[1]Crash Simulation Methodologies For Aircraft Structures Used within European Crashworthiness Research

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ABSTRACT

Within the Industrial and Material Technology Programs (IMT) „Crashworthiness for Commercial Aircraft“ (Framework 3) [1] - and „Commercial Aircraft - Design for Crash Survivability“ (CRASURV/Framework 4) [2] sponsored by the European Commission (CEC) - European partners participated with numerical crash simulation studies of metallic and composite sub-components of aircraft airframes . Both - hybrid simulation techniques (KRASH) as well as Finite Element (FE) based crash codes were used for the simulations. All simulation studies could or will be correlated with quasi-static test data and data of crash tests which were or will be performed within the programs. The FE based simulation studies and crash test correlation within the Framework 3 program with transport aircraft sub-structures comprised two metallic sub-cargo floor sections, two side shell sections, a rear fuselage bay structure below the passenger floor between two frames, and a fuselage section. Hybrid crash simulations using KRASH were performed comprising the above mentioned fuselage bay structure and airframe section, and also a so called „stick model“ of a full-scale aircraft (A320) was generated. For the section more than 80 correlation of the test results and pre-/post-test simulations were performed. Acceleration and velocities as well as displacements and forces were compared. Out of the investigations of the test and simulations with different KRASH section models, a design principle for the fuselage frame structure was proposed that should prevent some of the failure mechanisms which were observed in the crash test. With the full-scale aircraft stick model various crash scenarios resulting from actual accident data were simulated comprising cases with extended and retracted landing gears and various conditions that lead to separation of the engines from the wing. The FE based simulation studies within the Framework 4 program CRASURV are focused on composite sub-structures such as floor sections (GA/helicopters) and sub-cargo/sub-cabin structures (commuter and transport aircraft). The major tasks focus on material studies to increase the database and explore failure mechanism, failure criteria and the generation of new material models, new design concepts, numerical simulation studies and the correlation with crash test data. On successful completion the technology can be used for the design of airframes with structural components made out of composite materials.

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INTRODUCTION

The purpose of the IMT Research Program „Crashworthiness for Commercial Aircraft“ 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 3-years program was performed in the time frame 1993-1995 with the participation of 18 European partners from industry, research establishments and universities. 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, more detailed studies of immediate environment of the occupant and investigations into occupant reaction to crash impulse and interactions with the surrounding structure. The design guidelines resulting from the program were intended to provide a basis for improved aircraft safety. The program was split into four major Tasks:

- Establishment and distribution of background data with respect to airworthiness and human tolerance to injury.
- Establishment, verification and comparison of crash analysis methodologies (fuselage sub-structures, occupants).
- Studies of a major airframe structure comprised a full-scale drop test of a fuselage section and various numerical simulations of this test with Finite Element crash codes and one hybrid crash code.
- Studies of occupant and local structure focused on structural crash simulations, occupant response to crash impulse and interactions between occupants, their restraint system and local structure.

All structural components which were tested in the program could be taken out from an A320 fuselage which was used before for static testing within the certification process of the aircraft. The A320 is certified and fulfils the requirements of the JAR/FAR Part 25. It should be noted clearly that the crash impact conditions under which the components were tested in the FW3-project go far beyond any currently applied crash safety standards for transport aircraft. The component test were performed to get substantial damage in the structures and to provide a data base to validate the numerical simulation tools applied and developed in the project.

The research program CRASURV with a total number of 22 partners was started in 1996 with a 3 years duration to increase the knowledge of the crash behavior of lightweight composite structures and their application in aircraft fuselages. Besides fundamental work on basic materials and methodologies generic sub-floor box structures representative for GA-aircraft and helicopters and sub-floor belly structures of a commuter type aircraft and an airliner are being designed in composite materials, built and dynamically tested. In addition, the test will be simulated using modern explicit Finite Element codes (LS-DYNA3D, PAM-CRASH, RADIOSS) with enhanced composite materials models that are also developed within the research project. The project is split into the following Tasks:

- Material studies (database, failure mechanisms, failure criteria, material models).
- Development of energy absorption (EA) concepts and production of test structures.

- Analysis of impact loading and validation method.
- Structural tests.
- Occupant simulation
- Assessment of methodology of modelling composite structure due to crash loads.

DLR took part in the research activities of both programs with the generation of background data (crash scenarios, material and crushing data of components), component development and manufacturing (sub-floor sections), model generation and crash simulations. In the following sections, first FE and hybrid crash simulation tools are briefly described and second sample cases of both metallic (FW3) and composite (FW4) airframe sub-components are presented to demonstrate the methodology and its current status of validation.

NUMERICAL CRASH SIMULATION TOOLS

FE tools for crash 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, as is the case with hybrid simulation methods. However, the crash behaviour of an aircraft structure is extremely complex, involving both non-linear dynamic materials response and large structural deformations. Such analyses are at the limit of validity of current FE analysis codes, especially for non-metallic 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 [3] and PAM-CRASH [4], RADIOSS, and MSC-DYTRAN have been developed especially for impact and non-linear 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 method requires very small time steps for a stable solution. 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 non-linear 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. As design tools FE crash codes have gained wide acceptance in the automotive industry for vehicle crash simulations, but are only recently being considered for aircraft structures.

KRASH - A hybrid crash simulation method

The crash simulation program KRASH predicts the response of vehicles to multidirectional crash environments. KRASH provides the interaction between rigid bodies through interconnecting structural elements (beams), which are appropriately attached (pinned, clamped). These elements 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 hybrid modelling technique, large regions of structure are approximated in a simplified manner. Non-linear behaviour (e.g. force-deflection curves) of substructures, 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 or plastic hinges.

The program KRASH has a history of 25 years. The original version of KRASH was developed and experimentally verified under U.S. Army sponsorship between 1971 - 1974, especially for rotorcraft. Further developments sponsored by the FAA extended the capabilities of KRASH for application to general aviation and transport aircraft and culminated in the release of KRASH85 [4]. During the last 5 years KRASH was significantly improved by Dynamic Response Inc., California (DRI). A lot of new features have been added to the code, important especially for aircraft crash simulation. DRI-KRASH now includes additional injury criteria, e.g. HIC and SI calculations, an expanded oleo-pneumatic landing gear module, a soft soil module as well as a water impact module [5].

KRASH has been validated by more full-scale aircraft crash tests than any other crash impact structures program, and although originally developed for aircraft applications, it has in the meantime also been used for the crash simulation of cars, trains and other vehicles. 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 some leading aircraft manufacturers use the program KRASH. Representative KRASH models of various aircraft categories are shown in Figure 1.

