



**The Kinematics Model –
A Numerical Method for the Development
of a Crashworthy Composite Fuselage Design of Transport Aircraft**

M. Waimer^{*)} • D. Kohlgrüber^{*)} • Dr. D. Hachenberg^{**)} • Prof. Dr. H. Voggenreiter^{*)}

^{*)} *German Aerospace Center (DLR), Institute of Structures and Design, 70569 Stuttgart, Germany*

^{**)} *Airbus Operations GmbH, Numerical Simulation Development, Hamburg, Germany*

Abstract

Crashworthiness research for transport aircraft fuselage structures is important particularly with regard to the increasing ratio of CFRP in primary structures. Whereas today's aluminium fuselage structures offer sufficient crashworthiness purely due to the ductile behaviour of metal, the brittle behaviour of a CFRP fuselage structure implicates the need of special crash devices to take advantage of the high specific energy absorption capacity of CFRP material.

Certification rules for new aircraft with CFRP fuselage (incl. special conditions) demand a crashworthiness to be equivalent to that of a certified aircraft with a fuselage of similar size, usually made of aluminium alloys. To comply with these certification rules a specific crash design has to be developed for a CFRP fuselage structure. This involves the definition of trigger mechanisms, energy absorbing devices and their positioning in the fuselage and may lead to a mass increase of the structure compared to a design considering purely the other ground and flight loads.

The basis for the definition of the structural crash devices is a crash scenario assessment on fuselage section level. This approach considers a crash velocity purely in vertical direction. This simplified crash condition was selected to perform most of the previously performed crash tests on metallic fuselage structures and represents the basis for current certification routes.

For the numerical assessment of crash scenarios on section level a Kinematics Model was developed based on explicit finite element method and implemented in commercial tools. The essential of this Kinematics Model is the potential to define the behaviour of structural crash devices by characteristic input curves using macro elements in the frames, vertical struts and the sub-cargo structure. By varying the load-deformation characteristics of the regarded crash devices different crash scenarios can be defined, assessed and compared to each other.

Different potential crash scenarios for narrow-body fuselage structures were analysed using this modelling approach. Based on the finally selected crash scenario a pre-sized composite fuselage structure was re-sized to minimize the crash loads on passengers and structure and in subsequent second step to minimize the mass penalty.

1. Introduction

The increasing ratio of CFRP material used in primary structures of transport aircraft requires high efforts to define a crashworthy design. The brittle behaviour of CFRP material is still a challenge with respect to the crashworthiness of an aircraft structure. Special conditions demand a safety level of fuselage structures made of CFRP which has to be equivalent to that of certified aircraft which are traditionally made of metallic materials [31]. The basis for this comparison are several droptests of metallic fuselage sections which were

performed in the last decades by FAA and NASA, as well as in the scope of projects funded by the EC [1-16]. These droptests of today's fuselage structures represent the metallic equivalent. The motivation is to achieve in future CFRP fuselage structures the same level of crashworthiness as observed in these droptests.

One strategy to achieve the required level of safety for CFRP fuselages is the development of additional crash devices which are installed in the fuselage structure to control the sequence of the crash scenario and to absorb sufficient kinetic energy. Figure 1 illustrates examples of potential crash devices for individual installation areas. In the sub-cargo area, crushable elements made of CFRP could be a lightweight design solution. In a progressive crushing process a high mass-specific energy absorption can be achieved [20]. In the lower side shell, between cargo-crossbeam and the vertical support struts, the frames shall participate to provide sufficient crashworthiness. Especially with regard to single isle aircraft, the frames in the lower side shell play a major role as the crash distance influenced by the frames is obviously higher compared to the crash distance of the sub-cargo area. One potential design solution is the usage of hybrid laminas in the frame structure. The combination of CFRP and Titanium plies in the frame lamina is one design example, which is shown in Figure 1 and documented in [21]. Such a hybrid frame design could provide energy absorption in a frame bending process beyond the CFRP failure limit. Finally, the vertical support struts can be designed to install additional crash devices which absorb energy. One exemplary solution with a cutting and crushing device in the vertical CFRP struts is presented in [22].

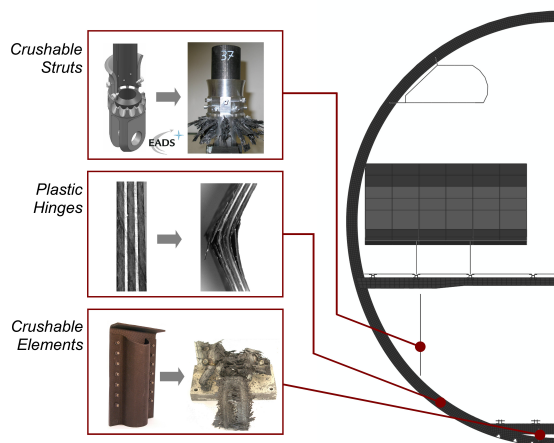


Figure 1: Potential design concepts of crash devices in a crashworthy CFRP fuselage

Based on design concepts of potential crash devices mentioned above the questions which have to be answered are: How to design these crash devices? What is the correct amount of energy which has to be absorbed in the individual device and how can the optimized trigger level be defined?

To achieve a crashworthy design all crash devices have to fulfil two different requirements. Firstly, they have to provide sufficient capacity for absorption of the kinetic energy. Secondly, they have to ensure a controlled crash scenario. This can be realised by a cascading scenario starting with failure and energy absorption in the sub-cargo area and progressing stepwise by the activation of other crash devices during the crash sequence. The activation of the individual crash devices has to be defined in such a way, that a cascading scenario is ensured. This includes the adequate definition of trigger loads to activate a crash device and to limit the load transfer in the energy absorption phase to prevent the activation/ triggering of the 'next-level' crash device.

The definition of adequate trigger loads and absorption levels of the individual crash devices can be supported by a numerical investigation on fuselage section level. As done in several previous studies on aircraft crashworthiness, only the vertical component has to be considered here.

2. Modelling approach of the Kinematics Model

Different modelling approaches can be used to investigate the design of crash devices on fuselage section level.

Hybrid codes, e.g. DRI-KRASH, are efficient to analyse such problems. Beam elements, bars and lumped masses are used here to represent the fuselage structure. Failure is described using macro elements. With respect to the design of crash devices this modelling approach is advantageous as the required characteristic of the individual crash device can be defined directly by the macro input. The main disadvantage of this approach is its coarse level of discretization. Detailed conclusions about the structural behaviour are hardly possible as several structural parts are not modelled in detail. For example, the interaction of frame and skin has a significant influence on the frame failure behaviour. In hybrid codes, the skin is smeared in the beam

elements, hence this effect can hardly be analysed.

