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Summary

Within the frame work of Brite-Euram programme CRASURV "Commercial Aircraft - Design for Crash Survivability", technology is being developed for the design of composite air frames with respect to crashworthiness. The ultimate goal of the project is to develop computer codes for the simulation of the crash behaviour of composite fuselage structures. A significant part of the project consists of the design, fabrication and drop-testing of two representative composite fuselage sections, to generate the experimental data needed for the validation of the new code developments. The present paper gives an overview of the development, test and numerical analysis of one of the fuselage sections, a one-bay section representative of a commuter aircraft like the ATR-42/72. The fuselage section consists of the sub-floor structure, which is the major area that will be crushed during a potentially survivable crash.

keywords: crashworthiness, energy absorption, composite materials, simulation

Contents

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(23 pages in total)

1. Introduction

Whilst crash avoidance has been and will continue to be the main theme in aircraft safety, the design for crash survivability has become of increasing importance, not in the least because so many crashes have been demonstrated to be potentially survivable. Crashes on take-off and landing around the airfields were shown to be the most common survivable crash scenarios [1]. The load cases under crash conditions are well established, hence, the design of traditional metallic aircraft structure with "crashworthiness" capabilities, i.e., capabilities to protect the passengers up to a certain limit, is quite manageable. A Brite-Euram project entitled "Design for Crash Survivability" was dedicated to this subject in 1992 [2].

Today's commercial aircraft are made mostly of aluminium, a material with considerable capacity for plastic deformation, hence, an inherent capability to absorb energy in crash situations. Since the last two decades, composite materials are used more extensively to build aircraft structures, although for civil aircraft, the use has been limited so far to the empennage and secondary structures. However, application of composite materials to aircraft fuselages rapidly becomes a feasible option, so the crashworthiness issue related to composite materials has now become a serious issue. Therefore, a subsequent Brite-Euram programme was defined in 1995, which will be completed in February 2000, entitled "Commercial Aircraft - Design for Crash Survivability" with acronym CRASURV [3]. The objective of this project is to develop the technology for the design of composite air frames with maximum safety with respect to potentially survivable crash scenarios.

2. The project

The project team was assembled from representatives of the aircraft industry, of aerospace research establishments, universities, and computer code developers (which qualify as "small and medium enterprises"). The specific task objectives were (1) to develop appropriate material models, (2) to design and build representative composite aircraft fuselage components, (3) to test these components, (4) to develop and validate computer codes to simulate crash behaviour, (5) to determine the effect of the crash loading on the occupants, and (6) to assess the newly developed methodology, and propose design guidelines.

3. The approach

The ultimate goal of the project is to develop computer codes with which crash behaviour of composite fuselage structures can be simulated. In the previous Brite-Euram project, the crash behaviour of metallic fuselages was simulated and validated by comparing numerical results with experimental results obtained from a drop test of a section of an Airbus A320 fuselage. For the present Brite-Euram project CRASURV, drop tests on sections of current air frames were not feasible, because aircraft with composite fuselages do not yet exist (other than small aircraft). Hence, a significant part of the project consists of the design, fabrication and drop-testing of two representative composite fuselage sections, in order to generate the experimental data needed for the validation of the new code developments.

One fuselage section, representative of a commuter aircraft like the ATR-42/72, was defined by Alenia. The second fuselage section, representative of a larger airliner like the Airbus A320, was defined by Aerospatiale. The principal difference between the two aircraft (with respect to crashworthiness) is, that typical commuter aircraft have a very small space between the cabin floor and the outer shell, while the larger airliner contains a cargo hold between the cabin floor and the outer shell, hence contains more space to allow deformations in a crash. The fuselage sections developed for CRASURV were limited to the sub-floor structures, including two frames. The sub-floor structure is the part of the fuselage below the cabin floor, which is the major area that will be crushed during a potentially survivable crash. The present paper gives an overview of the design, fabrication, test and numerical analysis of the commuter fuselage section.

4. The design and fabrication

An important design requirement for composite fuselages is obviously to provide a reasonable amount of crashworthiness to the passengers. "Copying" traditional aluminium design concepts for composite structures is clearly not providing this capability, because energy absorption due to plastic deformation will not occur. Hence, new design concepts for composite structures had to be developed first in a "building block" approach.

a. box programme

During the first part of the programme, generic box structures were designed by the German and Dutch aerospace research centers, DLR and NLR, respectively, using proven technology developed for crashworthy helicopter structures [4]. These boxes represent typical helicopter sub-floor structure, made up of lateral frame sections, longitudinal beams, and skin panels. First, individual components were designed, built, tested and analysed. These components were beam sections, cruciform connections between the frames and the beams, and "tensor skin" sandwich panels [5]. Subsequently, several complete box structures of different design were fabricated at NLR (Fig. 1) and DLR, drop-tested at DLR and analysed by DLR and the University of Limerick [6].