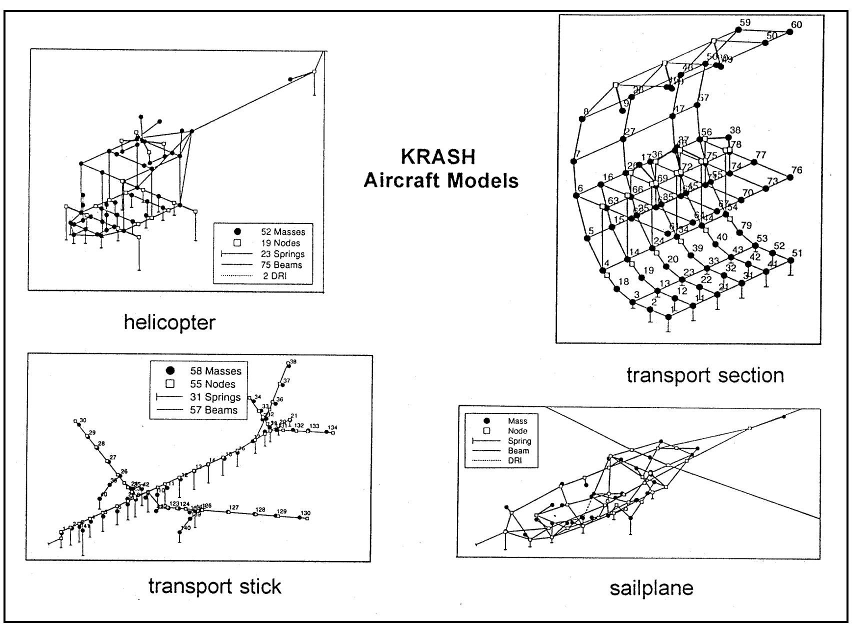


Figure 1. KRASH models of various aircraft categories

ALUMINIUM FUSELAGE SUB-STRUCTURES AND FULL AIRCRAFT STICK MODEL (FW3)

Material properties used in FE simulations

The material properties used in the simulations within the Framework 3-project were generated from the results of a comprehensive material test program performed by Liverpool University. Quasi-static and dynamic material tests have been performed to investigate the influence of the material direction of roll and the sensitivity of the properties on the strain rate. Because only a small influence of both effects could be found, an elastic-plastic material model with isotropic hardening has been selected for the simulations with PAM-CRASH. Strain rate effects were not taken into account.

The results of the material tests in engineering stresses and strains have been converted into true stresses and strains for further use in the simulations. The hardening of the aluminium alloys beyond the proportional limit is assumed to be governed by a power law of the following form:

$$\sigma = K (\varepsilon_o + \varepsilon_p)^n$$

In this formulation σ and ε are true stress and true strain components, and K and n are material parameters. The total strain is interpreted as a constant initial yield strain ε_o calculated from the Young's modulus and the initial yield stress of the material and the plastic strain ε_p which is calculated by PAM-CRASH for every element. Material rupture in the material model can be achieved by eliminating elements whose effective plastic strain reaches a value higher than a given limit strain. In Table 1 the material properties used for the simulations are summarised.

Table 1. Materials properties of the aluminium sub-structures

Material	*Al 2024*	*Al 7075*
Modulus GPa	73	71
Poisson's ratio -	0.33	0.33
Yield stress MPa	306	496
Yield strain %	0.418	0.7
Max. pl. strain %	16.0	9.2
Parameter K MPa	695	783
Parameter n -	0.15	0.092

Rivets: All parts of the fuselage structure were modelled separately and connected with rivet elements. In the FE code PAM-CRASH rigid bodies are used to represent the rivets. Two nodes are linked with such a rigid body and can move (translate and rotate) as a pair. The links between the nodes are allowed to separate upon violation of the following failure criterion:

$$\left(P_N / P_N^* \right)^{a_1} + \left(P_S / P_S^* \right)^{a_2} \leq 1$$

In this formulation the calculated normal and shear loads in the rivet P_N and P_S are related to the normal and shear failure loads P_N***** and P_S*****. By varying the exponents a_1 and a_2 the interaction between normal and shear failure can be modelled. In the simulations the following data were included:

Normal failure load P_N***:**	8 kN
Shear failure load P_S***** :	5 kN

Rear Fuselage Bay Structure - Component Dynamic Test 1 (D1)

*Structural details***:** As an example of the FE crash simulation of a metal sub-structure, the rear fuselage bay structure (D1) is selected and is discussed in more detail. The structural component was cut from the spherical part of the rear fuselage structure, Figure 2. Figure 2 also shows where other structural parts have been taken for component quasi-static and crash testing. The component D1 included all structural parts below the passenger floor between frames C57 and C58. The skin has been cut 100 mm in front of frame C57 and about 50 mm behind frame C58. The diameter of the structure was about 4000 mm and its total length was nearly 700 mm. The longitudinal cuts have been made on either side of stringers P22 and P´22. The component basically consisted of two frames, 45 stringers, the skin and the entire cargo and passenger floor structure.

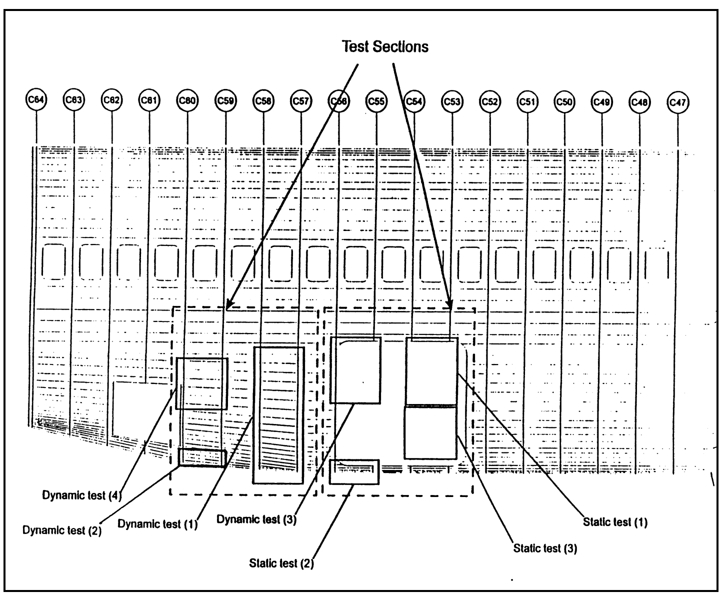


Figure. 2 Location of the structural components in the A320 fuselage

*Structural test***:** The crash test of component D1 was performed at the Cranfield Impact Center (CIC) in November 1994. In the dynamic crash test the structure was fixed at the seat rails and the frames on the passenger floor level and was loaded by a trolley hitting the structure with an initial velocity of 8.12 m/s. Due to the high mass of the trolley (1240 kg) and the limited EA capability of the structure the deformation has been limited to 320 mm with a bumper system made of aluminium honeycombs. During the test, the data of two accelerometers located on the trolley and three strain gage rosettes were measured. The test specimen was photographed before and after the test. Two high speed cameras and one video camera were also used for the documentation of the crash sequence.

Finite Element Models of component D1

Based on documents and drawings which were supplied by Daimler Benz Aerospace Airbus (DA), very detailed FE models (half models, whole models) have been created to perform pre- and post-test simulations of the complex behaviour of the structure under the described loading. All different parts of the structure like skin, stringers, frames and clips were modelled separately and connected with rivet elements that could fail during the simulation. In Figure 3 the final mesh of the whole post-test FE-model is displayed. This final mesh consisted of 66440 nodes, 58884 shell elements and additional 3485 rivets.

The clamping and loading conditions in the simulations were similar to those realised in the crash test. The displacements of the nodes along all four seat rails and at the frames on the passenger floor level were suppressed. The trolley was represented by a moving rigid wall with a mass of 1240 kg and an initial velocity as measured in the test just before the impact (8.12 m/s) was taken into account.

