CRASH AND IMPACT SIMULATION OF AIRCRAFT STRUCTURES – HYBRID AND FE BASED APPROACHES

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Abstract: The DLR has collaborated within European Commission (CEC) sponsored research programmes [1-3] on numerical crash and high velocity impact simulation studies of metallic and composite sub-components of aircraft structures. Simulations using the hybrid code DRI-KRASH were performed on transport aircraft metallic sub-structures comprising an airframe section and a ‘stick model’ of a full-scale aircraft. For the section measured accelerations, displacements and forces correlated well with simulated data. With the stick model various crash conditions were simulated including ditching on water. For ditching, a coupled global/local methodology was applied, where the ‘hydrodynamic elements’ were calibrated by FE simulations of the structure/fluid interaction of representative sub-structures of the airframe. An FE (PAM-CRASH) based simulation study of a rear fuselage bay structure showed good correlation to crash test data. FE crash simulations also focused on composite floor sections representative for light aircraft and helicopters and sub-cabin belly structures typical for commuter and transport aircraft. The major tasks focused on material studies, failure mechanisms and criteria, the generation of a new composite fabric model, new design concepts, numerical simulations and the correlation with crash test data. The technology can be used for future design of airframes with structural components made out of composite materials. A methodology was developed for simulating the response of composite aircraft structures to high velocity impacts (HVI), such as bird strike or foreign object damage (FOD), on wing leading edges, engine fan blades etc.. Procedures to measure the mechanical properties of composite materials under large strain and high strain rate loading were developed. New material constitutive laws and failure models for UD and fabric composites under HVI loading were developed and implemented into explicit dynamic codes such as PAM-CRASH. The FE based methodology was validated by simulating laboratory high strain-rate tests and high velocity impact tests on idealised composite structures.
1 INTRODUCTION

The purpose of the IMT Research Program „Crashworthiness for Commercial Aircraft“ [1] sponsored by the European Commission (CEC), was to provide guidelines for the improvement of crashworthiness design techniques by the extensive use of analytical studies supported by experimental work on materials, components and full-scale structure. The program intended to develop and validate non-linear dynamic analysis methodology in the commercial aircraft field and provided an integrated approach to the problem by a combination of studies into overall energy absorption (EA) mechanisms of airframe structures, and investigations into occupant reaction to crash impulse and interactions with the surrounding structure. All structural components which were evaluated in the program could be taken out from an A320 fuselage which was used before for static testing. As examples of the DLR research activities a rear fuselage bay structure was simulated with FE crash code PAM-CRASH [4] and was correlated with test data. Also, modelling and crash simulations of a fuselage section and a full-scale aircraft stick-model using DRI-KRASH [5] are presented.

With the arrival of a new generation of very large transport aircraft (VLT), aircraft manufacturers will show compliance with the FAR 25 ditching requirements either by performing new tests with scale models or use numerical simulation tools in order to demonstrate the ditching performance and evaluate the design strength. For ditching simulations, a local/global methodology is applied [6] by combining the Lagrangian Finite Element code PAM-CRASH and the hybrid impact analysis code DRI-KRASH. Local behaviour of structural sub-components are ascertained through the FEM technique and are then used to generate a DRI-KRASH global ditching model. The applicability of this local/global concept is demonstrated on a fuselage section.

The use of composite materials, such as carbon or aramid fibre reinforced plastics (CFRP, AFRP) is increasing in nearly all sectors of the transport industry. In aircraft structures these materials are already used in primary structures of several helicopters, light aircraft, commuter planes and sailplanes. In fixed wing transport aircraft composites are used in rudders, flaps, fairings, and vertical and horizontal tail planes. Due to their low density and high stiffness combined with a potential for the reduction of production costs with new fabrication technologies, there is also an increasing interest in CFRP for transport aircraft wings and fuselages.

Composites have high potential to absorb energy in the case of accidents or aircraft crashes. However, composites such as CFRP are inherently brittle and may exhibit a linear elastic response up to failure with little or no plasticity. Therefore, a proper design of energy absorbing devices and a good prediction of the composites failure in the design phase by numerical simulation are very important. In anticipation of this development, the European research program "CRASURV- Design for Crash Survivability" [2] was started in 1996 to
increase the knowledge of the crash behaviour of lightweight composite structures and their application in aircraft fuselages. Besides fundamental work on basic materials and methodologies generic composite box structures and composite sub-floor belly structures of a commuter type aircraft and an airliner have been designed, built and dynamically tested. In addition, the tests were simulated using modern explicit Finite Element codes with enhanced composite materials models that were developed within the research project. The DLR work concentrated on the analysis of structural intersections and sub-floor boxes which are typical components of modern helicopter and general aviation aircraft sub-floor assemblies. A summary of a comprehensive material test programme, the composite materials model in PAM-CRASH/PAM-SHOCK with an enhanced model for fabric plies and the final results of structural analyses are described.

Composite structures are vulnerable to impact damage and have to satisfy certification procedures for high velocity impact (HVI) from bird strike and foreign object damage (FOD). HVI in composite structures is being studied within a CEC funded research project on ‘High velocity impact of composite aircraft structures’ HICAS [3]. One aspect of this project is presented, namely the development and validation of FE codes for modelling the response of composite structures under impact loads. In polymer composite materials there are several different failure modes such as matrix cracking, ply delamination, fibre fracture. Furthermore the material properties may be strain rate dependent. Key issues are the development of suitable constitutive laws for the mechanical behaviour of composites up to failure and the measurement of appropriate materials parameters and the implementation of the materials models into commercial FE codes. The ply damage model based on continuum damage mechanics (CDM) for composites as developed by Ladevèze and his co-workers [7, 8] has been implemented in shell elements in the commercial explicit FE crash and impact code PAM-CRASH, and a novel numerical approach for delamination modelling was developed using stacked shell elements with a contact interface condition. As an example the code was applied to predict the response of a composite shell impacted at low velocity by a steel impactor, where both delamination and ply failures occur. A comparison between predicted structural response and failure modes with observed test results is given.