b. material selection

Composites are brittle materials with hardly any capacity for plastic deformation. It has been demonstrated, that composites can absorb an even superior amount of energy compared to metals [4], but that the failure mechanisms which govern the energy absorption are very different, based on fiber fracture, friction, etc.. In order to obtain sufficient fiber fracture, it is important to consider crashworthiness not just as a materials aspect, but as a combined materials/structures/fabrication approach. A combination of carbon fibers and aramid fibers was shown to give good results for components dedicated to energy absorption: carbon fibers for strength, stiffness and energy absorption and aramid fibers for post crash integrity. However, as energy absorption needs to be accomplished in components which are loaded in compression, providing stability against buckling of the crushing laminates is essential. Sine-wave beam sections and cruciforms with closed cross sections, assembled from laminates made of hybrid carbon/aramid reinforced epoxy pre-pregs, were shown to perform well, individually, but also when incorporated in box structures. Material data and models for these laminates were provided by NLR, DLR and the University of Liverpool.

c. design concept

Alenia was in charge of the design of the composite commuter fuselage structure. The baseline configuration was the current ATR-42/72 configuration, with ring frames, transverse floor beams, and inclined struts supporting the floor beams at points underneath the seats and connected to the frames below. However, to incorporate energy absorbing mechanisms into the structure, certain components had to be dedicated for this purpose, which changed the configuration. A new design concept was developed and discussed at several workshops by the partners responsible for the fabrication task of CRASURV: Alenia, Aerospatiale, NLR and DLR (Fig. 2).

The struts were replaced by longitudinal sine-wave beams for energy absorption, based on the favourable results obtained in the box programme. These beams were placed at a 10-degree angle with respect to the vertical plane. It was thought that the rotation of the frames during the crash might lead to a rotation of the beams to a more vertical position. Moreover, crashes do not always take place vertically, and lateral loading components can be expected to occur, so a sine-wave beam that is slightly loaded out-of-plane should still be capable of energy absorption. A previous inclined sine-wave beam test had shown this to be possible [7]. Sizing of these sine-waves was performed by DLR, using their analysis methods and database on sine-wave beams. The sine-wave beams contained a trigger mechanism along their lengths, consisting of dropped plies in the web near the bottom cap, to initiate crushing of the web at a dedicated location and at a well defined load.

As drop tests of ring-shaped fuselage frames by NASA [8] had shown before, composite ring-frames tend to fracture in several locations, at the impact point as well as at points higher up, thereby diminishing the integrity of the structure and the capability to absorb further energy in a controlled way. Hence, it was decided to abandon the ring-frame concept. Instead a concept was chosen, whereby the upper part of the ring frame was continued in the transverse floor beam, with the intention that this closed frame would remain intact and provide post-crash integrity, while the bottom part of the ring-frame (below the floor) was attached to the upper part by hinges, in order not to transfer bending moments that might induce fractures of the upper part of the frame. In order to provide controlled fracture of the bottom part of the frame, it was configured as two sections, connected by a splice plate at the impact point (Fig. 3). The sine-wave beams and the frames were not connected (Fig. 4) in order to prevent the frames to interfere with the crushing beams, which are meant to be crushed by the ground. After a certain amount of rotation of the frames, they would dig into the sine-wave beam webs, thereby providing a certain amount of lateral stability to the beams.

This design concept was subsequently evaluated at the component level: the sine-wave beam (Fig. 5) and the hinge-frame configuration (Fig. 6) with splice plate. NLR fabricated two specimens of each component, and tested one of each in static compression, while DLR tested the other two specimens "dynamically".

In the first of the tests carried out by DLR, the function of the frame assembly with a collapsible splice plate could be proved. The splice plate between the two stiff frame sections broke very early after the impact and then the frames started to rotate around the hinges, exactly in the way they were designed. The only point of concern that could be found in this dynamic test was the bonded connection between the skin and the flange of the frame. This bonded joint failed totally by peeling stresses, and caused disintegration of the frame and the skin. As an improvement of the fuselage design, a number of rivets were used in the section which was eventually drop tested, in addition to the bonding connection, to avoid this type of failure.

The excellent crushing behaviour of composite sine-wave beams in combination with a ply drop-off trigger was demonstrated in the second dynamic test carried out at DLR (Fig. 5). The 350 mm high sine-wave beam (rather high compared to typical helicopter beams) failed along the trigger line and showed now damage far away from the trigger area. A continuous crushing process with a nearly constant load level of about 50 kN was observed, from the point where the web, broken at the trigger line and translated downwards, contacts the lower flange again. Compared to the quasi-static compression test carried out at NLR, the crushing load is about 25 % lower (Fig. 7).

Based on the results of the component tests, the design of the commuter section was finalized by Alenia.

d. fabrication

The final assembly of the commuter sub-floor structure consisted of a number of pre-cured parts, which were bonded together, while some parts were also bolted together. The composite parts were the skin (two plates joined together by adhesive bonding along the impact line), with secondarily bonded I-shaped stringers, four C-section frame halves with bonded and bolted splice plates, two sine-wave beams, two lateral floor I-beams, each consisting of four parts, and two rail tracks on top of the sine-waves, of similar cross section as the floor beams. Aluminium brackets were used for the hinges, the connection between the ends of the floor beams and the skin, and the connections between the floor beams and the seat tracks. The connections between sine-waves and skin, and between frames and skin were bonded and also bolted (Fig. 8).

