Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2001-108

Development of a crashworthy composite fuselage concept for a commuter aircraft

J.F.M. Wiggenraad, D. Santoro*, F. Lepage**,
C. Kindervater*** and H. Climent Mañez****

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2001-108

Development of a crashworthy composite fuselage concept for a commuter aircraft

J.F.M. Wiggenraad, D. Santoro*, F. Lepage**,
C. Kindervater*** and H. Climent Mañez****

* Alenia Aerospazio- Aeronautic Division
** CEAT, Department Atterrissage Crash
*** DLR, Institute of Structures and Design
**** EADS - CASA, Development and System Division

This report is based on a presentation to be held at the 57th Annual Forum of the American Helicopter Society, Washington DC, USA, May 9-11, 2001.

Division: Structures and Materials
Issued: 9 March 2001
Classification of title: Unclassified

Contents

ABSTRACT 3

INTRODUCTION 3

APPROACH 4

DESIGN RATIONALE 4
Materials 4
Loading 5
Structural concepts 5

COMMUTER FUSELAGE DESIGN 5

FABRICATION 6

DROP TEST 6
Test configuration 6
Instrumentation 6
Failure mode 7
Lessons learned 7

NUMERICAL ANALYSIS 7

CONCLUSIONS 8

ACKNOWLEDGEMENT 8

REFERENCES 8

14 Figures

(13 pages in total)

Development of a Crashworthy Composite Fuselage Concept for a Commuter Aircraft

J.F.M. Wiggenraad
wigg@nlr.nl
National Aerospace Laboratory NLR
PO BOX 153, 8300 AD Emmeloord, The Netherlands

D. Santoro
dsantoro@aeronautica.alenia.it
Alenia Aerospazio- Aeronautic Division
Viale dell'Aeronautica, Pomigliano d'Arco (Na), Italy PC 80038 C.CIT

F. Lepage
fabrice.lepage@ceat.fr
CEAT, department atterrissage crash
31056 Toulouse CEDEX, France

C. Kindervater
christof.kindervater@dlr.de
DLR, Institute of Structures and Design,
Pfaffenwaldring 38-40, D-70569
Stuttgart, Germany

H. Climent Mañez
c80411@casa.es
EADS - CASA, Development and System Division
Avda. John Lennon s/n, 28906 GETAFE, Madrid, Spain

ABSTRACT

Within the framework of Brite-Euram programme CRASURV "Commercial Aircraft - Design for Crash Survivability", technology was developed for the design of composite air frames with respect to crashworthiness. The ultimate goal of the project was to develop computer codes for the simulation of the crash behaviour of composite fuselage structures. A significant part of the project consisted 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. The structure failed in a mode which was not predicted. The deficiencies of the model were repaired and a post-test analysis gave satisfactory results. The project has resulted in improved simulation capabilities. However, it cannot be concluded that the state-of-the-art is such, that the behaviour of new composite structures can be predicted accurately in the near future.

INTRODUCTION

Traditionally, fuselages of fixed-wing transport 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 in civil transport aircraft, applications are limited mainly to the empennage, the outer wing and secondary structures. However, application of composite materials to aircraft fuselages becomes feasible rapidly, and the crashworthiness aspect related to composite structures has become a serious issue. The composites used for aerospace structures are generally brittle materials with hardly any capacity for plastic deformation, so crashworthiness is no longer a materials aspect, but requires a combined materials/ structures/fabrication approach.

Presented at the American Helicopter Society 57th Annual Forum, Washington, DC, May 9-11, 2001.

The design for crash survivability has become of increasing importance during the last decades, 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 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]. A subsequent Brite-Euram programme was started in September 1996, and completed in February 2000, entitled "Commercial Aircraft - Design for Crash Survivability" with acronym CRASURV [3]. The objective of this project was to develop the technology for the design of composite air frames with maximum safety with respect to potentially survivable crash scenarios. The main activities within this project were the development of computer capabilities to simulate the crash behaviour of composite structures, and the design, fabrication and test of representative test articles for the validation of the computer codes. These articles consisted of a number of generic sub-floor "box" structures, typical for helicopters and small commuter aircraft [4, 5], and of larger sub-floor structures, typical for transport aircraft such as the Airbus A-320 and the ATR-42/72. The development of the latter structure and its numerical analysis is described in the present paper.

APPROACH

The project team was assembled from representatives of the European aircraft industry, aerospace research establishments, universities, computer code developers and several small businesses. The specific task objectives were to develop appropriate material models, to design and build representative composite aircraft fuselage components, to test these components, to develop and apply computer codes to simulate crash behaviour, to determine the effect of the crash loading on the occupants, and to assess the newly developed methodology, and propose design guidelines.