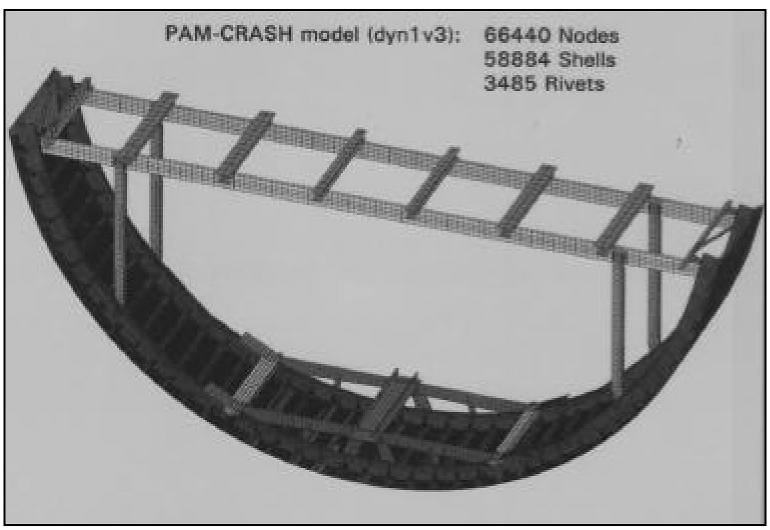


Figure. 3 FE model of Dynamic Test 1 (D1)

Correlation of FE simulation runs and crash test data of component D1

For the pre-test simulations of the component D1 only two half models of the structure were used, one taking into account rivet failure and a reduced friction coefficient of 0.2 between the rigid wall and the structure and for self contact. Although the fuselage structure is not exactly symmetrical it was assumed that preliminary results obtained with this half models including symmetric boundary conditions in the x-z-plane could give reasonable results for the trolley accelerations to help CIC to instrument the test.

The post-test simulations comprised one half model and nine different whole models of the component D1 taking into account combinations of rivet or no rivet failure, updated material data, material failure, and material definition with the Krupkowsky law. As a result of the post-test simulations with the whole structure, Figure 4 shows the deformed structure 45 ms after the impact. With a time increment of 10^{-3} ms, 45045 cycles were calculated. The total CPU-time on a HP9000/735 workstation was 37.6 h. Plastic deformations start on the left hand side of the structure between the second and third stringer position, very close to the location where the skin failed in the test. The plastic deformations in this region enlarge during the simulation and additional plastification occur just beside reinforcements around the intersection of the struts with the frames. In general, the correlation between the simulated deformations and those found in the dynamic crash test was very good.

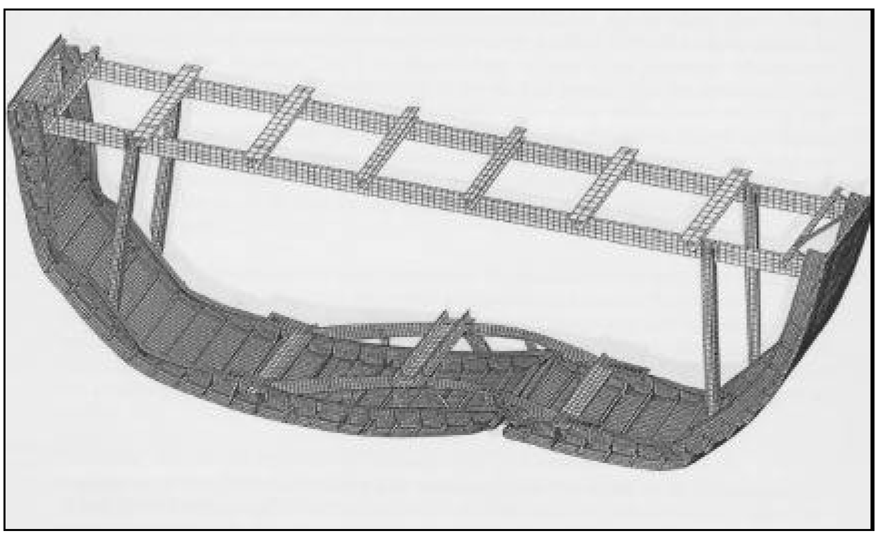


Figure. 4 Deformed component D1 at 45 ms

A comparison of simulations with measured test data is given in Figure. 5. In Figure 5 the time-integrated acceleration signal is plotted together with the velocity of the rigid wall which represents the trolley in the simulations. In the simulation which includes failure (Curve B) the velocity remains slightly higher after 17 ms when failure of rivets and elements started. While the results from the first simulation (Curve A; solid line) start to separate from the test curve the simulation with rivet failure correlates very well with the test up to the point where the aluminium absorbers suddenly stopped the trolley (Curve C, 42 ms). This comparison shows that a good modelling of the failure of rivets is necessary to calculate the structural behaviour correctly.

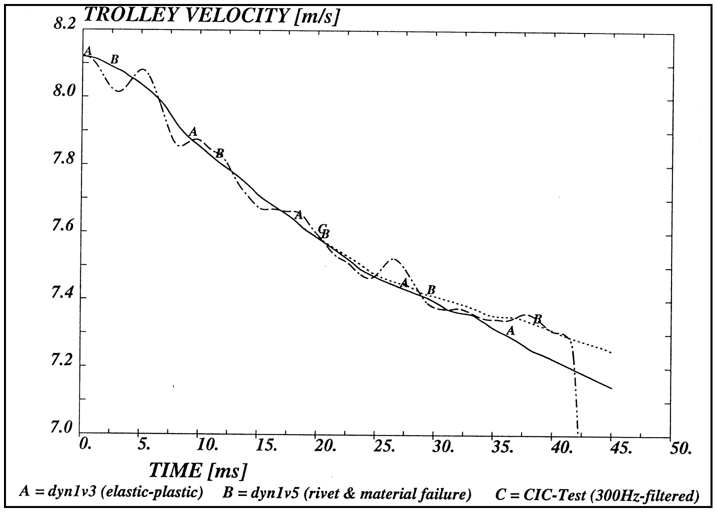


Figure. 5 Comparison of test and simulation of component D1 - trolley velocity

KRASH Simulation of the A320 Fuselage Section

Structural details: The fuselage section used for the crash test and crash simulations was a 3 m long part of section 17 which is located right after the wing of the aircraft. The diameter of the section was about 4 m and had a total mass of 2330 kg. It comprised 6 frames (C47 - C52). The section was equipped with 6 seat rows (18 seats) and 14 dummies, some of them represented by their corresponding masses. Two overhead bins with a mass of 254 kg were installed between frames C47 and C51.

Structural test: The drop test of the A320 fuselage section was carried out at CEAT/Toulouse in July 1995. The section was vertically dropped with a z-velocity of 7 m/s on a concrete surface. It was equipped with a total of 180 measurement channels: 48 at the dummies, 16 at the seats, 80 at the structure, and 36 at the overhead bins. The data aquisition was done by an onboard system with an aquisition frequency of 12,5 kHz. Different views of the test were filmed with standard videos (25 frames/s) and high speed cameras (500 frames/s).