5. The drop test

The commuter sub-floor structure was shipped from NLR to the Centre d'Essais Aeronautiques de Toulouse (CEAT), and drop tested on 27 November 1998.

a. test configuration

Because of the structural geometry and the requirement that the fuselage section must impact the ground in a vertical position, a guidance system was devised by CEAT which was able to lift the specimen to the predetermined height, to release the structure by a pyrotechnic system, and to guide the structure downward during its fall (Fig. 9). In order to take the friction due to the guidance system into account, various tests were performed to determine the height correction. Consequently, the structure was lifted to 2.6 m above ground level in order to reach the vertical speed of 7 m/s on impact.

To simulate the masses of occupants, seats, and the upper part of the fuselage, the structure was loaded with 40 kg at a position near the skin, and with 300 kg above each sine-wave beam. Part of the guidance system also contributed to the load above the hinge. To avoid tilting of the inner and outer masses, two stiff beams were used to connect the two masses. The 300 kg mass located above the sine-wave beams was distributed along the full 800 mm length of the beams. The structural mass was 720 kg, including the 30 kg mass of the specimen. The loading principle is shown in figure 10.

b. instrumentation

The instrumentation was configured, taking into account the suggestions made by partners involved in the pre-test structure and occupant simulation. Thus, different types of sensors were set up at various parts of the commuter structure in order to provide the partners with test data to correlate with their analysis results. Furthermore, the measurements were intended to support the analysis of the structural behaviour and to estimate the structural energy absorption which is needed to limit the load and acceleration of the occupants. The total number of measurement channels was 39: 18 strain gauges at the composite structure including the half frames and the cross beams, 4 strain gauges and 6 displacement cells at the left sine wave beam, 4 strain gauges at the seat floor attachment and also at the load masses, and 3 load cells at the reaction platform. Various high speed camera's were set up around the test facility: one video at 25 frames/s, two high speed motion camera's at 500 frames/s, and one high speed motion video (1000 frames/s).

c. failure mode

The actual impact velocity was 7.09 m/s, the energy at impact 19866J. At the first impact, the splice plates which connected the two halves of the frames did fail as predicted (after 7 ms). The frames did not immediately rotate about the hinge points because of their connection to the skin, and started to buckle (after 9 ms). The various stringers impacted the ground consecutively, and high postbuckling stresses occurred in the frames. The upper part of the frames then hit the sine-wave beams, cutting into the webs. Subsequently, the frames broke, one half at the hinge level, the other half at "stringer 3" level (after 10 ms), followed by frame/skin debonding (10-15 ms), and outward bending of the sine-wave beams (after 15 ms).

The sine-wave beams hit the ground (after 19 ms) at an angle of 10 degrees. The outer parts of the sine-wave beams (outside the two frames) broke away at about the same time as the failure of the trigger mechanism. However, the sine-wave beams did not crush, but bent outwards (after 22 ms) until they were stopped at the next stringers. They did not absorb a significant amount of energy. As a result, high forces were transferred to the lower flanges of the seat tracks, leading to distortions and fractures. After 22 ms, the sine-wave beams stopped crushing and absorbing energy.

The overall energy absorption was very low, and not by the mechanisms intended. However, the experimental data were useful to modify numerical models, and to validate the code developments. The failed structure, after being pulled up (it had been crushed flat), is shown in figure 11.

6. The numerical analysis

Partners Alenia, CASA, Dassault and Principia participated in the numerical analysis of the crash behaviour of the commuter structure. The discussion that follows corresponds to the pre-test analysis of Principia and the post-test analysis of Alenia.

a. Principia

The mesh used for pre-test analyses is shown in figure 12, with symmetry conditions imposed. Bonded and riveted joints were modelled as tied contacts between the different components. The masses that were added to represent occupants and upper structure are not represented in the figure. To represent these masses, beam finite elements were attached to the upper flange of the seat track. The finite element model comprised approximately 30000 elements, 32000 nodes, and had 190000 degrees of freedom.

The constitutive model for the material of the isotropic shells was an elastic-plastic model with isotropic damage and failure. For some components, those not expected to be critical, a simpler elastic-plastic model with strain softening was used. In the first material model, the elements are deleted from the mesh once the damage parameter reaches a certain value. In the second, simpler model, the elements remain in the mesh with independence of the magnitude of strains, but at a very low level of residual stress. The equivalent isotropic properties were determined by means of single element numerical tests, matching the response computed using the actual lay-up and the response of a single layer with isotropic properties. In the case of the sine-wave beam, calibration was refined further using the results of the dynamic test performed by DLR. Pre-test analyses were performed using the commercial version of ABAQUS/Explicit [9]. A typical 60 ms simulation took 80 CPU hours on a small UNIX workstation.