In contrast to hybrid codes, the modelling approach of detailed finite element methods offers the possibility of detailed analyses of structural effects. Here, the structure as well as the material characteristic is modelled very detailed. Therefore, the analysis of local effects such as the interaction of frame and skin or local buckling behaviour are standard procedures. However, the detailed modelling approach implicates also disadvantages. To represent the fuselage structure in sufficient detail a large amount of data is necessary to build up the model. As the crash aspect is analysed typically in the preliminary design phase of an aircraft development, these detailed data are partly not available. Assumptions can be used for missing data, but finally these details may have an important influence in some crash events and have to be considered as critical. In addition, the detailed FEM approach uses material formulations for CFRP which are still under development and not fully predictive. The results of such analysis will have a significant level of uncertainty, especially due to the absence of tests which can be used to verify the numerical results of such a complex crash scenario. Finally the detailed FEM approach in a narrower sense does not offer the possibility of macro input, as all damage and failure is described by material formulations in combination with the fine mesh representation. The required behaviour of the crash devices can not be defined in macro elements but have to be modelled in very detailed local models.

Based on the benefits and drawbacks of the modelling approaches discussed above a new modelling approach was developed. This so-called Kinematics Model is based on the commercially available explicit finite element method and aims to combine some advantages of hybrid code and detailed FEM. In this approach macro input enables the characterisation of the individual crash devices. On the one hand, this modelling is detailed enough to represent important structural effects. On the other hand, the modelling is as course as possible to avoid the need of data which is not available in a preliminary design phase. In addition, the courser level of modelling compared to detailed FEM reduces the calculation time and therefore increases the model efficiency. As a consequence of the modelling approach the fuselage structure is modelled using mainly

linear-elastic material characteristics. Uncertainties caused by damage and failure representation of CFRP material models are not existent in this approach. The danger of failure in the fuselage structure apart from the crash devices is assessed by the observation of local strains.

In the following, the modelling approach is illustrated in more detail. As already discussed, a well defined crash scenario for a CFRP fuselage structure allows the occurrence of failure exclusively in the crash devices. The surrounding structure has to remain undamaged. Otherwise uncontrolled failure of the brittle structure could lead to the loss of any structural integrity. Figure 2 illustrates this approach. The macro elements representing all failure in the model are highlighted in red colour. The remaining fuselage structure which is modelled linear-elastically is marked in green colour.

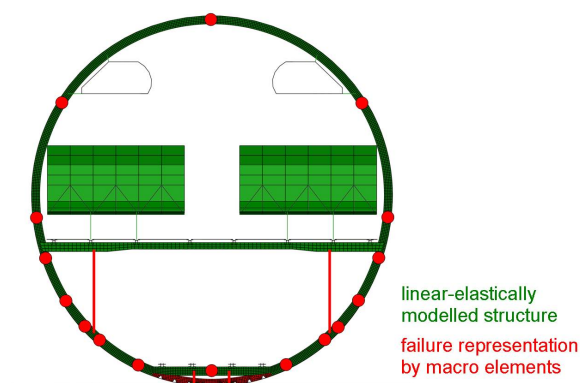


Figure 2: Modelling approach of the Kinematics Model

Based on the linear-elastically modelled structure an increased element size can be used for the representation of the fuselage structure. Additional model efficiency is obtained by a comparatively course model representation, stringers are modelled using beam elements and local details such as mouseholes, clips and cleats are not modelled.

One exception in this approach is the sub-cargo area. Here, complex crushing of the structure is expected which does not allow the distinction between crash devices and a surrounding structure which has to remain undamaged. Therefore, detailed FEM is used in this sub-cargo area to allow crushing of the structure and to avoid kinematic constraints which would occur in a linear-elastically modelled sub-cargo structure. Nevertheless, the main characteristic of the sub-cargo area is described by macro elements which represent

the crash absorber devices. Detailed FEM is used only for the additional parts of the sub-cargo area, such as frame and skin. The framework is described by macro elements.

3. Macro representation of crash devices

The macro elements are the central members of the Kinematics Model. They represent the main crash behaviour of the structure. An accurate modelling to represent realistic failure is of primary importance. Different macro architectures were developed to be used in the Kinematics Model to represent different structural failures respectively different energy absorbing mechanisms.

The first macro type offers an axial architecture which absorbs energy in a crushing process. This type represents the crash devices in the sub-cargo area as well as

in the vertical support struts. Although the energy absorbing concepts may be different, as illustrated in Figure 1, the absorbing kinematic is similar and can be described with the same macro architecture. In the Kinematics Model based on the explicit code ABAQUS/Explicit, a ‘connector’ element is used as macro element. The absorber characteristic can be defined using a force-deflection curve, as shown in Figure 3. In this exemplary force-deflection graph brittle behaviour is defined in tension. In compression the remaining force plateau after triggering implicates energy absorption by a stable crushing process. The connection of this macro element to the fuselage structure can be modelled either as fixed or articulated and is realised using rigid bodies.

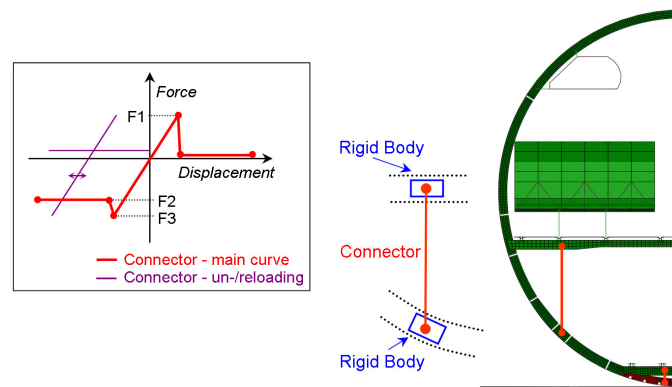


Figure 3: Macro architecture of axial crash absorber

Compared to the axial crash absorber, the second macro type is more complex. Here, energy is absorbed in a rotational motion of so-called ‘kinematic hinges’ that represent bending failure of the frame in combination with the skin. Similar to the axial macro architecture, connector elements are used in ABAQUS/Explicit. The input format for description of the frame failure characteristic is a moment-rotation curve, which is illustrated

in Figure 4. The exemplary graph shows brittle failure behaviour for an opening hinge rotation. Different moment plateaus for a closing hinge rotation represent the energy absorption capability of this frame failure characteristic. ‘Opening’ defines here a frame bending with a tensile loaded inner frame flange. Hence, a ‘closing’ hinge corresponds to frame bending with an inner frame flange loaded in compression.

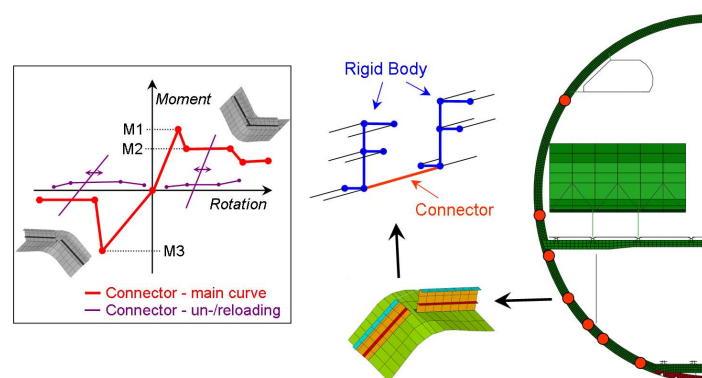


Figure 4: Macro architecture of rotational crash absorber

4. Detailed investigation of the macro representation of frame failure

An accurate representation of typical frame failure mechanism has to be guaranteed by the macro architecture. As this failure mechanism is generally complex, several detailed investigations were performed to check the kinematic hinge representation. Full FEM as well as experimental results from documented test programs were used for this study. In the following this investigation is discussed in more detail.