The ultimate goal of the project was 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 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 and helicopters). Hence, a significant part of the project consisted 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 the Italian aerospace company ALENIA. The second fuselage section, representative of a larger airliner like the Airbus A320, was defined by EADS France. The principal difference between the two aircraft (with respect to crashworthiness) is, that the ATR-42/72 has a very small space between the cabin floor and the outer shell, while the A320 contains a cargo hold between the cabin floor and the outer shell, hence contains more space to allow deformations in a crash. The two 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, carried out in co-operation between ALENIA, the Dutch and German aerospace research centers NLR and DLR, the French test center "Centre d'Essais Aeronautique de Toulouse" CEAT, and the Spanish aerospace company EADS-CASA.

DESIGN RATIONALE

Crashworthy structures are structures which are designed to sufficiently withstand survivable impacts, so the occupants will survive. For a crashworthy design, two important aspects have to be covered: for the passenger space a "livable" volume needs to be maintained, with sufficient potential for evacuation, and the impact accelerations submitted to the passengers need to be limited to well specified values, for impacts at various angles. So far, crashworthy aircraft structures made of composite materials have been developed and implemented for helicopter structures and small aircraft. In this field, design requirements were formulated, and design solutions were developed and demonstrated in tests. On a research scale, NASA has investigated the behaviour of fuselage frames for fixed-wing aircraft in impact tests. The following lessons were learned:

Materials
Metals absorb energy by plastic deformation. For metal structures, this applies to all failure modes: tension, compression, bending, etc. Composites absorb energy mainly by fiber breakage. It is important to break a fiber many times over, rather than once only. For composite structures, this seems possible

only in a compression mode without buckling, i.e., in a stabilized configuration. Failure in tension or bending usually doesn't lead to multiple fiber fractures. Helicopter technology has indicated that carbon-fibers are best for energy absorption, and aramid fibers are best to provide stability and integrity of a crushing structure. Solutions are therefore sought in mixed laminates of both fiber types, either as a laminate with different material plies or as hybrid fabrics.

Loading

Compression loading is prevalent in a crash, and a failure mode in compression is a suitable mode for energy absorption in a composite component. However, stability needs to be provided during the crush loading. Also, the initial failure load is usually much higher than the subsequent sustained crushing force. This high load leads to corresponding undesirable high acceleration levels. Therefore, "trigger" mechanisms in the form of local weak spots have to be integrated in the components which are dedicated to absorb energy. However, such weak spots may undermine the structural stability of the component. Trigger mechanisms also play a dominant role in the type of failure mode following the failure of the trigger, hence are very critical to the actual energy absorbed.

Structural concepts

The cylinder is the optimum configuration with inherent stability when loaded axially in compression, but not often a practical configuration. Sine-wave or corrugated beams are the next best component with inherent stability. However, after failure of the trigger, this inherent stability may be significantly reduced, and additional stability needs to be supplied by adjacent components in the lateral direction. Tension-loaded components made of composite materials, such as aircraft skins impacted on soft soil or water, are brittle and break directly. To provide resilience for such loading cases, the tensor-skin concept was invented, which provides a large pseudo-plastic deformation capacity to the skin [6]. Points of concentrated load-introduction in composite structures can be made more resilient, and even energy-absorbing, by introducing a large amount of aramid fibers in the particular area, leading to the loading pin to slide through the composite component.

The ring-frame configuration as commonly used in fixed-wing aircraft, is a difficult component for crashworthiness. NASA studies have shown, that the "point-load" applied by the ground leads to immediate fracture at this point, followed by severe bending, and further breakages of the frame higher up [7]. This may result in an early disintegration of the structure, and the bypassing of the dedicated energy-absorbing measures. The recommendations followed from these studies were, to separate the livable volume "on top" from the energy absorbing components "below". Hence, a sufficiently strong, closed ring-frame, meant to survive the impact, should be positioned on top of an expandable energy absorbing structure. This concept was adopted by both the commuter and the airliner configurations developed in CRASURV.

COMMUTER FUSELAGE DESIGN

Based on the lessons learned from the proven technology summarised above, the following choices were made. For energy absorption, two longitudinal sine-wave beams were selected, using the material configuration and trigger mechanism as used in the boxes (see Fig. 1), but adapted for the required dimensions (height) and load. Closed frames, placed on top of the sine-wave beams, were obtained by continuing the super-floor frame sections into the floor beams, and connecting the sub-floor frame sections to the super-floor sections by means of discrete hinges, rather than (more complicated and unpredictable) pseudo-plastic hinges, see Fig. 2. This would prevent the transfer of bending moments from the sub-floor frame sections to the super-floor sections. The sub-floor frame sections had to be maintained to withstand the cabin pressure.

The sub-floor frame sections were expected to break at the ground impact point, and were configured with a breakable splice plate, see Fig. 3, to control the failure. These frame sections were to be loaded by bending, due to the impact force, and the reactions of the hinges and the sine-wave beams, and possibly to buckle. However, with the crushing of the sine-wave beams by the dummy passenger mass placed above, and the ground reaction from below, the sine-wave force on the sub-floor frame sections would diminish, and the frames might rotate around the hinges. However, this would require the skin to break near the hinges, which was expected to occur without the need to trigger this failure.