Figures 13 and 14 present two views of the deformed shape at 60 ms. The failure of the specimen during the drop test, predicted by the pre-test simulations, consisted of the rupture of the frames at several locations, followed by the impact of the bottom of the sine-wave beams with the ground. It was predicted that this impact would produce the peak deceleration at passenger level and would lead to the tearing of the sine-wave webs at the position of the trigger. Then, the edge of the web was predicted to contact the inner surface of the skin and to slide sideways, increasing the angle of the web with the vertical. With respect to the behaviour expected by the designers, the most remarkable feature was that the web of the sine-wave beam did not crush in the analysis as much as expected, but the bottom of the web slid sideways.

Hence, the behaviour obtained in the pre-test analyses was more or less in agreement with the failure mechanism observed in the test. In the test, however, the webs of the seat tracks broke, since they were not strong enough to keep the sine-wave beams in position after the bottoms of the sine-wave webs tore along the triggers. Once the seat tracks broke, the bottoms of the sine-wave beams were free to slide over the skin. The latter phenomenon is similar to what the pre-test analyses showed. However, the pre-test analyses predicted a reduction of the velocity from 7 m/s to 2.4 m/s in 60 ms, far in excess of what was observed in the test. This led the analysts to the erroneous conclusion that the overall design of the specimen was correct from a crashworthiness standpoint.

Post-test analyses showed later that, from a global point of view, test results could be matched by introducing a more brittle behaviour in the material models, even if simple equivalent isotropic material models were used to represent the actual laminates. It appeared that very sophisticated material models, involving anisotropic damage or plasticity, were not needed, at least for representing the kind of behaviour observed in the test for quasi-isotropic laminates. The excessively ductile behaviour of materials used in pre-test analyses was the result of the process of material property calibration. It was concluded that material models should be adjusted based on careful calibration with experiments reproducing the expected failure mode. For pre-test analyses, the sine-wave beam material model was calibrated using the results from a dynamic test performed by DLR, in which the failure mode was the controlled crushing of the sine-wave web.

The main lesson for future simulations is that, due to the limitations to simulate the actual physical phenomena during crushing with regular shell finite elements, material models to be used for this kind of analyses should be calibrated according to an expected failure mode. As an alternative, shell-type finite elements able to properly represent the mechanism of delamination might be used. However, these kind of elements are not available at the present in the most popular commercially available computer codes used for simulating crash tests.

b. Alenia

Within the scope to assess effective design guidelines for crashworthy aircraft structures, Alenia aimed its post-crash comparison of numerical and experimental results towards the understanding of why the pre-test simulations did not predict the unstable behaviour of the sine-wave beams. In fact, it has to be noted that the common decision by all CRASURV-partners involved, to take the risk of a vertical impact with approximately 20 KJ, was also based on the generally positive results of the numerical simulations performed before the drop test; such analyses foresaw a stable sine-wave behaviour (the sine-wave beams were the only energy absorbing components), even if different than the expected behaviour. Moreover, before the drop test, sub-component crash tests on sine-wave beams and frames demonstrated the energy absorption capability of the structure.

The post-test analysis, using PAM-CRASH, was performed in collaboration with CIRA s.c.p.a., the Italian Aerospace Research Center, at their own facilities. First, numerical runs at sub-component level were performed in order to determine the energy absorbing characteristics of each of the main structural components, and to highlight possible weaknesses in the design assembly. Then, the sub-component energy absorbing characterisation was scaled up by simulating the complete structure.

It was concluded from the Alenia-CIRA post-test numerical simulation that the pre-test simulation failed because erroneous assumptions had been made for the coefficient of friction between the sine-wave beams and the ground, for the disbonding/rivet allowables between the skin and the frames, and for the rotational weakness at the joint of seat-track and sine-wave beam (Fig. 15). It was also concluded, that the crash tests of the sub-components were not representative of the actual loading conditions within the overall assembly of the complete commuter structure.

7. Conclusions

A design concept was developed for a sub-floor structure of a fuselage, representative of an "ATR-type" commuter aircraft, made largely out of fiber reinforced composite material, with the requirement for the structure to be crashworthy. As composite fuselages for such large aircraft satisfying this requirement have never been built before, the exercise can be considered to be the first of its kind, and of a highly explorative nature. The structure was built and tested by dropping it at a vertical velocity of 7 m/s, while loaded with dummy masses to represent the passengers and the structural weight of the super structure. The test data was successfully used to validate the computer software developed for the simulation of crashing composite aircraft structure.

The design concept was not successful, in that the energy absorption capability was significantly less than foreseen. This capability was to be provided by the controlled crushing of longitudinal sine-wave beams. However, due to the lack of lateral support, these beams slipped sideways, and escaped most of the compressive loading. In box type structures tested earlier, this phenomenon did not occur, which indicates the importance of the presence of rigidly connected lateral support structure to stabilize those components which are dedicated to absorb energy in a compressive mode.

