass fibre tabs (the characteristics of epoxy glass fibre were found in literature), the transverse loading conditions due to the grips. This last point is particularly important because many experimental ruptures occurred near or between tabs, due to obvious coupling effects between longitudinal and transverse stresses. The load level applied by grips has been measured and defined as displacements which have been imposed on the model. For each simulation, it has been checked that the measured transverse stress state was verified by the model. As for single elements, validations with specimens were done for most of the tested directions and materials.

Figure 6 is a comparison between a force/ displacement static test response and the corresponding simulation in a 45° specimen tension test. The difference which appears shows that the usual material parameters extrapolation which is processed from tests (the stress is estimated as the ratio of the force by the initial specimen section) is not valid. Indeed if the material composites tests specimens are now considered to be small structures with an inhomogeneous stress state, the obtained stress/ strain curves lead to approximate parameters. Once these parameters have been optimized, the simulation gives better results as the figure shows.

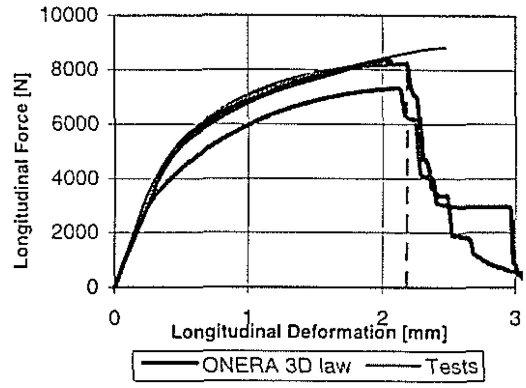

Figure 6 - Optimisation of material models through the simulation of tests specimens

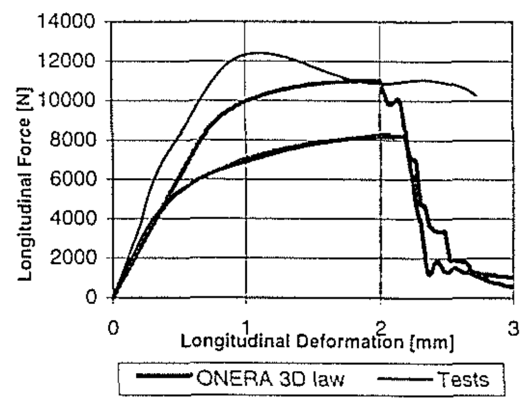

Figure 7 - Influence of dynamics on the simulation of the tested specimens

The dynamic influence on the load level is also very well modeled, see Figure 7, which compares quasi-static and dynamic data (upper curves) and simulations in the same 45° tension test.

2.4. Hybrid Segment Crush Specimens

Segment crush specimens made of a carbon/aramid/epoxy laminate have been impact tested at DLR-Stuttgart**. The hybrid specimens have the laminate layup [A_{45}, A_{45}, C_{45}, C_0, C_0, C_{45}, A_{45}, A_{45}], where A_{45} is a 45° aramid ply, C_{45} a 45° carbon fabric ply, C_0 a 0° UD carbon ply, and the ply angle is with respect to the segment axis. Simulations have been performed with an FE solid model containing the correct segment geometry, laminate and trigger.

Figure 8 gives a comparison between different simulations and the test results. Using a standard 3D material law without calibration leads to very poor agreement with the test. Once calibrated, the results are better, but the calibration consists in replacing the UD carbon elastic brittle behaviour by an elastic-plastic model without rupture, which is not physically realistic. The ONERA-Lille* material model enables us to reach an improved agreement without calibrating the material parameters. This is at the expense of an increased computing time (80 CPU hours instead of 4 CPU hours on a workstation), but this added cost is also due to the fact that ONERA-Lille* has not optimized its material law implementation.