KRASH Model of the Section

Model description: Three partners in the project simulated the section crash test with FE crash codes. DLR focused on the KRASH approach for the section. A half model of the test section was generated. In the lower part of the fuselage section where the main deformation of the structure occurred, all 6 frames (C47 - C52) were represented with KRASH elements (beams, springs, masses). Figure 6 shows a 3-D representation of the KRASH section model. In the region above the floor the major load carrying frames 47, 49, 51 (location of the hatrack z-fittings) and 52 were represented in the model. The properties of the upper parts of frames 48 and 50 in this area which bear less load, were distributed to the four other frames. This had to be done to the limitation of the maximum number of 80 mass points that could be used for a half model with the KRASH version that was used for the section drop test simulations. The section half model consisted of 79 masses, 23 massless nodes, 30 springs, 136 beams and 42 plastic hinges. Three masses at the locations of C47 (M9), C49 (M29), and C51 (M49) were used to represent one hatrack. The mass of the seats and dummies was mainly distributed to 3 additional mass points located in the common center of gravity of the seats and dummies in each row (M17, M37, M38) and were partly distributed to the respective seat track locations.

Linear properties of the KRASH model: For the definition of the linear beam properties and the structural mass distribution the NASTRAN file of the drop test section, supplied by DA, served as the main input. A computer program was developed that reads all relevant NASTRAN cards. It calculates the local as well as the global stiffness at predefined cuts between two frames and provides the linear beam properties for those KRASH beams which are oriented in the longitudinal direction (x-direction) of the fuselage. In the first step the program user has to define the y- and z-positions of all those KRASH beams which connect two frames of the section. For the KRASH section model, 21 beams were selected for the connection of two frames. In a second phase the program distributes the cross-sectional areas and stiffnesses of all NASTRAN elements (beams, rods, shells) to the KRASH beams. A simultaneously applied error distribution algorithm ensures that the global properties of the two models are balanced.

Non-linear properties of the KRASH model: External springs and plastic hinges were used in the KRASH section model as non-linear elements. The results from D2 and PAM-CRASH simulations were used to define the non-linear load deflection properties of the springs below the cargo floor. For the definition of the plastic hinge moments, the results of Static Test 3 (part of the fuselage shell) and D1 were used as well as their respective KRASH and PAM-CRASH simulations.

Correlation of KRASH simulation runs and crash test data of the section

Pre-test simulations: With a first KRASH model of the section various pre-test simulation were performed to define the impact velocity and the total mass of the section and to support CEAT with preliminary information of accelerations, velocities, displacements and global deformation behavior of the structure to define the final set up for the crash test. The recommendation resulted in a total mass of the section of 2330 kg, an impact velocity of 7 m/s and an initial kinetic energy of 57 kJ. The pre-test simulations showed that most of the energy would be absorbed by beams/plastic hinges (about 49 kJ), and the external spring would absorb much less energy (about 7 kJ). At the center of gravity an average acceleration up to 80 ms of 4g was predicted. Between 80 and 110 ms, the acceleration increased up to 22g. The pre-test simulations predicted a maximum z-displacement of 0.52 m and a duration up to zero velocity of 110 ms.

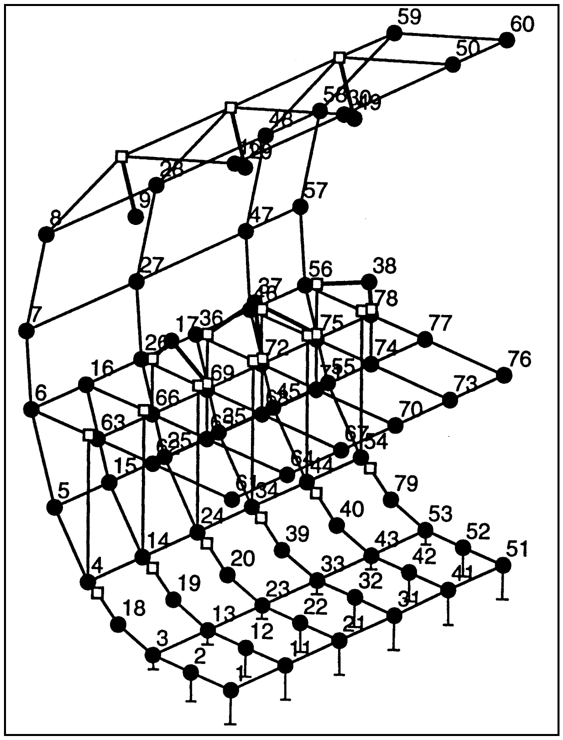


Figure. 6 KRASH model of the A320 crash test section

Post-test simulations: Results from the KRASH pre-test simulations for about 50 different accelerometer locations were published before the crash test. After the test, more than 80 correlation of test results and KRASH pre-test simulations were performed. The KRASH pre-test model was very good in the prediction of the vertical accelerations, velocities and deformations as well as of the EA mechanisms. However, it did not represent the outward movement of the lower region of the struts correctly. Therefore, several changes to a post-test model were made: the beams below the cargo floor were modelled more accurately with a second beam added and shorter crush spring elements were used. Also, the plastic hinges at the cabin floor level were removed. Plastic hinges were added to the model in order to represent the behaviour in the area of stringers P21. An overlay of the deformed structure gained from the crash test high speed film and the KRASH post-test model is shown in Figure 7 at 100 ms. The global deformation behavior is represented very well. Compared to the pre-test simulation, the y-displacement of the struts and the bending of the floor are in much better agreement with the test.

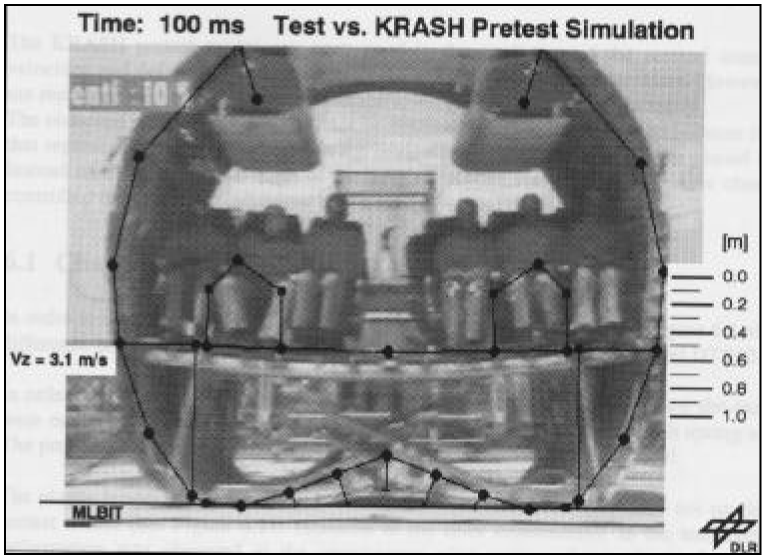


Figure. 7 Deformed structure and KRASH model at 100 ms

Figure 8 shows correlation of velocities for different locations within frame 51 (hatrack, floor and strut). For the hatrack, there is only a difference for the short period between failure of the z-fittings and reloading via the retaining cables. All other correlation are in very good agreement with the test results.

