

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

D. Schwinn, J. Scherer, D. Kohlgrueber, K. Harbig

German Aerospace Center (DLR), Institute of Structures and Design (BK),
Department of Structural Integrity (SI),

Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

Dominik Schwinn, Aeronautical Engineer

THEME

Analysis Management – Automation of Analysis

SUMMARY

In the preliminary design phase of an aircraft development trade studies are conducted to find an optimized design for an aircraft fuselage which calls for fast and efficient model generation.

Based on the standardized aircraft description format CPACS, a fully parameterized fuselage modelling tool was developed to generate global aircraft FE models for static sizing using shell elements for the skin and elastic beam elements for reinforcements and the floor structures.

For a subsequent investigation of the crash behaviour the models can be refined locally in the expected impact regions by the use of fine shell elements to account for energy absorption methods - plasticity in case of a metallic or damage introduction in case of composite construction. Likewise some other regions may be modelled using a fine shell element mesh, e.g. the door surround structure which must not deform plastically in survivable crash load cases to assure its function as an emergency exit.

In this paper the process chain and its data processing methods are presented in detail. Also benchmark tests for model generation were conducted and evaluated. Concluding, an outlook shows possible further development steps and potential future applications.

KEYWORDS

Mesh generation, sizing, crash simulation, parameterized modelling, process chain

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

1: Introduction

Changing environmental conditions lead to a need to reduce emissions caused by traffic. Besides the development of new aero engines the reduction of structural mass is a key driver in reducing fuel consumption.

One approach is the use of multidisciplinary optimization: As an aircraft is a highly complex vehicle combining multiple disciplines, e.g. structures, aero- and thermodynamics, aero-elasticity and many more, engineers in general and designers in particular as well as airlines desire an optimized global solution. Howe calls this process of aircraft design “a complex combination of numerous disciplines which have to be blended together to yield the optimum configuration to meet a given requirement” (Howe, 2000).

Therefore the design process for a new aircraft is an iterative development which can be divided into three major phases (Raymer, 1992; Hürlimann, et al., 2011):

- Conceptual design,
- Preliminary design and
- Detailed design.

In the conceptual design phase the viability of different designs is investigated with respect to market and customer requirements respectively. This phase is mainly driven by the creativity and experience of the designers, as also very unconventional approaches are investigated, as well as new ideas and technologies. The conceptual phase usually ends with the identification of suitable aircraft designs.

Consecutively, in the preliminary design phase, these selected aircraft designs are evaluated and benchmarked regarding their performance. The objective of the preliminary design phase is to create a loft and to find an optimal design which will then be investigated in detail in the final period – the detailed design phase.

Due to the nature of the different design phases it is most cost effective and less time consuming to alter the design during the preliminary phase. Thus so-called trade studies are conducted in this period. The high amount of required computations calls for fast and reliable tools. Despite the computational power which is nowadays available, the generation of an appropriate FE model still takes a lot of time, even though some models are very similar to each other.

As disciplines influence each other, multidisciplinary approaches during the preliminary design phase become state-of-the-art. Exemplarily mentioned is

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

the versatile influence of statics and dynamics. The aircraft has to be sized according to static load cases, e.g. the deformations of the structures must remain in the elastic region as plastic deformations call for repair and downtimes respectively. Contrary in case of an emergency landing the high kinetic energy should be reduced by transformation into deformation energy – either by plastification in case of metallic or damage initiation in case of composite structures. If the structure is designed too stiff the resulting impact forces could be lethal for the passengers. On the other hand, if the structure is too deformable, load cases like gusts or landing shocks could deform the structure plastically.

In this paper the development of a parameterized process chain will be presented which automatically generates FE (Finite Element) models for static sizing as well as dynamic crash computation.

2: CPACS

If a multidisciplinary approach is used, a need arises for a common interface which couples the different analysis tools. This common interface is a basic standardized aircraft description which serves as in- and output respectively for all involved design tools. This interface also serves as a common language between the tools. Thus the possibility of errors with respect to e.g. reference values, units, coordinate systems, sign conventions is drastically reduced.

DLR started work on coupling multidisciplinary tools in 2005 in the TIVA (Technology Integration for the Virtual Aircraft) project. In the course of this project CPACS (Common Parameterized Aircraft Configuration Schema) was developed (CPACS, 2013).

CPACS is a XML-based (Extensible Markup Language, (XML, 1996 - 2003)) database which was designed to host relevant data for numerous disciplines in a common dataset. The main advantages of XML are its hierarchical data structure which allows for good data mapping and its representation in ASCII making it easy to handle. To each *.xsd file a corresponding *.xml file is linked. While the *.xml-file hosts the values, the *.xsd file contains the corresponding schema which serves as validation reducing the risk of using invalid or inconsistent data respectively.

CPACS does not only contain the geometric data of the initial aircraft configuration but also tool-specific parameters, i.e. specific data necessary to run certain analysis tools. An extract from the CPACS schema is depicted in Figure 1.