4.1 Positioning of the kinematics hinges

In a first investigation, the positioning of the kinematic hinges along the frame was analysed. In contrast to the axial absorbers, which represents explicitly local crash devices, frame failure could occur along the whole frame. Hence, frame failure behaviour of a typical fuselage structure has to be investigated

to finally define potential frame failure locations.

Typical failure locations can be identified by evaluating the frame failure behaviour of fuselage section droptests performed in several projects in the past [1-19]. Valuable results were also obtained by several tests on frame components [23-26]. An additional method is required to analyse all potential frame failure locations, especially for an individual fuselage design. This was realised modelling the fuselage structure in a first step without any kinematic hinge. The strain distribution along the frame gives valuable information about the probability of potential frame failure at individual time. Figure 5 presents such a strain distribution in an early phase of a crash. The local strain maxima and minima in the frame inner and outer flanges indicate locations of potential closing respectively opening frame failure. Therefore, the kinematic hinge macros were positioned at these indicated locations.

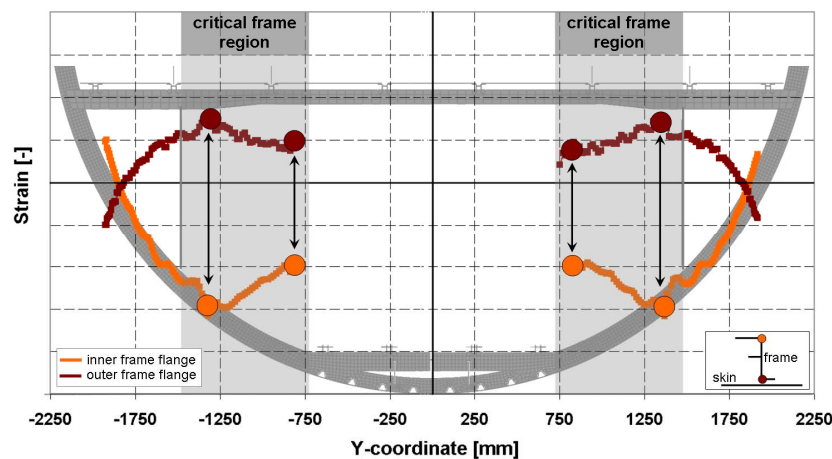


Figure 5: Strain distribution along the frame indicates potential frame failure locations

4.2 Elastic behaviour

In a further investigation, the elastic behaviour of a skin-stringer-frame model was analysed. This investigation was performed using full FEM. A wide range of typical LCF-frame profiles was considered. Frame flange thicknesses between $t_{\min}=2.5\text{mm}$ and $t_{\max}=9\text{mm}$ as well as frame heights from $H_{\min}=90\text{mm}$ to $H_{\max}=120\text{mm}$ were analysed. The focal point of this investigation was the shift of the neutral axis in dependence of the frame cross section. Based on the identification of this elastic behaviour a general trigger criterion for the kinematic hinge was derived.

Figure 6 demonstrates the shift of strain distributions in the LCF-frame profile depending on different cross section areas. The

increased frame stiffness, realised by an increased layup, shifts the neutral axis to a position near the middle frame flange, Figure 6a). In contrast to this, the neutral axis is close to the skin with a filigree frame design, Figure 6b). In the whole range of LCF-frame profiles the inner frame flange was identified to be the most critical location. The graphs in Figure 6 illustrate this for a closing hinge rotation. This outcome can be used to define trigger criteria of a kinematic hinge based on the frame inner flange strain.

In addition, the frame inner flange strain can be used in the remaining frame structure, which is modelled linear-elastically, to check for potential strain exceeding during a crash

event. This would indicate potential failure

besides of the kinematics hinges.

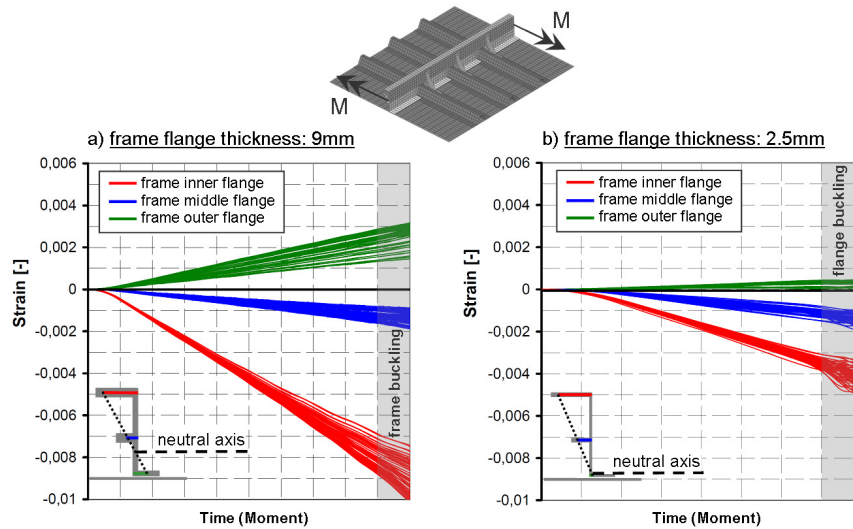


Figure 6: Investigation on the elastic behaviour of a skin-stringer-frame model

4.3 Post-failure behaviour

The post-failure behaviour of a skin-stringer-frame structure is of high interest. Investigations were performed to identify typical hinge kinematics and to adapt these kinematics to the hinge macro architecture. Experimental results of several well documented test programs were evaluated to identify kinematic tendencies based on a wide range of frame structures [4-8, 11, 14-18, 23-28].

The investigation of the elastic behaviour already exemplified the influence of the skin. In the elastic phase up to failure the neutral axis is generally between the skin and the middle flange of a LCF frame, depending on the share of frame and skin cross sectional area. After failure initiation, the frame stiffness is reduced and subsequently the pivot point of frame bending shifts to the skin plane. Finally, with continuing failure of the frame and potential rupture the skin is the integrity part of the fuselage shell structure. With respect to this hinge kinematics a similar behaviour was observed for metallic structures (Fig. 7c)+d)) as well as for CFRP structures (Fig. 7a)+b)).

This behaviour was considered in the hinge macro architecture. The macro element is positioned in the skin plane. The connection to the frame structure is modelled using rigid bodies. Figure 7 compares the bending behaviour of different frame structures with the Kinematics Model hinge architecture.

As an assumption for the numerical study rivet and bonding failure between frame and skin are not considered in the representation of the

post-failure behaviour of a skin-stringer-frame structure. Hence, potential separation of frame and skin can not be represented. The separation was not foreseen in the kinematics hinge architecture as such separation could lead to an uncontrollable progression of the crash scenario and has to be avoided to obtain a robust crash design.