Originally, the sub-floor frame sections were thought to be connected to the sine-wave beams, alike the cruciform joints in the composite box structures. Hence, the sine-wave beams were placed at a slight angle, in order to follow the expected rotation of the frames. Sine-wave beams, even when placed at a slight angle, and tested as a singular, laterally supported component, had been shown to absorb a significant amount of energy [8, 9]. Moreover, a commuter aircraft should be able to crash at a modest bank angle without loosing its crashworthiness. In a later stage of the design, it was decided to eliminate the connection between sine-waves beams and frames, see Fig. 4, to prevent the deforming sub-floor frame sections to destabilize the sine-wave 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.

FABRICATION

The fabrication and final assembly of the commuter sub-floor structure, carried out at NLR, 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).

DROP TEST

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, common to the speed at which the metal A320 section was tested in the preceding Brite Euram programme. The selection of the dummy mass to represent the passengers and super-structure was controversial. For a successful test result for code-validation, which was the primary objective, a lower mass was suggested by several partners, but to validate the (first-of-its-kind) structure for the ultimate design requirements, a higher mass was proposed by other partners. A compromise was found: the impact energy was therefore 20 KJ, by coincidence equal to that for the boxes, and twice the energy applied later to the airliner sub-floor structure.

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 Fig. 10.

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)

Failure mode

The actual impact velocity was 7.09 m/s, the energy at impact 19866J. The commuter test resulted in an unexpected (and by the codes not fully predicted) failure mode, and failed without absorbing the required amount of energy. Upon impact, the splice-plates broke correctly, and the sine-waves triggered correctly too. However, the now destabilized sine-wave webs slid across the fuselage skin in the outward direction, rather than staying in plane to absorb energy by compression. The out-of-plane movement of the webs induced significant unexpected torsion moments on the (I-section) seat tracks, which failed unintendedly. As the skin did not fracture near the hinges, the frames were prevented to rotate, so that they bent, buckled and failed. 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 Fig. 11.

Lessons learned

The major fault of the design was the fact that the sine-wave beams had no lateral support, for instance by lateral sine-wave beams such as in the boxes. An improved solution might have been found by connecting the frames to the sine-wave beams, as originally intended. However, these frames cannot support the sine-wave beams over the full height, because they are much lower. Another solution might have been to provide a "stopper" for the sliding sine-wave beam web, but that is probably a less efficient mechanism. The trigger of the sine-wave beam was still providing a rather high peak force. A trigger with reduced strength might have improved the failure mode. The skin did not break near the hinges. A trigger line, for instance provided by a rivet row, might have initiated failure of the skin, thereby improving the chance that the frame section would rotate as intended. The failure of the seat tracks was not important, because it was consequential to the undesirable failure mode.

NUMERICAL ANALYSIS

Several partners participated in the numerical analysis of the crash behaviour of the commuter structure. The discussion that follows corresponds to the pre- and post-test analyses of EADS-CASA: pre-test simulations with the PAM-CRASH code and post-test simulations with the PAM-CRASH and LS-DYNA3D codes.

The mesh of the finite element model, used in all simulations, is shown in Fig. 12. The structure was modelled with shell elements, with an average length of 10 mm. The various components of the model were connected by rivets and/or adhesive, which were modelled as rigid body multi-point constraints with rupture criteria. The masses, representing passengers, seats and the test guiding system were modelled with solid elements, attached to the top of the model. To avoid penetration between of the components during the collapse of the model, a self-contact algorithm was used. The ground was modelled as a rigid wall with a sliding surface, with a friction coefficient of 0.6. The vertical velocity of 7 m/s was applied to all nodes of the model, while a gravity field of 9.81 m/s was considered. Summarising, the model had approximately 75000 nodes, 71000 elements and 12000 rigid bodies.

Several pre-test simulations were performed with PAM-CRASH, with the objectives to prove the effectiveness of the energy absorbing concept, in order to minimize the test risks, and to provide predictions for comparison with the experimental results. Sensitivity analyses were carried out with regard to material properties, total mass, rivet and adhesive failure and other aspects. The composite material model used was a multi-layered unidirectional "bi-phase" model (material 130 in PAM-CRASH), which allows to specify separately the ply properties for fiber and matrix. The input data were taken from reports generated by partners EADS-DBA, DLR and ESI. For the metallic behaviour, elastic-plastic models with isotropic hardening were used (material 102 in PAM-CRASH). The results of the pre-test simulations showed that during the collapse sequence, the sinewave beams did not hit the ground perpendicularly (with the corresponding risk of bending and sliding), and the frames almost did not rotate around the hinges as expected by the designers. The contact between frames and sine-wave beam webs did not allow the trigger mechanism to work properly, especially near the frames. Figs. 13-14 show the deformed shape at 60 ms, when the vertical speed has decreased to zero, and the model starts to rebound.