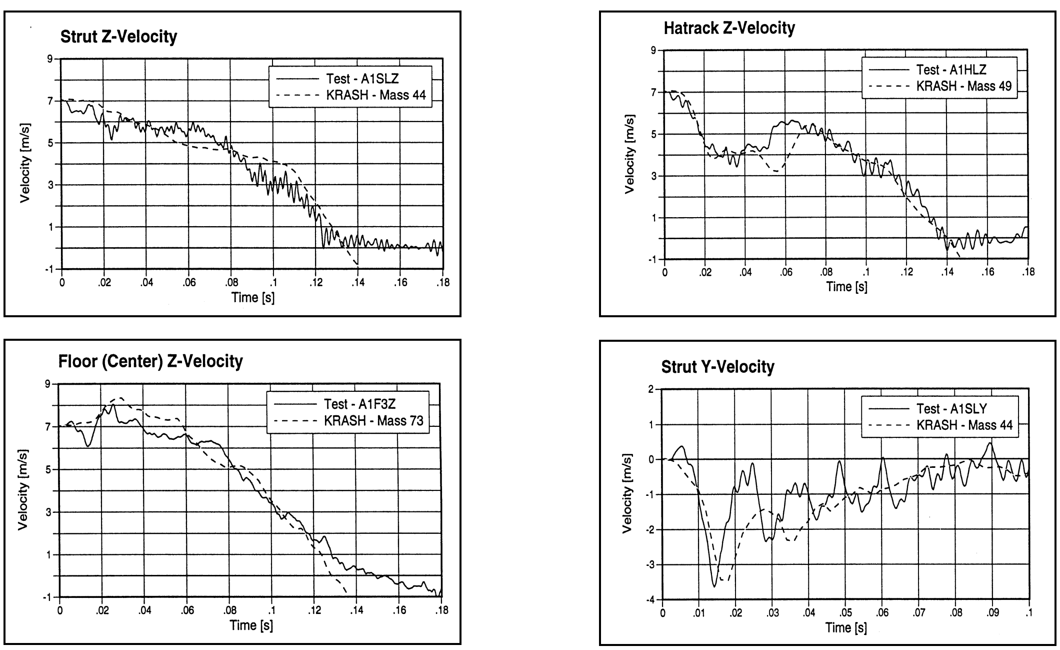


Figure 8 Velocities at frame 51- test versus KRASH post-test simulation

Enhanced crashworthiness of the fuselage

A main goal of crashworthy design is the integrity of the structure surrounding the occupants. A rupture of the cabin cross beams, as observed in the crash test should be prevented. The reason for this failure was identified by the evaluation of test data: the bending moment in the floor cross beams is mainly a function of the y-displacements of the struts and the frames in the area of stringers P30-P33. In the current design of the fuselage, the arc of the frame/skin between the struts pivots about the point of impact, causing an outward y-displacement in the struts. Energy is mainly absorbed by beam bending (plastic hinges).

In the proposed improved design, Figure 9, the cargo cross beams are strengthened so that besides the energy which is absorbed by plastic hinges, a larger energy share is absorbed by crushing below the cargo floor. The cord length (= length of the cargo cross beam) is then in control of the kinematic behaviour instead of the larger arc length (frame/skin). The y-displacements of the struts are then significantly reduced.

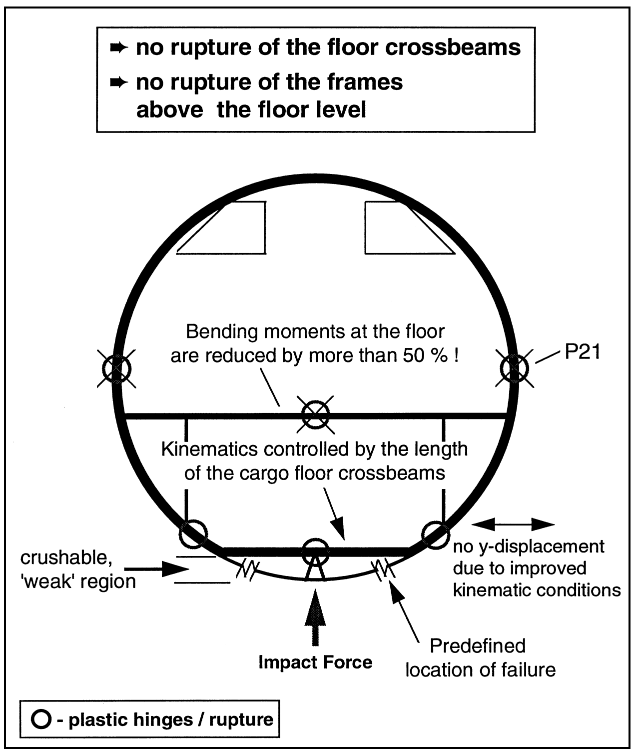


Figure. 9 Proposal for improved CW fuselage design

Full-scale stick model 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 stabiliser: 11,76 m. The maximum take-off weight is 65500 kg.

Model description: Modeling was started by determining the mass distribution and by defining the location and the properties of the beam elements. 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 crushing zones of the aircraft (the lower part of the fuselage, the landing gear and the engine nacelles). NASTRAN files provided by DA were used as basic input to generate the mass distribution and the beam properties. In the NASTRAN input files, the A320 half model is represented by 66 single masses, 94 grid points, 51 beams and 46 rigid bars. The areas connecting the wings and fuselage with stabilizers are represented in a more complex way using 30*30 and 45*45 stiffness matrices. In order to automate as much as possible of the modelling process, a computer program (NAS2KR) was developed which reads the relevant NASTRAN files and writes parts of the KRASH input file. Figure.10 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.

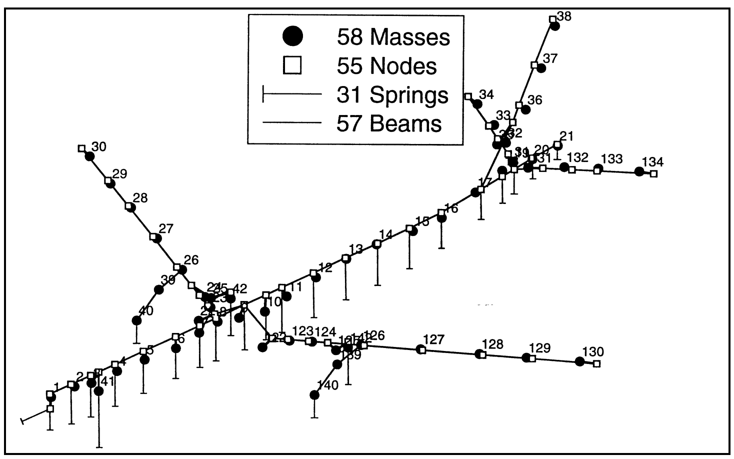


Figure 10 A320 KRASH stick model

Beam elements: Most beam properties of the structure could be generated by using the program NAS2KR from the NASTRAN file. The properties of beams which connect the wings and stabilisers to the fuselage were approximated by extrapolation of the wing and stabiliser stiffness, respectively. Different loading conditions under which the landing gear collapses and the engines separate from the wings were known. The maximum landing gear loads and the loads when the engines separate from the wing were modelled either as plastic hinges and hinge moments or the definition of maximum loads in the relevant beam elements.

Spring elements: DA supplied load-deflection curves for the engine nacelle, the main and the nose landing gear. For the fuselage springs, the load-deflection curves were obtained by evaluation of the structural data of the fuselage. The comparison with other aircraft and their respective KRASH models was useful in the process of defining the spring characteristics. The sub-structure tests within the IMT research program could only be used to a certain extend, as the deformations in these tests were small compared to the requirements for the stick model. However, the results of the section drop test served as excellent data base for the generation of the global force deflection curves.

