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Detailed FE aircraft fuselage sections for water impact simulations in the pre-design process chain

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Abstract. The automatic generation of representative fuselage section models with a detailed discretization for the application in computer-aided transient dynamic simulations in the aircraft pre-design process chains is described in this paper. The process consists of Python routines to select and reduce the section from the full fuselage and to refine the mesh and extrude cross-sections in arbitrary zones of the section. By this, different mesh qualities can be integrated in the model according to its individual application. These functionalities were integrated in the structural modelling and sizing framework PANDORA. A simple reinforced panel was used to investigate its structural behaviour with different discretization options under a bending loading condition. Also, a fuselage section model reinforced using either one of the discretization options was subjected to a quasi-static loading. The model was then simulated under crash conditions to investigate its non-linear structural behaviour. The focus of this paper lays on the application and the local structural analysis of the detailed fuselage section in water impact simulations.

1. Introduction

Accurate predictions in early aircraft design stages contribute to the assessment of different concepts, by this supporting the development of novel aircraft designs. Alongside top-level aircraft requirements including flight range, performance, and fuel consumption, assumptions regarding structural aspects must be complied according to certification requirements. To include all disciplines in the development of a novel model a multidisciplinary design process chain is required. An iterative and efficient approach in terms of cost and time is done by using a virtual process chain with different computer-aided tools, each dedicated to the generation of specific disciplinary inputs. Different structural design tools like PrADO (Preliminary Aircraft Design and Optimization) [1] or MIDAS (Multidisciplinary Interactive Design and Analysis System) [2] are found in the academic and research field. Applications like LAGRANGE [3] or FAME-W (Fast and Advanced Mass Estimation-Wing) [4] are used in the industry. Other multidisciplinary structural tools are described in more detail e.g. in [5].

The structural design must also be compliant to crashworthiness requirements. Besides the investigation of the aircraft for certain crash loading conditions, the aircraft manufacturer must demonstrate the behavior of the airframe in the case of a planned emergency landing on water, known as ditching. This event is characterized by high hydrodynamic loads at the impact and the presence of hydrodynamic phenomena during landing, which may affect the structural integrity and the kinematics of the aircraft resulting in decelerations experienced by the occupants. Ditching can be analyzed with experimental tests with sub-scale models, by comparisons with previous certified aircraft using

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grandfathering assumptions or virtually using computational methods. The latter offers advantages in terms of repeatability, parametric variation, and time and cost efforts. Virtual models can be calculated with low-fidelity methods using analytical or semi-analytical approaches or as a high-fidelity computation using advance numerical methods. A dedicated low fidelity virtual tool based on v. Karman and Wagner formulations for the analysis of ditching is DITCH++, developed at the Technical University of Hamburg [6]. This tool is integrated in the suit DFTS (Ditch Floatation Tool Suit) of the company IBK Innovation for the visualization and post processing of results.

At the Institute of Structures and Design of the DLR (German Aerospace Center) high fidelity Finite Element (FE) methods are used for structural and ditching analysis. Its Python-based multidisciplinary framework PANDORA (Parametric Numerical Design and Optimization Routines for Aircraft) incorporates functionalities for parametric modelling, sizing and high-fidelity static structural analysis [7]. In addition, PANDORA was extended for the generation of representative models for short time dynamic analysis with an explicit time integration schema, with special focus on fluid structure interaction (FSI) simulations [8]. In the past, simplified models in global FE quality (GFEM) were used on such applications. Motivated by the possibility to use generic models suitable to represent more precisely the structural behavior in transient dynamic simulations this work focuses on the integration of processes and features to automatically generate detailed FE models (DFEM) for the application in water impact simulations.

The first part of this paper explains the structural analysis in the scope of a multidisciplinary process chain and the numerical method used for high fidelity FSI calculations. The next section presents the extension of capabilities of the tool PANDORA for the generation of detailed models and related investigations. Then, the following section is dedicated to the application of representative DFEM sections in water impact simulations. Finally, conclusions of this work are provided in the last sections.