The sequence of events observed in the pre-test simulations was partially in agreement with the test results. The splice plate failure, the impact angle of the sinewave beams, and the functioning of the trigger mechanism occurred at about the same time as in the test. However, the friction coefficient between the sinewave beam and the skin was too high, which prevented the web of the sinewave beams to slide, and the web of the seat track did not break as in the test. As a result, the pre-test simulations predicted a far too large amount of energy absorption by the sine-wave beams, compared to what was observed in the test.

For the post-test simulation with PAM-CRASH, the model was slightly modified. In order to get a more realistic failure (rupture), i.e., less ductile behaviour, the properties of the composite materials of the frames, the sine-wave beams and the seat tracks were embrittled. The ultimate failure loads of rivets and adhesive, friction coefficients and element elimination criteria (maximum strain) were decreased. In addition the actual test conditions were imposed: 7.09 m/s and a total mass of 719 kg. As a result of these modifications, the analysis predicted a collapse sequence which was well in agreement with the observed failure mode (see Figs. 13-14).

Subsequently, the post-test analysis model of PAM-CRASH was translated to a LS-DYNA3D model. In this case, the composite material model was a damage model with the Chang matrix failure criterion, combined with strain limiters (material 54 in LS-DYNA3D), which is able to perform a progressive softening (reduction of material strength and Young's modules) of those elements, of which the neighbouring elements have already failed. The input data, generated by partners in the consortium, were embrittled as for the PAM-CRASH post-test simulations. The analysis results showed a similar crash sequence as observed when using PAM-CRASH.

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. It is believed, that given such additional lateral support, the energy absorbing concept will work for commuter aircraft made of composite materials. However, alternative design concepts can be contemplated, possibly by developing entirely new and innovative energy absorbing frame concepts.

Based on the simulations of the commuter drop tests performed by CASA, it can be concluded that PAM-CRASH and LS-DYNA3D have proved to be robust tools for this application. A major inconvenience was the large CPU time required, that in some cases was close to 30 days for a 90 ms simulation, which is a problem that will be overcome with time. A major problem was the use of material data generated in detail tests, representative of failure modes which were not actually encountered in the drop test of the commuter structure.

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.

ACKNOWLEDGEMENT

CRASURV – Design for Crash Survivability is an RTD project, partially funded by the European Union under the Aeronautics Area of the programme on Industrial and Materials Technology (BRITE/EURAM).

REFERENCES

1. Frijns, R.H.W.M., Wiggenraad, J.F.M., Schaefers, A.T.M., "Assessment of Survivable Crash Scenarios During the Period 1980-1992”, NLR CR 94012, 1994.

2. Brite-Euram project IMT Area 3 Aeronautics: "Crashworthiness for Commercial Aircraft" AERO-CT92-0030, 1993-1995.

3. Brite-Euram project CRASURV "Commercial Aircraft - Design for Crash Survivability", CT96-0207, 1996-1999.

4. Johnson, A.F., Kindervater, C.M., Thuis, H.G.S.J., Wiggenraad, J.F.M., "Crash Resistant Composite Subfloor Structures for Helicopters", AGARD FVP-Symposium: Advances in Rotorcraft Technology, Ontario, Canada, 1996.

5. McCarthy, M.A., Wiggenraad, J.F.M., "Numerical Investigation of a Crash Test of a Composite Helicopter Subfloor Structure", Composite Structures 51, 2001.

6. Michielsen, A.L.P.J., et al, "Design, Test and Analysis of Tensor Skin Panels for Improved Crashworthiness in Case of Water Impact", American Helicopter Society, Specialists' Meeting "Crash Safety Challenges and Innovative Solutions", Phoenix, Az, USA, 1998.

7. Jackson, K.E., Kellas, S., Kindervater, C.M., Luetzenburger, M., "Experimental and Simulated Crash Responses of Composite Airframe Structures", American Helicopter Society 50th Annual Forum, Washington, USA, 1994.

8. Michielsen, A.L.P.J., Wiggenraad, J.F.M., "Review of Crashworthiness research of Composite Structures, Part 1: NLR-contribution", NLR CR 97046 L, 1997.

9. McCarthy, M.A., Harte, C.G., Wiggenraad, J.F.M, et al, "Computational Analysis of Energy-Absorbing Composite Aerospace Structures under Crash Loading", International Symposium on Composite Materials, International Conference on Computational Engineering Science ICES '98, Atlanta, Ga, USA, 1998 .