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

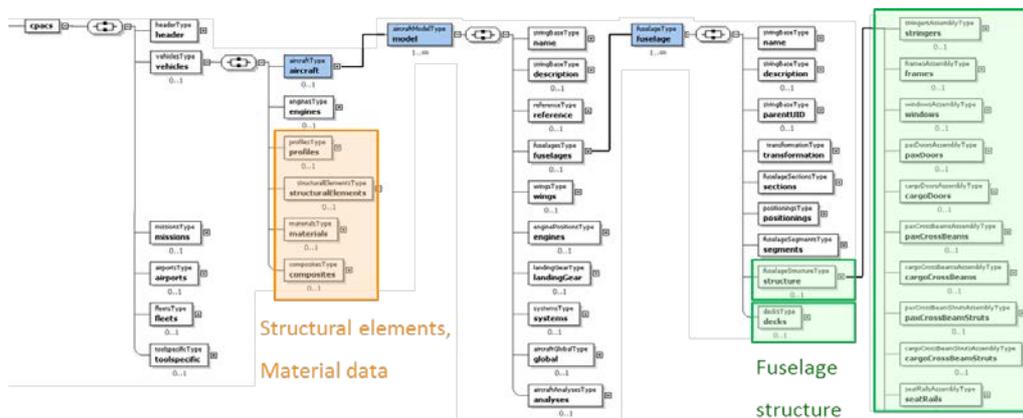


Figure 1: CPACS schema (extract)

The individual analysis modules building the toolset of the environment are located on locally distributed servers at the corresponding DLR institutes, thereby enabling the discipline experts to perform maintenance work on the program code as well as monitoring the calculations which results in a black-box system to all other users (Zill, et al., 2012).

As CPACS is a parameterized schema the user can easily alter the parameters for the computation of different aircraft configurations. This circumstance turns CPACS into a powerful tool for the preliminary aircraft design.

Two important libraries have to be mentioned too as they are an integral part of the data processing chain:

- **TIXI (TIVA XML Interface)**, which was developed to simplify the access to the central data format and to shield the application developer from dealing with the complexities of XML structure handling and
- **TIGL (TIVA Geometric Library)**, which was developed to easily process the geometric information in CPACS files. By the use of TIGL functions it is possible to directly execute geometric functions on the fuselage and wing geometries.

It should be noted that the development of CPACS is not solely sufficient for a multidisciplinary approach without the development of a corresponding infrastructure which is able to use all the mentioned benefits. Further information about the development of the corresponding integration framework, TIXI and TIGL can be found in (Liersch & Hepperle, 2011; Bachmann, et al., 2009; Bachmann, et al., 2010; Rizzi, et al., 2012; Zill, et al., 2011).

NASA developed a similar tool named VSP (Vehicle Sketch Pad) using XML and recently published it Open Source (OpenVSP, 2012; Hahn, 2010;

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

Fredericks, et al., 2010). A basic comparison between both tools is conducted in (Liersch & Hepperle, 2011).

Until today CPACS, which is in operational use by all DLR aeronautical institutes, is under steady development with continuous enhancements. The current released version is 2.01 and the official release for version 2.1 is planned for early 2013.

3: Process Flow

This section gives an overview of the software development as well as of the process flow and the data management from the initiation of the process chain to the evaluated results.

For the development and versioning of the process chain source code and tools respectively, a repository (Repository, 2013; Distributed Revision Control, 2013; Apache Subversion, 2013; Apache Software Foundation, 2012) is used. Figure 2 shows how this technique is applied. The tools TRAFUMO (static sizing) and AC-CRASH (crashworthiness proof) will be introduced later.

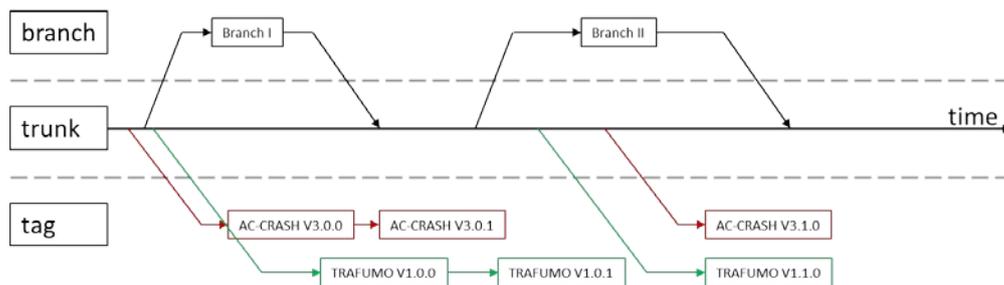


Figure 2: Repository workflow

The main development is done using the trunk folder. As soon as a tool gets released a tag will be created. All files in this tag refer to a certain distinct version of all files and tools, i.e. the files in the trunk folder may be altered but the tag always refers to the version of the corresponding files in the past, e.g. tool releases are tag versions. The branch folder is used parallel to the trunk folder if special developments have to be conducted which may influence other developments. After the problem or development step has been resolved in the branch version, these files have to be merged back to the trunk folder to grant further development.

The overall process flow of the multidisciplinary process chain is illustrated in Figure 3. Assuming that an initial CPACS dataset is given (by statistics or by the use of handbook methods), the static sizing process is conducted which leads to an optimized structure which then will be stored in a new CPACS file. This new CPACS file will then be computed regarding its crashworthiness. If

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

the results match the aviation authorities' crashworthiness requirements (FAA, 2013; EASA, 2013), the detailed design phase may be initiated. If the crashworthiness proof fails, the static sizing has to be conducted again by adapting the design variable limits.

