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# Integration of cabin environment into the aircraft crashworthiness assessment process

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**Abstract**
Passenger safety is a primary concern of non-conventional aircraft design, involving new safety problems to explore and strict regulation requirements. For these configurations, the crash load mitigation may affect the overall fuselage design, hence it must be considered from the earliest design phases. A multidisciplinary aircraft design process chain is established at the German Aerospace Center (DLR). This collaborative process, which includes plenty of DLR institutes, relies on the parametric CPACS data format to exchange models and results across disciplines and levels of detail. The Institute of Structures and Design actively contributes to the process chain with its Python tool PANDORA. This design environment can automatically generate CPACS-based aircraft Finite Element (FE) models, to perform structural analysis, crashworthiness assessment and sizing. In this paper, PANDORA is extended to generate automatic multi-fidelity fuselage FE models, including the cabin environment and dummies. As a result, the generation of a cabin based on CPACS geometric and structural data is rapidly achieved, enabling parametric crashworthiness studies of full aircraft models. Preliminary results, automatic injury criteria post-processing and validation benchmarks are presented to illustrate the novel methodology. The implementation aims to support the development of innovative aircraft concepts, allowing designers to consider occupant safety from the first design iterations. This is the first step towards establishing a process chain to tackle safety challenges of novel designs, such as zero-emission configurations or high-density cabins, in which the design space is yet to be explored and parametric analysis is of fundamental importance.

**Keywords** Fuselage crashworthiness · Occupant safety · FEM · Design process chain · CPACS · PANDORA

## 1 Introduction

Addressing environmental concerns is the top priority in the aviation industry agenda, alongside safety and security [1]. Ambitious goals have been set to reduce emissions connected to air transportation, aiming for net-zero CO2 emissions by 2050 [2].

Driven by the recent rise of interest in sustainable aviation, aircraft design is becoming increasingly complex, moving away from traditional designs in favour of greener solutions. The pursuit of carbon neutrality in aviation is paving the way for novel disruptive configurations across various fields of aeronautics. Hybrid-electric propulsion, unconventional high-efficiency wings, lighter materials, and the adoption of high-density cabin layouts, are among the trends indicative of this shifting landscape [3, 4].

Within this evolving context, the design of the fuselage presents significant challenges due to its substantial implications across several disciplines including structural design, cabin layout, industrialization, and human factors. Particularly in the case of transport aircraft, the fuselage structure assumes a fundamental safety role in mitigating loads exerted on the occupants to a tolerable level, in case of an emergency landing scenario [5]. Hence, crash load mitigation has an influential role in the overall design of a transport aircraft. It must, therefore, be considered in an early phase of the design process [6], to prevent potentially costly and time-consuming modifications at subsequent, more detailed design stages.

Historically, the occupant safety of traditional aircraft configurations is addressed independently of the airframe

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structure, whose behaviour is presumed from test and historical accident data [7]. In the case of traditional aircrafts, the certification process requires the application of standardized acceleration pulses directly to the seat structure (e.g. EASA CS-25.562) [8–11].

However, with the recent shift in regulations since 2017, the Certification Specifications (CS) for small aircraft (CS-23) now include a comprehensive approach. This alternative approach takes into account the combined crash performance of seats integrated with the airframe, rather than assessing them separately [12].

Furthermore, new transport aircraft incorporating unconventional features, such as advanced lightweight materials, need to adhere to tailored certification requirements defined by the regulatory body. These requirements, so-called Special Conditions, have been employed in the certification of novel aircrafts, such as the Boeing B787-8 [13] and Airbus A350–900 [14], characterized by carbon-fibre reinforced plastic (CFRP) used in the construction of the fuselage. In these cases, the applicable airworthiness regulation is not considered adequate for the new design features. Special Conditions are defined with additional safety standards that the regulator considers necessary to establish a level of safety equivalent to the existing standards for traditional configurations [13, 14].

Compliance with such Special Conditions has become a critical topic in the design of innovative concepts since crashworthiness has a completely different significance and complexity compared to the former traditional aircraft configurations [6]. The transition from prescriptive to performance-based certification criteria urges the establishment of an integrated safety approach. However, given the limited data obtainable from aeronautics full-scale instrumented tests and their prohibitive costs [15], the development of numerical tools to assist the certification process is of primary importance.

To accelerate the advancement and adoption of innovative aircraft concepts, the DLR Institute of Structures and Design (BT) has committed to developing advanced modelling techniques for the simulation of crash scenarios for transport aircraft. These methods aim to enhance the accuracy of crash simulations, thereby providing a crucial understanding of the unique crash dynamics and safety characteristics connected to each innovative configuration.

This paper details the development of the methodology for the automatic generation of full-scale FE structural models complete with passengers and cabin environment.

This methodology enables a comprehensive safety evaluation at different levels of fidelity. The initiative reflects a concerted effort to consolidate and aggregate the extensive crashworthiness simulations expertise of the department. The outcome of this study is integrated as a new essential component of the existing DLR's process chain for aircraft design.

## 2 Process chain for aircraft design

The design of a novel aircraft is a complex multidisciplinary task that aggregates plenty of mutually dependent disciplines, such as aerodynamics, structural design, cabin concept, flight mechanics, costs, and many others. These unique expertise areas are often sourced from various specialized DLR institutes and external organizations, and together, they contribute to defining the best trade-off configuration to fulfil certification and the Top-Level Aircraft Requirements (TLARs).

The design process consists of three subsequent phases, as suggested by [16]. First, the conceptual design stage is primarily characterized by the consideration of a large number of possible design and trade-off studies in highly multidisciplinary analyses. At this point, the process is generally iterative, where the acquired results at each iteration serve in turn as input for new calculations, thus increasing the level of detail surrounding the new concept, while reducing uncertainties and narrowing the design space.

In the subsequent preliminary design phase, more detailed calculations are performed to define the layout and general dimensions of the aircraft. The preliminary design phase is also the area of application of the newly developed tool described in the paper, which serves to assess the cabin crashworthiness from an early design, before entering the final, so-called detailed design phase.

The aerospace industry has been a pioneer in adopting computational tools for product development. However, today's challenges necessitate a disruptive digital transformation that goes beyond the use of computational methods for isolated analyses. This is because of the multidisciplinary nature of the aircraft development process, where the influence of integration effects between multiple disciplines often blurs or even eliminates the improvements achieved in the individual disciplines.

This interconnectedness magnifies the complexity and size of the design space, which is further affected by time and resource constraints. Hence, engineers require highly automated tools integrated into a virtual design chain, to be able to consider all aspects of the problem and aim for the optimal cost-effective solution of such a complex Multidisciplinary Design Optimization (MDO).

Within the multidisciplinary process chain established at DLR, the Institute BT deals with structural and crashworthiness topics. This includes the design of lightweight aircraft structures capable of withstanding the loading scenario defined by the certification requirements, and at the same time, ensuring occupant safety in case of emergency. The two structural requirements may conflict with each other, as static design approaches prioritise lightweight robust structures, while crashworthiness design prioritizes the absorption and distribution of impact energy through the controlled deformation or failure of the structure, during a crash event, in order to minimize the sudden deceleration forces experienced by passengers, reducing injury risks [5].

The institute has implemented a specialized software, named PANDORA (Parametric Numerical Design and Optimization Routines for Aircraft) [17]. This design environment, which is developed for the numerical assessment of aeronautic structures, became an integral part of the DLR design process chain. The software tool plays a fundamental role in predicting and mitigating the hazards associated with each specific cabin configuration, thus enhancing passenger safety.