2. Structural aircraft fuselage analysis in a multidisciplinary aircraft design process chain

The design of generic aircraft models in the pre-design phase is performed at DLR using a multidisciplinary process chain embedded in a virtual framework. The disciplines contributing to the design interact with each other using the XML-based data format CPACS (Common Parametric Aircraft Configuration Schema) [9]. This schema allows to store data from individual design tools in specific discipline-related branches. Newly generated inputs can then be exchanged with other tools in the design loop by using the CPACS file. Structural related branches include geometry, structural description, loads, and materials. In this multidisciplinary process the structural analysis of the fuselage is performed using PANDORA. The tool has an interface to CPACS to retrieve its input which is then used for the visualization of the geometry model and for the generation of the structural FE representations for the numerical analysis.

2.1. PANDORA framework

The tool has been developed since 2006 with the philosophy to incorporate functionalities of individual structural tools on a single framework and for the continuous development of new functionalities. The framework is based on the python programming environment and built using a modular architecture with packages to perform specific operations [7]. Main applications are the estimation of the structural mass of the fuselage and the generation of high-fidelity models for quasi-static or transient dynamic calculations. In general, PANDORA uses the data stored in CPACS to generate a FE model. The mesh, properties, materials, boundary conditions and load cases are stored in an internal data format. By using conversion algorithms in the FE_CONVERTER package, the FE data can be converted to various proprietary code formats for numerical calculations. In addition to the model generation and conversion functions, PANDORA includes auxiliary packages for mathematical transformations, geometrical tasks or for the visualization of data in an integrated GUI (graphical user interface). Major packages of the framework and a visualization of an exemplary generated FE surface model are shown in Figure 1.

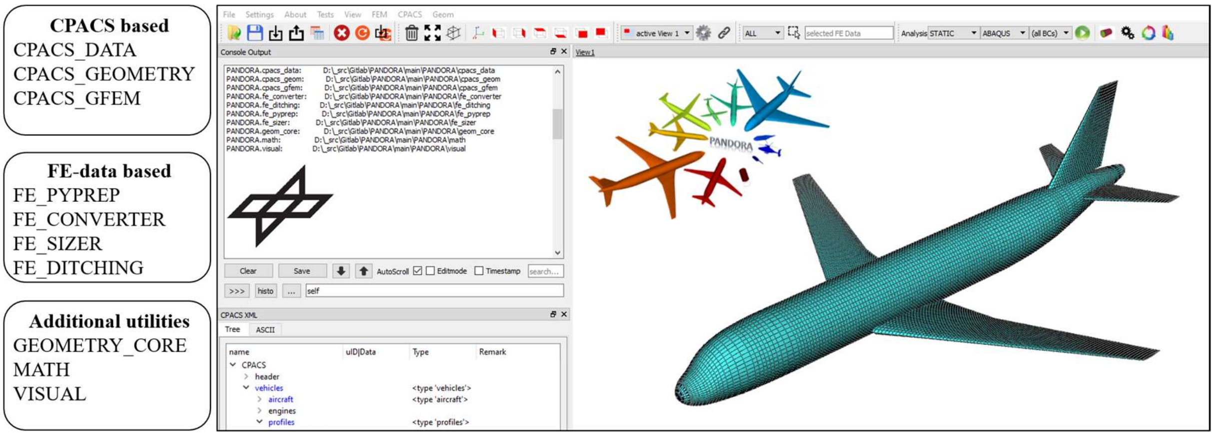

Figure 1. PANDORA framework. Left: main packages and classes. Right: FE model in the GUI.

For the structural crashworthiness analysis, the package FE_DITCHING was integrated based on the former DLR pre-processing ditching tool AC-Ditch. Python routines are used to generate a fluid domain and to include the equation of state and FSI features in a parametrical fashion, allowing to extend the functionalities to different fluid modelling approaches with method-specific inputs. The water domain is modelled according to the selected global dimensions as a basin in calm with a flat top water surface. The main modelling approach is hybrid, where the continuum is discretized in the impact zone by particles while the surroundings are modelled using FEs. The domain is fixed in space using boundary conditions. Further information about the functionalities for FSI is available in [8].