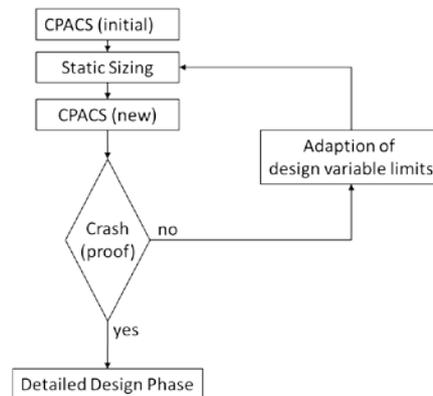


Figure 3: Overall process flow

Figure 4 and Figure 7 indicate the process flow for TRAFUMO (TRansport Aircraft FUselage MOdel) and AC-CRASH (AircrASH).

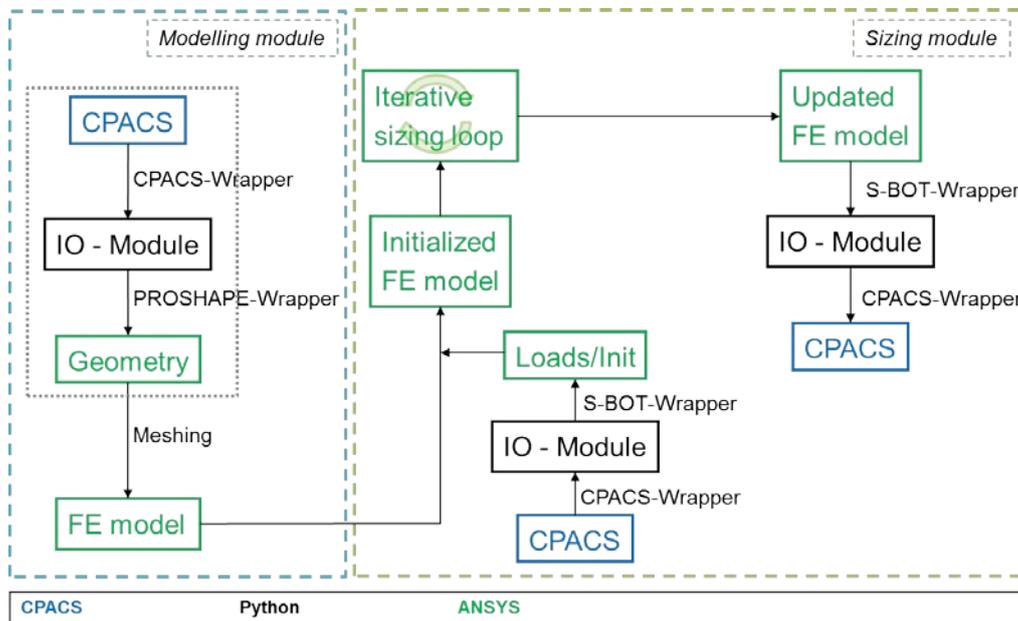


Figure 4: Static sizing process flow

The chain starts with the initialization of the CPACS-Wrapper. All the data in the CPACS file gets stored internally in Python lists and dictionaries, called Input/ Output modules (IO-Module). Thus all model information can be accessed much faster (compared to opening CPACS, reading the relevant

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

information and closing the CPACS file each time the chain requires CPACS data).

After all information is stored in the IO-Module, the PROSHAPE-Wrapper gets initialized executing two main operations:

- Calculation of beam properties: The PROSHAPE-Wrapper reads the specified profiles, creates the section definitions in ANSYS, computes their properties, e.g. cross sectional area, moments of inertia, centers of gravity (exemplarily see Figure 5) and writes them to a file (one file for each profile). For the crashworthiness proof these files get read later on by the PAMCRASH-Wrapper when writing the part input cards.
- Generating the geometry: This operation is the main operation and will be described in detail subsequently.