At DLR, the interactions between all the contributors within the pre-design design chain are organised through a hierarchical data framework, named CPACS. This parametric schema represents the starting point of the PANDORA modelling chain, as the resulting structural models are based on the parametric description of the aircraft. A better view of the CPACS data frame and the PANDORA software is given in the following sections.

## 2.1 CPACS

The Common Parametric Aircraft Configuration Schema (CPACS) format was established with the objective of unifying the data format used by the different parties involved in the aircraft design process chain [18].

It constitutes the interface, which serves to collect and distribute knowledge across various disciplines, at different levels of detail, ranging from simple statistical models to high-fidelity methods like computational fluid dynamics and FE analysis [19]. In particular, the CPACS framework is devised to facilitate the efficient exchange of aircraft and rotorcraft models in a reliable and structured manner. Its data structure is both easily interpretable and efficient for data parsing and handling.

The whole aeronautic system is described using a standardized hierarchical structure, where parameters are systematically organized into branches according to the specific discipline and stored as nodes within an XML file.

The open-source schema of CPACS demonstrated its robustness in several aircraft design processes. Several tools are developed within [20, 21] and outside DLR [22, 23] to read or manipulate models stored in the XML framework and feed data back within the process chain.

The CPACS capability to describe complex aircraft or rotorcraft systems, under various degrees of detail, provides a solid starting point to define, among other things, Finite Element Models (FEM) for structural assessment.

## 2.2 PANDORA

To condense department tools and experience in the field of modelling and assessment of aeronautic structures, the development of the internal design environment PANDORA was started in 2016 and persistently expanded to achieve increasing levels of detail and automation.

Currently, PANDORA is an established tool of the DLR process chain, for the automatic generation of global and detailed FE structural models for static and dynamic analysis (crash and ditching) and subsequent structural sizing of both fixed- and rotary-wing fuselage structures.

The software framework is based on Python and it is implemented in a modular schema that includes only open-source external modules. Each module is dedicated to specific functions, such as reading CPACS data, creating geometries, creating and managing FE data or writing output files for external commercial solvers.

The PANDORA process is generally based on the CPACS definition of the aircraft within the DLR process chain. The CPACS interface of PANDORA fetches the parametric description related to the geometry, structure, profiles, loads, materials, and cabin environment, among others. The Global Finite Element Model (GFEM) module elaborates and integrates this information, subsequently defining an initial FE model.

The description of all FE entities such as nodes, elements, boundaries or properties, are stored in the internal native data format, as defined by the FE_PYPREP module. This module features countless options for accessing and managing specific entities within the model, making the pre-processing capability of PANDORA virtually unlimited. Such an adaptable framework ensures that large-scale complex models can be handled with ease and precision, thereby enhancing overall model development and application.

The Detailed Finite Element Module (DFEM) module contains a large set of pre-processing options to modify and add details to the simple initial FE model.

Finally, multiple interfaces from the native PANDORA data format to specific solver formats are provided by the CONVERTER module, ensuring the interchangeability of different commercial FE solvers.

Further modules are present for specific applications which are not discussed in this paper (e.g. structure sizing).

Additional widgets are included to launch the process also using a Graphical User Interface (GUI), as displayed in Fig. 1. This is implemented to conveniently handle and visualize models outside the less user-friendly Python environment.

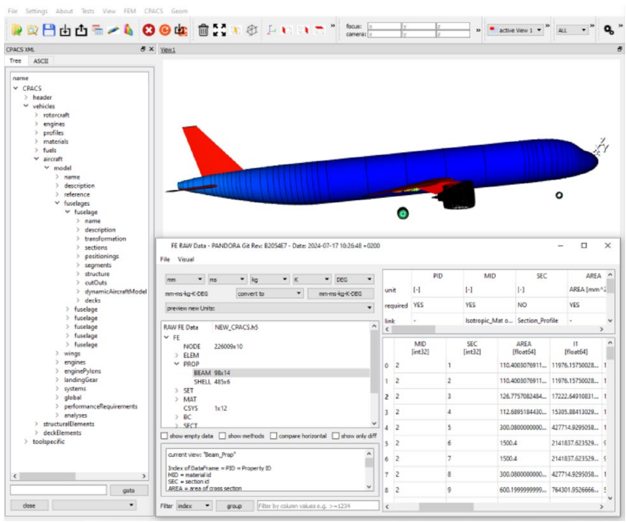

**Fig. 1** PANDORA GUI overview: CPACS data structure and resulting aircraft FE model

A detailed overview of the process chain and capabilities of the software is given in the next section.

## 3 Process chain for model generation

The presented work is developed as part of the DLR project ARCADIA, (Automated and Reconfigurable Cabin Development Process in Aircraft design) which spans across the various disciplines involved in cabin design. In the framework of this project, DLR-BT focuses on the development of automatically generated aircraft structures with integrated cabin environment. This implies the generation of finite element models, the integration of dummy models, and cabin equipment (hatracks, seats, linings, etc.).

PANDORA is expanded with the capability of generating full-automatic adaptive models and a full-integrated cabin environment. The focus is kept on the establishment of the methodology and the validation steps that are deemed necessary to generate complex FE models in a reliable and automatic manner.

The aircraft models presented and analysed in this paper are created by the DLR Institute of System Architectures in Aeronautics, thanks to their knowledge-based tool FUGA (Fuselage Geometry Assembler) [24] and described in CPACS format, before being discretized by PANDORA as a Finite Element model for crashworthiness analysis.

The model generation is achieved automatically thanks to the PANDORA process chain, by following the listed steps:

- Creation of the GFEM based on the CPACS database: This model represents the most basic and coarse numerical approximation of the aircraft. In this representation, only a single quadrilateral shell element is created between two adjacent stringers and frames, while reinforcements (struts, frames, stringers, etc.) are represented by beam elements.
- Reduction of the model to the section of interest.
- Mesh refinement by element splitting, with multiple refinement levels in user-specified areas. A maximum mesh size can be specified to split any element with a larger dimension through multiple splitting iterations. As a result, a quadrilateral structured mesh is always achieved, with few triangular elements at the interface between coarser and finer mesh zones.
- Extrusion of the beam cross-section into their three-dimensional shell representation in areas demanding higher accuracy. The feature can be applied to frames, stringers, struts, cross-beams and longerons which are modelled as beams in the original GFEM. Tied interfaces are defined to couple adjacent extruded beams, while rigid nodal bodies are defined on the cross-section at the transition from beam to extruded representations. The model with extruded sections is referred as DFEM in this paper.
- Lumped masses (e.g. cargo, hatracks, etc.) can be included in the model and linked to the primary structure through non-rigid nodal connections.

The aforementioned process chain steps are documented in detail in a previous paper [25].

When the model generation is completed, the internal FE database of PANDORA, built on a NASTRAN-like data format, is converted to a selected solver's format.

The selection of the solver is typically driven by the intended application. This is because each methodology to translate the generic FE database into a specific format is purposefully developed and tailored toward certain applications, often leveraging the intrinsic strengths of the associated solver.

The currently available interfaces include standard structural solvers (i.e. ANSYS, NASTRAN) and dynamic solvers (i.e. VPS, LS-DYNA) with an explicit time integration schema (Fig. 2).