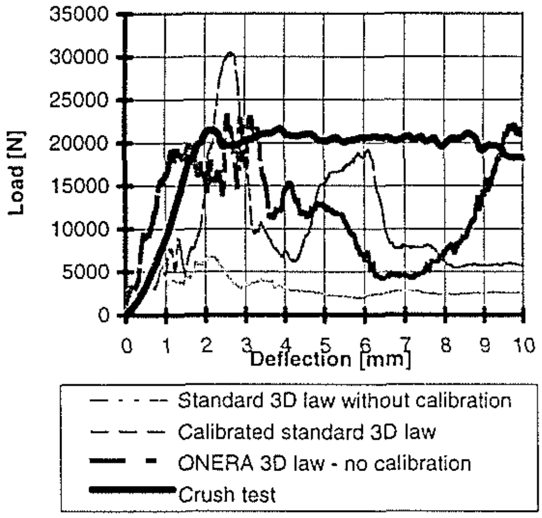

Figure 8 - Comparisons of 3D simulations of the segment crush specimen

Though the agreement has been improved with the material law developments, the simulation still diverges from the test results after the first few millimetres are crushed. The reason is that a global buckling mode appears and prevents the progressive crushing failure mode being kept. The peeling mode is well initiated thanks to the modeling of the trigger, but its propagation is stopped. A reason why such a buckling mode appears though a quite constant load level is being applied could be that the boundary conditions change. Studies are in progress to explain and solve this difficulty.

3. SIMULATION OF SUBFLOOR STRUCTURAL ELEMENTS

In this section DLR studies are presented on the application of the commercial explicit FE code PAM-CRASH [7] to simulate the behaviour of composite helicopter subfloor elements under low velocity crash conditions (up to 15 m/s). Detailed materials properties such as the data presented above are thus used to calibrate idealised composites models already available in the commercial code.

3.1 Modelling composites properties in PAM-CRASH

PAM-CRASH contains several materials models and special elements for laminated composite materials, which are discussed in [8]. These 'bi-phase' models have been developed mainly for UD laminates, and allow fibre and matrix damage to be modelled separately. They have not been specifically validated for fabric laminates, which are the reinforcements of interest here. It was considered that a homogeneous orthotropic elastic damaging material was the most appropriate model for fabric laminates, as this model is applicable to brittle materials whose properties are degraded by microcracking. This type of material may be modelled in PAM-CRASH as a 'degenerate bi-phase' model in which the UD fibre phase is omitted, and the 'matrix' phase is assumed to be orthotropic. The assumed stress-strain relation in the model then has the general orthotropic form

$$\sigma = E\ \varepsilon, \qquad E = E_0\,[\,1 - d(\varepsilon_{II})\,],$$

where σ, ε are the stress and strain tensors, E the stiffness matrix with initial values E_0 , and d is a scalar damage parameter. This takes values $0 < d < 1$ and is assumed to be a function of the second strain invariant ε_{II}, or the effective shear strain. The composite fabric ply or laminate has orthotropic stiffness properties, but a single 'isotropic' damage function which degrades all the stiffness constants equally.

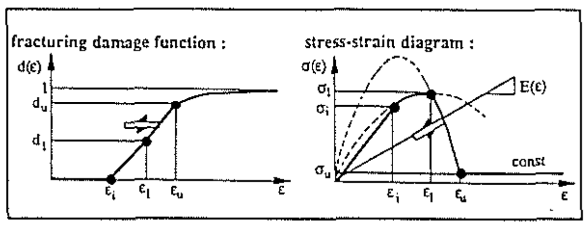

Figure 9 -. Schematic fracturing damage function and corresponding stress-strain curve [7]

Uniaxial stress-strain curves for fabric reinforced composites are assumed to have the general form shown in Figure 9, where ε_i is strain at the onset of initial damage, ε_1 is the strain at the peak failure stress σ_1, and ε_u is a limiting strain above which the stress is assumed to take a constant value σ_u. These curves can be modelled by a bilinear damage function (Figure 9) with two damage constants d_1 and d_u to be determined. Typical stress-strain curves for fabric composites in tension and compression (see Figures 2 and 3) are in this general form and can be used to calibrate the materials model and to determine the damage parameters d_l and d_u for the analysis. The parameter d_l measures the departure from linearity at the first knee in the stress-strain curves, and is thus small in tension, whilst the parameter d_u determines the residual value σ_u. For the FE analysis it is not good practice to reduce the material stresses directly to zero at material fracture, as this may lead to numerical instabilities. Thus under tensile stresses typically $d_u \cong 0.9$, indicating that the element is nearly fully damaged, whilst in compression $d_u \cong 0.5$ to model the compression crush stress allowing the element to retain a load carrying capability after initial damage.