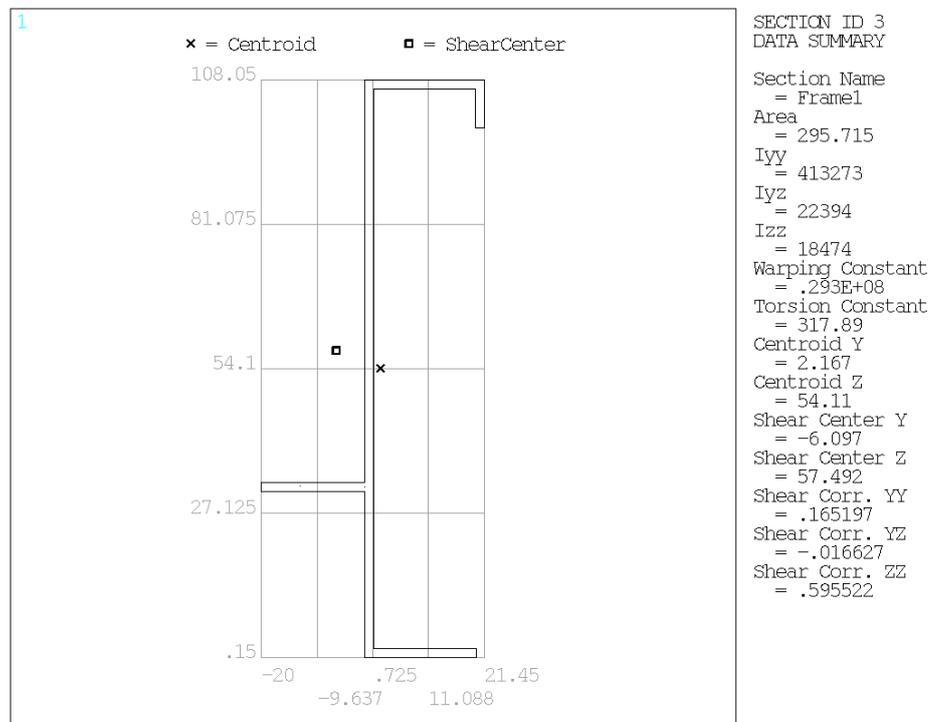


Figure 5: Computed beam properties of a generic frame profile

The geometry generation starts with the creation of the loft. The frames and the splined stringers are generated creating key points at their intersections. Every key point receives its own unique OID (Object ID), so each subsequently generated geometry can be addressed to this point – independent of the amount of structural components that have to be generated.

After the generation of the loft, frames and stringers, the inner airframe structures get created. Due to the hierarchical approach and parameterized

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

description of these components, these components are put on the OIDs which supersedes the knowledge of the corresponding key point numbers.

The following schema, which corresponds to the grey dotted box in Figure 4 and Figure 7, may be helpful in understanding how the different wrappers and files interact during geometry interaction.

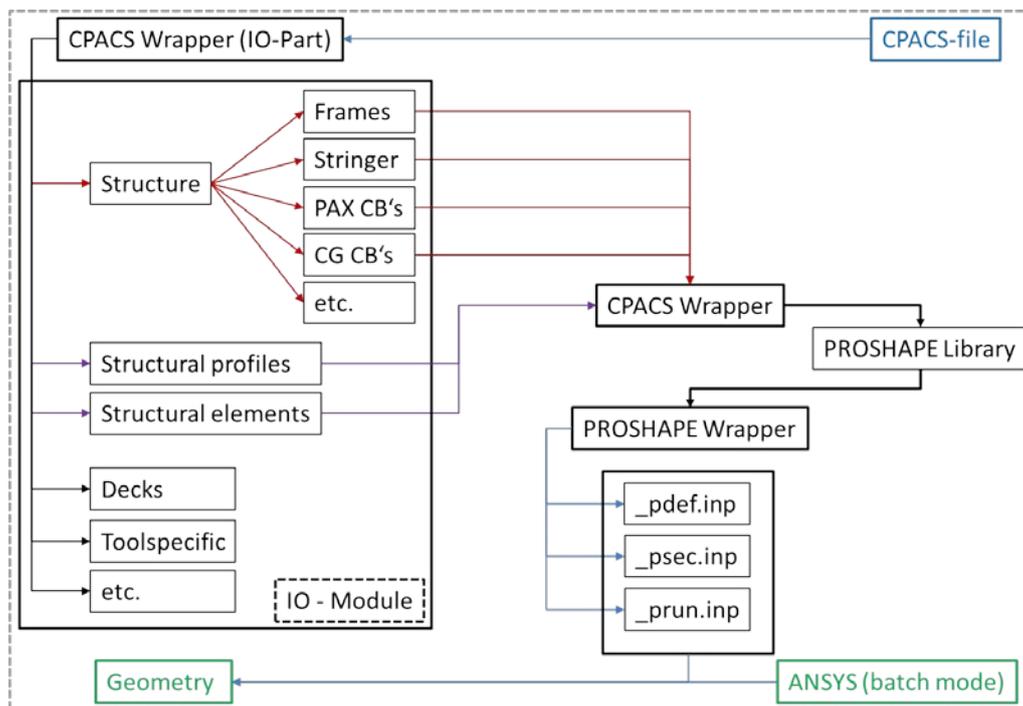


Figure 6: Process flow during geometry generation

Figure 6 indicates that the CPACS-Wrapper serves as an interface between the model data (IO-Module) and the PROSHAPE-Wrapper which writes the input files (`_pdef.inp`, `_psec.inp`, `_prun.inp`) for the ANSYS batch run.

Being given the basic geometry and beam properties of the structural components, the TRAFUMO model generator tool adds specific material properties and initializes the corresponding material models defined in CPACS, before the meshing of the static model on global level is done. The fuselage FE model is completed by the following adding of CPACS-defined secondary masses and master nodes for the introduction of wing and empennage loads and stored to a `*.db` ANSYS format file.

This file is the basis for the following sizing procedure carried out by the APDL (ANSYS Parametric Design Language) based S-BOT static sizing module (Sizing RoBOT, see 4: Static Sizing). S-BOT initializes the sizing run by generating specific load and input files from the data defined in CPACS, again making use of the CPACS-Wrapper and the IO-Module, as well as a S-

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

BOT-Wrapper module. According to the given load cases the FE models' element properties are adapted during the iterative sizing loop until convergence or the maximum number of iterations allowed is reached.