KRASH stick model simulations

Simulations with extended landing gear: The following impact conditions were used for all simulations with the KRASH stick model:

Velocity	[m/s]
v_x	75
v_y	0
v_z	8
Attitude	[deg]
Roll angle	0
Pitch angle	2 (nose up)
yaw angle	0

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, Fig. 11 shows the simulated crash sequence of the aircraft with extended landing gear, a stepwise reduction of the lift forces from 100% (0 ms), 70% (500 ms), and 20% (1000 ms), 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.

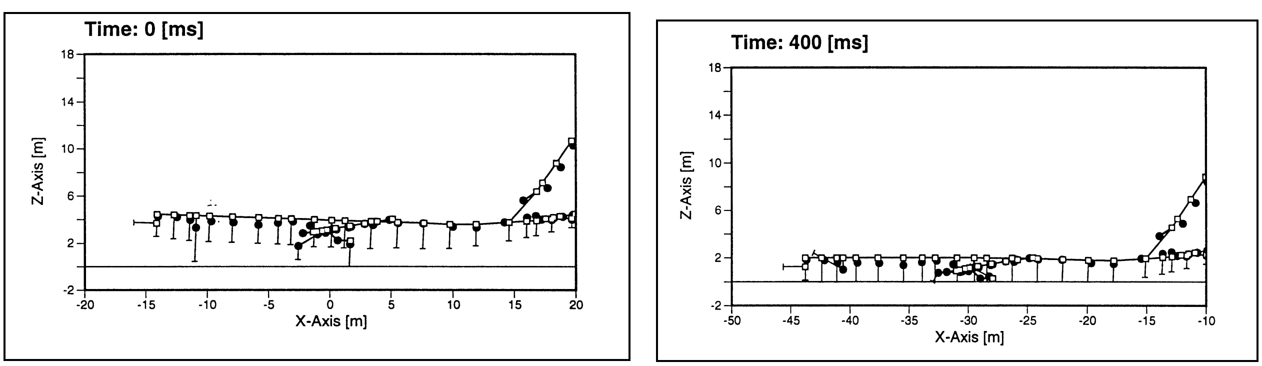


Figure 11 Simulated crash sequence with extended landing gear (KRASH A320 stick model)

A comparison with other simulation studies 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.

COMPOSITE AIRFRAME SUB-COMPONENTS (FW4)

Modular Sub-floor Section Design Concept

To demonstrate one of the crash simulation methodologies used within the CRASURV project, the modular sub-floor section design concept is briefly described. The development of the concept was intensively supported by using PAM-CRASH simulation studies before the manufacturing of tools and crash test components was initiated.

The modular design concept for aircraft sub-floor sections comprises various modules which can be optimised separately in a first step with regard to EA performance and load carrying capability analytically with FE techniques and which can be assembled in a second step to a sub-floor section. This design and analysis phase is followed by a selection of promising concepts, manufacturing of structural elements or sub-floor sections, and experimental evaluation of the structural performance or EA capability under crash loads in a drop tower to prove the concepts and to validate the analytical predictions. The design concept shown in Figure 12 comprises module 1 as intersections/cruciforms, module 2 as lateral beam or bulkhead section, module 3 as longitudinal beam, and module 4 as the outer skin. In addition a fifth module representing the cabin floor panel can be considered. Existing modules or module combinations (sections) which have been analysed and partly tested to date are also given in Figure 12. The investigated load cases using FE techniques for whole modular section concepts comprise pure bending, pure torsion and transverse compression/crushing (crash loading normal to cabin floor level). The crushing (EA-) performance is evaluated using PAM-CRASH; representative simulation results are presented in a later chapter.

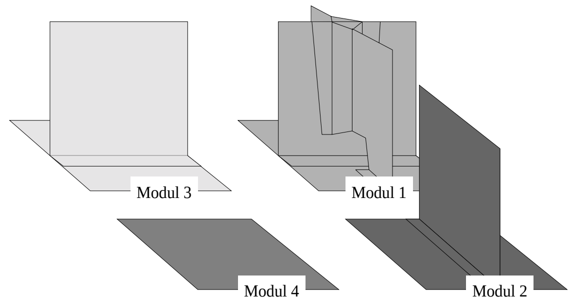
Sub-floor element (module) designs

Sub-floor beams and bulkheads: Composite beams with sinusoidal or trapezoidal corrugated webs are the most efficient aircraft sub-floor design concepts yet evaluated. They are efficient at carrying shear and compression loads in normal flight, have high EA under crushing loads and, with hybrid lamination techniques, have good structural post crash integrity. Drawbacks of the sine wave concept, however, are the high fabrication costs, the interface with other structural elements (i.e. adjacent fuel tank bladders) and the difficulty of incorporating suitable trigger mechanisms, which reduce peak loads when the beam is crushed in the web direction during impact, without lowering the shear load performance. The determination of the static load capacity which in thin shell structures is limited by buckling, the influence of materials hybridisation and geometry on crush characteristics, and the selection of trigger mechanisms are the main design aspects of beams or bulkheads with corrugated webs.

Module 1: Cruciform 1.) Simple Intersection
2.) HTP - Cruciform

Modules 2/3: Beams 1.) Plain webs
2.) Integrally stiffened web
3.) Sine-wave Beam
4.) Trapezoidal Beam

Module 4: Skin 1.) Plain Skin



Investigated Subfloor Boxes:

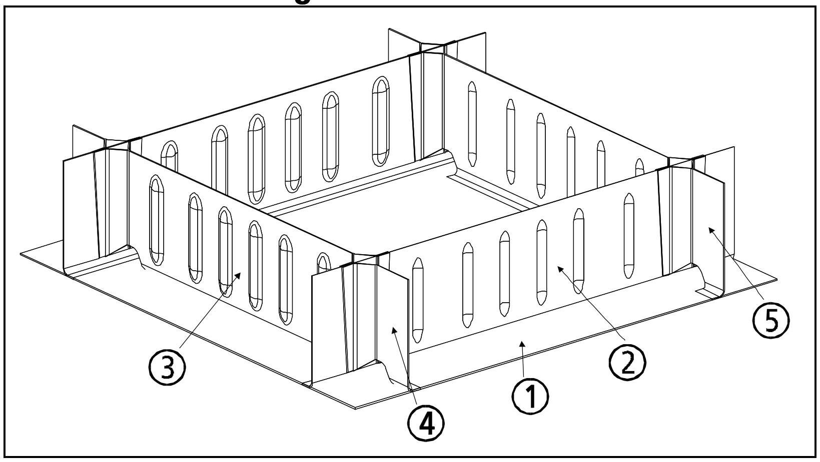
Analysis	Intersection	Web Design	Skin
Box 1	HTP-Element	plain webs	plain
Box 2	HTP-Element	integrally stiffened	plain
Box 3	HTP-Element	sinusoidal corrugated	plain
Box 4	HTP-Element	trapezoidal corrugated	plain
Box 6	Simple Inters.	plain web	plain

Figure 12. Modular construction of sub-floor aircraft sections

Embedded ply drops provide under dynamic crushing a stable and reproductive failure initiation and an initial peak load reduction of about 40-60% compared to the untriggered version without reducing significantly the beam shear strength and stiffness. Corrugated beams with ply-drop triggers have been tested and found to have no or a shear load reduction of less than 5% compared to the untriggered beam. Therefore, embedded ply drops are currently the preferred trigger concept.