2 NUMERICAL CRASH SIMULATION TOOLS

2.1 Dynamic FE simulation

FE simulation techniques allow the engineer to predict the crash response of a structure directly without having to make use of structural test data to calibrate elements in the analysis. However, the crash behaviour of an aircraft structure is extremely complex, involving both nonlinear dynamic materials response and large structural deformations. Such analyses are at the limit of validity of current FE analysis codes, especially for nonmetallic structures. The established FE codes in the aircraft industry are the implicit FE codes, such as NASTRAN, which are used widely for structural analysis, buckling calculations, and for prediction of
dynamic vibration response. In the last 15 years several commercial FE codes such as LS-DYNA3D, RADIOSS and PAM-CRASH have been developed especially for impact and nonlinear dynamic simulations. These newer crash simulation codes are explicit FE codes which use a Lagrangian formulation with an FE mesh fixed in the material and which distorts with it. The equations of motion are integrated in time explicitly using central differences. The method requires very small time steps for a stable solution, thus it is particularly suitable for impact and crash simulations and less appropriate for equilibrium structural analyses. The main advantages of the explicit method is that the governing equations are uncoupled allowing an 'element-by-element' solution, with no global stiffness matrix assembly or inversion required. The method is generally recognised to be very robust for highly nonlinear problems. The codes contain materials models for metals and composites, and most important for crash analysis, contact in the structure is easily and efficiently handled by introducing temporary 'penalty forces' as additional external forces to resist penetration and control sliding. In response to the needs of the automotive industry there are also models of safety features such as airbags and occupant dummies which can be incorporated into the structural analysis.

2.2 KRASH hybrid code

The crash simulation program KRASH predicts the response of vehicles to multi-directional crash environments. KRASH provides the interaction between rigid bodies through interconnecting structural elements (beams), which are appropriately attached (pinned, clamped). Beams represent the stiffness characteristics of the structure between the masses. The equations of motion are explicitly integrated to obtain the velocities, displacements and rotations of the lumped masses under the influence of external and internal forces. In the modelling technique, large regions of structure are approximated in a simplified manner. Non-linear behaviour (e.g. force-deflection curves) of sub-structures, that is already known from tests or other analyses can be introduced into the model by use of macro elements like springs, non-linear beams, plastic hinges or hydrodynamic elements. The fact that a KRASH model requires only a small number of elements results in very short CPU times. The user can quickly perform parametric studies, since changes in the KRASH model can be realised in short time. These features make KRASH a very cost effective tool in the field of the crash simulation programs.

KRASH has a history of 25 years. New features of DRI-KRASH now include additional injury criteria, e.g. HIC and SI calculations, an expanded landing gear module, a soft soil module as well as a water impact module. The FAA and the British Air Accident Investigation Board (AAIB) are sponsoring efforts to develop air accident reconstruction/ investigation tools, with KRASH as its core program. Today all American and European helicopter manufacturers as well as the leading airplane manufacturers use the program DRI-KRASH.
3 ALUMINIUM AIRCRAFT STRUCTURES [1]

3.1 Rear fuselage bay structure

Structural details and FE model: The bay structure which was cut from the rear part of a A320 fuselage consisted of two half frames, 45 stringers, the skin and the entire cargo and passenger floor structure. The diameter was about 4000mm, the total length was 700mm. The final FE mesh consisted of 66440 nodes, 58884 shell elements and additional 3485 rivets. The trolley used in the test was represented by a moving rigid wall.

Correlation of FE simulations and crash test: The structure was fixed for the crash test at the passenger floor level and was loaded in the z-direction by a trolley having a mass of 1240 kg and an initial velocity of 8.12m/s. Trolley acceleration and three strain gage rosettes were measured. Two high speed cameras and one video camera were also used for the documentation of the crash sequence. Pre- and post-test simulations with different half and full models were performed. The simulation of a full model in Figure 1 shows the deformed structure 45ms after the impact. Plastic deformations started very close to the location where the skin failed in the test. Additional plasticity occurred just beside reinforcements around the intersection of the struts with the frames. In general, the correlation between the simulated deformations and loads and those found in the crash test was very good.

Figure 1: Deformed component D1 at 45 ms
3.2 KRASH Simulation of a Fuselage Section

Structural details and KRASH model: The structure represented a part of section 17 of the A320. Six seat rows, 14 dummies, and two overhead bins were installed. The KRASH 3D-half model of the section consisted of 79 masses, 23 nodes, 30 springs, 136 beams and 42 plastic hinges. The linear beam properties and the structural mass distribution were determined from the NASTRAN model of the section. The non-linear properties of the springs and plastic hinges were generated from component crash test data and the respective PAM-CRASH simulations.