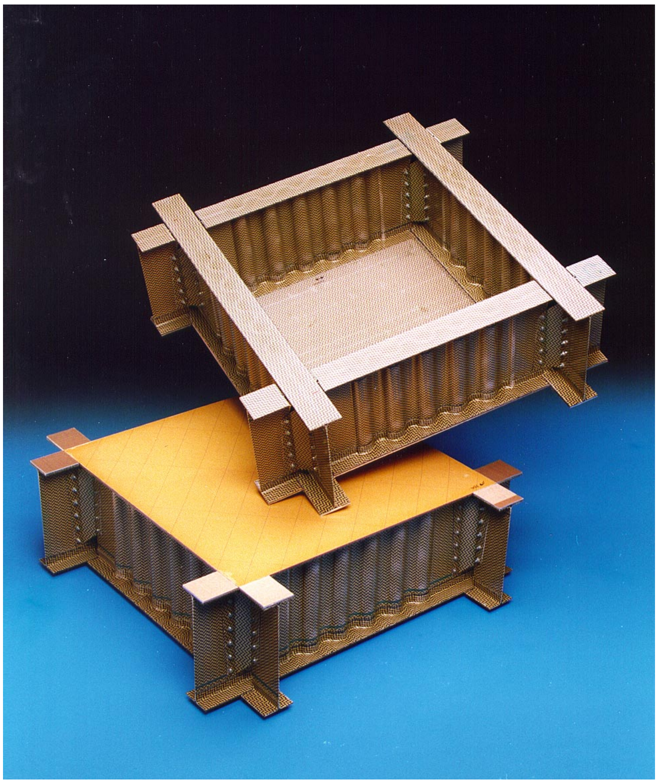

Fig. 1 Sub-floor box structures (NLR)

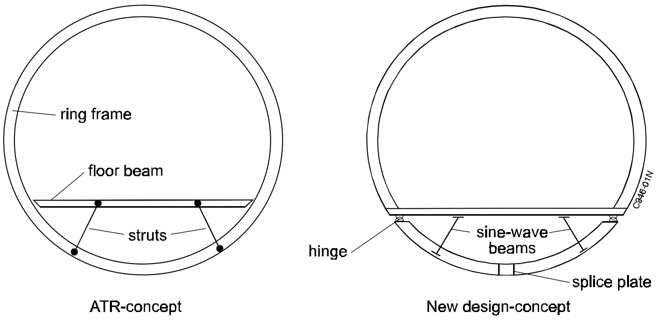

Fig. 2 Design concept composite commuter

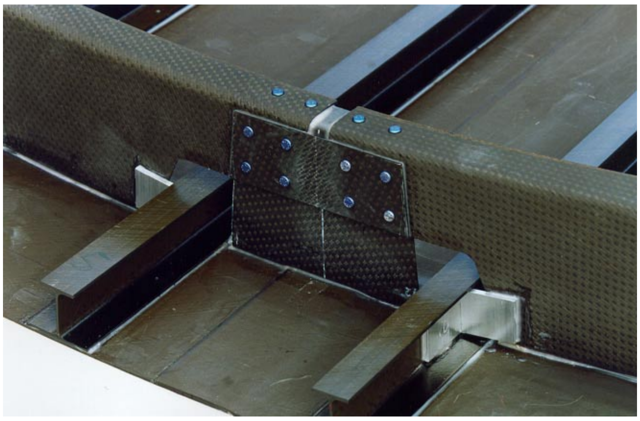

Fig. 3 Splice plate

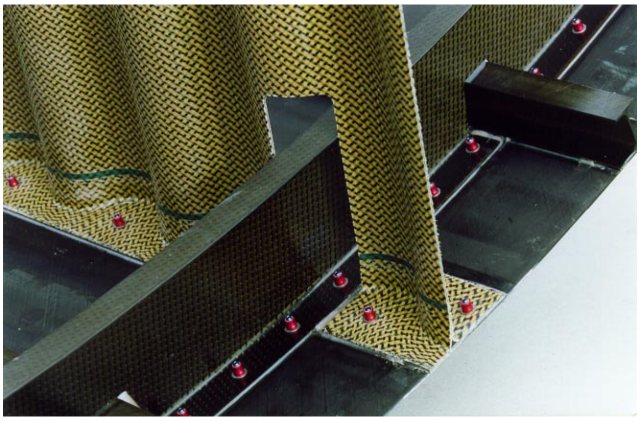

Fig. 4 Frame-beam intersection

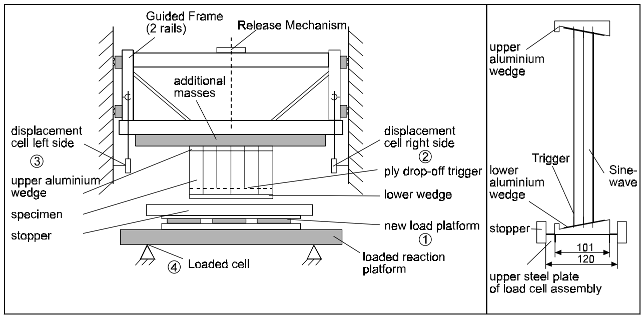

Fig. 5 Test set-up for the dynamic sine-wave beam test (DLR)