The objective of the research programme was very ambitious: new computing capabilities were to be developed and validated, by comparison with experimental results obtained for novel composite structures which had to be developed simultaneously. The experimental outcome of the design effort presented here points at the need to dedicate a future research programme entirely to the development of successful design concepts for crashworthy composite fuselage structures, now making use of the computer simulation capabilities developed within the Brite-Euram CRASURV programme.

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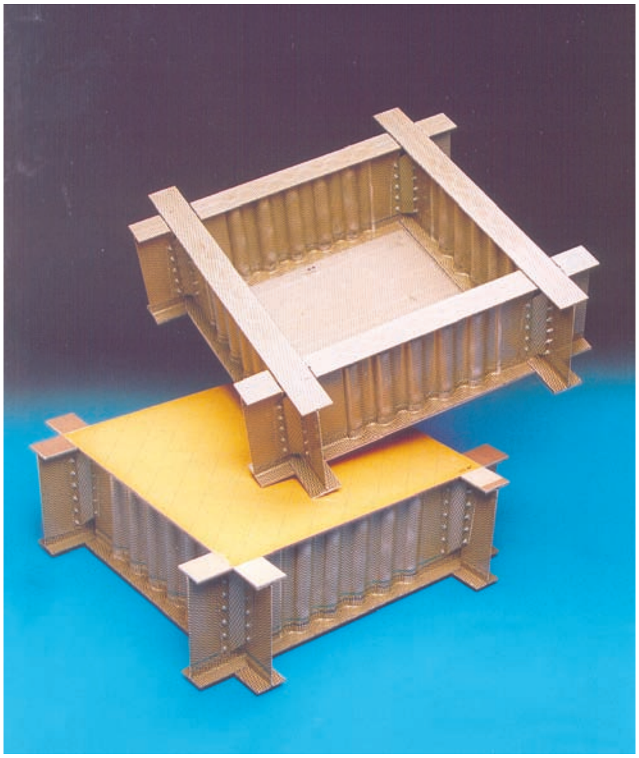

Fig. 1 Sub-floor box structures (NLR)