Comparison with the ONERA-Lille materials law described above shows the following simplifications here. Rate dependence is not included, and the degradation in properties is described by a single strain dependent damage function, rather than the 5 functions of the plastic work. Note that this simplified composites materials law cannot model correctly both the 0°-ply tension and the 45°-ply tension data shown for example in Figures 1 and 2. In practice most composites structures are laminates with both 0° and 45° plies and errors in modelling individual 45° plies at large strains can be unimportant if the laminate failure properties are controlled by the 0° plies at lower strains. This simplified approach has been used successfully to simulate the crash response of a quasi-isotropic carbon fabric/epoxy laminate airframe structure in [9]. Here it is applied in a pragmatic way to a number of orthotropic and quasi-isotropic fabric composite helicopter sub-floor structural elements. These structures have been designed for high energy absorption and consist of hybrid laminates of carbon and aramid fabric/epoxy. The appropriate parameters for the PAM-CRASH materials law were determined from a materials test programme on M10 epoxy resin prepregs [10] similar to that reported above. The tests were carried out quasi-statically and materials rate dependence is not included in the modelling discussed in this section.

3.2 Simulated crash response of cruciform element

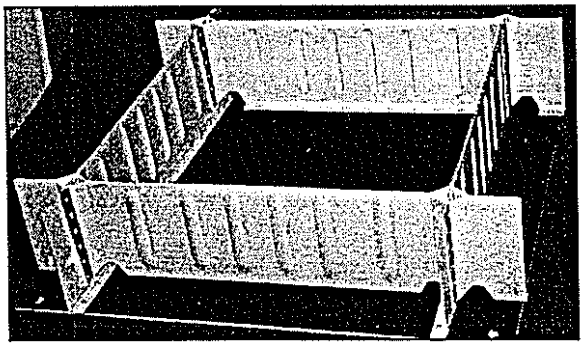

Figure 10 - Helicopter subfloor box with stiffened webs and HTP-cruciforms

A helicopter design concept which meets the structural and crashworthiness requirements should provide a protective shell for the occupants, with energy absorbing elements incorporated in the landing gear, the subfloor and the seats. The subfloor structure Figure 10 typically consists of a framework of longitudinal beams and lateral bulkheads covered by the outer skin and cabin floor. The total structural height is often only about 200 mm. The design of intersections (cruciforms) of beams and bulkheads, the beam webs, outer skins, and floor sections (boxes) contribute essentially to the overall crash response of a helicopter subfloor assemblage. In this sub-section the dynamic crush response of a typical composite subfloor cruciform element is simulated with PAM-CRASH.

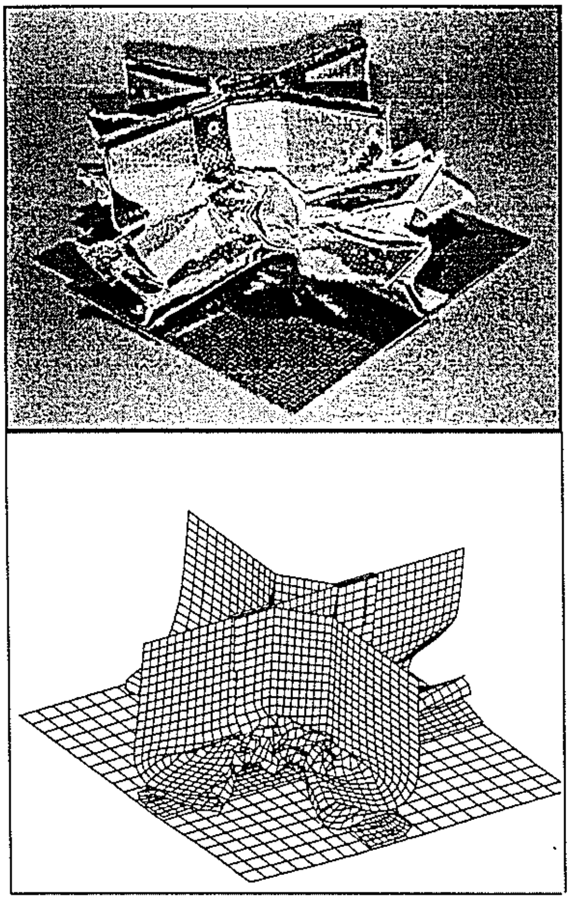

Figure 11 - Cruciform element: comparison of FE simulation with element impacted vertically