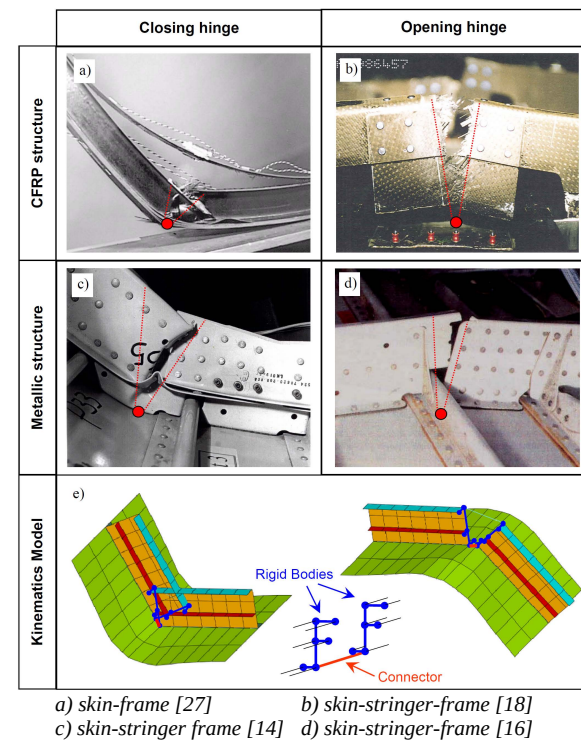


Figure 7: Hinge kinematics of a typical (skin-stringer-) frame structure

4.4 Modelling simplifications

Further detailed investigations were conducted to analyse the influence of modelling

simplifications on the accuracy of the structural skin-stringer-frame behaviour. The approach to model the fuselage structure linear-elastically enables the usage of a coarse FE mesh and accordingly results in a reduced calculation time. In this investigation the Kinematics Model approach was compared to a full FEM model.

As an outcome of this work, the coarser modelling of the Kinematics Model was defined in a way to reduce the loss of accuracy to a minimum. For example, the number of elements along the flange width is a parameter which was adapted to achieve sufficient accuracy. Based on the linear shape function of typical shell elements used in explicit codes a

minimum number of elements is necessary to represent potential buckling modes. Figure 8 compares the strains along the inner frame flange of Kinematics Model and full FEM model under pure bending condition. The graph shows similar linear-elastic behaviour of both models. With respect to the initiation of instabilities, local buckling of the inner frame flange, a small difference is observable. This difference of $\Delta\epsilon < 0.1\%$ can be accepted in a preliminary design phase. The increase of model efficiency with the price of marginally reduced accuracy is reasonable in this case, especially because empirical crippling criteria are used to represent the strain limit values.

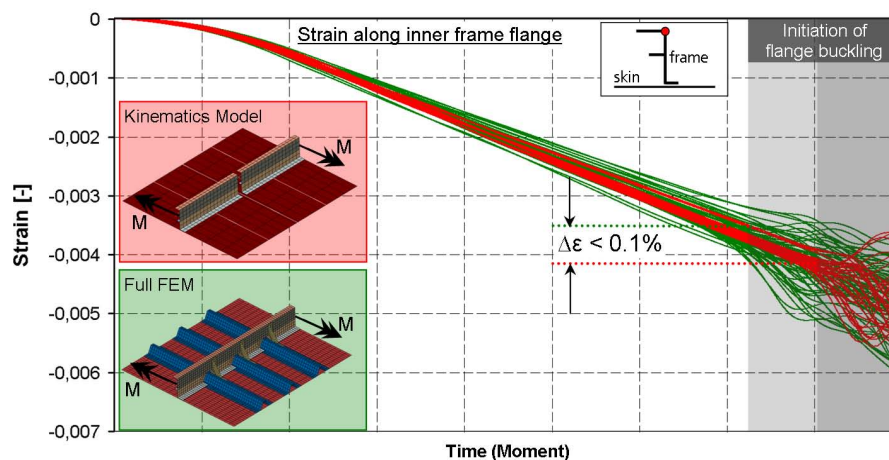


Figure 8: Accuracy of Kinematics Model compared to full FEM model

4.5 Lateral frame stability

Lateral frame stability is a further point which has to be discussed. In a typical fuselage structure cleats support the frame and prevent lateral frame buckling under typical crash loads which include high compression and bending.

The Kinematics Model does not provide the modelling of cleats as this detailed design is typically not available in a preliminary design phase. The neglect of lateral frame support may lead to an over-dimensioned frame design. At least, lateral support has to be defined at several locations along the frame to prevent an over-sizing of the frame structure.

Here, the kinematic hinge architecture is used to provide lateral frame support. The macro elements in the hinge architecture are connected to the surrounding frame structure using rigid bodies. These rigid bodies have a stiffening effect which provides lateral support in a way comparable to that provided by cleats. The influence of different lateral supports on

the lateral frame buckling behaviour was analysed under typical crash loads. Figure 9 illustrates the strains along the inner frame flange in the critical region between cargo-crossbeam and vertical support strut. Without lateral support, the strain distribution clearly indicates lateral frame buckling. In contrast to this, the variants with cleat support at each stringer position and the Kinematics Model show similar results. Although the lateral stiffness in the Kinematics Model is slightly reduced compared to the variant with the cleat support at each stringer, the strain distributions do not indicate extensive lateral buckling in both variants.

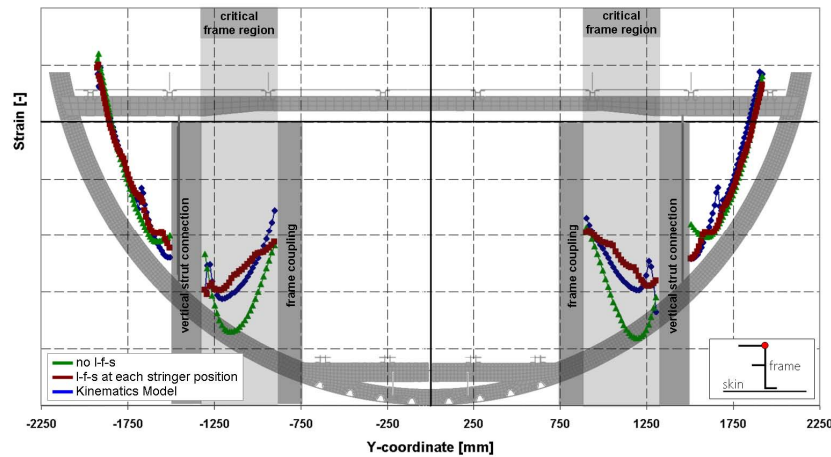


Figure 9: Influence of different lateral frame supports (l-f-s) on lateral frame buckling

4.6 Influence of loading conditions

Finally, the kinematic hinge architecture was verified against the influence of different loading conditions. The typical load in a frame during a crash event is a combination of bending and compression. The acting bending-compression ratio strongly depends on the frame location in the fuselage as well as on the crash phase. For that reason, the behaviour of the kinematic hinge architecture was analysed under different bending-compression ratios to ensure accurate hinge representation for different loading conditions.