Correlation of KRASH simulations and crash test: The section having a mass of 2330 kg was dropped with a z-velocity of 7 m/s on a concrete surface. The measurement channels comprised 48 at the dummies, 16 at the seats, 80 at the structure, and 36 at the overhead bins. Different views of the test were filmed with standard videos and high speed cameras. More than 80 correlation of test results and KRASH simulations were performed. An overlay of the deformed structure and the KRASH post-test model is shown in Figure 2. The global deformation behaviour is represented very well and also accelerations, velocities and displacements at different locations were in good agreement with the test results.

![Figure 2: Deformed structure and KRASH model at 100 ms](image)

3.3 Full-scale stick model simulations of the A320

Details of the A320: The A320 took off for its maiden flight in February 1987. The A320 is a short to medium range aircraft with 150 - 176 seats. The main dimensions are: Wing span: 34.1 m, fuselage length: 37.57 m, height at vertical stabilizer: 11.76 m. The maximum take-off weight is 65500 kg.
**Stick model description:** NASTRAN files provided by DASA were used as basic input to generate the mass distribution and the beam properties. In order to automate as much as possible of the modelling process, a computer program was developed which reads the relevant NASTRAN files and writes parts of the KRASH input file. For the representation of the undercarriage failure or engine separation, collapse loads were defined for the respective beams in the KRASH model. Springs were added to the model in order to represent the lower part of the fuselage, the landing gear and the engine nacelles. Figure 3 shows the A320 KRASH stick model which finally comprised 58 masses, 55 nodes, 31 springs, and 57 beams. The number of masses had to be condensed, due to the limitation of mass points (80) that could be used in the KRASH version which was used for the simulations.

![Figure 3: A320 KRASH stick model](image)

**KRASH stick model simulations:** The following impact conditions were used for all simulations with the KRASH stick model:

<table>
<thead>
<tr>
<th>Velocity</th>
<th>[m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>v_x</td>
<td>75</td>
</tr>
<tr>
<td>v_y</td>
<td>0</td>
</tr>
<tr>
<td>v_z</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Attitude</th>
<th>[deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll angle</td>
<td>0</td>
</tr>
<tr>
<td>Pitch angle</td>
<td>2 (nose up)</td>
</tr>
<tr>
<td>yaw angle</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1: Impact conditions for stick model
Simulations with extended landing gear: The parameter variations in the simulations included the influence of lift forces and two conditions for the engine separation (condition A: drag load failure, condition B: vertical load failure). Representative for the simulation studies, Figure 4 shows the simulated crash sequence of the aircraft with extended landing gear, a stepwise reduction of the lift forces and the engine failure condition B. The landing gears failed between 110 and 130 ms, the engines failed at 140 ms without separation from the wing. The first ground contact of the fuselage occurred at 260 ms, the maximum deformation of 250 - 400 mm of the fuselage occurred between 450 and 550 ms. Maximum acceleration peaks reached 15g. Most of the other peaks were observed between 4g to 6g. A comparison with other simulation runs showed that a complete disconnection of the engines and the wings (condition A) caused about two times higher fuselage deformation. Also, not taking into account any lift forces, led to much higher fuselage deformations.

Simulations with retracted landing gear: In this crash scenario the aircraft hits first with the engine nacelles. After 80 ms the connection to the wings failed without separation (condition B, further transfer of loads to the wing). The first fuselage contact occurred at 117 ms, a maximum deformation of 500 - 700 mm of the fuselage was observed. Compared to the scenario with extended landing gear, nearly twice as big wing amplitudes could be observed.
Water Impact Analysis of aircraft structures [6]

Water modelling: In the explicit Finite-Element Code PAM-CRASH, the water continuum is modelled with a Lagrangian mesh or the “Smooth Particle Hydrodynamics” (PAM-SPH) is applied. The Lagrangian approach was chosen to model its properties with an isotropic elastoplastic hydrodynamic solid material law whose pressure-volume relationship is governed by the following equation of state:

\[
p = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + \left( C_4 + C_5 \mu + C_6 \mu^2 \right) \varepsilon
\]

where \( \rho_0 \) is the reference water density, \( \rho \) the current water density, \( \varepsilon \) the internal energy and \( C_i \) are material constants. The water is modelled as a quasi-incompressible material, which in practice means that the shear modulus is equal to one hundredth of the bulk modulus and \( C_1 \) is set to the bulk modulus of water. In the used material model no fluid viscosity is available. Modelling entrapped air between the impactor and the water free surface provides a cushion effect and therefore reduces contact forces. The water model was validated first with a rigid sphere, and second, by simulating the vertical impact of a non-rigid fuselage model, for which the test results were available.

DRI-KRASH water crash analysis tool - the coupled approach: For impact on water the crash code DRI-KRASH provides an uncoupled and a coupled approach. In the coupled option, the structure/water interactions are modelled with "hydrodynamic elements" [5]. Each of them consists of at least one lift surface and one drag surface model. The lift surface model mainly causes a vertical deceleration of the impactor whereas the drag surface model is responsible for horizontal decelerations.

Taking into account the advantages of FE and hybrid crash codes, it is possible to combine both codes in the following way. Local behaviour on sub-components of the structure are analysed with the FE code PAM-CRASH. The acquired data are then used to determine the input data necessary to the definition of the DRI-KRASH global model for simulation of the full-scale structure, Figure 5. According to the simulation results obtained from this combination, global weaknesses of the structure can be detected and as a result, changes in the design of sub-components can be carried out and then numerically re-tested with the Finite-Element approach. DRI-KRASH input data have then to be re-calibrated for a new global run. An optimization loop process takes place.