Intersection/cruciform elements: Various cruciform designs have been investigated in the past. Design improvements led to a hybrid cruciform variant - the HTP-element. This cruciform has a column like mid-section formed by a Y-shaped split of the shear web laminate, an integrated bevel trigger at the bottom of the shear webs, and tapered edge joints at the keel beam attachments. The keel beam and shear web laminates have a J-shaped connection to the outer skin. The newest cruciform design is the so called HCP-element. It accounts for improved soft soil penetration resistance and higher EA capability. The cruciform formed by the inner and outer bulkhead and the longitudinal beam has a conical mid-section, having the smaller diameter on bottom and the larger one on top. Therefore the crushing resistance increases with increasing deformation. The sub-floor sections shown in Figure 13 comprise HTP-elements in combination with integrally stiffened beams and bulkheads (basic design) and HCP-cruciforms in combination with trapezoidally corrugated longitudinal beams and angle stiffened bulkheads (improved design).

Basic DLR box design



Improved DLR box design

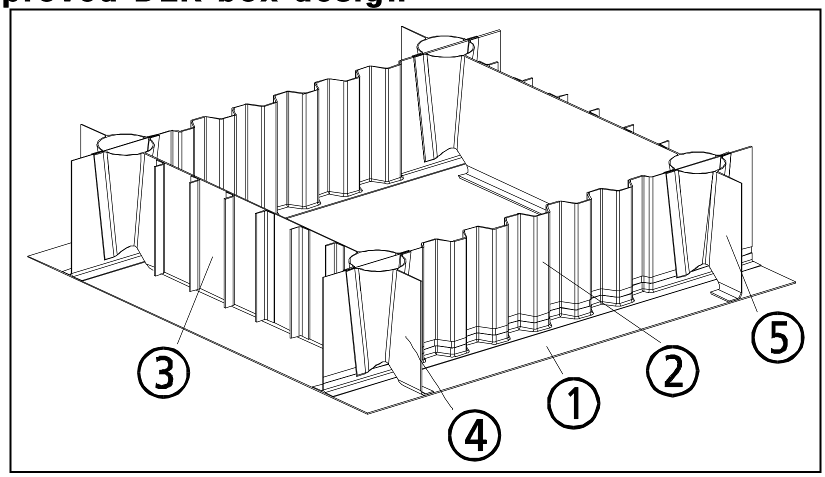


Figure 13. Sub-floor section designs comprising HTP- and HCP-cruciforms

PAM-CRASH composite Bi-phase model

The so-called composite Bi-phase model in PAM-CRASH was initially developed to model the behaviour of composite plies with unidirectional fibre reinforcements (UD-plies). To model the failure of the fibres and the matrix individually 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 materials 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 α_f.

$$\sigma = \mathbf{C_{UD}}\,\varepsilon \qquad \text{with} \qquad \mathbf{C_{UD}} = \mathbf{C_m} + \mathbf{C_f}$$

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

$$\mathbf{C_m}(d_m) = \mathbf{C_{m0}}\,(1-d_m) \text{ and}$$
$$\mathbf{C_f}(d_f) = \mathbf{C_{f0}}\,(1-d_f)$$

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

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

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 ε_v and ε_s. The volumetric equivalent strain ε_v is the trace of the total strain tensor (1st invariant) and the equivalent shear strain ε_s can be interpreted as the 2nd invariant of the deviatoric strain tensor. The damage parameter for the fibre damage $d_{f,v}$ is based on the strain in the fibres. 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 matrix phase is defined to be in tension when the equivalent volumetric strain ε_v (first strain invariant) is positive, while the fibres are in tension when the fibre strain is positive. The basic shape of each of the damage curves is shown in Figure 14.

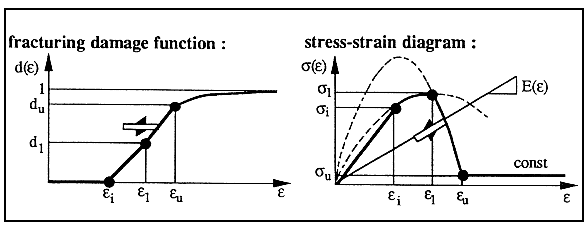


Figure 14. Schematic fracturing damage function and corresponding stress-strain curve

The damage is assumed to be zero for equivalent strains below the initial threshold strain ε_i (volume as well as shear). Then the damage parameter d grows linearly between $\varepsilon_i < \varepsilon < \varepsilon_1$ and $\varepsilon_1 < \varepsilon < \varepsilon_u$, where ε_1 is an intermediate equivalent strain with the corresponding intermediate damage d_1, and ε_u is the ultimate equivalent strain with the ultimate damage d_u. This bi-linear growth of the damage with increasing strains leads to a shape of the stress-strain curve with two parabolas. Beyond the ultimate damage d_u the residual stress in the stress-strain curve is supposed to be constant. Therefore, the damage functions are assumed to grow and asymptotically reach the value 1.

As input for each individual ply the equivalent strain parameters ε_i, ε_1 and ε_u and the damages d_1 and d_u have to be given for both kinds of matrix damage and the fibre damage in tension and compression. The total number of input parameters just for the description of the damage evolution is therefore 30.