Currently, the characteristic of the kinematic hinge is described purely by a moment-rotation relation. Discrepancies are expected in case of increased compression loads. Figure 10 illustrates this relation and compares the strains along the inner frame flange. In case of pure bending load the inner flange strain of the hinge and the remaining structure corresponds very well, Figure 10a). In contrast to this,

slight discrepancies can be observed for low bending-compression ratios, Figure 10b). Here, the elastic behaviour in frame normal direction is not accurately represented in the kinematic hinge. This discrepancy can lead to early initiation (triggering) of the kinematic hinge.

However, low values of the moment-compression ratio as presented in Figure 10b, are reached only in very few crash phases. One example is the impact of the vertical support struts on the ground at a late state of a crash sequence, which can induce high compression peaks. To guarantee accurate hinge macro behaviour in such cases an advanced hinge architecture is under development. In this advanced version, the macro element will be represented by a user programmed element (VUEL). Additional input characteristics in frame normal direction as well as a trigger criterion based on inner flange strains shall ensure correct hinge representation under all loading conditions.

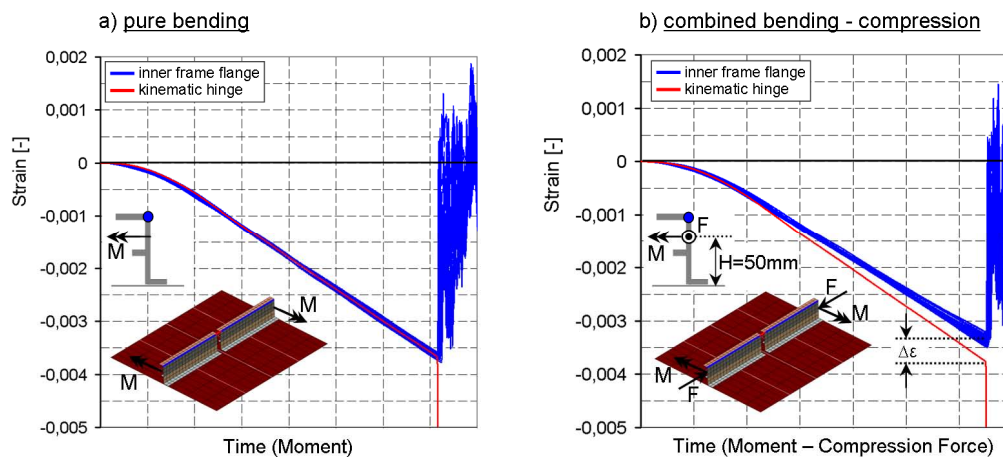


Figure 10: Influence of different loading conditions on the kinematic hinge accuracy

The detailed investigations presented above verified the developed modelling approach for the kinematic hinge macros. Sufficient precision with respect to a preliminary design tool could be demonstrated. In addition, potential deficits were identified and improvements were presented.

In the following, an exemplary crash design process is discussed which uses the Kinematics Model.

5. Crash design process using the Kinematics Model

The crash design process is demonstrated here exemplarily based on a generic CFRP structure of a single-aisle transport aircraft fuselage with a LCF frame design.

The final target of this design process is the characterisation of the crash devices in a way that an optimized crash kinematics leads to reduced loads acting on passengers and fuselage structure and in a following step to a reduced structural mass.

In a first step the optimum crash kinematics solution was identified for the considered fuselage design. A crash scenario assessment was performed to determine all aspects of different crash scenarios. Generally, a lightweight design solution of a crash concept aligns to the natural crash kinematics of a fuselage structure. Consequently, it is important to understand the natural crash behaviour. All attempts to achieve a crash kinematics differing from the natural structural behaviour will lead to additional weight penalty. In the past, several tests of fuselage structures were performed with respect to crash relevant loads. Fuselage section droptests performed in the last decades give valuable information about the natural crash kinematics of typical fuselage structures. In addition, several tests of structural components, such as frames or fuselage shells, provide useful data, too. Based on this wide range of test results two general crash kinematics of typical fuselage structures could be identified. Figure 11 illustrates both kinematics and compares the schematic scenarios with test results from documented droptests. Parameters like the stiffness of passenger- and cargo-crossbeam as well as different loading conditions influence the formation of the natural kinematics.

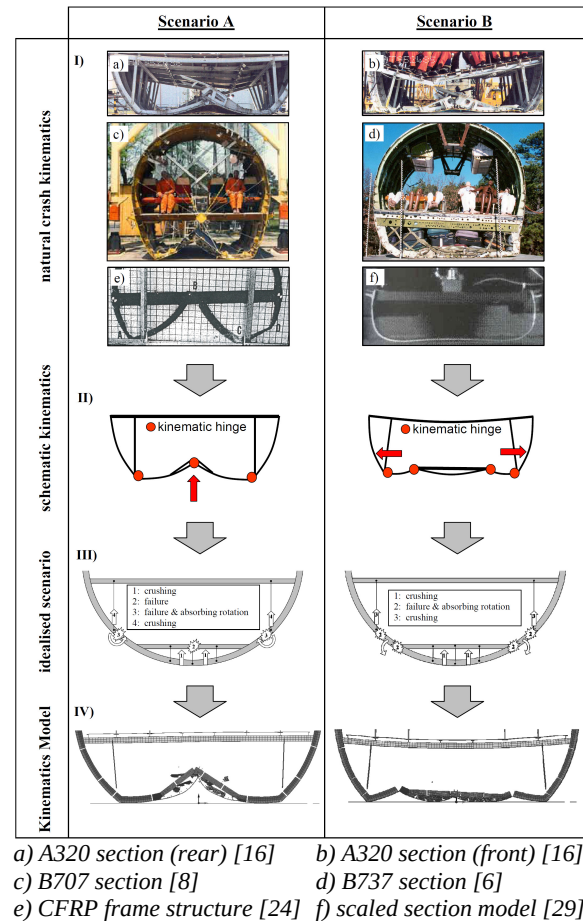


Figure 11: Natural crash kinematics

Regarding the assessment of both natural crash kinematics, idealised crash scenarios were defined on the basis of a pre-sized CFRP fuselage structure. An additional crash concept was used here which specifies a stiff cargo-crossbeam to provide sufficient support for the crushing of the sub-cargo structure in a first crash phase. Both idealised scenarios are illustrated in Figure 11 III). After the first crash phase, where energy is absorbed by crushing absorbers below the cargo-crossbeam, scenario A specifies failure of the cargo-crossbeam which initiates the characteristic unrolling of the lower fuselage shell. Following, frame failure is initiated close to the vertical support struts and energy is absorbed in a bending process. In this second crash phase, scenario B does not specify failure of the cargo-crossbeam. Without failure in this crossbeam the flattening effect of the lower fuselage shell is initiated. In scenario B, frame failure is specified close to the cargo-crossbeam as well as near the vertical support struts. Energy is absorbed in a frame bending process. Finally, in a third crash phase, additional energy absorption capacity is

defined for both scenarios in a crushing process of the vertical support struts.