In the following sections, the PANDORA process chain is further expanded to achieve complete automation in creating numerical models to study crashworthiness and occupant safety of transport aircrafts.

In the first section, the process chain is enhanced to achieve complete automation in creating FE models of the primary structure. This automation is sought through the implementation of a new modelling strategy to generate FEM for the commercial solver LS-DYNA. The solver is selected for its widespread use in crashworthiness analysis, and its large availability of virtual dummy models, including

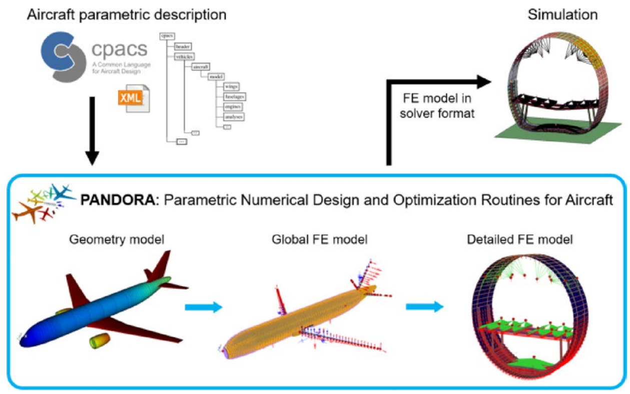


**Fig. 2** PANDORA modelling chain overview

various body sizes, multiple numerical fidelities and human body models.

The second section addresses the numerical representation of the cabin environment and its integration into the overall model. This section reflects the shift of focus from pure structural analysis to a more comprehensive assessment of occupant safety, which implies the modelling of passengers and cabin environments through dummies and meshed geometries rather than considering them merely as point masses for the application of loads within the primary structure.

A particular attention is given to the principal contributors of occupant safety, such as v-ATDs (virtual Anthropomorphic Test Devices) and seats, but it includes considerations on other cabin elements such as hatracks, cabin linings and others, which are not used for FE analysis at the moment.

A practical example to demonstrate the capabilities of the new implementation is detailed in Chapter 4, where the full process chain is used to generate the numerical model of a fuselage section of a DLR concept and to post-process some exemplary occupant-safety-related results.

### 3.1 Primary structure FE modelling methodology and validation

The aim of this section is to demonstrate the continuity of the newly implemented modelling methodology with the ones already in use at the institute, as well as compare different discretization methods to characterise their potentialities and limits.

The definition of a cabin FE model offers countless possibilities for approximations and mathematical formulations. To maximise the reliability of such a large model, a validation process is defined through a series of numerical benchmarks, to be compared against different modelling strategies and different levels of fidelity.

This new modelling methodology (referred to in this paper as "Extended-Method" or "Ext_M") is developed with a structured, step-by-step bottom-up approach, through increasingly complex benchmarks ensuring that the conclusions drafted in each phase are implemented for the following more sophisticated benchmarks.

Each benchmark is defined in PANDORA format, with the aim of representing the most critical bricks that compose a typical aircraft FE model. Their output, obtained with the new modelling strategy, shall be consistent with the outputs from well-established standard strategies in use at the institute to define structural models with an implicit time integration schema (named "Reference-Implicit-Method" or "Ref_i") and with an explicit schema (named "Reference-Explicit-Method" or "Ref_e").

Furthermore, the full automation of the process chain is achieved by integrating the information provided by CPACS, with a set of best practices coming from the institute's expertise in modelling aeronautic structures.

The benchmarks presented in the following subsections make use of the explicit time integration schema since the final application on crash simulations is characterized by short and highly nonlinear transient dynamics.

Therefore, the comparison with the "Reference-Explicit-Method", which is currently mainly used for ditching investigations [25] is studied for all benchmarks.

In Sects. 3.1.1 and 3.1.3, the explicit quasi-static simulations use a linearly increasing load, reaching the final load after 1.5 s and 0.1 s, respectively. Notably, numerical damping is omitted in all simulations, allowing structures under quasi-static load cases to oscillate freely at their natural frequency. This allows to observe if the oscillation frequencies are consistent across different formulations, to ensure a comparable mass and stiffness distribution of the mechanical system.

In the following benchmarks, the material properties are assigned by PANDORA, which can both read CPACS material data, or assign material properties to each structural component according to their general use in the aircraft structure. These general assumptions are often necessary at such an early design phase, where materials may not yet be fully identified.

Currently, PANDORA selectively assigns either Aluminium 2024 or 7075. The material properties and the structural members to which they are assigned are listed in Table 1. The plasticity curve is described through the Power Hardening Law, with the strain hardening coefficients "B" and "n". The element failure criterion is based on the maximum effective plastic strain, and strain rate hardening, typically negligible for aluminium, is omitted for simplicity.

The keywords *MAT_PIECEWISE_LINEAR_PLASTICITY and *MAT_SIMPLIFIED_JOHNSON_COOK are used to represent the PANDORA-defined material in LS-Dyna, for shell and beam elements, respectively.

**Table 1** Materials properties and their application in the fuselage structure

| Properties | Al2024 | Al7075 |
|---|---|---|
| Density [Kg/mm$^3$] | $2.8 \cdot 10^6$ | $2.8 \cdot 10^6$ |
| Young's modulus [GPa] | 72.14 | 69.48 |
| Poisson's ratio | 0.33 | 0.33 |
| Maximum Strain [%] | 16 | 9.6 |
| Yield Stress [GPa] | 0.326 | 0.505 |
| B coefficient | 0.6 | 0.53 |
| n coefficient | 0.4 | 0.52 |
| Automatic material assignment to: | *Skin* | *Stringers* |
| | *Frames* | *Longerons* |
| | *Cargo struts and crossbeam* | *Cabin struts and crossbeam* |

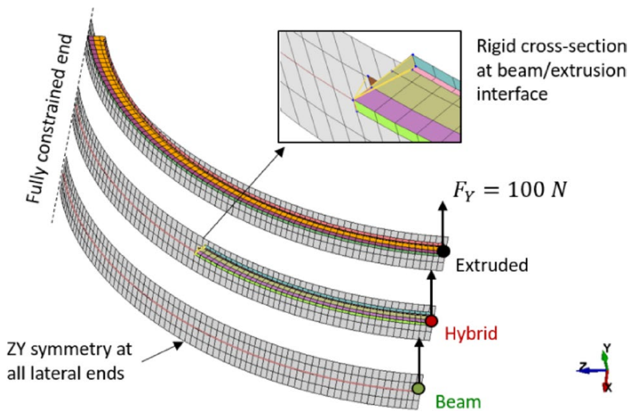


**Fig. 3** Reinforced panel load case and boundaries

### 3.1.1 Reinforced panel

The first case is defined to validate the structural behaviour in elastic regime of low and high-fidelity discretization.

The comparability of the behaviour must be ensured for the beam approximation, the complete three-dimensional shell representation, and the hybrid model that includes the two formulations.

The reinforced panel chosen for the analysis consists of a portion of skin and frame extrapolated by the metallic single-aisle DLR aircraft D150 [26]. The reinforced beams' extremities are fixed at one end, loaded at the other end's central node (0.1kN in Y direction), and constrained on the sides with YZ-plane symmetry boundary conditions.

Three reinforcement formulations are defined:

- The low-fidelity or "beam" formulation consists of beam elements defined between skin nodes. The mechanical properties and centre of gravity are calculated by PANDORA thanks to the knowledge of the representative cross-section defined in CPACS.