Finally the updated FE model is analysed by the S-BOT-Wrapper and changed properties are transferred to the original CPACS file using the output functionalities of the CPACS-Wrapper and the IO-module respectively.

After the static sizing run has been finished, the crashworthiness computation is initialized. The generation of the geometry proceeds exactly like for the static sizing run, except that the basic CPACS file is the optimized one.

Figure 7 explains the AC-CRASH process flow in detail.

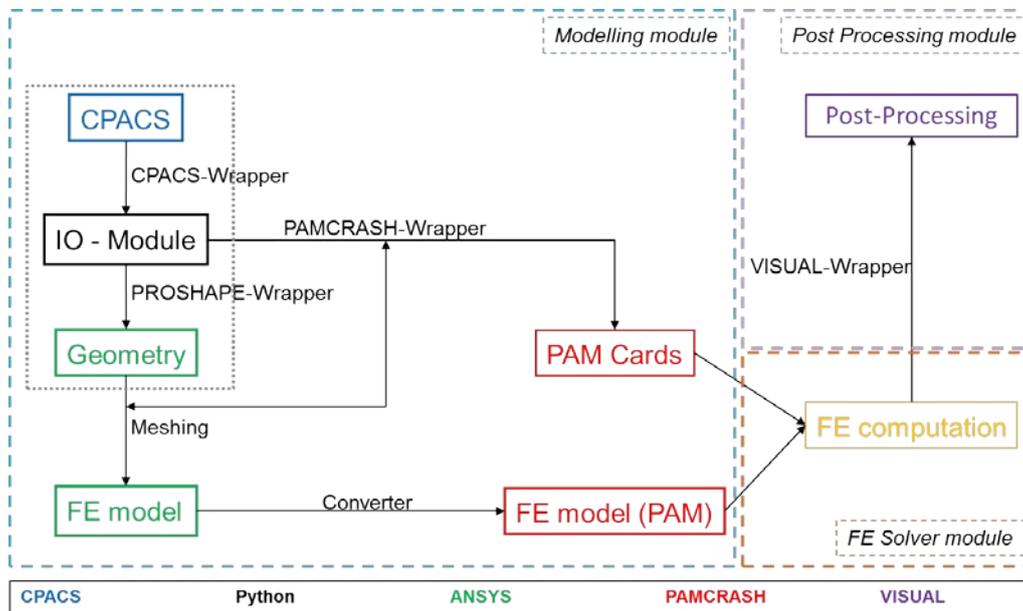


Figure 7: AC-CRASH process flow

After the generation of the geometry model has been completed, the mesh process starts by calling the mesh routine defined in the PAMCRASH-Wrapper. In advance of the meshing command, all structural components (uID's – unique ID) are investigated regarding:

- Component name
- Discretization method (element type)
- Structural profile
- Material
- Thickness

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

This step is necessary as these five parameters mark parts in PAMCRASH. In order to group all similar parts (respectively all elements) giving them the correct properties the PAMCRASH-Wrapper needs to create a relation between the part number and the structure transferring this information to ANSYS.

At this point in the process chain all the required boundary conditions for PAMCRASH are written. This process includes material cards, contact definitions, tied interfaces, load conditions etc.

Subsequently the meshing process itself is initialized: ANSYS selects all uID's forming the corresponding part number and meshes them allocating all elements of this part to the corresponding same REAL number.

After all generated geometries/parts have been meshed the FE model in the *.db ANSYS format is finished. The model file is – internally by ANSYS – written as a *.cdb file which in turn can be read by the in-house converter translating the file to the *.pc PAMCRASH format.

When the mesh is generated, the PAMCRASH-Wrapper checks the model for the interfaces between shells and beams at the detailed region boundaries (see 5: Crashworthiness Proof): The corresponding nodes are stored to a file for each interface. These files are read and reprocessed later generating the MTOCO Cards (Multiple nodes To One Nodes COnstraint, see 5: Crashworthiness Proof) for PAMCRASH. This process has to follow the actual meshing process as node numbers have to be defined first before of the MTOCO cards can be done.

As the passengers are modelled as mass points, the same circumstance acts for the generation of the nodal masses. For writing the mass cards, the corresponding node numbers have to be known. That is the reason why this process is conducted after meshing the model.

4: Static Sizing

This section describes the functionality of the static sizing module and the different tools involved.

The static sizing module consists of the model generator TRAFUMO and the structural analysis and sizing tool S-BOT.

The aim of the static sizing module is to transfer an arbitrary fuselage CPACS definition from being described with initial (knowledge based) structural properties, which is often the case in early design stages, to a more realistic one by analysing and updating its properties with respect to a given set of load cases defined in CPACS, thus forming a basis for the subsequent crash analysis.

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

The process flow of the static sizing module is as follows (see Figure 4): First TRAFUMO generates a FE Model of an arbitrary transport aircraft fuselage including external loads and added masses, making use of the ANSYS pre-processor PREP7 as well as the PROSHAPE toolbox developed at DLR-BK, that extends the functionalities of APDL (Harbig, 2010). Then the S-BOT-Wrapper module generates the load files and the S-BOT pre-processing routine initializes the model for the subsequent sizing. Next, the iterative sizing loop is started. In this loop all defined load cases are analysed and the sizing itself is performed. After each loop the new properties (material thicknesses) are applied to the model until convergence is reached. Finally the output files are generated and the new model properties are written to CPACS.