The Kinematics Model used for the assessment of these scenarios was built up with axial macro architectures in the sub-cargo area and in the vertical support struts. Kinematic hinge architectures were positioned at several locations, representing the crash devices in frame and cargo-crossbeam. The development of both scenarios with the Kinematics Model was conducted only by modification of the input characteristics of the macro elements. The realised scenarios from the numerical simulations are presented in Figure 11 IV). In this Figure only the sub-floor area of the Kinematics Model is illustrated. The simulation results of the Kinematics Model analysis gave valuable information about the advantages and drawbacks of both crash scenarios. Assessment criteria like passenger accelerations or structural loads were analysed.

In addition, criteria regarding the crash devices were assessed. For example, the maximum rotation angle of the kinematic hinges depends strongly on the crash scenario. This value is important for the development of such devices. High rotation angles in the frames will increase the complexity of absorbing concepts. Therefore a crash scenario with minimum frame rotation is preferred with respect to this assessment criterion.

Further structural effects were analysed. For instance, the assessment identified critical tensile loads in the vertical support struts in scenario B. These tensile loads are caused by the flattening effect of the lower fuselage shell and may complicate the development of an appropriate trigger mechanism in the crash device of the vertical support struts.

Finally, some practical effects were considered, such as the influence of cargo loading. In case of container or bulk loading high interaction is expected in scenario A. The constrained unrolling of the lower fuselage shell could lead to a switch of the crash

scenario with a flattening of the lower fuselage part.

The verification of the scenario assessment results provides a good basis for the further proceeding in the crash design process.

In the following paragraphs, the crash concept development is discussed for scenario A.

Based on the selected crash scenario, the following crash design study was performed starting with a stiff and heavy frame design and reducing this frame design by optimisation of the crash loads. Starting from a frame design with large cross sections avoids the occurrence of extensive instabilities during the optimisation process.

Detailed specifications were considered in this further crash design phase. As one example, the idealised scenario was specified in a way that the vertical support struts shall stay passive (not participate to the energy absorption) for a standard drop case with a vertical initial velocity of $v_0=22\text{ft/s}$. Further energy absorbing capacity was provided in the vertical support struts for higher energetic crash cases or critical robustness cases, such as drop cases with small initial roll conditions or unsymmetrical loading. With this specification, all kinetic energy has to be stored elastically in the structure or absorbed by the crash absorbers in the sub-cargo area as well as by the crash devices in the frames.

In the following procedure, adaptations of the macro input characteristics were performed to optimise the crash scenario. The targets of this optimisation were on one hand to end the standard crash scenario shortly before the impact of the vertical support struts on the ground. On the other hand, the optimisation target was to achieve constant crash loads over the whole crash distance which implicates minimised loads acting on the structure and the passengers. Figure 12 shows the crash sequence of this optimised crash scenario. The crash event ends with the ground contact of the vertical support struts.

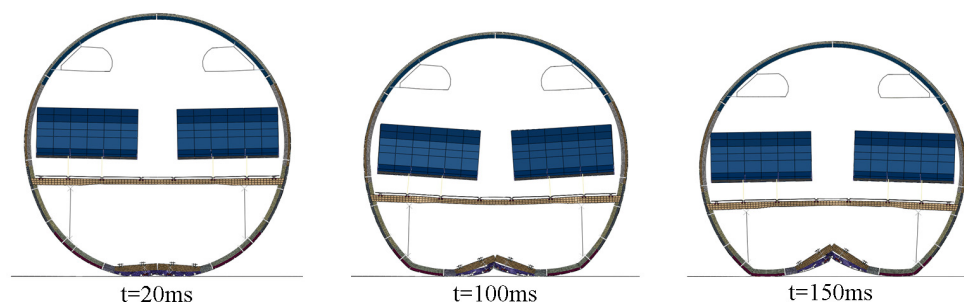


Figure 12: Crash sequence of optimised scenario

Based on the strains measured at the most critical frame inner flange, the reserve factors (RF) of the heavy initial frame profile distribution were analysed. According to these reserve factors the frame cross sectional profiles were reduced and adapted to the maximum crash loads of the individual frame regions. With respect to the initial frame design of the starting configuration the structural mass of the frame could be reduced significantly. Nevertheless, the structural mass

of this crashworthy design is still higher compared to the initially, statically pre-sized frame structure. This outcome shows that crash aspects affect the frame design and therefore the crash design should be considered already in the early design phase. Figure 13 illustrates the identification of the frame reserve factors and the determination of the required frame profile distribution. This frame distribution is the proposal for the final crash design which is used in the detailed design phase.

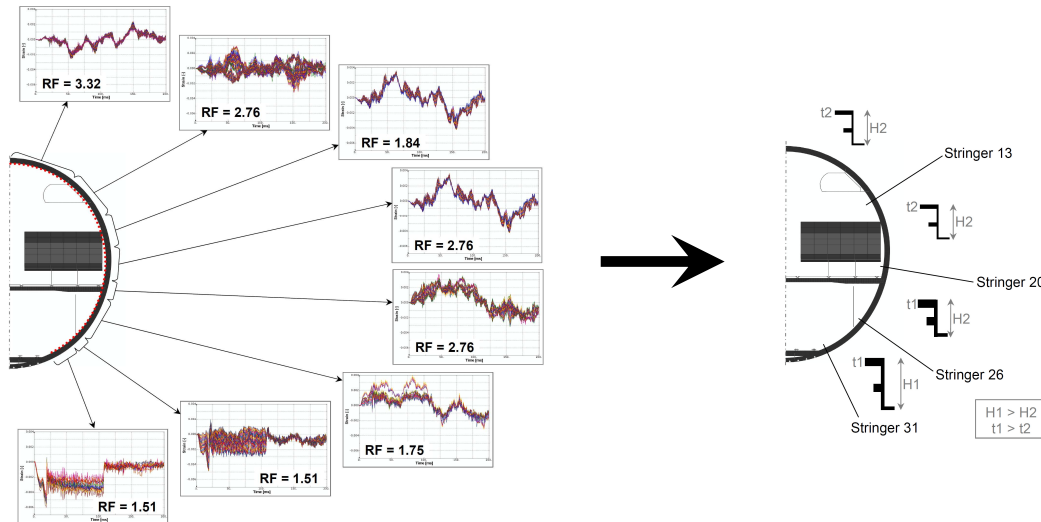


Figure 13: Determination of final frame profile distribution

Two different main criteria were used to evaluate the final crash design. The first main criterion is the evaluation of the passenger loads. In the Kinematics Model a simplified seat-passenger model is used which represents the passenger with a single mass element. Different connector elements between the passenger mass and seat structure represent the seat cushion stiffness and the harness system.

For that reason a whole-body tolerance criterion is used to evaluate the passenger loads, the Eiband curves [30]. This criterion is valid as the passengers typically experience one-dimensional loads in a droptest. Figure 14 displays the passenger accelerations of one seat-row in the Eiband chart. All six curves (PAX A-F) are located clearly below the limit of severe injuries.