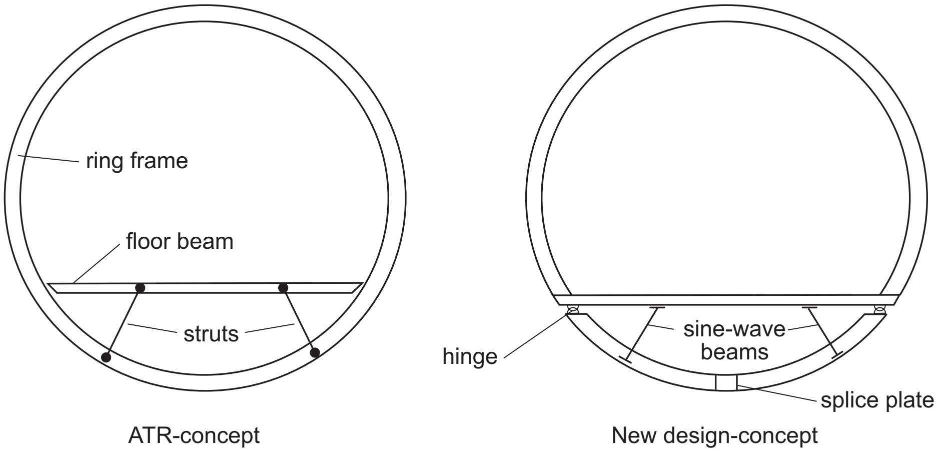

Fig. 2 Design concept composite commuter

Fig. 3 Splice plate

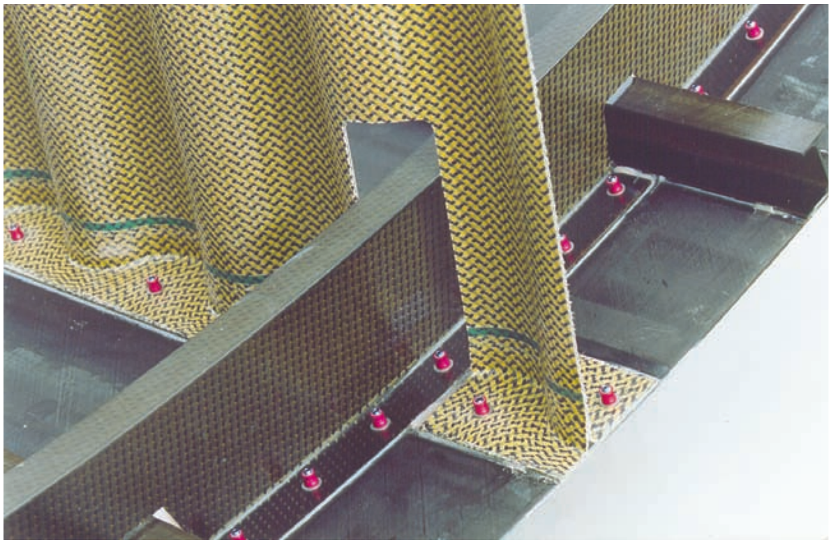

Fig. 4 Frame-beam intersection

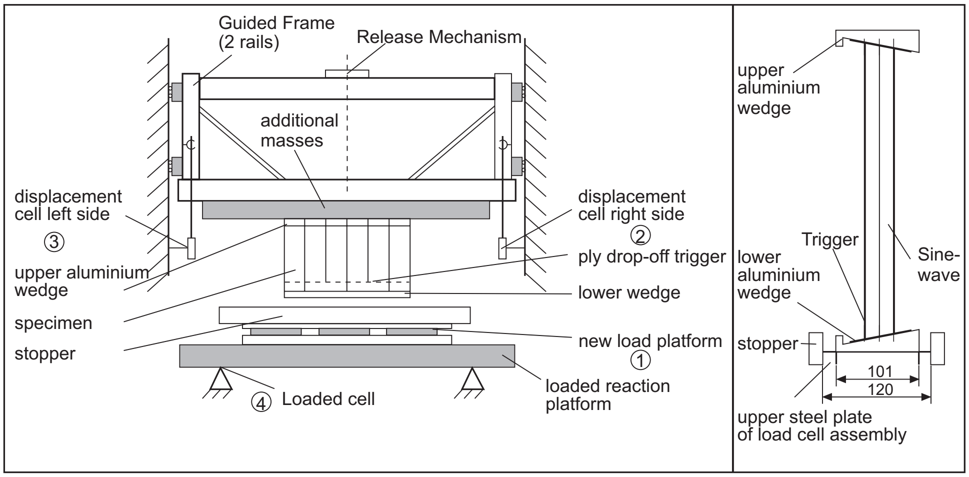

Fig. 5 Test set-up for the dynamic sine-wave beam test (DLR)

Fig. 6 Frame components with hinges

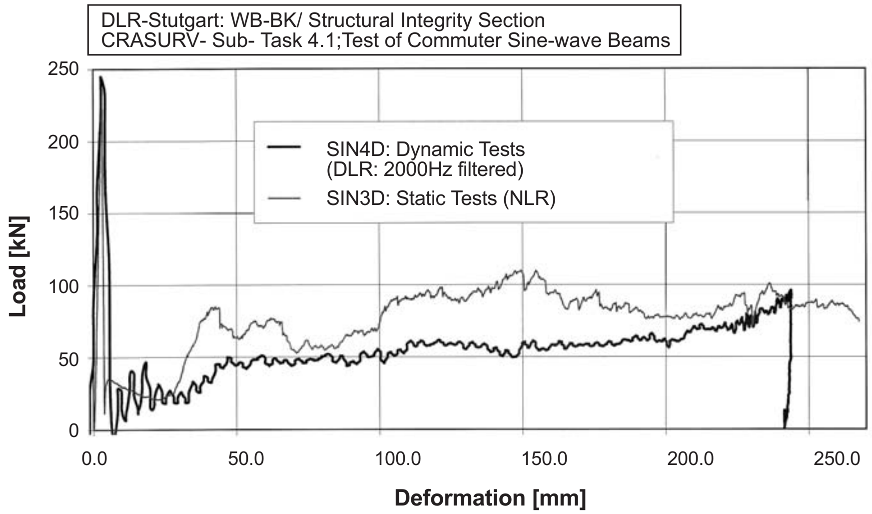

Fig. 7 Comparison of static and dynamic sine-wave beam tests (DLR)

Fig. 8 Final assembly of Commuter sub-floor struct. (NLR)