In the current version the following structural components are modelled:

- **Skin:** The skin is modelled using shell elements. The properties (material selection and sheet thickness) are defined according to the different panel definitions in CPACS. Default panel properties are used for any skin element not included in the panel definitions.
- **Stringers and frames:** Stringers and frames are discretized using beam elements, which are modelled along the fuselage skin as defined in CPACS. The properties of the beam elements are calculated automatically from the corresponding definition of the beam cross sections in CPACS (see Figure 5).
- **Floor structures:** Floor structures are modelled using beam elements as defined in CPACS. Both floor structures (PAX (passengers) and cargo) comprise of crossbeams, support struts and longitudinal rails. The properties of the beam elements are calculated automatically from the corresponding definition of the beam cross sections in CPACS (see Figure 5).
- **Bulkheads:** The pressure bulkheads of the fuselage are positioned at a predefined frame. The bulkheads are modelled as a combination of shell and beam elements as defined in CPACS. In addition to the bulkhead membrane definition a set of beam reinforcements may be defined. In this case the properties of the beam elements are again calculated automatically from the corresponding definition of the beam cross sections in CPACS.
- **Centre fuselage area:** A simplified modelling of the complex centre fuselage area, comprising center wing box, main landing gear bay, pressure bulkheads and the keel beam, is implemented as standard in the current version of TRAFUMO. This complex region is simplified as a cut-out in the fuselage which is later defined as a rigid region by using constraint equations.

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

- **Doors and windows:** In the current version of TRAFUMO fuselage cut-outs such as PAX doors, cargo doors and windows are not modelled. These structural components may be considered as additional masses in the global structural analysis. A more detailed representation of these cut-outs shall be added in future versions of TRAFUMO.
- **PAX and seats:** PAX masses and seats are not modelled explicitly (in contrast to the fine section model in AC-CRASH, see section 5: Crashworthiness Proof). However, the corresponding mass can be considered in the list of additional masses.

In Figure 8 – 10 some exemplary pictures of a TRAFUMO mesh, generated on the basis of a standard single aisle aircraft, are presented.