In the case of an aircraft fuselage, crash analyses have shown that most of the energy absorption occurs through the formation of plastic hinges and deformation in the cargo area.
The location of plastic hinges in a cross-section of a fuselage as well as their moment-angular deflection characteristics can be evaluated through PAM-CRASH simulations. The lift surface model of a "Hydrodynamic Element" in the case of a vertical impact can be calibrated from the contact force time history obtained from the FE analysis of the region where a hydrodynamic element is attached to a mass. Drag coefficient required in the definition of the drag surface model have still to be evaluated from test data or through empirical methods.

**Application of the local/global methodology:** The local/global methodology was applied to a cross-section of an aircraft impacting water. A sub-component of the fuselage section below the passenger floor was analysed using PAM-CRASH. This sub-component has been chosen for the water impact analysis because its behaviour (deformation, eventually rupture) would dictate the behaviour of the whole aircraft during impact. The value of the impact velocity has been set to 7 m/s in order to cause substantial damage to the structure. The half cross-section sub-component has been modelled with about 29,000 shell elements and the water block with about 93,500 hexahedral solid elements. An elastic plastic material law with isotropic hardening has been chosen for the fuselage sub-structure together with the previously described hydrodynamic material model for the water block. Various plastic hinges were formed in the frames and the skin. The unfolding of the skin in contact with water caused a horizontal outward displacement of the struts. The FE analysis showed that most of the energy
is absorbed through the formation of the plastic hinges. It should be noted that the severity of the impact investigated here is well above the condition encountered during ditching, where sink rates usually do not exceed 2 m/s.

Results obtained from the PAM-CRASH analysis are furtheron used to generate a DRI-KRASH model of the same half cross-section sub-component to demonstrate the equivalency of both models. The DRI-KRASH half model consisted of 20 masses, 30 beams, 8 plastic hinges and 10 hydrodynamic elements (figure 6a). Plastic hinge characteristics have been defined, respectively, from the moment and the angular deflection calculated with PAM-CRASH and lift surface models have been calibrated from the PAM-CRASH computed contact forces. The impact conditions are the same as those used for the previous Finite-Element model.

![Diagram](image)

Figure 6: (a) DRI-KRASH model of the cross-section sub-component; (b) acceleration time histories at a mass point of DRI-KRASH model and on a corresponding beam of PAM-CRASH model.

Figure 6b shows the acceleration time history calculated at the centre of gravity of the outer floor beam in PAM-CRASH and at the corresponding mass in DRI-KRASH. Both curves agree very well, which demonstrates that the calibration of the DRI-KRASH model with PAM-CRASH output was successful and provided the basis for a full-scale aircraft ditching model.

4 CRASH SIMULATIONS WITH COMPOSITE STRUCTURAL COMPONENTS [2]

4.1 Material tests

To obtain appropriate input data for the simulation of the composite components and for the validation of the improved material models in PAM-CRASH a comprehensive test program with both quasi-static and dynamic materials tests has been carried out with two basic materials, a carbon and aramid fabric material with an epoxy resin system:
Carbon Fabric VICOTEX G803/ M10 290g/m²
Aramid Fabric STRAFIL AT285/ M10 200g/m²

In addition, similar tests were performed on specimens with a frequently applied hybrid lay-up made of these two basic materials. This hybrid lay-up was also used in the sub-floor components and boxes:

\[ [\pm 45^\circ A, \pm 45^\circ A, \pm 45^\circ C, 0^\circ/90^\circ C]_S \quad t_{\text{nom}} = 2.1 \text{ mm} \]

Standard tension and coupon compression tests were performed in 0° (warp), 90° (weft) and in the ±45°-direction to evaluate the shear properties. Further tension and compression tests were performed on specimens which were cut under 15° and 30° to one of the fibre directions. The purpose of these non-standard configurations was to get data for the validation of the material models under a combined normal and shear loading. In Figure 7 some of the stress-strain curves measured in the tensile tests on the basic materials are presented.

Figure 7: Results of tensile tests on different composite material specimens

In addition, quasi-static and dynamic crushing tests on tube segments were performed. These specimens, developed at DLR, give an indication of the crushing behaviour of larger structural components made of the same material. The drop tower tests were carried out with initial velocities of 5m/s and 10m/s. Again both fabric materials were tested with fibre orientations 0°/90° and ±45°, together with the standard hybrid lay-up. In Figure 8, one specimen of each of the tests series is shown. In Figure 9 one load-deformation curve of each test series is presented. The carbon specimens absorbed energy by a continuous crushing process after the failure of the bevel trigger with little oscillations of the load. The aramid segments tended to buckle in a metal like folding mechanism. In the segments with the hybrid lay-up the energy was absorbed similar to the carbon segments, but the tougher outer aramid plies provided a minimum structural integrity and prevented the disintegration of the carbon debris. The measured loads decreased with increasing test speed. With the carbon and hybrid segments the load level was reduced up to 25%, the reduction on the aramid specimens was found to be only about 10%.
4.2 Validation of composite fabric model

Based on the results of the materials tests, input data for a newly developed fabric material model in PAM-SHOCK were derived and then validated with simulations on single element, specimen and structural component level. First, short descriptions of the basic composite bi-phase model in PAM-SHOCK and the recent developments are given.
Composite Bi-phase model: The composite bi-phase model in PAM-CRASH/PAM-SHOCK [4] was initially developed for UD-plies. The composite is assumed to be a heterogenous material with a matrix and a fibre phase. These two phases have their own rheological behaviour and individual representation of failure. The elastic behaviour of each composite ply is calculated by a combination of the orthotropic behaviour of the matrix phase and a one-dimensional reinforcement in the direction of the fibres. The share of the fibres in the composite is given by a fibre volume ratio $\alpha_f$.