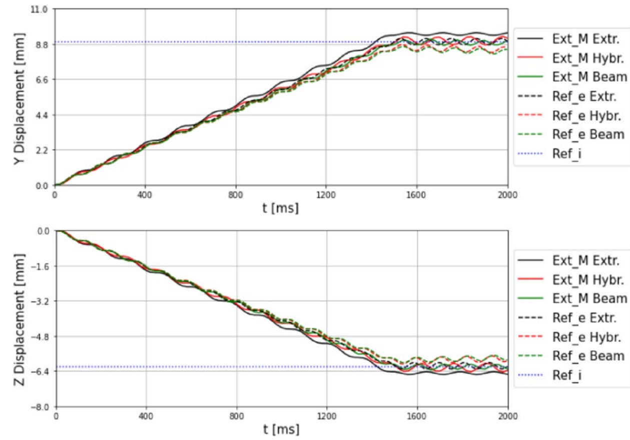


**Fig. 4** Y (top) and Z (bottom) displacement of beam edge resulting from the different solvers and formulations

- The high-fidelity or "extruded" formulation offers a more detailed three-dimensional shape of the reinforcement, discretized through shell elements and tied to the underlying panel.
- The "hybrid" case incorporates both the "beam" and "extruded" formulations. A rigid nodal constraint is automatically defined between the two fidelity levels as visible in Fig. 3. This case serves to verify the continuity across the interface of different fidelities.

Beam elements are defined by PANDORA using a resultant formulation (ELFORM 2 in LS-DYNA), where only cross-sectional area, section centre of gravity offset and inertia matrix are defined. While it provides a robust formulation to model CPACS-defined beams into the various solver interfaces of PANDORA, the absence of cross-sectional geometry precludes a direct computation of local strains and contact distances, affecting the accuracy of plasticity, failure, and contact algorithms. Moreover, the section shear centre is not defined. To avoid any unrealistic twisting behaviour given by incorrect torsional loads, the beam torque stiffness calculated by PANDORA is increased by 10 times.

The displacements in the bending directions Y and Z shown in Fig. 4, reveal an excellent consistency across the different formulations and solvers (Ext_M, Ref_e andRef_i).

The beam formulation is the base of GFEM models, that are well-suited for structural, floatation and ditching analysis in early design phases thanks to the minimal design definition required for the generation, and the fast computation. However, beams shall be limited in crash analysis to areas where contacts, torque, plasticity or buckling are not expected, typically far from impact surfaces and occupants, as shown for the fuselage models at Chapter 3.1.4 and Chapter 4. The implementation of beam elements with cross-section integration (ELFORM 1), coupled with the cross-section description (*INTEGRATION_BEAM), would widen the domain of application of beam elements thanks to the more representative post-yield behaviour.

#### 3.1.2 Lumped mass pendulum

The second case aims to assess the interpolation elements, also called RBE3. These are utilized to connect the primary structure to the nodal masses representing non-structural aircraft components through their inertia properties. The loads induced by the mass are transmitted to the structure according to a kinematic interpolation (Fig. 5).

The study compares multiple pendulum models: shell and beam pendulums, with fixed or moving hinges. The comparisons give an almost identical kinematic for the two explicit solvers, however, different formulations for the interpolation elements are needed when linking beams, shells, and their combination to ensure numerical stability. The issue is tackled by a new PANDORA logic that manages RBE3-type connections according to the connecting structure.

#### 3.1.3 Fuselage section: static load case

The typical section of the CPACS-defined D150 aircraft is quasi-statically loaded to assess the properties of the integrated fuselage and the stability of the automatic modelling chain. Resulting displacements are compared for the two levels of fidelity and the two different solver modelling strategies.

Both low- (GFEM) and high-fidelity (DFEM) models are partly refined through element splitting using PANDORA pre-processing features. A subsequent further splitting is used to define three progressively increasingly refined zones towards the bottom of the fuselage, with the intention to use the same model also for a dynamic crash case. The upper fuselage area is kept at low fidelity also in the DFEM model since it does not undergo high loads, torsion or contact, following the observations made in Sect. 3.1.1.

A novel algorithm is defined to automatically assign tie constraints and contact definitions within the fuselage structure. The general modelling-rule-based logic manages each structural element according to its class (stringer, frame, etc.), resulting in the following definitions:

- An AUTOMATIC_SINGLE_SURFACE contact that includes all the fuselage structure governs the mutual interactions between all the structural elements.
- An AUTOMATIC_SURFACE_TO_SURFACE contact is defined between the fuselage skin and the impact plate. By including the skin alone, the contact excludes any influence of internal framework edges extending beyond the fuselage perimeter. In fact, to ensure a cost-efficient and high-quality mesh, the PANDORA algorithm meshes each structural member with an independent structured mesh [27]. To prevent mesh distortions, the cross-section of longitudinal member extremities, such as longerons and crossbeams, is perpendicular to the profile direction. However, this may lead to some structural elements protruding beyond the fuselage boundary.
- The connections between the independently meshed structural members rely on a robust design-rule-based logic. This applies a series of three proximity-based SHELL_EGDE_TO_SURFACE_BEAM_OFFSET tie contact definitions to connect respectively: skin with frames and stringers, frames with crossbeams and struts, and crossbeams with longerons and struts.
- The failure criteria are omitted from the constraint, due to the undefined design of bolt or clip connections during pre-design.

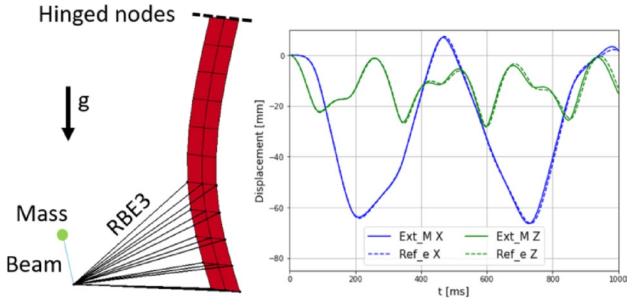


**Fig. 5** Fixed-hinge shell pendulum case and plane of oscillation kinematic for the two solvers

A fuselage section of about 1 m (2 frames span), with non-structural components represented as lumped masses, is utilized for the study. The complete model has a total mass of 1141 kg, with the cargo masses accounting for 475 kg.

A 1 kN downward force is applied at the two top stringers, while the bottom stringer is clamped. The value of nodal force is chosen to avoid plastic deformation. Symmetry boundary conditions are defined at both section cuts of the fuselage. Gravity and internal atmospheric pressure are also defined. The two analysed models are displayed in Fig. 6, highlighting the load case in the left figure.

The displacement shown in Fig. 7 is measured in Z for the top node where the load is applied, and in Y between two longerons mid nodes, to measure the crossbeams elongation.

All four models (two fidelity levels and two solvers) show a comparable deformation and oscillation frequency, which suggests a good agreement of the stiffness and mass distribution in the studied elastic regime.