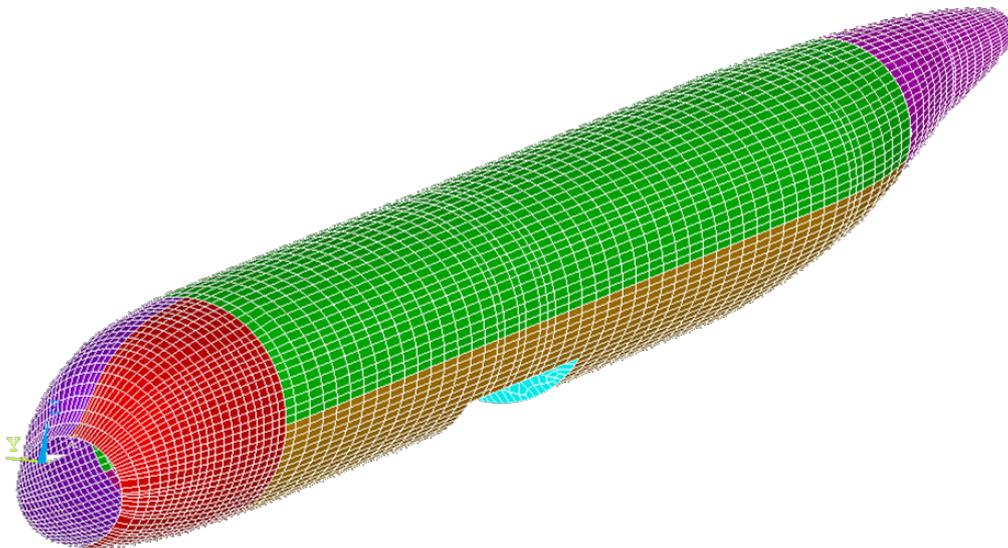


Figure 8: Fuselage model (skin) with few different panels on the outer surface

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

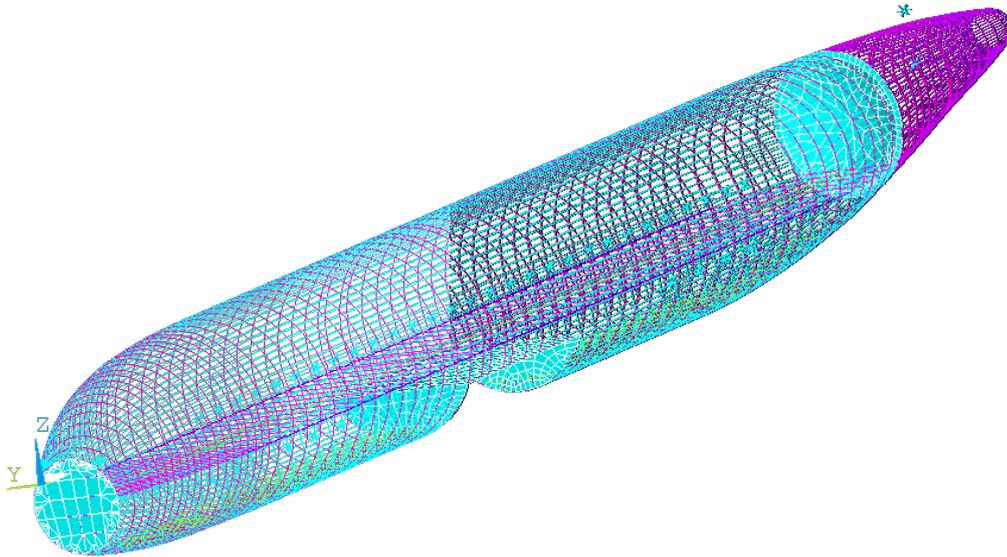


Figure 9: Fuselage model showing beam elements (skin removed)

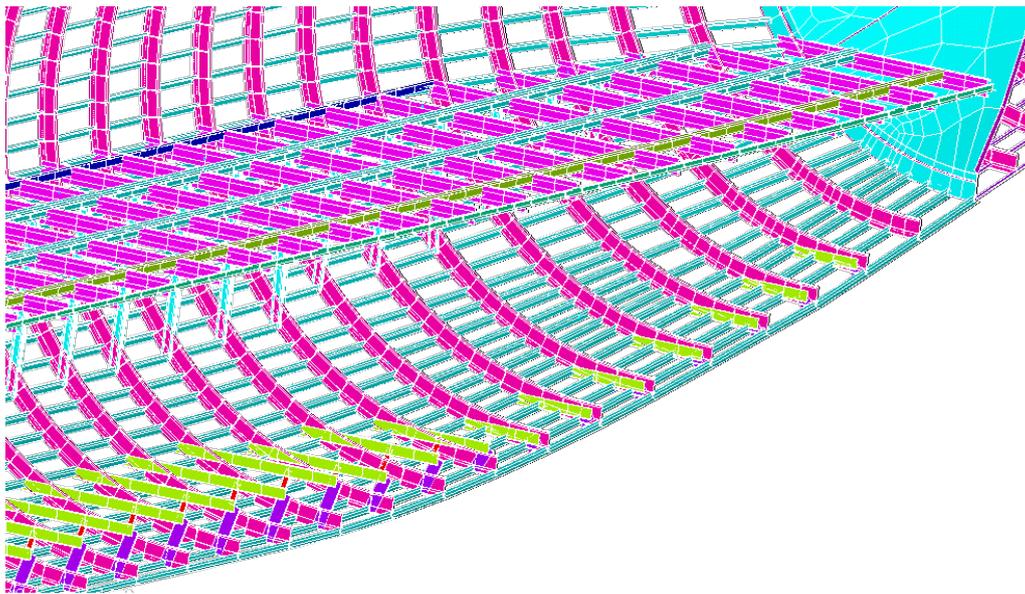


Figure 10: Beam elements with display of cross sections (/ESHAPE option)

In addition to the mesh generation, added masses as well as external loads are modelled. The wing, the horizontal and vertical tail plane are substituted by so-called master nodes which are used to add the respective wing masses and to introduce the external loads. Each master node can be loaded with three forces and three moments. The external forces are distributed to a certain area in a simple way by defining a so-called rigid region. In ANSYS all nodes in this rigid region are coupled using constraint equations. In Figure 11 the tail section

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

of the aircraft fuselage model with the external horizontal and vertical tail plane force and the corresponding rigid regions is illustrated. Additionally a constant acceleration field acting on the entire fuselage and static pressure acting on the fuselage outer shell between the forward and rear pressure bulkheads can be applied.

For each load case the actual values for the external forces, the acceleration field and the static pressure are read from CPACS and written to a separate load file by the S-BOT-Wrapper during S-BOT initialization.

An arbitrary number of non-structural masses (static masses) can be added to the fuselage (incl. systems, seats, PAX, cargo, etc.). Each static mass definition consists of a scalar value of the mass and a centre of gravity in global Cartesian coordinates. In the current version of TRAFUMO each static mass is distributed over a certain selection of nodes using RBE3 constraints (Figure 12). The selection of nodes to which the added mass is distributed is defined in CPACS.