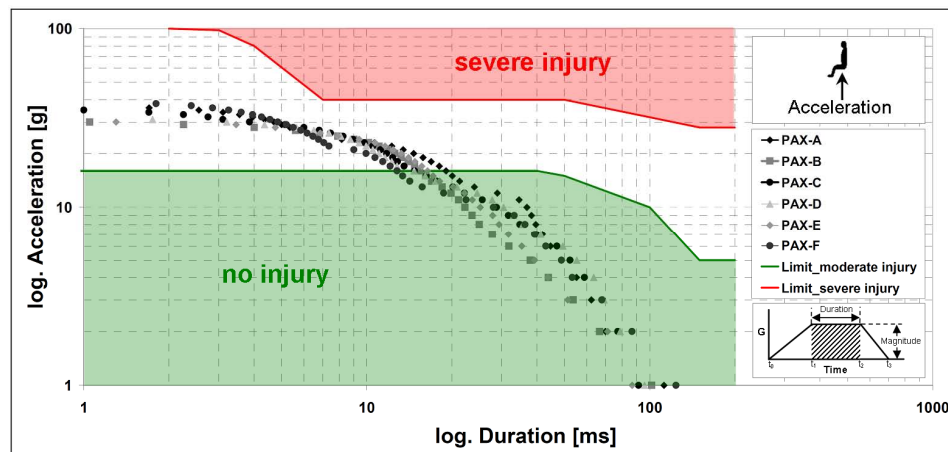


Figure 14: Passenger loads in the Eiband diagram

The second main criterion for the evaluation of the final crash design are the structural loads, more precisely the frame loads. These loads were evaluated using the calculated strains along the frame inner flange. Figure 15 gives an overview of the frame loads over the crash duration. All strain values along the critical frame region between cargo-crossbeam and vertical support strut are displayed in this chart. On the one hand the curves show very clearly that no strain value exceeds the critical limit. Here, this limit is a crippling criterion of the inner frame flange. On the other hand, the strain values are very close to that strain limit, which implicates a well utilisation of the frame structure and therefore a good adaptation of the frame profiles to the optimised crash loads.

The chart in Figure 15 gives additional information about the structural frame loads in the individual crash phases. In the first phase, the crushing of the sub-cargo area, the strain values along the critical frame region increase up to the failure initiation of the kinematic hinges. After triggering of these kinematic hinges the strain values drop to a nearly constant level which is directly affected by the absorbing moment in the kinematic hinges. Finally, after the absorbing capacity of the kinematic hinges is used up the strain values decrease again. As different frame profiles are defined along the whole frame of the fuselage section this diagram has to be generated for each local frame region.

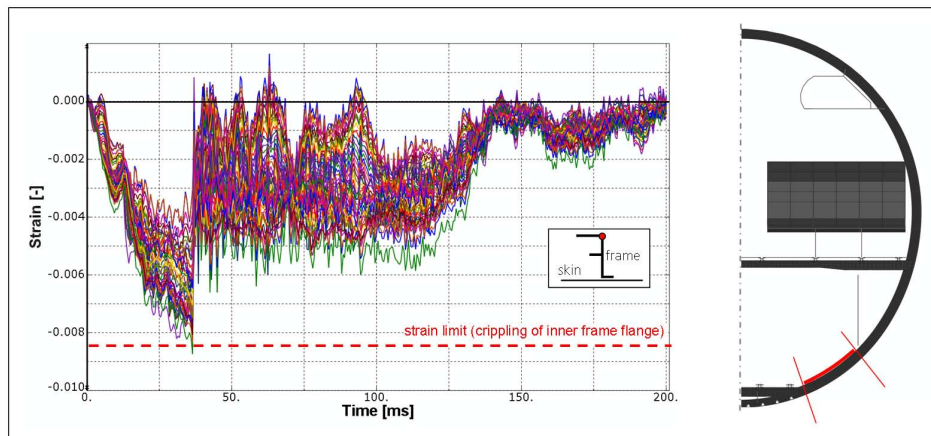


Figure 15: Structural loads in the frame

In the last step of this crash design phase the input characteristics of all macro elements were identified. These trigger loads and absorption levels provide the basis for development of local crash devices. On small component level the concept ideas can be developed to technically mature crash devices. Finally, they can be designed to fulfil the required trigger loads and absorption levels.

In Figure 16, the final input characteristics of the crushable elements and the kinematic hinges are illustrated exemplarily. On the right hand side of Figure 16, tested components of generic crash devices are pictured which potentially are sufficient to generate the desired characteristics.

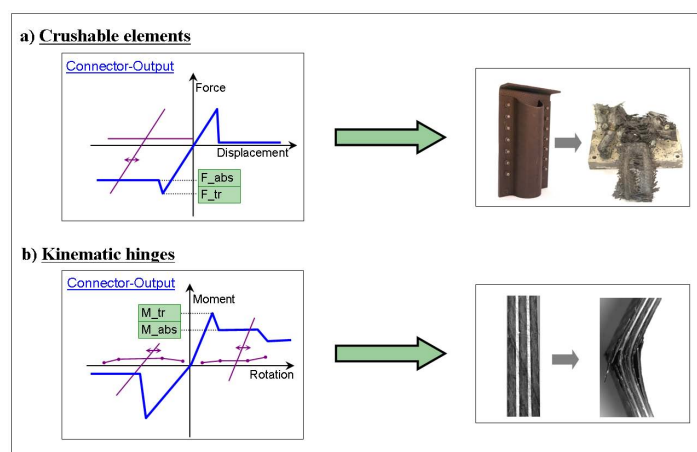


Figure 16: Identification of macro characteristics for crash device development

6. Summary

A new modelling approach, the Kinematics Model, was developed for the crash concept development in a preliminary design phase of new transport aircraft. This modelling approach is based on explicit finite element method in a commercial ABAQUS/ Explicit environment. The essential of the Kinematics Model is the potential to define the behaviour and interaction of structural crash devices by characteristic input curves using macro elements. The remaining fuselage structure is modelled linear-elastically.

Several investigations were performed to analyse the behaviour of structural components and to ensure an accurate modelling architecture representing the crash devices.

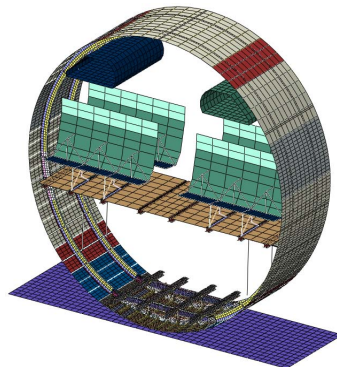
The design process using the Kinematics Model was demonstrated exemplarily. Starting with an assessment of different, typical crash

scenarios of fuselage structures a detailed crash design was developed based on a generic single-aisle CFRP fuselage structure. The crash scenario was optimised to reduce the crash loads. In a further step the critical fuselage structure, the frame, was adapted to the optimised crash loads. Finally, the developed crash concept was evaluated based on criteria for passenger loads and structural loads.

The adapted frame structure provides a crash related basis for the detailed design of the fuselage structure.