The DLR has designed several different cruciform elements with different peak load and energy absorption (EA) characteristics. The element chosen for detailed study is a hybrid tapered pole (HTP) design [1], [2], as shown at the corners of the box in Figure 10. It is designed to absorb energy under vertical impact loads and retain some structural integrity, thus the composite materials selected are hybrid laminates of carbon and aramid fabric/epoxy. The FE model of the HTP cruciform element contained about 5200 4-node orthotropic layered shell elements to simulate the composite laminates, together with 22 rigid body elements which simulated the rivets in the structure. A rivet failure model was not used, since in tests rivet failures never occurred. Structural tests on the cruciforms are carried out in a drop weight tower where the upper edges are embedded in an aluminium plate, which is impacted at about 10 m/s by a 100 kg mass. In the model the nodes of the upper edges form a rigid body with the added mass at the centre of gravity, and a rigid wall was modelled below the base plate. The materials model appropriate to these fabric reinforced laminates is the orthotropic elastic damaging material described in §3.1. The laminate construction varied between different plate elements in the cruciform, for example in the transverse floor beam direction the laminate construction is a symmetric hybrid 8 ply layup $[A_{45}/A_{45}/C_{45}/C_0]_S$, where A and C refer to aramid and carbon fabric prepregs and the subscript is the fabric angle to the vertical direction. Test specimen data on the ply materials were used to generate stress-strain curves and suitable values for the elastic constants and damage parameters in the materials model were determined.

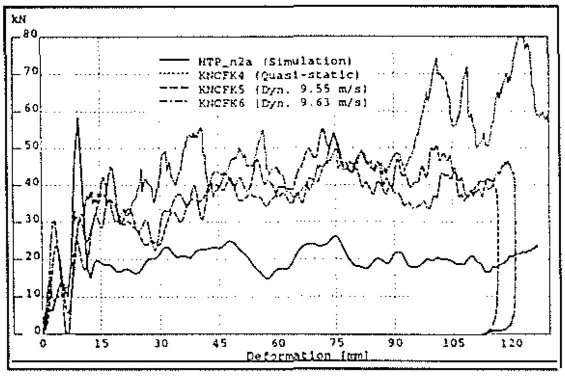

Fig. 12 Load-deflection response of cruciforms under impact at 10m/s (comparison test results and FE simulation)

The results of the dynamic simulations of vertical impacts on the cruciform elements showed excellent agreement between the predicted mode of failure and that observed in tests, as Figure 11 shows. In tests the element fails by regular folding of the vertical webs in contact with the base plate, initiated by the J-trigger at this position, with crushing in the central column. This is clearly seen in the FE simulation of Figure 11 after 12 ms. Folding failures occur because of the hybrid laminate chosen, in which the more ductile aramid fabric plies are on the outer faces where the bending stresses are higher, which seems to inhibit brittle failures associated with carbon fibre composites. Figure 12 compares the predicted load-deflection response under impact compared with test data on 3 hybrid cruciform elements. One of the tests was performed quasi-statically, the other two were impact tests in a drop weight tower. There was not a significant difference between the quasi-static and dynamic test data. There is general agreement in the shape of the load-deflection curves between test and simulation. However the load levels, and hence the total energy absorbed in the simulations, are typically about 50% below the test results, which shows that there are deficiencies in the dynamic model of these hybrid laminate materials currently implemented in the FE code.

3.2 Simulated crash response of helicopter subfloor boxes

A versatile FE model has been developed [1] which allows different beam and cruciform elements to be used within a subfloor box, so that both the static structural integrity and the dynamic crush response of a range of different boxes may be simulated. Based on the experience with the simulations of the cruciform elements mentioned above, different subfloor concepts have been analysed, using FE-meshes created in the modular sub-floor box model presented in [11]. In this modular FE model different structural intersections (simple connection, HTP cruciform element) can be combined with different modules for the skin, the keel beam and bulkhead sections. Up to now plain webs, integrally rib-stiffened webs and sinusoidal and trapezoidal corrugations have been investigated. In Table 1 the combinations that have been used in the crash simulations are summarised. The drop mass that has been used in this parameter study is 75kg plus the mass of the individual composite box; the initial velocity at the first contact is 10 m/s.