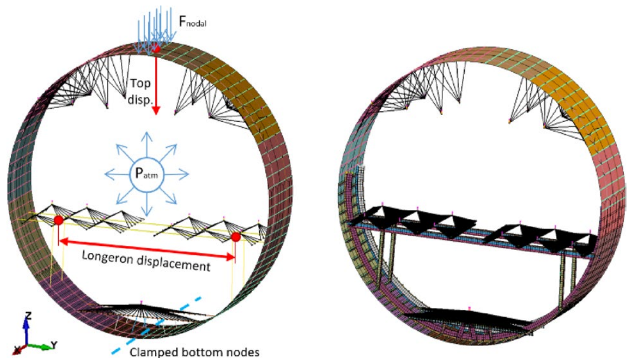


**Fig. 6** GFEM (left) and DFEM (right) defined though the Extended-Method. Static load case and measured node positions shown on the left model

### 3.1.4 Fuselage section: dynamic load case

The final benchmark aims to assess the capability of the developed methodology directly in its intended field of application, the crash analysis of an aircraft fuselage section. The same fuselage discretisation created in the previous static benchmark is used for the drop test. A new implementation automatically defines the rigid impact surface, loads, contacts, as well as initial and boundary conditions. This PANDORA feature allows the automatic definition of FEM representing typical crash scenarios of fuselage sections. The impact with a starting velocity of 30ft/s and gravity load is studied for the DFEM and GFEM models on both available explicit solvers.

The study yields two main observations, on one hand, the good comparability with the previous modelling strategy, and on the other hand the inadequacy of the "beam"

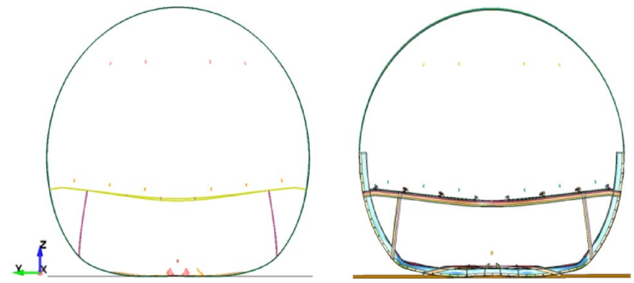

**Fig. 8** Deformed geometries at 50 ms (hidden RBE3) of GFEM (left) and DFEM (right) solved in LS-DYNA

formulation to simulate the dynamic behaviour in the vicinity of the impact zone.

Crash kinematics, energy balance, and overall contact forces are compared.

When comparing the different fidelities, the lower-fidelity model demonstrates significant computational efficiency, requiring only 4% of the computational time needed by the higher-fidelity model. However, a kinematic comparison shows substantial differences in contacts, failure and buckling modes between the two formulations (Fig. 8).

A reasonably comparable trend is observed comparing the energy balance and reaction force in Fig. 9 for models with the same level of fidelity, even in this context of highly non-linear simulations. Nevertheless, significant deviations are evident when comparing low- and high-fidelity models, particularly in the energy slope and the initial peak of the contact force.

This deviation suggests that the efficient beam formulation used in PANDORA should be avoided in areas undergoing plasticization, buckling or contacts. The current formulation relies on a mechanical description of the

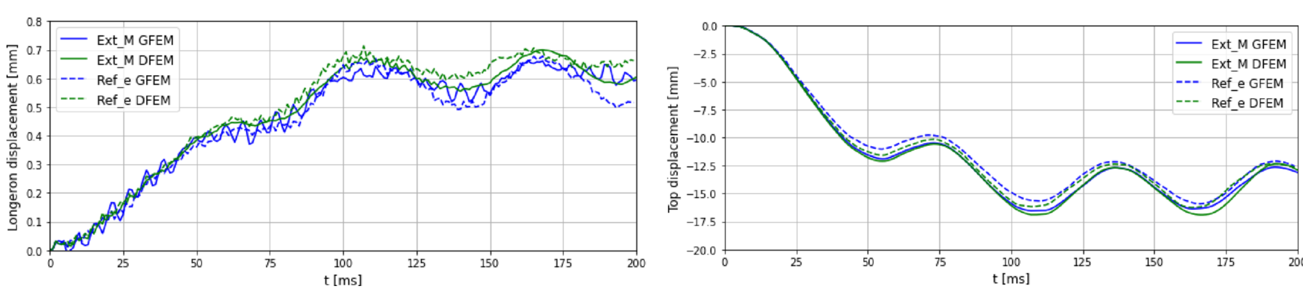


**Fig. 7** Mid-longerons differential displacement (top) and top displacement (bottom) for both fidelities and solvers

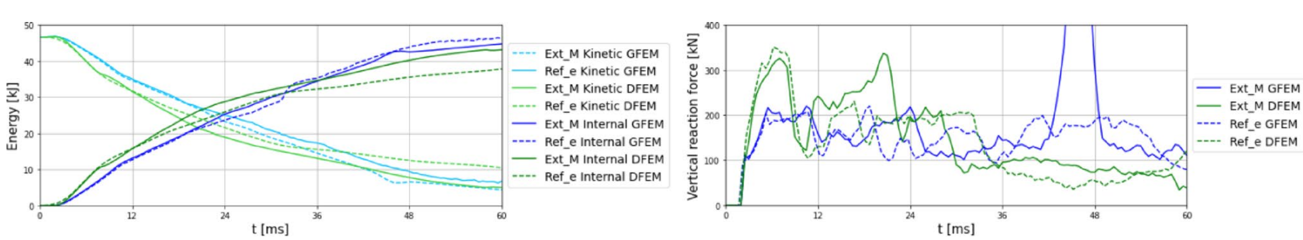


**Fig. 9** Energy balance of the fuselage section (top) and vertical reaction force of the impact surface (bottom) for both fidelities and solvers

cross-section based solely on its inertia properties, without considering the specific cross-section of the profile.

The absence of geometry data may affect the detection of contacts and the onset of the creation of plastic hinges, potentially resulting in unrepresentative structural responses. For instance, the peak observed in the reaction force of the rigid surface after 40 ms is caused by the complete flattening of the cross-beam connected to the cargo mass and the contact of the latter with the rigid surface.

## 3.2 Cabin environment model and integration

As part of the department's effort to develop an integrated safety modelling approach in aeronautics, prior studies have been performed to develop and validate general methods for passenger safety simulations [28], involving dummy positioning techniques, seatbelt materials and contract types, among other factors. The resulting methodology and considerations from [28] are here incorporated into the primary aircraft structure, to establish a systematic approach for the analysis of new aircraft concepts, with a focus on occupant safety. The abovementioned technique is applied to multiple types of virtual ATD and to the numerical seat currently in use at DLR-BT, resulting in an essential brick of the newly developed process chain for crashworthiness evaluation.

The first subsection presents the cabin definition within the CPACS framework and discusses the associated challenges. Then, the two following subsections describe the approach implemented in PANDORA for the automated and reliable generation of finite element models of the cabin environment, including virtual dummies. Finally, the integration of the deck into the primary structure is addressed.