2.2. Numerical methods for fluid structure interaction calculations

During a water impact simulation, the hydrodynamic loads acting on the structural surface cause a non-linear behavior of the structure. Simultaneously, due to the nature of the impact the fluid is expected to show large local displacements. To solve this challenging multi-model problem a high-fidelity approach using advanced numerical methods and an explicit time integration schema is considered. The interaction between fluid and structure is handled in a monolithic two-way approach, in which in the same computation the fluid flow is affected by the structural displacements caused by the fluid pressure. The structure is modelled by FEs using a conventional Lagrangian formulation. Further, the fluid is discretized by a set of mesh-free particles using the Smoothed Particle Hydrodynamics (SPH) formulation, where the flow condition of each particle at any position is the weighted average of the properties of the neighboring particles estimated using a kernel function [10]. The coupling between both sub-models is achieved by a penalty contact formulation.

The highest computational effort of the multi-model is caused by the SPH domain. For efficient and affordable computations, particles are limited for the range of the fluid domain with the highest displacements while FE brick elements are applied in its boundaries and coupled to the SPH domain using a node-to-surface contact formulation. This type of approach also avoids numerical boundary effects that may occur in a full SPH pool. The coupled SPH-FE water impact model explained in this work is computed with the proprietary explicit FE code Virtual Performance Solution (VPS).

3. Detailed fuselage sections for water impact simulations

For transient dynamic simulations such as crash or ditching the refinement and level of detail of the mesh is relevant to sufficiently describe the large expected structural deformations and potential failure. However, calculations with full detailed models are associated with very long computational times and high computational resources, limiting the application of such models in the preliminary aircraft design phase. An automatic modelling approach to generate a representative fuselage section with a detailed discretization limited to critical areas of the structure was developed in the framework PANDORA. The foreseen application of this aircraft section is on affordable water impact calculations.

3.1. Model generation

The fuselage section is modelled following subsequent steps in an automatic manner using python routines. The process initiates with the generation of a CPACS-based fuselage model in GFEM quality, which means one quadrilateral shell element between a pair of stringers and frames. Reinforcements are represented by beam elements. A feature to select the fuselage section inside a box-like domain defined by inputs in global coordinates was implemented. Different types of elements or entities like nodes and property groups can be considered in the domain. For the selection three criteria are defined, including elements either with all its nodes, with only one of its nodes, or with its centre inside the domain.

The following step is to isolate the selected section from the rest of the FE model by reducing the FE data corresponding only to this section. Global entities like materials, properties and constraints are kept for the elements in the selected domain. Next is the refinement of the mesh by splitting elements with a predefined minimum length in a selected domain. In general, each refinement iteration divides in half the edges of the element. For this reason, usually more than one iteration may be used to reach the favoured mesh density. The interface between finer and courser mesh is modelled with quadrilateral and triangular shell elements to adapt the mesh.

In addition, a feature to extrude beam cross-sections to profiles modelled with shell elements was developed. This allows to include a three-dimensional representation of the frames, stringers, struts, cabin cross-beams and longerons. Tied interfaces are used to couple the adjacent surfaces of the extruded profiles with the skin. Furthermore, for models stiffened with a combination of extruded profiles and beam elements the intersection between both representations is coupled by nodal one-to-set rigid body coupling models. Finally, an option to include lumped masses attached to the structure was also implemented. Figure 2 shows the process to generate detailed fuselage sections with PANDORA. In total, the automatic generation of detailed fuselage section models is completed in less than one minute using a personal computer. Additional widgets were included also to launch the process using the GUI.