The final macro characteristics, which are the result of an inverse engineering approach, are the basis for the development and design of local crash devices.

The modelling approach and design process discussed in this paper demonstrates one solution to analyse crash aspects in a preliminary design phase.



References

- [1] McGuire, R.J.; Nissley, W.J.; Newcomb, J.E.: "Vertical Drop Test of a Metro III Aircraft"; FAA document DOT/FAA/CT-93/1; June 1993
- [2] McGuire, R.J.; Vu, T.: "Vertical Drop Test of a Beechcraft 1900C Airliner"; FAA document DOT/FAA/AR-96/119; May 1998
- [3] Abramowitz, A.; Ingraham, P.A.; McGuire, R.J.: "Vertical Drop Test of a Shorts 3-30 Airplane"; FAA document DOT/FAA/AR-99/87; November 1999
- [4] Abramowitz, A.; Smith, T.G.; Vu, T.; Zvanya, J.: "Vertical Drop Test of an ATR 42-300 Airplane"; FAA document DOT/FAA/AR-05/56; March 2006
- [5] Abramowitz, A.; Smith, T.G.; Vu, T.: "Vertical Drop Test of a Narrow-Body Transport Fuselage Section With a Conformable Auxiliary Fuel Tank Onboard"; FAA document DOT/FAA/AR-00/56; September 2000
- [6] Abramowitz, A.; Smith, T.G.; Vu, T.; Zvanya, J.R.: "Vertical Drop Test of a Narrow-Body Transport Fuselage Section With Overhead Stowage Bins"; FAA document DOT/FAA/AR-01/100; September 2002
- [7] Logue, T.V.; McGuire, R.J.; Reinhardt, J.W.; Vu, T.: "Vertical Drop Test of a Narrow-Body Fuselage Section with Overhead Stowage Bins and Auxiliary Fuel Tank on Board"; FAA document DOT/FAA/CT-94/116; April 1995
- [8] Williams, M.S.; Hayduk, R.J.: "Vertical Drop Test of a Transport Fuselage Section located Forward of the Wing", NASA Technical Memorandum TM 85679; August 1983
- [9] Williams, M.S.; Hayduk, R.J.: "Vertical Drop Test of a Transport Fuselage Center Section Including the Wheel Wells", NASA Technical Memorandum TM 85706, October 1983
- [10] Fasanella, E.L.; Alfaro-Bou, E.: "Vertical Drop Test of a Transport Fuselage Section located Aft of the Wing"; NASA Technical Memorandum TM 89025, September 1986
- [11] Johnson, D.; Wilson, A.: "Vertical Drop Test of a Transport Airframe Section"; FAA document DOT/FAA/CT-TN86/34; October 1986
- [12] FAA Technical Center: "B-707 Fuselage Drop Test Report"; Document of FAA Technical Center, Atlantic City Airport, N.J. 08405; March 1984
- [13] FAA Technical Center: "DC-10 Fuselage Drop Test Report"; Document of FAA Technical Center, Atlantic City Airport, N.J. 08405; September 1984
- [14] Hashemi, R.: "Sub-Component Dynamic Tests on an Airbus A320 Rear Fuselage"; Cranfield Impact Centre document of European project 'Crashworthiness for Commercial Aircraft'; December 1994
- [15] Hashemi, R.: "Sub-Component Quasi-Static Tests on an Airbus A320 Rear Fuselage"; Cranfield Impact Centre document of European project 'Crashworthiness for Commercial Aircraft'; March 1994
- [16] Le Page, F.; Carciente, R.: "A320 Fuselage Section Vertical Drop Test. Part 2 : Test Results"; CEAT test report N° S95 5776/2, European project 'Crashworthiness for Commercial Aircraft'; October 1995
- [17] Le Page, F.: "Results of the Airliner Sub-Passenger Floor Structure Drop Test"; CEAT test report N° S98/4449000 P5, European project 'CRASURV'; September 1997
- [18] Le Page, F.: "Results of the Commuter Sub-Passenger Floor Structure Drop Test"; CEAT test report N° S98/4449000 P3, European project 'CRASURV'; September 1997

- [19] Le Page, F.: "Results of the Airliner Sub-Cargo Floor Structure Drop Test"; CEAT test report N° S98/4449000 P1, European project 'CRASURV'; September 1997
- [20] Kindervater, C.M.; Georgi, H.: "Composite Strength and Energy Absorption as an Aspect of Structural Crash Resistance"; P.189-235 of 'Structural Crashworthiness and Failure'; Elsevier 1993
- [21] Wild, P.: "Untersuchung hybrider Werkstoffkombinationen zur Verbesserung des Crashverhaltens von Transportflugzeugen"; DLR report IB435-2009/18; April 2009
- [22] Heimbs, S.; Strobl, F.; Middendorf, P.; Guimard, J.M.: "Composite Crash Absorber for Aircraft Fuselage Applications"; Structures Under Shock and Impact XI, WIT Transactions on The Built Environment, Vol. 113; 2010
- [23] Carden, H.D.; Boitnott, R.L.; Fasanella, E.L.: „Behaviour of Composite/Metal Aircraft Structural Elements and Components Under Crash Type Loads – What Are They Telling Us?"; NASA Technical Memorandum TM 102681; May 1990
- [24] Boitnott, R.L., et al.: "Impact Response of Composite Fuselage Frames"; SAE Technical Paper 871009; April 1987
- [25] Boitnott, R.L.; Fasanella, E.L.: "Impact Evaluation of Composite Floor Sections"; SAE Technical Paper 891018; April 1989
- [26] Moas, E.; Boitnott, R.L.; Griffin, O.H.: "An Analytical and Experimental Investigation of the Response of the Curved, Composite Frame/Skin Specimens"; Journal of the American Helicopter Society; July 1994
- [27] Pérez, J.G.: "Energy Absorption and Progressive Failure Response of Composite Fuselage Frames"; Master thesis at Virginia Polytechnic Institute and State University; July 1999
- [28] Pilkington, L.O.: "Impact Response and Failure of a Textile Composite Fuselage Frame"; Master thesis at Virginia Polytechnic Institute and State University; July 2004
- [29] Meng, F.X., Zhou, Q., Yang, J.L.: "Improvement of Crashworthiness Behaviour for Simplified Structural Models of Aircraft Fuselage"; International Journal of Crashworthiness Vol. 14, No. 1, 83-97; January 2009
- [30] Eiband, A.M.: "Human Tolerance to Rapidely Applied Accelerations: A Summary of the Literature"; NASA Memorandum MEMO 5-19-59E; June 1959
- [31] Federal Aviation Administration: "Special Conditions: Boeing Model 787-8 Airplane; Crashworthiness"; US Federal Register, Vol. 72, No.111, Docket No. NM368 Special Conditions No. 25-07-05-SC; June 2007
- [32] Waimer, M.; Kohlgrüber, D.; Hachenberg, D.; Voggenreiter, H.: „Development of a Crashworthy Composite Fuselage Design Using a Kinematics Model"; EUCOMAS Conference Proceedings; June 2010