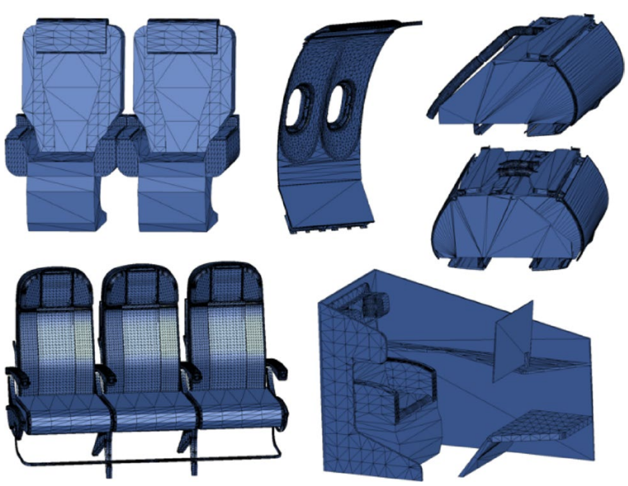

**Fig. 10** Illustrative cabin elements from CPACS library

### 3.2.1 Parametric cabin description

The XML-formatted CPACS definition of the cabin layout consists of a hierarchically structured description of each component (seats, overhead bins, linings, etc.) [19]. Cabin components are detailed with parametrical information including their position, orientation, connected structural elements or number of passengers in the case of seats. Yet, the geometric representation of each cabin component type is provided by a library of high-detailed STL-meshed geometries referenced by CPACS (examples in Fig. 10).

The handling of such geometries poses a challenge to the automatization of the process. First, accurate defeaturing and remeshing are needed for the geometry to be used in a FEM structural analysis. Second, mechanical properties, materials, and connections to the primary structure must be defined with accurate engineering judgment, to ensure consistency with the fidelity level of the structural model generated by PANDORA.

Finally, the definition of a numerical seat model and the integration of v-ATD on the seats are complex specialized tasks that can significantly impact the accuracy of simulation results, particularly in the assessment of occupant safety.

### 3.2.2 Library approach for FE models

Encountering the issues mentioned in Sect. 3.2.1 a modular approach is implemented for the creation of the numerical cabin environment, where each CPACS geometry is associated with its FEM counterpart. Each FEM is a fully defined model encompassing all necessary approximations and mechanical properties.

The objective of this approach is to maximize the adaptability of model generation across a wide range of aircraft configurations by minimizing the dependency on the source geometries.

The resulting FEM counterparts are manually pre-defined and stored in a PANDORA library, from which they can be utilised in the automated process chain after a trivial space and index transformation.

This approach confers the flexibility to model a component according to different levels of fidelity and then select the most suitable pre-defined model for each simulation. The procedure is particularly efficient for seats, dummies and cabin elements (i.e. overhead bins, cabin lining, etc.), as discussed in detail in the next subsections.

### 3.2.3 Seat and v-ATD integration

In this section, the methodology for defining FEM library sub-models is presented. The discussion focuses first on the modelling of seats and dummies, then it expands towards the other cabin elements.

A variety of seat geometries are available in CPACS, differentiated by class (first, business, economy), number of passengers (1 to 4), and position in the fuselage (centre, side). Given its primary importance in crashworthiness, the seat geometries are modelled on the base of a numerical seat model exchanged with an aircraft OEM in the 1990s.

Each seat geometry is approximated as a combination of FE single-seat units, derived from the available numerical seat. The structural continuity of the assembly is maintained through rigid links connecting the adjacent interfaces of the seat's structural beams as shown in Fig. 12.

The necessity of a modular implementation arises from the need to bring together manual and automatic procedures in the PANDORA process chain. Specifically, the integration of a v-ATD into its seat represents a structured engineering process, comprising a sequence of well-defined steps that necessitate specific expertise, specialized software and a series of pre-simulations.

Four "Hybrid III" dummy types, provided license-free by LSTC, are integrated into the numerical seat following the SAE guidelines [29] and are made available in PANDORA as library items.

Each type represents a distinct level of accuracy ("FAST" and "DETAILED") or passenger weight (5th percentile female, 50th percentile male, and 95th percentile male).

The considered free-license v-ATDs are designed for automotive applications, nevertheless, the implementation of aerospace-approved dummies and the development of a more accurate numerical seat are set to be among the next steps of the project.

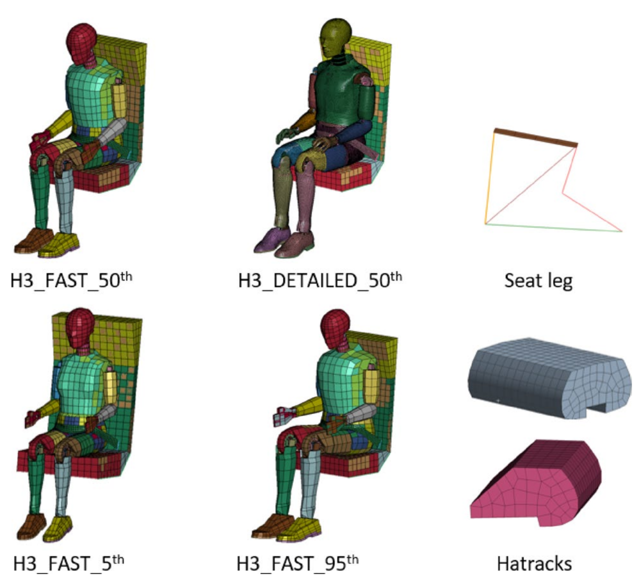


**Fig. 11** PANDORA library of pre-assembled models

While the seat layout is set by CPACS, the user can choose a custom distribution of dummy types around the cabin.

A new PANDORA module is implemented to automatically evaluate the safety criteria, as defined by the regulation for emergency landing conditions of transport aircraft [30]. While the regulation is currently limited to seat testing, we believe that a comprehensive safety assessment, including the fuselage structure, will be essential for evaluating disruptive aircraft designs, often characterized by reduced energy-absorbing areas beneath the passenger floor, similar to CS-23 type aircraft.

For virtual ATD, the SAE Aerospace Recommended Practice 5765B [29] provides the guidelines for the evaluation of safety criteria, filtering and output frequency, which are followed in the PANDORA module.

As the seats, further cabin items are stored in a PANDORA library prior to integration into the full structural model. However, contrary to seats, cabin elements FEM are defined starting from the small set of geometries defined in CPACS, which are manually defeatured, meshed, and completed with the necessary mechanical features. The same cabin element can be defined in different fidelity, from coarse and rigid, to finely meshed and with sophisticated materials definition, depending on the specific intended application.

Aiming for enhanced quality and reliability, the automatic on-the-fly meshing approach was discarded in favour of a more deliberate and controlled manual process. As an illustrative example, preliminary hatrack models are shown in Fig. 11.

### 3.2.4 Cabin environment integration

The final step deals with the creation of the cabin floor and with the integration of the previously defined FE sub-models, by means of ties, contacts, or rigid and RBE3 constraints.

A new PANDORA feature generates the floor mesh and its mechanical properties as defined in CPACS or by the user. The integration phase starts after the generation of the floor when all the FE sub-models are already defined and placed according to the parametric layout. This phase serves to ensure structural continuity and interaction across the multitude of generated sub-models in the cabin assembly, as in the example of Fig. 12.