Table 1. Summary of generic composite box models

Analysis ID	Intersection Design	Web Design	Skin Design
Box 1	HTP	plain webs	flat
Box 2	HTP	integr. stiffened	flat
Box 3	HTP	sinusoidal	flat
Box 4	HTP	trapezoidal	flat
Box 6	simple inters.	plain webs	flat

Selected results are presented in Figure 13. The individual plots show the different quarter models of the box designs 2, 4 and 6 after the initial impact at 8 ms. While the plain webs as well as the integrally stiffened webs (Box 2) tend to buckle and fail without absorbing much energy, the corrugated beams (sinusoidal as well as trapezoidal (Box 4) fail progressively and absorb much more energy. The worst combination is Box 6 with plain webs and a simple intersection. The webs just buckle and create a single fold and the simple intersection also fails without crushing and high energy absorption. The graph in Figure 13 shows the velocity of the additional mass located on top of the sub-floor box plotted vs. deformation. When this velocity reaches zero it indicates that the box has stopped the impacter and absorbed the impact energy. While the best design (Box 4) can absorb all the initial kinetic energy

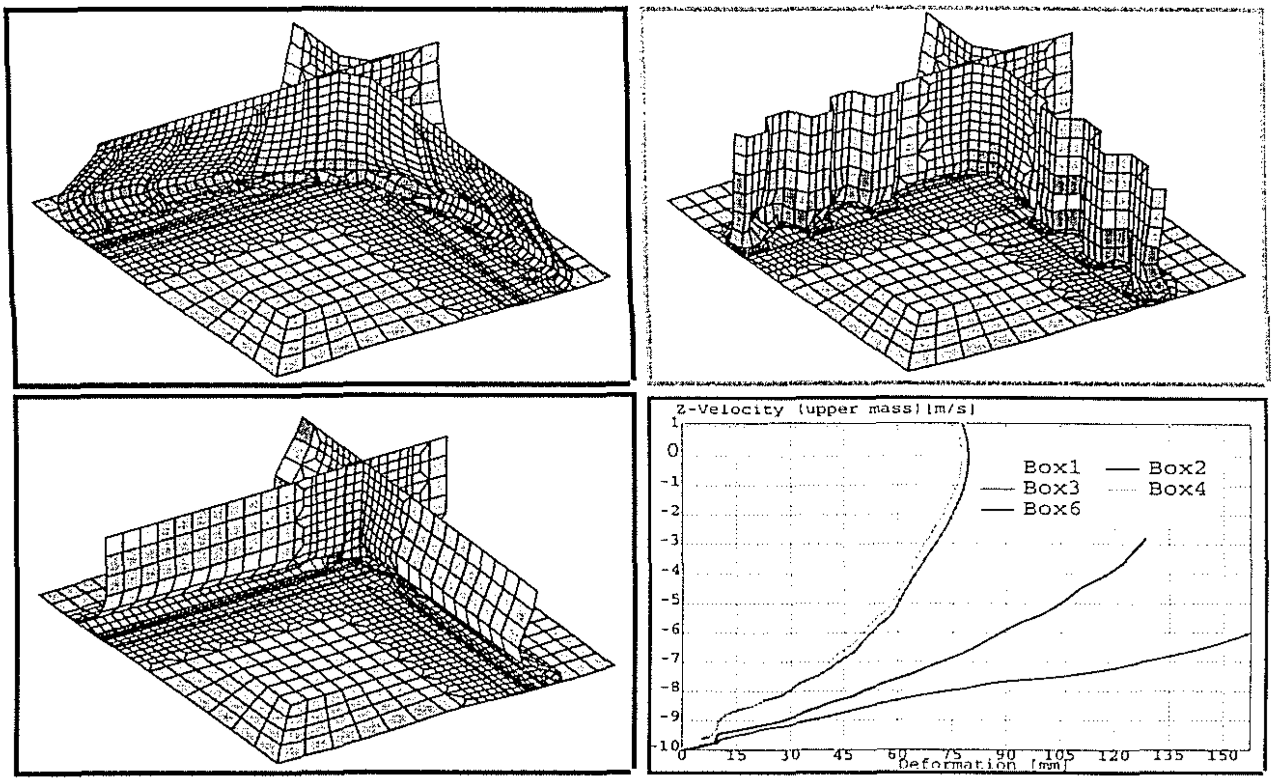

Figure 13 - Comparison of different subfloor box designs under impact load

within less than 80 mm of deformation, the worst design (Box 6) could not stop the mass until the simulation was stopped after about 160 mm of deformation. At that point the downward velocity of the additional mass is still 6 m/s. Thus the graph may be used as a simple design chart to evaluate the efficiency of different subfloor box designs under crash conditions.