$$\sigma = C_{UD} \varepsilon$$ with $C_{UD} = C_m + \alpha_f C_f$  
(2)

Both, the matrix phase and the fibres may undergo modulus fracturing damage after an initial linear elastic phase according to:

$$C_m(d_m) = C_{m0} (1-d_m)$$ and  $$C_f(d_f) = C_{f0} (1-d_f)$$  
(3)

where $C$ is the instantaneous modulus matrix in $\sigma = C_{UD} \varepsilon$, $C_0$ is the undamaged initial modulus matrix and $d$ is a scalar damage parameter that depends on strains. The damage parameters for matrix and fibre phase can be expressed as follows:

$$d_m(\varepsilon) = d_{m,v}(\varepsilon_v) + d_{m,s}(\varepsilon_s)$$  
$$d_f(\varepsilon) = d_{f,v}(\varepsilon_f)$$  
(4)

The scalar functions $d_{m,v}(\varepsilon_v)$ and $d_{m,s}(\varepsilon_s)$ for the matrix damage parameters describe the evolution of damage with respect to the equivalent strains $\varepsilon_v$ and $\varepsilon_s$. The individual damage functions $d_{m,v}$, $d_{m,s}$ and $d_{f,v}$ can be defined individually and different in tension and compression. The principle shape of each of the damage curves and the resulting stress strain curve are shown in Figure 10.

![Figure 10: Schematic fracturing damage function and stress-strain curve [4]](image)

The volume and shear damage is assumed to be zero for equivalent strains below the initial threshold strain $\varepsilon_i$. Then the damage parameter $d$ increases bi-linear up to the strain level $\varepsilon_u$ with the corresponding ultimate damage $d_u$. The bi-linear growth of the damage leads to a shape of the stress-strain curve with two parabolas. Beyond the ultimate damage $d_u$ the residual stress is supposed to be constant. The damage functions are assumed to grow and asymptotically reach the value 1.

One common way to calibrate the fabrics behaviour is to use a 'degenerated' bi-phase model with neglected fibre properties ($\alpha_f=0$). Using that option the orthotropy of the
individual ply is represented by orthotropic properties of the matrix phase and the damage is calibrated with a single damage parameter within the matrix phase. In most cases the deviatoric (shear) damage parameter is used to calibrate the damage of the fabric material. Using this calibration it is impossible to model the brittle behaviour in the fibres direction and the non-linear shear behaviour correctly (see \( \pm 45^\circ \) tests). To overcome this deficiency, a new fabric material model was implemented into PAM-SHOCK which allows two arbitrary fibre directions in each ply, which do not have to be orthogonal. During the elements deformation both fibre directions are updated individually and therefore the skewness of the fibres, e.g. in the \( \pm 45^\circ \) tests, is modelled correctly.

**Validation of fabric model data set on cruciform level:** With the availability of the fabric material model and the parameter sets derived from the material tests some cruciform and sub-floor box simulations were performed using the new fabric model. In Figure 11 the simulated crushing sequence of a HCP-cruciform on a rigid surface is shown 1ms, 5ms and 15ms after the first contact together with a picture of a real specimen after a quasi-static crushing test. In this simulation an additional mass of 50kg is distributed over the upper row of nodes which form a ‘rigid body’. The initial velocity in the simulation is 10 m/s. The first failure and the intersection crushing is predicted well in the simulation (t=5ms) and corresponds with the deformations seen in the crash tests. Up to a deformation of 55mm, which corresponds to t=8ms, the correlation of test and simulation is excellent, beyond that point the load is calculated too low compared with the test.

![Figure 11: Crushing sequence of HCP-element at t=1, 5 and 15 ms; static test result](image)

**Validation with Sub-floor Boxes:** Based on the previous experience, a complete composite sub-floor box structure (800x780x180mm) has been designed, build and dynamically tested. This box consists of two trapezoidal corrugated longitudinal beams with embedded ply-drop-off triggers above the lower flange and two angle stiffened transverse beam sections with a conical split laminate at the connection to the longitudinal beams, forming HCP-cruciforms. In the drop test with a total mass of 501kg and a drop speed of 9.2 m/s, the trapezoidal beams and the central part of the intersections started to crush, the transverse beams just broke close to the trigger radius to the skin flange and moved in the outward direction.
A detailed FE-model of a quarter of this new box design was created with 8200 shell elements. The crushing behaviour was simulated with the new fabric model and loading similar to the crash test. Trapezoidal keel beams failed progressively in the region of the trigger, while the transverse beams tended to buckle outwards, as was seen in the test. In Figure 13 the calculated load curve is compared to the load curve measured in the drop test. The integration of the contact forces between the skin of the sub-floor box and rigid wall located below the structure has been used for the comparison first, but the agreement was very poor. Therefore, the FE model of the box was extended to take the flexibility of the drop tower load platform into account, which was modelled using solid elements. In a final analysis with the flexible load platform the load at the real location of the load cell was calculated, which correlates much better to the test results (curves 2 and 3).
5 FABRIC COMPOSITES DAMAGE MODEL FOR HVI SIMULATIONS