Fig. 6 Frame components with hinges

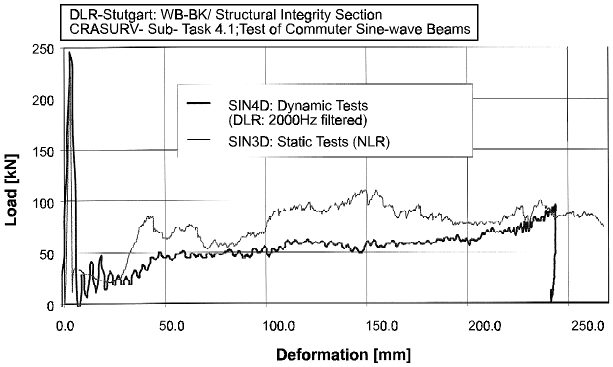

Fig. 7 Comparison of static and dynamic sine-wave beam tests (DLR)

Fig. 8 Final assembley of commuter sub-flor struct (NLR)

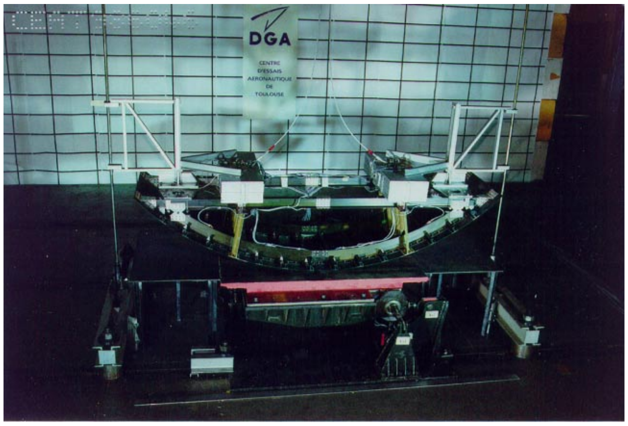

Fig. 9 Test set-up CEAT

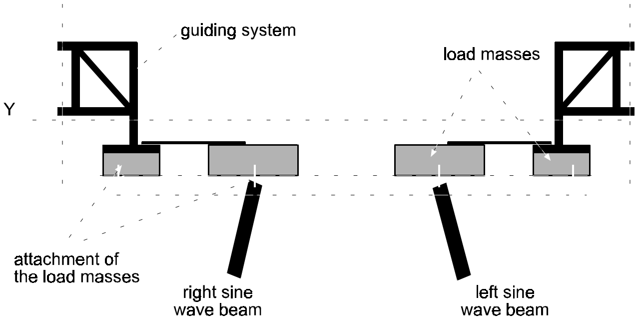

Fig. 10 Loading principle (CEAT)

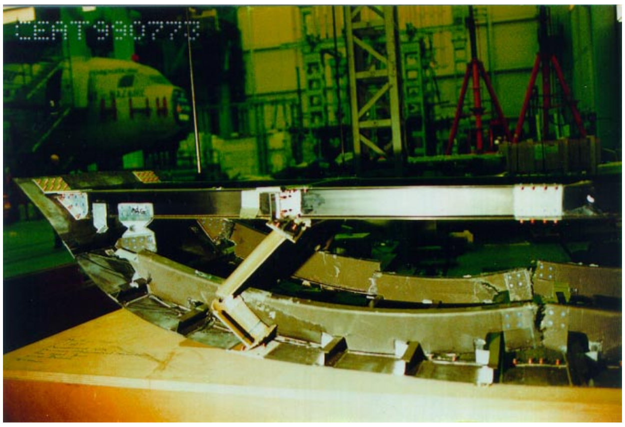

Fig. 11 Post-test configuration (CEAT)