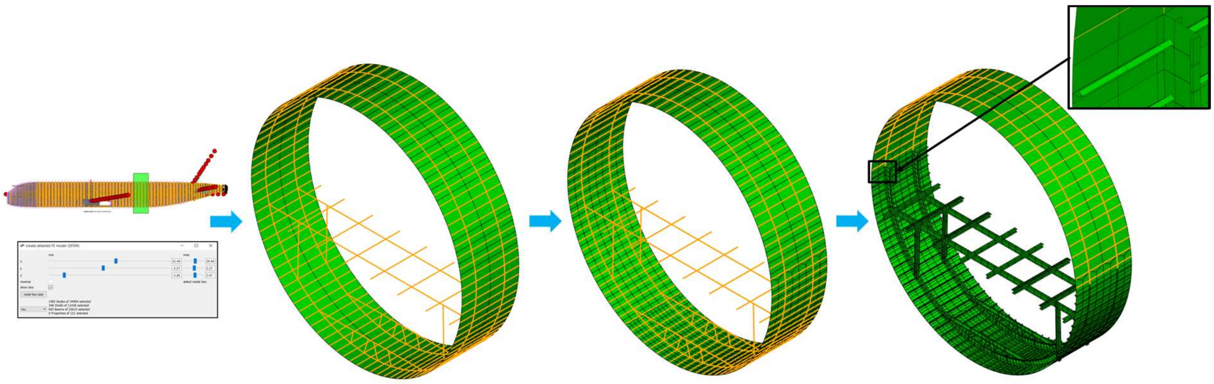

Figure 2. Stepwise DFEM fuselage section generation using PANDORA. Beam elements in yellow.

3.2. Investigations of the model

The investigations are based on the geometry and structural design of the generic metallic single-aisle short-range aircraft model D150 (Figure 1). Three reinforcement options are considered for the model generation, namely a purely beam or shell stiffening approach and a combination of both. For the basic verification of the reinforce options, a flat strip consisting of two rows of quadrilateral shell elements stiffened in longitudinal direction was modelled. The strip is clamped on one end and subjected to a single positive bending load of 0.1kN at the front central node. An unsymmetrical profile with a hat-like upper flange, similar to a standard stringer profile, was chosen for the reinforcement (Figure 3, left).

In a subsequent step a section of a length of 1066.8mm that includes the frames FR53 and FR54 in the rear fuselage of the D150 aircraft was chosen for investigations. The detailed modelling was limited to the bottom of the section below the cargo cross-beams. The section is subjected to a load of 1kN on the upper two stringers of the section and clamped on the bottom centerline. Again, the three reinforcement options were considered. For the partially extruded section, extrusions were limited to the lower half of the section. In Figure 3, right, the beam-stiffened fuselage section is exemplary presented.

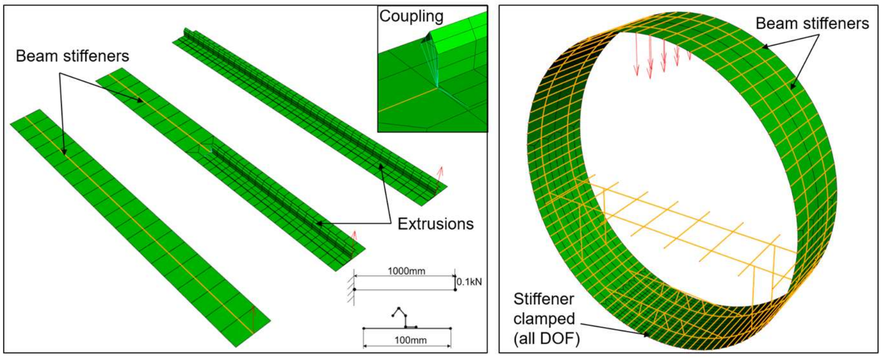

Figure 3. Models investigated under vertical loads. Left: strip stiffened with three discretization options. Right: exemplary detailed fuselage section.

Since the final application is on transient dynamic simulations, computations were launched using an explicit time integration schema with a linear increasing load over 1000ms to reach the final loading condition, which is then kept constant until 2000ms. In Figure 4 the contour plot and the time history plot of the nodal vertical displacement are presented for each model, respectively. Results are compared to a quasi-static calculation using a proprietary implicit solver.