In addition to structural constraints and contacts described in Sect. 3.1.3, further definitions are needed for the cabin environment. Figure 13 displays the modular assembly of a seat, generated according to the CPACS parametric description that defines the type of seat (e.g. position, number of adjacent seats, etc.), and its connections with primary structure elements. The seat legs are placed above the connecting

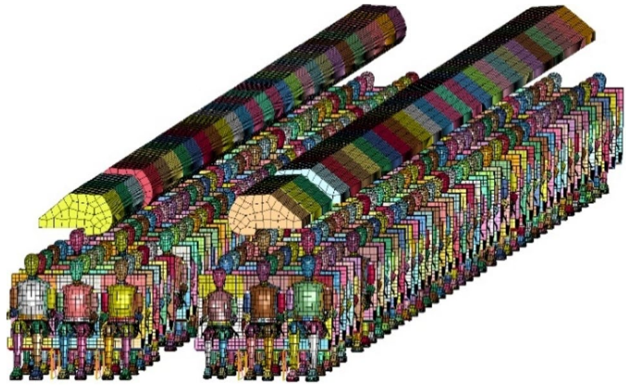

**Fig. 12** Single-aisle cabin environment resulting from assembling library FE sub-models

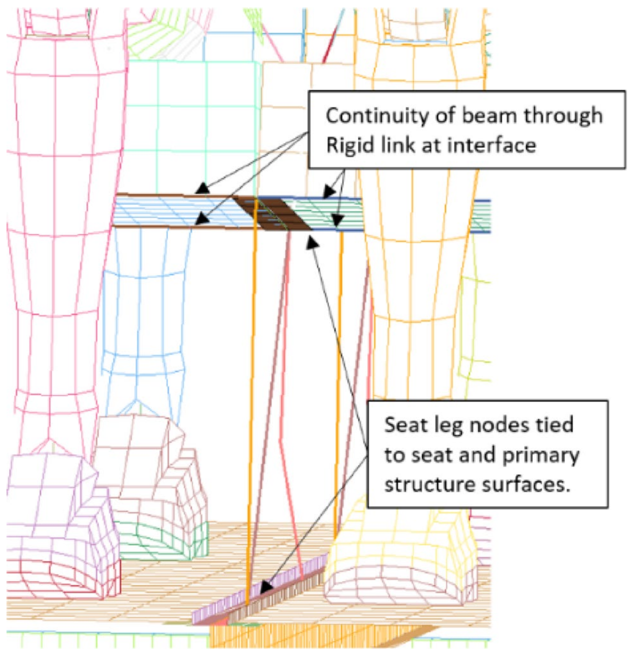


**Fig. 13** Seat-to-seat and structure adaptive connection

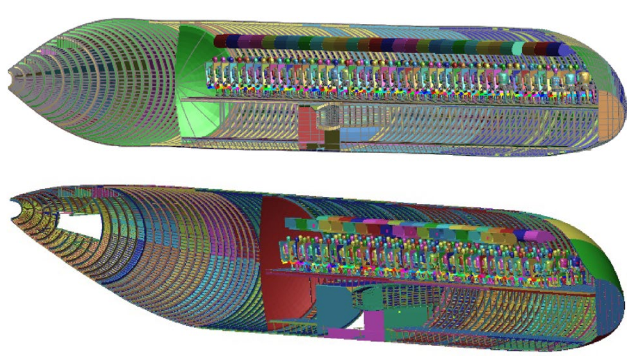

**Fig. 14** Full-scale FEM of LH2-propelled concepts in double- (bottom) and single-aisle (top) configuration

primary structure, and tie connections are defined with both primary structure and ATD-seat sub-models. The lateral continuity of the beam structure between adjacent seat sub-models is ensured though the rigid connection of the ending beam nodes of adjacent seat. The ATD and belt specific contacts are imported from the dummy-seat sub-model. These include an ATD-to-belt surface-to-surface contact and a surface-to-surface contact between the dummy external shell and the surrounding domain, excluding the dummy internal contacts which are managed by the various ATD-specific contacts.

The full-scale Finite Element Model of two novel LH2-propelled single- [31] and double-aisle [32] DLR concepts is created to test the new process chain (Fig. 14):

## 4 Crashworthiness analysis of parametric FE model

This paragraph aims to show the potential of the model generator, in a qualitative case study that makes use of all steps of the novel PANDORA process chain.

The model is based on a typical forward section of a DLR aircraft concept with hydrogen propulsion. The 2.6 m long (5 frame spans) FE model is generated in 4 min (40 s for ATDs and cabin environment integration) by the extended PANDORA process chain described in the paper, starting from the CPACS parametric description.

The crash case is also defined automatically through symmetry boundary conditions, rigid impact surface, gravity and an initial vertical velocity of 30 ft/s, as quoted exemplarily by the special conditions defined for the Airbus A350-900 aircraft [14].

The fuselage's mesh is increasingly refined in areas closer to the impact, while a low-fidelity beam discretization is kept for the upper cabin. Overhead bins and their content are modelled as lumped masses connected to the frame through RBE3 elements, while no cargo masses are considered.

The resulting output file from PANDORA can be ran directly in the commercial solver LS-DYNA without needing manual modifications.

### 4.1 Simulation outcomes

The 200 ms simulation is computed in less than 3 h on 16 cores of a local workstation.

The fuselage section contains 18 LSTC FAST H3 v-ATDs, of which, four 5th (in seats 1A, 1B, 1C and 3A), four 95th percentile (in seats 2A, 2B, 2C and 3C) and the remaining 50th percentile.

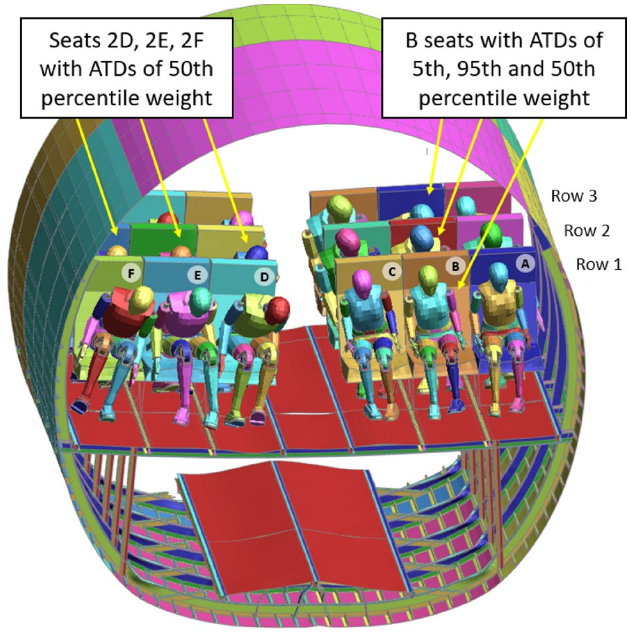


**Fig. 15** Crash outcome on structure and occupants after 200 ms and position of analysed dummies

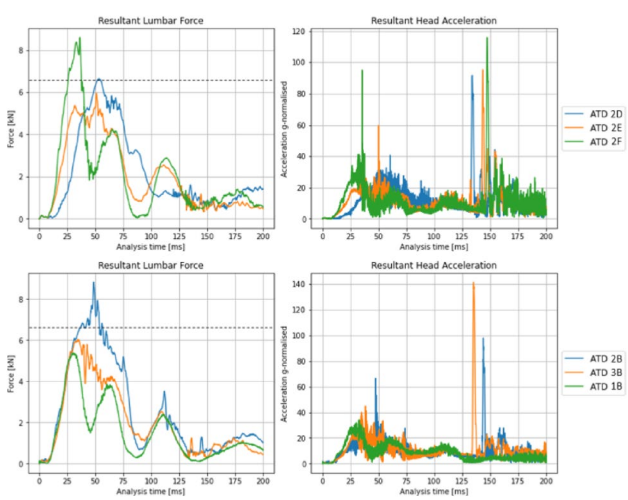


**Fig. 16** Resultant acceleration and lumbar load, for different dummy types at the same seat position and same dummy type in different seat positions. The Dashed line represents the 6.8 kN lumbar load limit according to 14 CFR, Part 25.562 (c)(4) [30]

The ATDs are placed in a way to get an insight into the influence on safety criteria of dummy weight and position in the cabin.