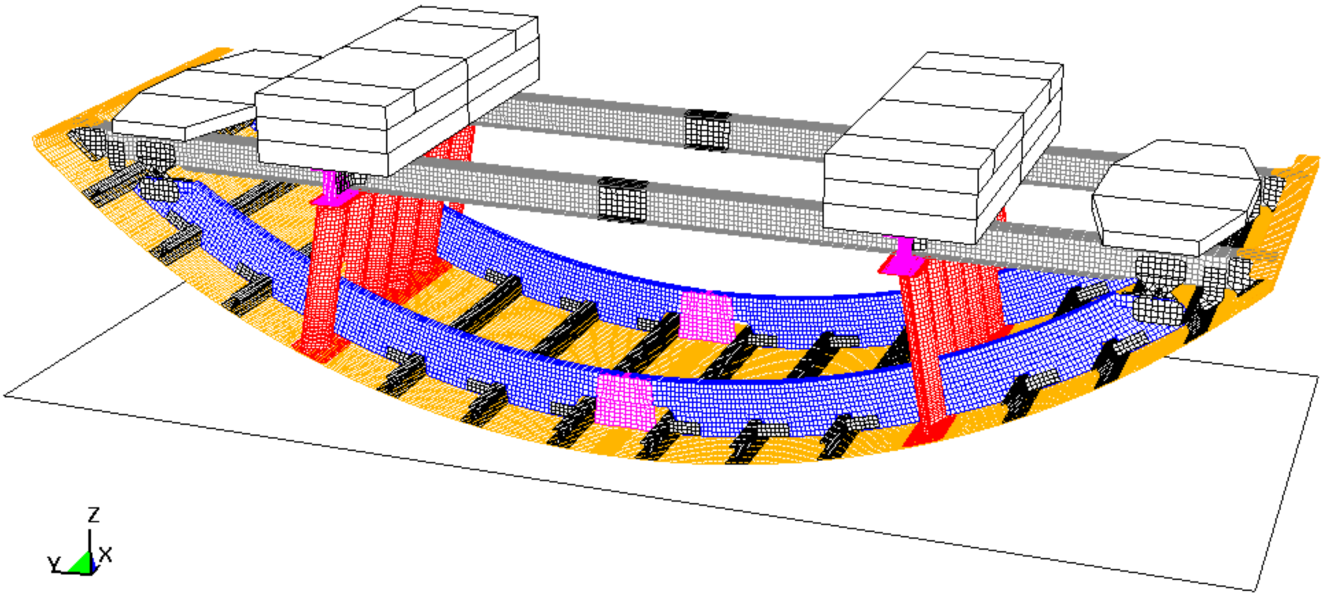

Fig. 12 Commuter FEM model for numerical simulations (CASA)