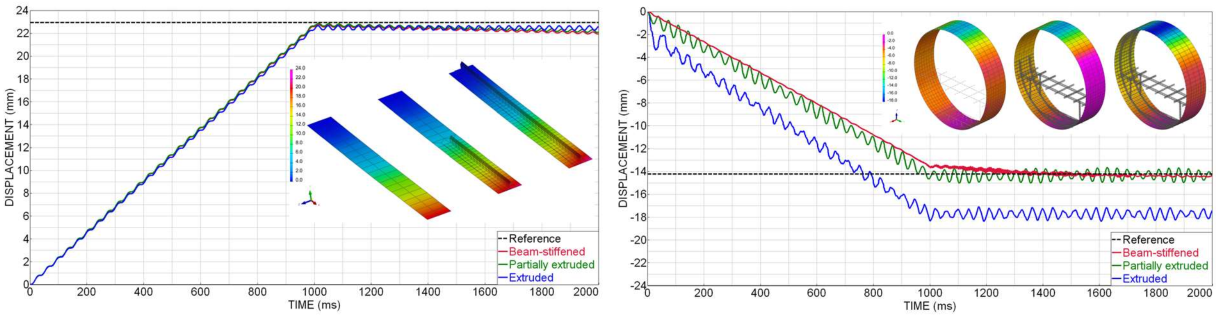

Figure 4. Time history plot and contour plot of the vertical displacement (at 1500ms) from the quasi-static calculations using different discretization options. Left: front central node of the stiffened strips. Right: topmost central node of the section. Reference values (strip / section): 22.94mm / -14.23mm.

Results show a very good agreement of the differently stiffened reinforced strip compared to the reference when the final vertical load is reached. Oscillations occur due to the nature of the explicit calculation. The stripe with the fully extruded cross-section reveals a slightly higher displacement of the right front corned due to the unsymmetrical profile compared to the applications with the simpler beam elements. In general, the behavior of the strip is comparable for the three modellings approaches, proving the application of the three different discretization approaches by the tool.

For the quasi-static calculation using the fuselage section, on one side, results from the partially extruded and the beam-stiffened sections are comparable to the displacement calculated by the reference. Also, the contour plots for both models show a similar behavior of the section under this loading condition. On the other side, the vertical displacement of the model including the fully extruded cross-section is around 30% higher than the partially extruded and the beam-stiffened models. The deviation in the displacement can be associated with the mesh size of the skin at the top half of the section and to the related tied interface. For the application in transient dynamic calculations the detailed zone is focused on the bottom area, with the possibility to use a simpler discretization in the upper part of the model. Nevertheless, these deviations must be considered in further investigations.

3.3. *Transient dynamic scenarios*

The detailed FE fuselage section introduced previously for quasi-static calculations was used for a vertical drop on a rigid surface in a transient dynamic simulation over 200ms. In the model secondary masses located inside this section were considered and attached to the structure. Two scenarios were simulated, one with passengers and carry-on masses and another with additional masses for the unit load devices and their content, adding 477kg to a total mass of 1664kg. Further, comparisons were carried out between the fully beam-stiffened and the partially extruded section. The impact velocity was $8ms^{-1}$. Exemplary results of the simulation with the section excluding cargo masses are presented in Figure 5.

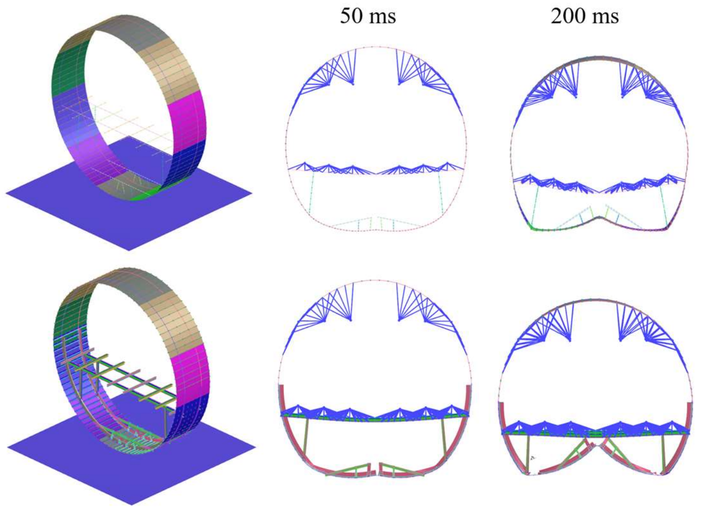

Figure 5. Vertical drop case model. Left: detailed fuselage section and impact surface at 0ms. Masses hidden for visualization of the discretization. Right: front view of the sequence of the simulation. Top: fully beam-stiffened section. Bottom: partially extruded section. The nodal mass attachment using an interpolation constraint is depicted in blue.