5.1 Elastic ply damage mechanics model

The fabric reinforced composite ply is modelled as a homogeneous orthotropic elastic or elastic-plastic damaging material whose properties are degraded on loading by microcracking prior to ultimate failure. A CDM formulation is used in which ply degradation parameters are internal state variables which are governed by damage evolution equations. Constitutive laws for orthotropic elastic materials with internal damage parameters are described in [7-10] and take the general form

\[ \varepsilon^e = S \sigma \]  

where \( \sigma \) and \( \varepsilon^e \) are vectors of stress and elastic strain and \( S \) the elastic compliance matrix. For shell elements a plane stress formulation with orthotropic symmetry axes \( (x_1, x_2) \) is required. The in-plane stress and strain components are

\[ \sigma = (\sigma_{11}, \sigma_{22}, \sigma_{12})^T, \quad \varepsilon^e = (\varepsilon_{11}^e, \varepsilon_{22}^e, 2\varepsilon_{12}^e)^T. \]  

Using a strain equivalent damage mechanics formulation, the elastic compliance matrix \( S \) may then be written:

\[
S = \begin{pmatrix}
1 / E_1(1-d_1) & -\nu_{12} / E_1 & 0 \\
-\nu_{12} / E_1 & 1 / E_2(1-d_2) & 0 \\
0 & 0 & 1 / G_{12}(1-d_{12})
\end{pmatrix} \]  

where \( \nu_{12} \) is the principal Poisson’s ratio, which for simplicity is assumed here not to be degraded. The ply model introduces three scalar damage parameters \( d_1, d_2, d_{12} \) which have values \( 0 \leq d_i < 1 \) and represent modulus reductions under different loading conditions due to microdamage in the material. For fabric plies \( d_1 \) and \( d_2 \) are associated with damage or failure in the principal fibre directions, and \( d_{12} \) controls in-plane shear failure. In the general damage mechanics formulation [6] ‘conjugate forces’ or damage energy release rates \( Y_1, Y_2, Y_{12} \) are introduced corresponding to ‘driving’ mechanisms for materials damage, and it is shown that with the compliance matrix (3) they take the form:

\[
Y_1 = \sigma_{11}^2 / (2E_1(1-d_1)^2), \quad Y_2 = \sigma_{22}^2 / (2E_2(1-d_2)^2), \quad Y_{12} = \sigma_{12}^2 / (2G_{12}(1-d_{12})^2)
\]  

The damage parameters are defined in terms of the damage evolution functions \( f_1, f_2, f_{12} \) and have the general form: \( d_1 = f_1(Y_1, Y_2, Y_{12}), d_2 = f_2(Y_1, Y_2, Y_{12}) \) and \( d_{12} = f_{12}(Y_1, Y_2, Y_{12}) \).
Specific forms for the evolution equations are required which should be consistent with test data. The elastic damage mechanics ply fabric model is based on the following assumptions:

a) Fibre and shear damage modes are decoupled, with fibre damage determined by $Y_1$ and $Y_2$, and shear failure by $Y_{12}$.

b) Fibre damage development may be different in tension and compression.

c) For balanced fabrics ($E_1 = E_2$) damage development in the two fibre directions may be different, thus $d_1 \neq d_2$. However, it is assumed that $f_1$ and $f_2$ will have the same functional form ($f_1 = f_2$).

d) The ply material is 'non-healing': therefore damage during unloading is held constant until positive loading is applied which causes further damage accumulation.

e) Damage development does not necessarily lead to ultimate failure of the ply and a global failure criterion is also necessary.

Due to condition (d) above, the damage evolution equations are based on the maximum value of the damage forces reached during the previous loading history. We thus introduce the quantities $Y_1$, $Y_2$, $Y_{12}$ which are defined in terms of the maxima of $\sqrt{Y_i}$. Test data on UD composites [7] has shown that the square root of the damage forces is the quantity which arises more naturally, therefore:

$$Y_1(t) = \max \{ \sqrt{Y_1(\tau)} \}, \quad Y_2(t) = \max \{ \sqrt{Y_2(\tau)} \}, \quad Y_{12}(t) = \max \{ \sqrt{Y_{12}(\tau)} \}, \quad \tau \leq t \quad (9)$$

Taking into account (a) and (c) above, and assuming an elastic region without damage at the onset of loading, leads to the following expressions for the lower and upper thresholds of damage:

$$d_1 = 0, \quad Y_1 < Y_{10} \quad \quad d_1 = \alpha_1 (Y_1 - Y_{10}) \quad \text{for} \quad Y_{10} < Y_1 < Y_{1f}$$

$$d_2 = 0, \quad Y_2 < Y_{10} \quad \quad d_2 = \alpha_1 (Y_2 - Y_{10}) \quad \text{for} \quad Y_{10} < Y_2 < Y_{2f} \quad (10)$$

$$d_{12} = 0, \quad Y_{12} < Y_{120} \quad \quad d_{12} = \alpha_{12} (\ln Y_{12} - \ln Y_{120}) \quad \text{for} \quad Y_{120} < Y_{12} < Y_{12f}$$

Linear forms for $d_1$ and $d_2$, were found to be good approximations for fabric plies, and an equation linear in $\ln(Y_{12})$ was found to be required for modelling the shear behaviour at larger strains. Thus the evolution equations for a balanced fabric ply require the determination of two slope parameters $\alpha_1$, $\alpha_{12}$ and four damage threshold parameters $Y_{10}, Y_{120}, Y_{1f}, Y_{12f}$.