A composite subfloor box using hybrid laminates in a design similar to that of the model Box 2 consisting of 4 HTP-cruciform elements and integrally stiffened keel and transverse beam sections has been built and tested in vertical impact on the rigid load reaction platform of DLR's drop tower facility. In Figure 14 this box is shown after the impact test at 10 m/s. The HTP-cruciform elements failed in the same way as seen in the component tests with crushing in the central parts, and the stiffened webs just buckled and broke at the lower edge of the stiffeners. Figure 14 also shows FE simulations of this test. Compared with the simulations shown in Figure 13 a finer mesh has been used which enabled the stiffeners to be modelled more realistically. The box failure initiated by global buckling along the lower edge of the stiffeners is also predicted in the simulations, although the total rupture of the webs here was not found in the simulations. Figure 14 does confirm the success of PAM-CRASH in predicting modes of failure in composites structures. Once again, a comparison of the predicted load pulse with test data showed load levels at about 50-60% of measured data.

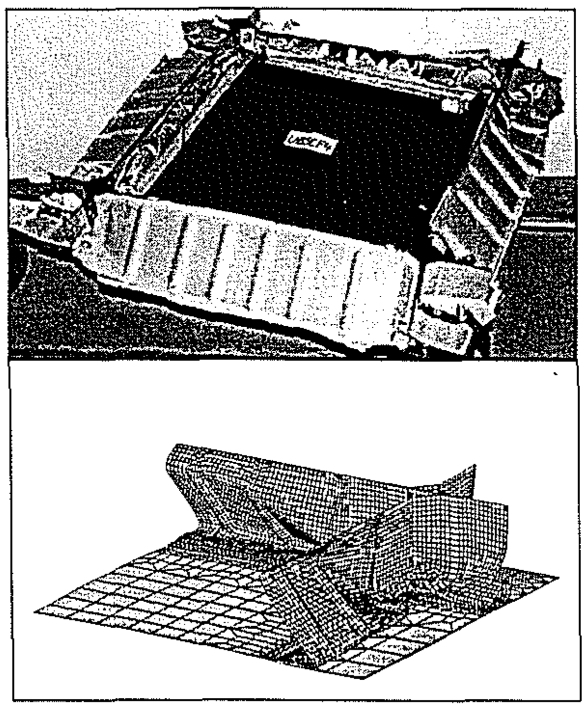

Figure 14. - Generic DLR subfloor box: comparison of FE simulation with box impacted vertically at 10 m/s

4. SUMMARY AND CONCLUSIONS

The paper has described recent progress made under a joint German/French research cooperation to develop and validate FE simulation methods for evaluating the crash behaviour of composite structures under low velocity impact loads. The work has included:

- Measurement of the quasi-static and dynamic mechanical properties of composite laminates with carbon and aramid fibre reinforcements in epoxy and PEI resins. The materials selected are being used in current helicopter structure development programmes.
- Modelling of composites failure behaviour, including failure properties and dynamic rate influences, with the implementation of a new 3D materials law in the RADIOSS code.
- Use of the composites test data to calibrate the RADIOSS and existing PAM-CRASH materials models for crash analyses.
- Validation of materials models by simulations on test specimens and composite structural elements.
- Comparison of FE simulations with impact test results on helicopter subfloor structures.

The work is continuing in an ongoing research programme. The main conclusions at this interim point are:

- In the ONERA-Lille contribution an improved materials law has been implemented for composites in the commercial explicit FE code RADIOSS. This has been validated through the modeling of tests specimens and the comparison with standard material laws based models. The simulations proved that the modelling of the orthotropic dynamic behaviour of composites can be improved using enhanced material law developments. However, the models and data required are complex and are currently not very suitable for crash simulations on larger structures. The main objectives now are to evaluate the introduction of damage/plasticity coupling and to optimise the implementation in order to reduce computing times.

- In using PAM-CRASH for the structural analyses of hybrid cruciform elements as well as subfloor box-structures the results of numerical simulations at the DLR show reasonable agreement with quasi-static and dynamic crush test results. The failure phenomena, buckling or crushing, can be predicted quite well; however the load levels and energy absorption calculated are low due to oversimplifications in the 'degenerated' bi-phase model used. Current work is thus concentrating on further improvements to the composites models available in the code.

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