Results show a similar structural behavior between the beam-stiffened and the partially extruded section. At 50ms, right after the impact, the failure of the cargo cross-beams is evidenced in both models, resulting in a local bending of the fuselage skin. Later in the simulation, at 200ms the plastic deformation of the section is especially notable at the base of the cabin floor struts, also due to the inertial loads. For the partially extruded model the bending of the bottom surface is higher compared to the beam-stiffened model. This is due to the failure on the stiffeners which are more accurate represented using the shell models than the simpler beam representations. In the case of the section including cargo masses, the bending of the bottom section is counteracted by the vertical loading of the masses located above the center part of the cargo cross-beams. Also, a higher concave bending of the cabin floor structure was observed. However, the structural behavior was similar for both sections.

The simulations were launched using a personal computer. For the beam-stiffened section the elapsed time was less than a minute, while the partially extruded section took around 7 minutes to be concluded. In general, the model using beam elements is in good agreement with the partially extruded model in the vertical crash simulation. The faster calculation with the beam-stiffened approach is beneficial for the application of the model in a water impact, where generally lower structural deformation is expected.

4. Application in water impact simulations

A beam-stiffened refined fuselage section based on the metallic D150 aircraft model and a representative pool were generated using PANDORA for a vertical water impact simulation over 200ms. The length of the section is 2152mm and includes the frames FR53 to FR56 in the rear part of the fuselage. The finer mesh is located in the bottom area of the section, with 8 elements between a pair of frames and 2 elements between a pair of stringers. The total mass of the structural model including secondary cabin and cargo masses is 2734kg. The water domain was discretized using the hybrid SPH-FE approach. The core of the pool is modelled using over 550k SPH particles and has as an extension of 8600mm. The surroundings consist of around 630k FE volume elements. The total length, width and depth of the pool is 6400mm, 11600mm and 2000mm, respectively. The impact velocity is 3.8ms^{-1}, similar to the sink rate from the Hudson river accident [11]. The model was calculated in a computer cluster using 48 cores. The model and two plots of the simulation sequence are shown in Figure 6. Results of the structural response of the section to the hydrodynamic loads are presented in Figure 7.

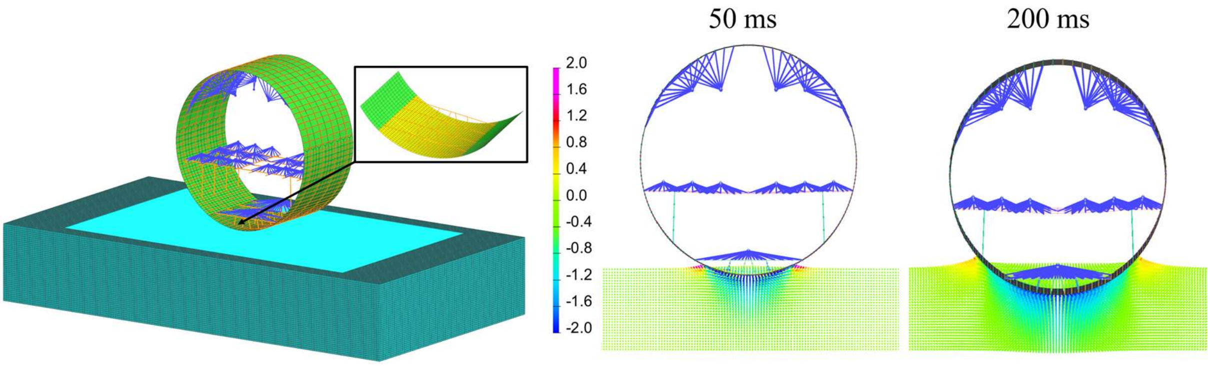

Figure 6. Left: vertical water impact model at 0ms. Refined bottom area in yellow. Right: front view of the sequence of the water impact simulation. Contour plot of the vertical particle velocity in ms^{-1}.