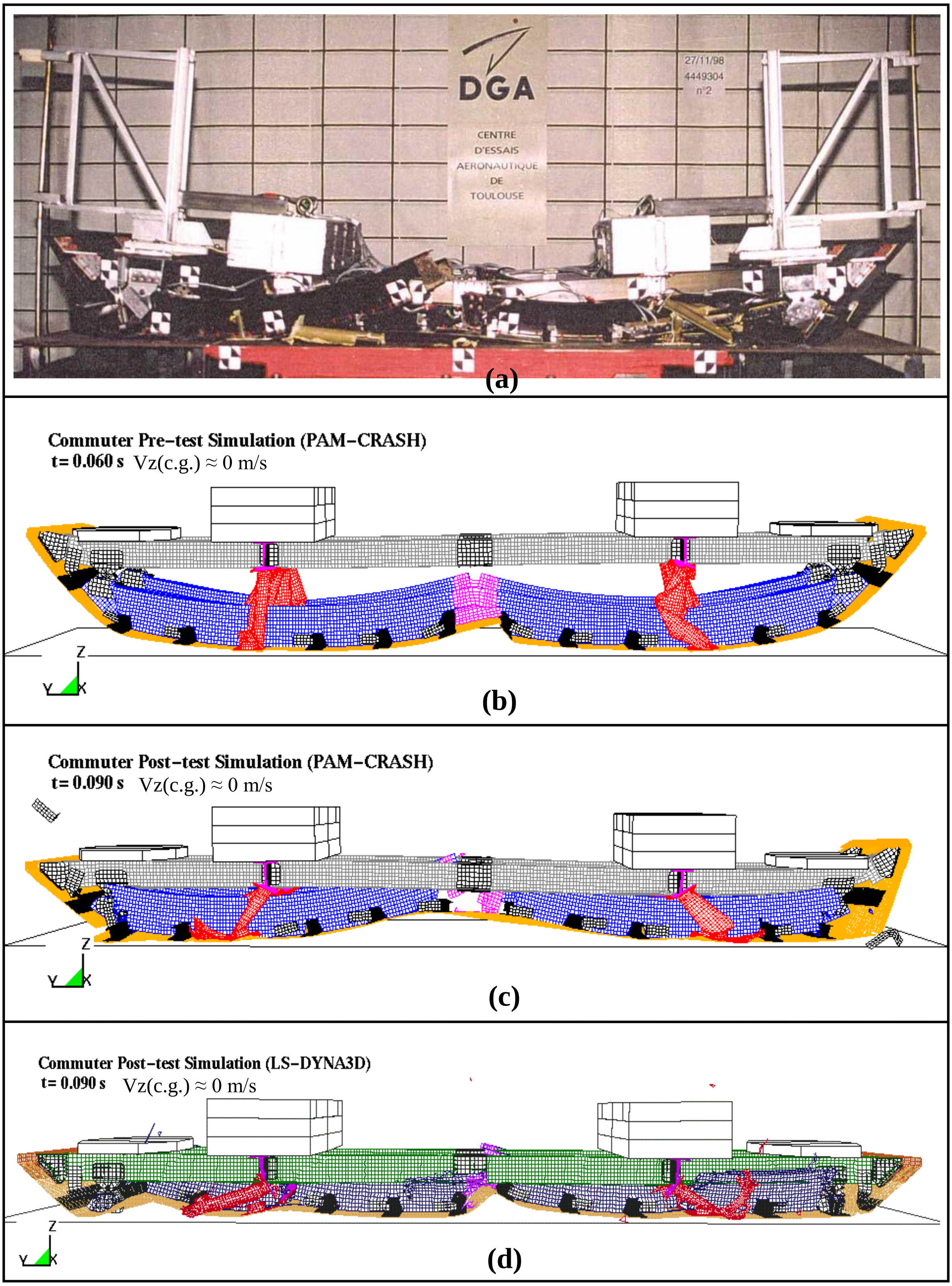

Fig. 13 Test/simulations comparisons of defomred shape at total vertical speed equal zero (CASA)

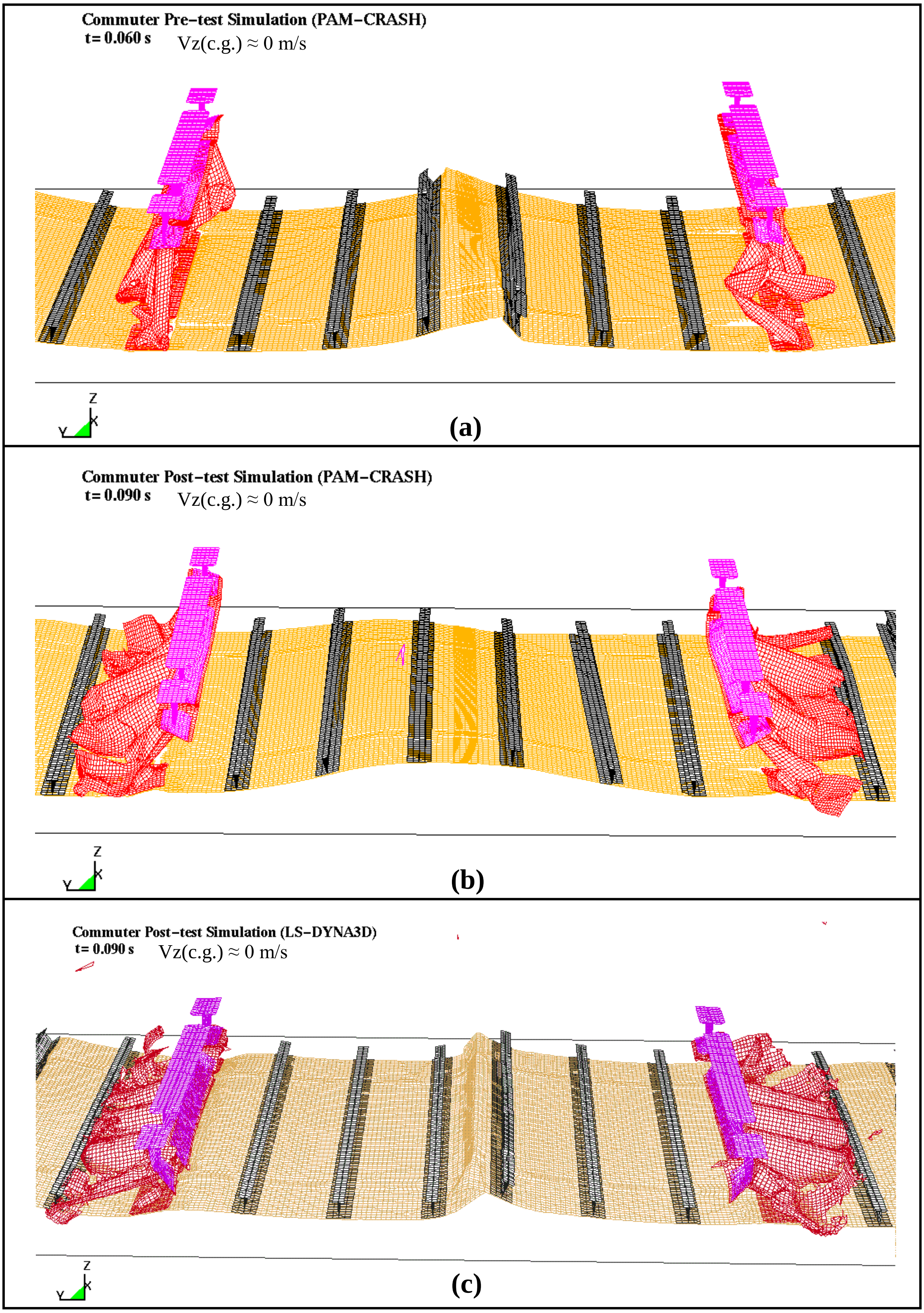

Fig. 14 Detail of SWB deformed shape at total vertical speed equal aero (CASA)