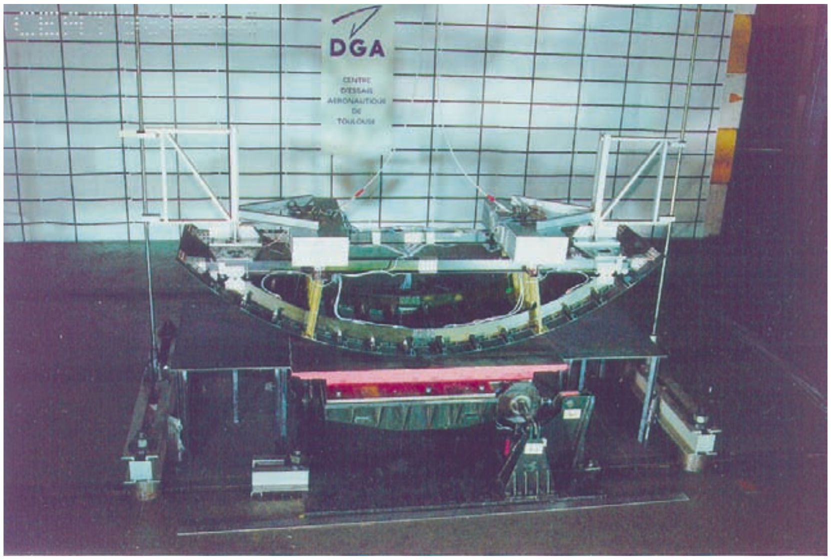

Fig. 9 Test set-up at CEAT

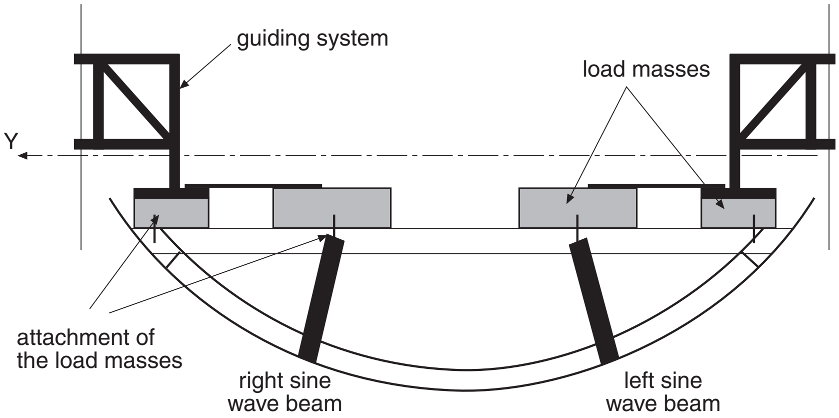

Fig. 10 Loading principle (CEAT)

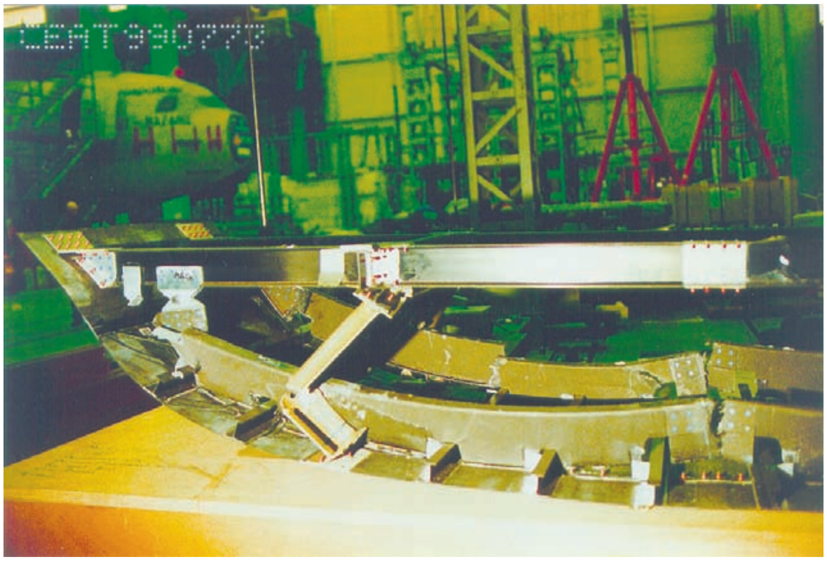

Fig. 11 Post-test configuration (CEAT)

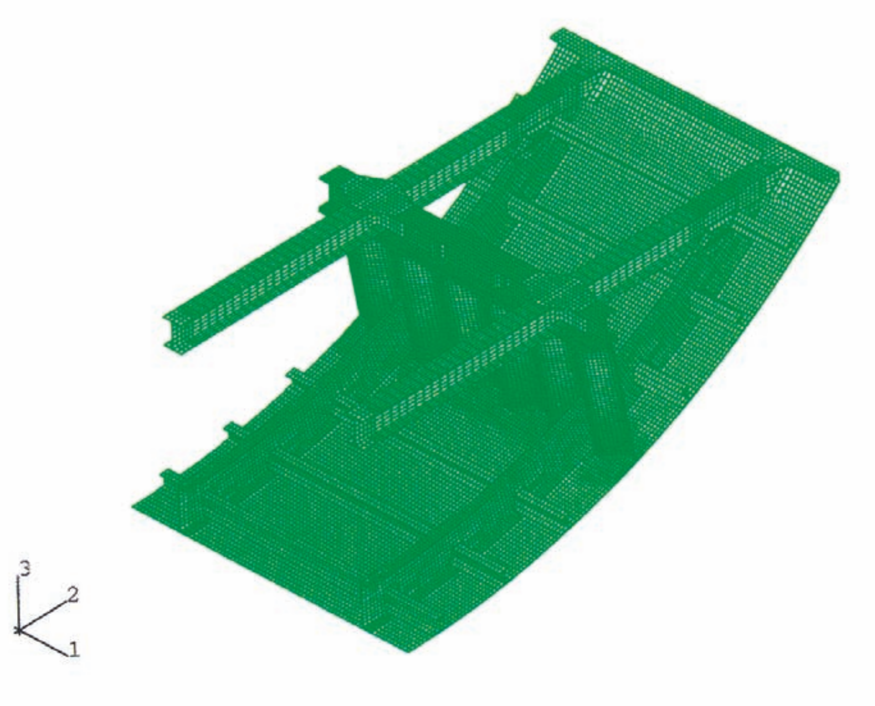

Fig. 12 Finite element mesh for pre-test analyses (Principia)