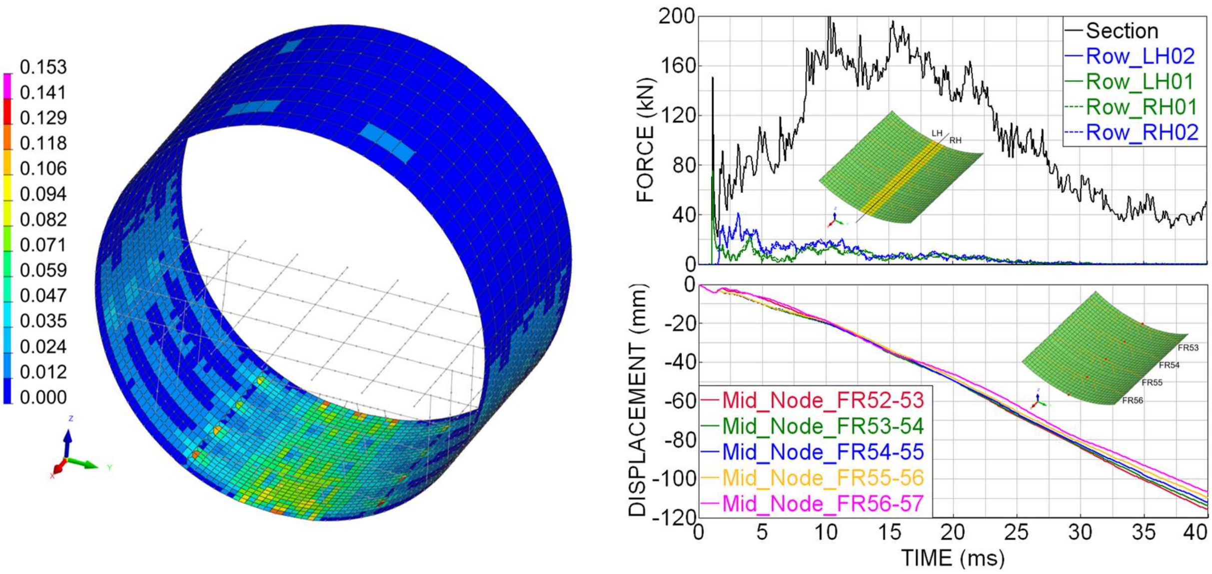

Figure 7. Left: contour plot of the v. Mises stress in the shell elements at 10ms. Right: Time history plots. Vertical contact forces of the fuselage section and of selected element rows in the longitudinal direction (top). Displacements in vertical direction of the bottom nodes between frames (bottom).

Compared to the crash on solid ground with a higher impact velocity, only elastic deformations are visible for the water impact (Figure 6, right). Different stress levels can be identified between frames and stringers in the finer mesh, with the highest local stresses located in the bottom area at the front and rear end of the section (Figure 7, left). In the first 10ms this behavior is also observed with the higher outer nodal displacements compared to the mid bottom nodes (Figure 7, right-bottom). After 35ms the fuselage section slightly rotates around the transversal axis resulting in the continuous differences in the vertical displacement. Since the impact occurs with symmetrical initial conditions, the first part of the section impacting the water corresponds to the lowest mid stripes of the bottom area, showing these the highest picks in the vertical contact force (Figure 7, right-top). In addition, this plot illustrates the highest energy absorption in the first 30ms, decelerating the motion for the rest of the simulation.

The fuselage section and the water domain were generated in less than 4 minutes on a personal computer. The total elapsed time on the cluster was of 3.5h. In general, the generation of more detailed fuselage section models increase the information about the local structural response of the model in transient dynamic simulations significantly. Additionally, the comparably low computational times makes the approach of using more detailed section models feasible in the pre-design loop.

5. Conclusions

A fast modelling approach to generate representative fuselage sections with a finer and more detailed discretization within the PANDORA tool is presented in this work. After the generation of a classical GFEM model the extended process consists of element selection, model reduction, element splitting and optional extrusion of the beam cross-section. Investigations using beam-stiffened models or partially extruded reinforcements demonstrated to be in a good agreement with the reference and to show comparable structural behavior in different transient dynamic scenarios. In water impact simulations, the finer represented bottom area is relevant to sufficiently describe structural deformations while the low model generation time and moderate computational times demonstrates the feasibility for the application in the aircraft pre-design phase, also in an industrial driven environment. In a further step, the development modelling and simulation method will be transferred to a full aircraft ditching model.

Acknowledgments
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