As displayed in Fig. 15, dummies in 2D, 2E and 2F are 50th percentile dummies placed at different seat positions, while dummies in 1B, 2B and 2C are respectively 5th, 95th and 50th percentile ATDs, placed at the same central-seat position.

As a result of the impact, cargo crossbeams and struts fail, while frames buckle near the cabin struts attachment. The resultant safety hazard on the occupant can be assessed by the safety criteria that are automatically computed by PANDORA.

According to the model results in Fig. 16, the occupant positioned closer to the window (seat 2F) bears the highest and earliest peak of both lumbar load and head acceleration. The comparison between different ATD types highlights the influence of body weight on the safety indicators. In the simulation, the heavy dummy (seat 2B) presents a considerably higher lumbar load. Furthermore, heavy- and average-weight dummies hit the forward rows of seats. This event represents a common safety hazard accounted for by the HIC defined in the regulation [30]. The outcome of the contact between the head and seat is visible as a sudden surge in the head acceleration at around 150 ms. The seat row in front of the light dummy (seat 1B) is not modelled due to the symmetry, however, its contact would not be observed within the 200 ms on the analysis due to their lower forward head displacement.

It is worth clarifying that 5th and 95th percentile occupants are not included in the regulation. Their use in the process chain aims to study the fuselage structural behaviour under the different inertia loads that may occur in a real cabin. Furthermore, LSTC FAST H3 ATD dummies provide limited accuracy due to their coarse mesh and curved spine, typical of automotive ATD.

Currently, the automatic postprocessing includes only the computation and visualization of lumbar load and head acceleration. The head acceleration is not itself an injury criterion, but its time-integral during head impacts is the so-called Head Injury Criterion (HIC). The implementation of methods to compute the complete set of injury criteria will follow the integration of higher fidelity aviation ATD in the process chain.

## 5 Conclusions

### 5.1 Results

The presented work aimed to expand the DLR pre-design process chain to account for crashworthiness and occupant injury assessment. The objectives of project ARCADIA are successfully met thanks to the new capability to generate full-scale and fully integrated aircraft models according to their parametric CPACS definition.

The in-house developed design environment PANDORA is employed as the base of this project and the new functionalities are added as new features of the existing program which is intensively used at the Institute of Structure and Design, for the creation of geometric models, finite element structural models, sizing, etc. The design environment employs a general algorithm to efficiently model generic aircraft architectures, thanks to the CPACS framework that allows a detailed description of different configurations under the same schema and ontology. The algorithm is continuously updated to ensure its general aeronautic application, accounting for each design novelty that new unconventional configurations may present.

The novel implementations consist of two essential parts. First, PANDORA is expanded with the feature to generate full-automatic adaptive models for the commercial solver LS-DYNA. The methodology used to model the primary structure is validated through a series of increasingly complex numerical benchmarks which are compared with results from the previous modelling methodology in use for a different proprietary explicit solver.

The study shows the comparability between the newly developed and the well-known previous modelling strategy.

Simultaneously, the low- and high-fidelity formulations available in PANDORA are extensively studied to highlight their strengths and limitations. Worth noting, the study is currently based on a purely numerical comparison; nevertheless, a comprehensive experimental validation of PANDORA-generated fuselage models is underway to evaluate the accuracy of the model results.

Secondly, to align with the project's emphasis on occupant safety, the passenger and first cabin environments are modelled as numerical dummies and meshed geometries, rather than simple lumped masses. A modular approach is defined to overcome the limitations posed in defining an automatic process chain by the necessary manual integration of dummies and the non-parametric geometric definition of the cabin environment in CPACS.

A set of pre-assembled FE models is defined including seats, dummies and cabin items. These fully defined models are stored in the PANDORA internal library in order to be successively employed as sub-models for the cabin environment generation. Each independent sub-model can be transformed and assembled automatically to compose any type of cabin layout, according to the aircraft CPACS parametric definition. The new modular approach is highly versatile and reliable to generate fully-defined FE models that can be directly run by the solver.

The process chain is successfully applied to generate the full-integrated and full-scale model of two representative aircraft designs described in CPACS, proving itself stable for each case.

As a first demonstration of the novel capabilities of PANDORA, a classical single-aisle cabin concept is numerically modelled and simulated. The simulation of a section containing 18 v-ATD is modelled in 4 min and it runs in 3 h. A crash scenario mentioned in the special conditions set for recent innovative aircrafts is modelled and an example of an automatic dummy postprocessing is presented.

The extended potential of the PANDORA tool, implemented and numerically validated under the project ARCADIA, is expected to accelerate the development and certification process of upcoming innovative aircraft and cabin concepts. Furthermore, the highly automated pre-processing for typical crashworthiness analysis and the resulting efficient model generation are fundamental features for potential future optimisation routines or advanced statistical evaluations of the cabin crashworthiness.

At the time of this publication, two major aspects limit the quality of safety assessments using the novel process chain. First, there remains the lack of an experimental validation of PANDORA-generated models in LS-DYNA. Second, the inadequate level of detail of seat and ATD model compromise the result accuracy, due to their primary influence on the injury metrics [28, 33].

### 5.2 Future works

Future development of PANDORA will cover two critical aspects: the predictive accuracy of generated models and the robustness of simulation results.

Two ongoing research initiatives focus on the accuracy and reliability of occupant safety analysis. A comprehensive experimental validation of PANDORA-generated LS-DYNA structural models is underway to verify the reliability of the presented modelling approach. Additionally, a multi-fidelity seat model, is being developed for the integration into the PANDORA environment, replacing the current numerical seat. The novel seat geometry is based on a state-of-the-art certified aviation seat, it is experimentally validated, and it maintains a modular design. However, the use of aviation ATD and detailed seat models sharply increases the runtime, that would lead to an unfeasibly long time needed to perform basic iterative analysis typical of the preliminary design phase. The problem is being addressed, with the development of an AI surrogate model trained on a small-scale detailed model of seat and ATD, to evaluate injury criteria based on the passenger's floor kinematics. This allows to decouple occupant safety evaluations from primary structure analysis, where simplified seat-dummy models are used only to load the structure.

Regarding the robustness of the simulation's results, the focus will be on the introduction of statistical methodologies for the estimation of the uncertainty in the numerical results. The crashworthiness assessment procedure introduced in this paper is until now fully deterministic. We believe that an approach based on Uncertainty Quantification and Management (UQ&M) statistical strategies will be necessary to bridge the gap between the existing tool capabilities and the regulatory bodies' certification requirements [34].

This natural development of PANDORA is facilitated by its already-established capability to create and run FE models fully automatically. Furthermore, the possibility of creating models of varying levels of fidelity is crucial for statistical campaigns in which a large number of simulations with multivariate inputs is often required. This extension of PANDORA will aim to empower its application in the field of certification by analysis.

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**Author contributions** Marconi L. wrote the manuscript and implemented the work. Kohlgrüber D. revised the manuscript and supervised the research project. Petsch M. developed the software PANDORA, which is extended in this paper. Wegener N. developed the methodology to pre- and post-process dummies which is used in this work.

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**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing interests** The authors declare no competing interests.



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