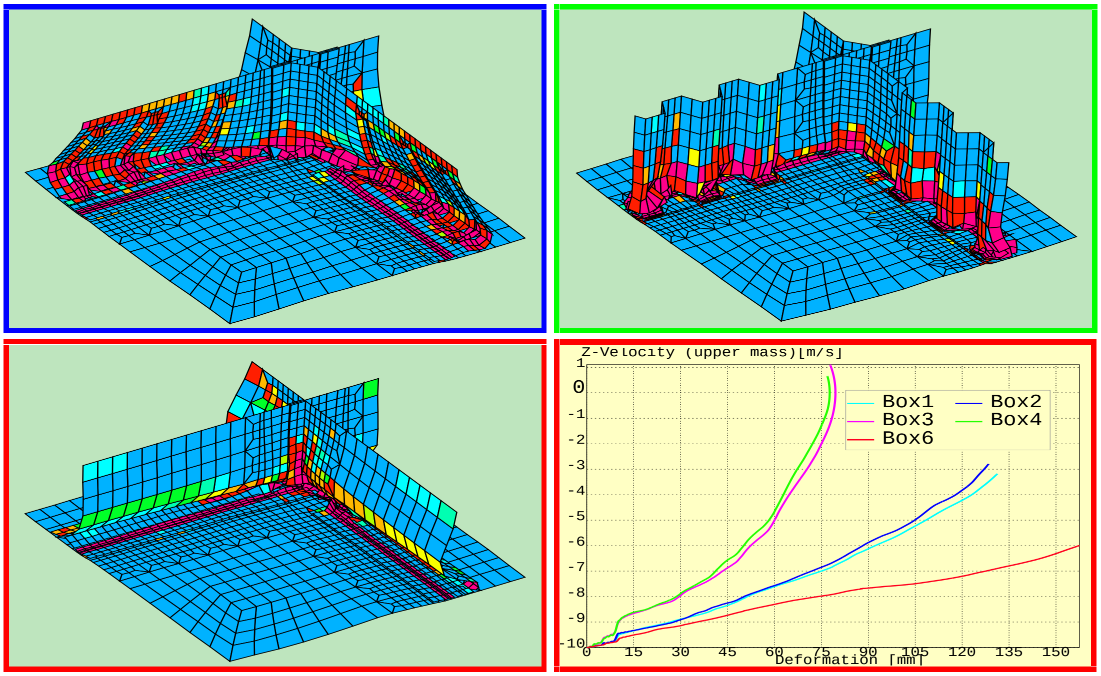


Figure 15. Comparison of different composite sub-floor section designs

PAM-CRASH application to the modular sub-floor section concept

Based on the experience with the simulations of cruciform elements, different sub-floor concepts have been analysed, using FE-meshes created in the modular sub-floor section model. Selected results are presented in Figure 15. The individual plots show the different quarter models of the box designs 2, 4 and 6 8ms after the first impact. 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. In the graph in Figure 8 the velocity of the additional mass located on top of the sub-floor box is plotted vs. deformation. While the best design (Box 4) can absorb all the initial kinetic energy within 120 mm of deformation, the worst design (Box 6) could not stop the mass until the simulation was stopped after 180 mm of deformation. At that point the downward velocity of the additional mass is still 6 m/s.

Based on the results of the numerical simulations and the first dynamic drop test with the box structure an improved composite box has been designed using a trapezoidal corrugated keep beam (2) with a so-called ply-drop-off trigger 10 mm above the lower flange in combination with the improved conical HCP cruciform element (4, 5) (ref. to Figure 13). A detailed FE-model of a quarter of this new box design has been created with 8200 shell elements. With the same loading as used in the test of the first box structure the crushing behaviour has been predicted. In Figure 16 the mesh is given 10 ms after the first contact. The different colours (gray-scales) represent the damage of the individual finite elements. In this simulation the trapezoidal keel beam as well as the angle stiffened transverse beam seem to crush in a much better way than predicted for the first box, combined with a higher EA potential.

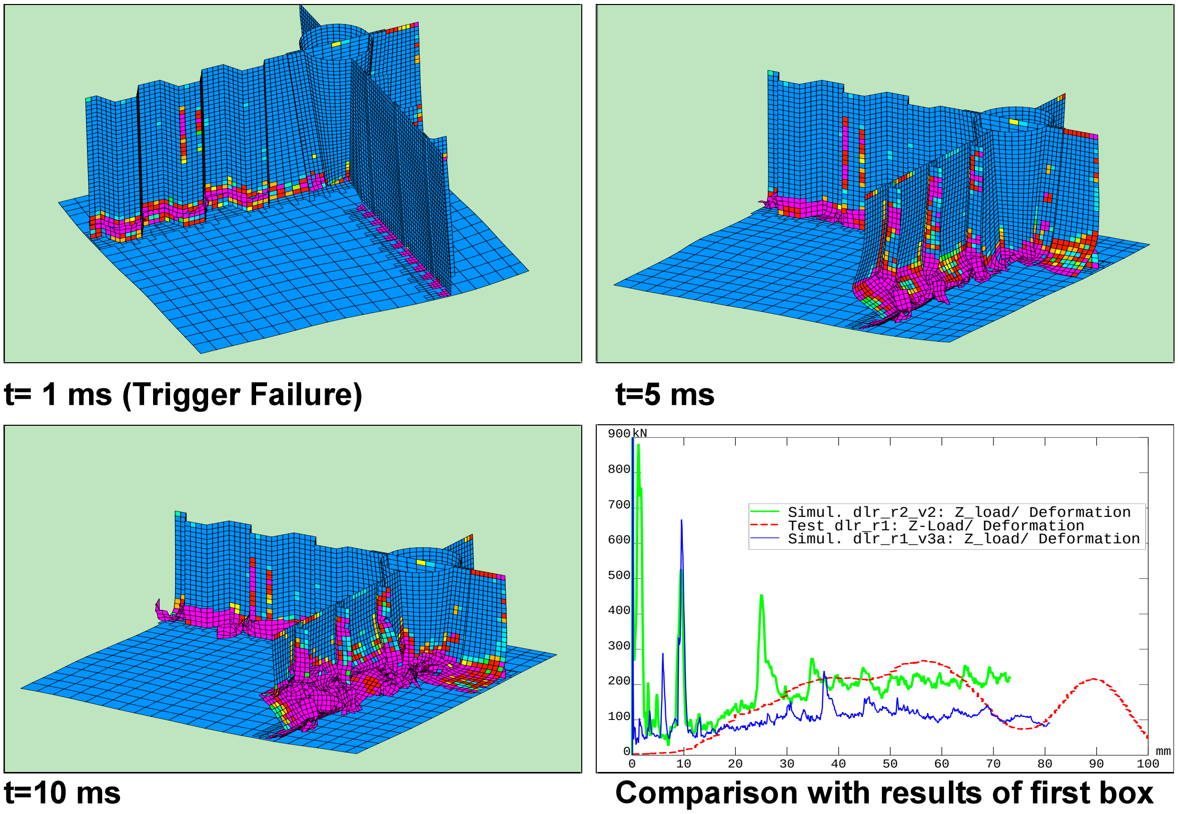


Figure 16. Predicted Failure of improved sub-floor box (t=10 ms)

CONCLUSIONS

FE codes such as PAM-CRASH, although well accepted in the automotive industry, are not yet established in the aircraft industry. The simulations have shown that very detailed geometrical models with suitable materials models and property data are required for good structural failure predictions. With large models the FE simulations must be run on fast workstations or main frame computers, and may require days of CPU time. Thus FE crash simulations are expensive in manpower and computers. At present it is not practical to carry out such a detailed simulation for a complete aircraft.

The main advantage of the FE simulation is that it is a complete predictive tool - being based only on a geometry model with appropriate materials constitutive laws and property data. Any testing required is on materials specimens, not at the substructure level. Where further work is still required is in the modelling of non-standard materials, particularly failure properties, and the implementation of these models into the FE codes. For composites under dynamic loads there are many possible failure modes such as crushing, fibre fracture, delamination, matrix shear, etc., and new materials models with associated test methods for measuring failure and damage parameters are currently active research areas.

A hybrid code such as KRASH is well established in the aircraft industry and has been developed specifically for crashworthiness studies. Geometrical models are relatively simple as is demonstrated by the complete A320 section and full-scale stick model. The designer can carry out in short time parameter variation studies with the program. On the other hand considerable engineering experience is required to obtain good results with hybrid codes. Skill is required in the idealisation of the geometry model, in determining mass distribution and spring stiffness characteristics so that essential structural features are included. Where spring properties are highly non-linear, as in crush elements, it is necessary to carry out crush tests on critical elements in order to characterise spring properties. Thus the hybrid method becomes semi-empirical and not a complete predictive tool.

For future vehicles - cars and aircraft - crash requirements will be of growing importance concerning operation licenses. Ultra-light structural concepts will be required to account for low pollution and effective engine concepts with respect to environmental aspects. Therefore, composite crushing behaviour will be a matter of enlarged interest for the manufacturers. A lot of different composite element configurations were crash tested in the past and further tests must be carried out. Development of computer codes and approximation formulae must be continued. However, unrealistic emphasis on exaggerated exactness postulation should be avoided due to the typical scatter of response of crashing structures.

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