### 5.2 Elastic-plastic model for a fabric composite ply

For in-plane shear, deformations are controlled by matrix behaviour which may be inelastic, or irreversible, due to the presence of extensive matrix cracking or plasticity. On unloading this can lead to permanent deformations in the ply. The extension of the fabric model to include these irreversible damage effects is now considered, based on the following main assumptions:

f) The total strain in the ply is split into the sum of elastic and plastic (or inelastic) parts.

g) Plastic strains are associated only with the matrix dominated in-plane shear response.
h) A classical plasticity model is used with an elastic domain function and hardening law applied to the 'effective' stresses in the damaged material.

i) Inelastic or plastic strain increments are assumed to be normal to the elastic domain function.

From (f) above the total strain \( \varepsilon \) can be written as the sum of elastic \( \varepsilon^e \) and plastic strains \( \varepsilon^p \) (\( \varepsilon = \varepsilon^e + \varepsilon^p \)). The elastic strain component is given by (2). A plane stress model for a thin ply is assumed and only shear strain contribute to plasticity (\( \varepsilon_{11}^p = \varepsilon_{22}^p = 0 \), \( \varepsilon_{12}^p \neq 0 \)). Following [6], an elastic domain function is introduced \( F(\tilde{\sigma}_{12}, R) \) where \( \tilde{\sigma}_{12} \) is the 'effective' shear stress \( \tilde{\sigma}_{12} = \sigma_{12}/(1-d_{12}) \) and \( R \) is an isotropic hardening function. \( R(p) \) is a function of an inelastic strain variable \( p \). The elastic domain function has a simple form here since only the effective shear stress leads to plastic deformation:

\[
F = \frac{\sigma_{12}}{1-d_{12}} - R(p) - R_0 \quad (11)
\]

where it is assumed that \( R(0) = 0 \) and that \( R_0 \) is the initial threshold value for inelastic strain behaviour. The condition \( F < 0 \) corresponds to a stress state inside the elastic domain where the material may be elastic damaging. It follows from the normality requirement (i) that \( F = 0, \dot{F} = 0 \) hence from (7) it can be shown that the plastic strain \( p \) is defined by

\[
\varepsilon_{12}^p = \dot{p}/(1-d_{12}) \quad \text{or} \quad p = \int_0^{\varepsilon_{12}^p} (1-d_{12})d\varepsilon_{12}^p \quad (12)
\]

showing that \( p \) is the accumulated effective plastic strain over the complete loading cycle. The model is completed by specifying the hardening function \( R(p) \). This is determined from cyclic loading tests in which both the elastic and irreversible plastic strains are measured. A typical form assumed for the hardening function is an index function, which leads here to the general equation:

\[
R(p) = \beta p^m \quad (13)
\]

so that the shear plasticity model depends on the parameters \( \beta \), the power index \( m \) and the yield stress \( R_0 \).

5.3 Delamination model

Delamination failures occur in composite structures under impact loads due to local contact forces in critical regions of load introduction and at free edges. They are caused by the low, resin dominated, through-thickness shear and tensile properties found in laminated structures. In composites delamination models the thin solid interface is modelled as a sheet of zero thickness, across which there is continuity of surface tractions but jumps in displacements. The equations of the model are given here for the case of mode I tensile failure.
at an interface. Let $\sigma_{33}$ be the tensile stress applied at the interface, $u_3$ the displacement across the interface, and $k_3$ the tensile stiffness. Following an elastic damaging interface stress-displacement model is assumed:

$$\sigma_{33} = k_3 (1 - d_3) u_3, \quad d_3 = c_1 \left( 1 - \frac{u_{30}}{u_3} \right), \quad \text{for } u_{30} \leq u_3 \leq u_{3m},$$

with tensile damage parameter $d_3$, and $c_1 = u_{3m} / (u_{3m} - u_{30})$. It can be verified that with this particular choice of damage function $d_3$, the stress-displacement function has the triangular form shown in Fig. 1, and $u_{30}$, $u_{3m}$ correspond to the displacement at the peak stress $\sigma_{33m}$ and at ultimate failure. The damage evolution constants are defined in terms of $\sigma_{33m}$ and $G_{IC}$, the critical fracture energy under mode I interface fracture, by $u_{30} = \sigma_{33m} / k_3$ and $u_{3m} = 2G_{IC} / \sigma_{33m}$. From these expressions it can be shown that the area under the curve in Fig. 1 is equal to the fracture energy $G_{IC}$. This interface model therefore represents an initially elastic interface, which is progressively degraded after reaching a maximum tensile failure stress $\sigma_{33m}$ so that the mode I fracture energy is fully absorbed at separation.

For mode II interface shear fracture there is a similar damage interface law to (14), with equivalent set of damage constants, $u_{130}$, $u_{13m}$. In general there will be some form of mixed mode delamination failure involving both shear and tensile failure. This is incorporated in the model by assuming a mixed mode failure condition, which for mode I/mode II coupling could be represented by a quadratic interface failure envelope such as:

$$\delta = \left( \frac{u_3}{u_{3m}} \right)^2 + \left( \frac{u_{13}}{u_{13m}} \right)^2 \leq 1$$

Failure at the interface is imposed by degrading stresses when $\delta < 1$ using (14). When $\delta \geq 1$ there is delamination and the interface separates.
5.4 Simulation of Composite Shell Impact Test

In the HICAS project [3] an extensive materials test programme has been carried out on carbon and glass fabric reinforced epoxy materials including in-plane and through-thickness tension, compression and shear tests. Cyclic shear tests to determine the plastic strain contribution have also been conducted. Test data were used first to justify the chosen forms for the damage evolution equations and shear plasticity hardening law, then to obtain the required materials parameters for the model. The materials data set obtained was used as the basis for code validation on single elements and for the shell impact simulation described below.