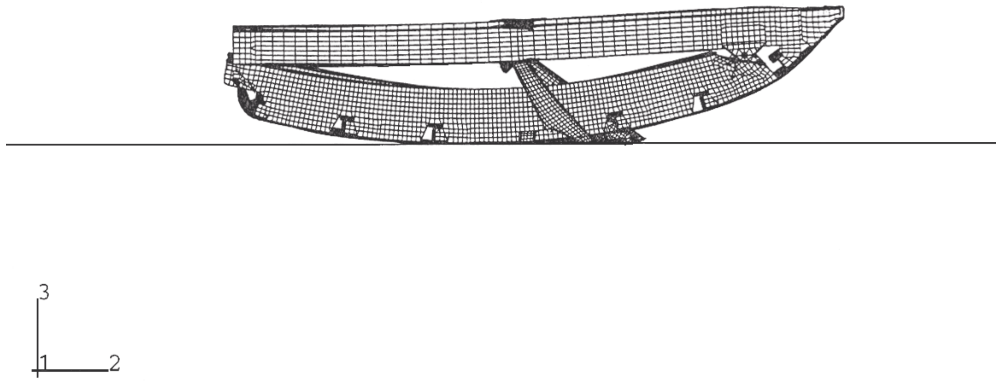

Fig. 13 Deformed shape predicted by pre-test analyses at 60ms (Principia)

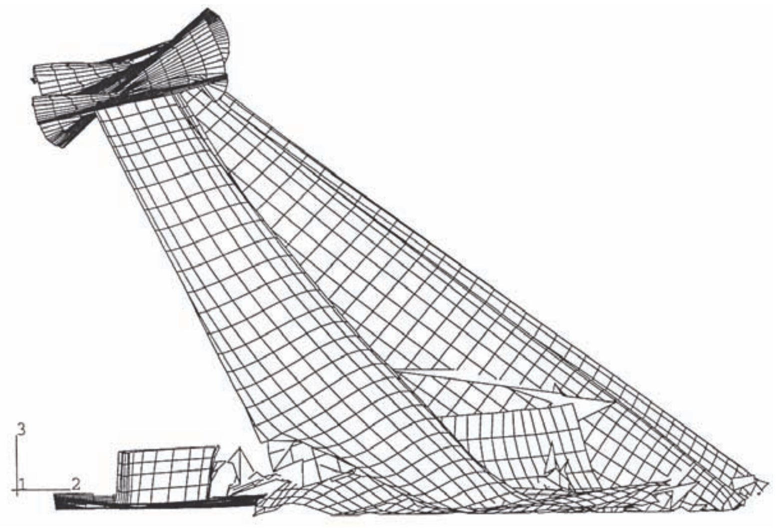

Fig. 14 Detail of sine-wave beam predicted by pre-test analyses at 60 ms (Principia)

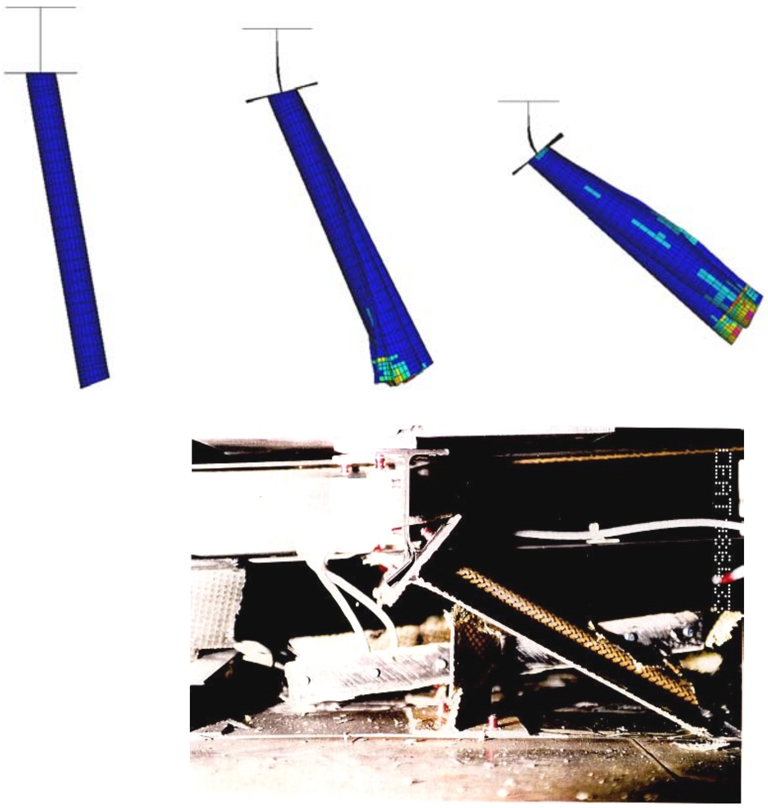

Fig. 15   Lateral instability of the sine-wave beam (Alenia)