The fabric composite ply damage model was implemented in shell and layered composite shell elements in the commercial explicit FE crash and impact code PAM-CRASH. The laminate was modelled using one shell element per ply or ply group and the ply elements are then mechanically tied together via contact interface constraints. The interface model was applied to determine tractions and displacement discontinuities at the interface.

Within the HICAS project a structural impact test programme was carried out which included low and high velocity impact tests with steel and gelatine impactors on CFRP and GRP plates and shells. The impact case considered here is a glass fabric/epoxy half cylinder shell clamped to a rigid frame and impacted at the centre of the convex face by a steel spherical indenter attached to a falling mass in a drop tower. The shell has a radius 100 mm and is 200 mm long. The shell laminate is 6 mm thick and made up of 24 plies of glass fabric/epoxy with quasi-isotropic layup. Test conditions in the DLR drop tower were total impactor mass 41.2 kg, impact velocity 6.02 m/s, with impactor kinetic energy 747 J. In this low velocity test the shell deformed in cylindrical bending along the zenith line and after
about 55 mm vertical displacement the impactor rebounded with a velocity of 4.85 m/s. The shell was cracked along the zenith line with some fibre fracture. Post-test ultrasonic C-scans showed delamination over about 70% of the shell area centred on the zenith line.

In the PAM-CRASH simulation the cylinder was modelled using 24 plies in stacked shell elements separated by delamination slidelines. Each fabric composite ply was modelled using the fabric damage model with shear plasticity. The half cylinder was assumed to be clamped to the base plate, with free curved edges as in the test. The impactor was modelled as a rigid hemispherical shell. Materials parameters for the ply model were determined from a materials test programme in on the glass fabric/epoxy material, which included quasi-static tensile, shear and cyclic shear tests. Figure 15 is the simulated deformed shell structure at 3.5 ms. It shows the global cylindrical bending and extensive delaminations over a large area of the shell as observed in the test. Figure 16 compares the measured and simulated loads on the impactor. The simulated peak load of 19.45 kN at 3 ms is well predicted in the simulation, but the simulated load falls more rapidly. Due to numerical instabilities this trial simulation was terminated at 3.7 ms. These early results with the new composites failure models are very encouraging since they predict the correct global response and the observed delamination failure mode and extent.

6 CONCLUSION

• A very good correlation to crash test results of a rear fuselage bay structure could be achieved with PAM-CRASH. However, detailed modelling of the structural components was necessary and also material rupture and rivet failure had to be taken into account.
• The simulation of a fuselage section drop test using the hybrid code DRI-KRASH gave an excellent prediction of the global deformation, acceleration and load levels.
• A systematic approach was shown to built up a DRI-KRASH stick model of a whole aircraft. Such models are well suited for parameter studies taking into account various crash scenarios.
• The Lagrangian approach used to model water delivered good results for the first milliseconds of the impact on water. As fluid viscosity is not available in the water model only cases where viscosity can be neglected, namely vertical impacts, have been investigated.
• The local / global methodology is based on the combination of a Finite Element code (PAM-CRASH) and a hybrid code (DRI-KRASH). The main idea is first to investigate the behaviour of critical sub-components of a whole structure with the Finite Element technique. From those Finite-Element analyses, elaborated input data, usually acquired from tests, like nonlinear characteristics for springs and plastic hinges or calibration of hydrodynamic elements, can be generated for the hybrid code input data. Various scenarios can then be investigated very quickly with DRI-KRASH.
Due to the orthotropic nature of the composite fabric materials, tests have to be performed on specimens with different fibre orientations, at least in $0^\circ/90^\circ$ and $\pm 45^\circ$ direction.

The tube segment specimen developed at DLR was found to be a valuable specimen to measure the crushing properties of different composite materials. In the dynamic tests the average crushing stresses as well as the specific absorbed energies were about 10% to 30% lower than in the corresponding quasi-static tests.

With this new fabric composite model in PAM-SHOCK the behaviour of fabric materials in $0^\circ/90^\circ$ and $\pm 45^\circ$ direction could be modelled much better in single element tests and also on specimen level.

In structural analyses of hybrid cruciform elements as well as sub-floor box structures the results of the numerical simulations correlate well with quasi-static and dynamic crush test results. The failure phenomena, buckling or crushing, could be predicted quite well; also the loads were calculated fairly good up to a point, when secondary failure modes are predicted, which could not be observed in real tests.

Although still some deficiencies can be seen in the analyses, the numerical simulations, especially with the fabric model in PAM-SHOCK, seem to be a valuable tool to assist the design of composite subjected to crash loading.

A materials failure model for composites with fibre fabric reinforcement was developed and implemented in the dynamic FE code PAM-CRASH. The model includes both intraply damage and plasticity, and interply delamination. An important feature of the model is that it distinguishes clearly between different failure modes in the structure.

Validations have been successfully carried out on single elements and both in-plane and fracture mechanics materials test specimens. A trial structural simulation of a drop tower impact test on a composite shell is described, which gives good correlation with test data.

It is possible to follow the progression during impact of the fibre and shear damage parameters in the shell, the irreversible plastic shear strains, the fibre strains and the extent of delamination. Ongoing work is concerned with studying methods for bringing composites rate dependent properties into the materials models and the FE code, and with the application of the model to impact in larger composite shell structures.

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8 REFERENCES