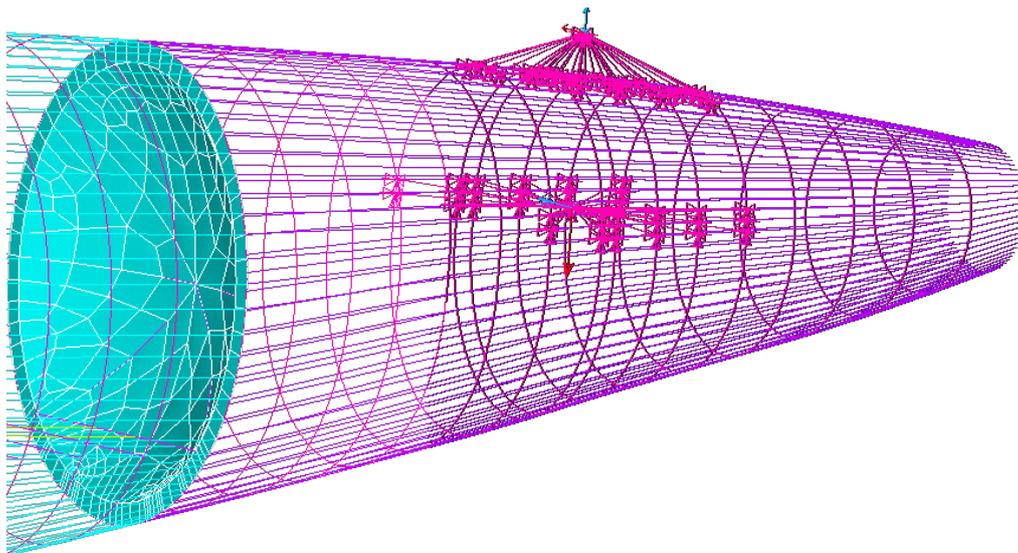


Figure 11: Fuselage tail section with HTP and VTP forces and corresponding rigid regions

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

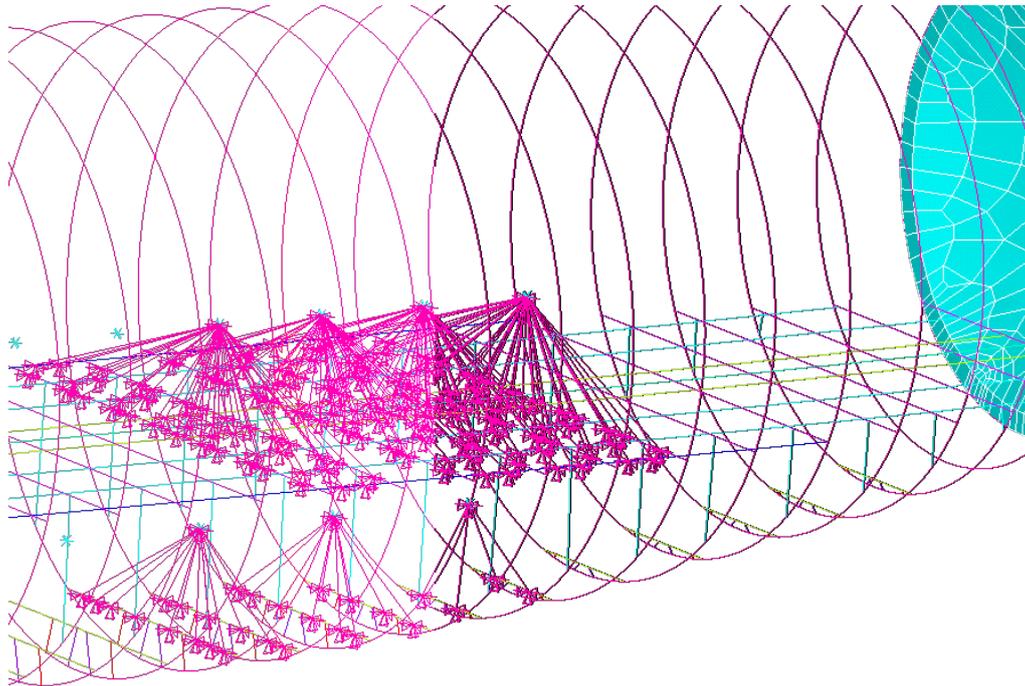


Figure 12: Illustration of the distribution of 4 passenger and 3 cargo masses via RBE3 constraints

The static analysis and sizing tool S-BOT is implemented in APDL and has originally been developed by the DLR Institute of Composite Structures and Adaptive Systems (Nagel, et al., 2006; Nagel, et al., 2008). For fuselage sizing purposes it has been adapted at DLR-BK (Scherer, 2011). The additional inputs needed for the sizing run and the load files, both defined in CPACS, are compiled by a newly developed Python based S-BOT-Wrapper module and stored to separate APDL input files.

For the computation of the material thicknesses S-BOT uses an analysis according to fully stressed design principles. Additionally to the fully stressed design analysis for both shells and beams, a stability analysis has been implemented for shells. Ultimate as well as fatigue load cases can be analysed. For the latter the material limits are reduced by a fatigue factor defined in the CPACS material model.

The current version of S-BOT only allows for isotropic materials (e.g. metal). For the fully stressed design of shells and beams, the user can choose between von Mises (von Mises, 1913) and maximum stress criterion. Additionally, shell elements are analysed according to the shell buckling equations described by Bruhn (Bruhn, 1973) in a way that shell buckling is prevented by a thickness increase of the respective element.

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

During each sizing loop all load cases defined are analysed separately. S-BOT then determines the critical load case and the highest absolute material thickness necessary for each element. Due to e.g. manufacturing constraints it can be necessary to define areas with constant material properties (thicknesses). Therefore, so-called optimisation areas can be defined by the S-BOT pre-processing routine. After each sizing run, the maximum material thickness that occurs in an optimisation area is applied to all included elements.

After the iterative sizing run has converged and the FE-model has been updated with the final material thicknesses, the S-BOT-Wrapper analyses the model and updates the original CPACS file with the determined properties.

Figure 13 shows the final distribution of material thicknesses of an exemplary sizing run on the basis of the data of a standard single aisle aircraft and five load cases.

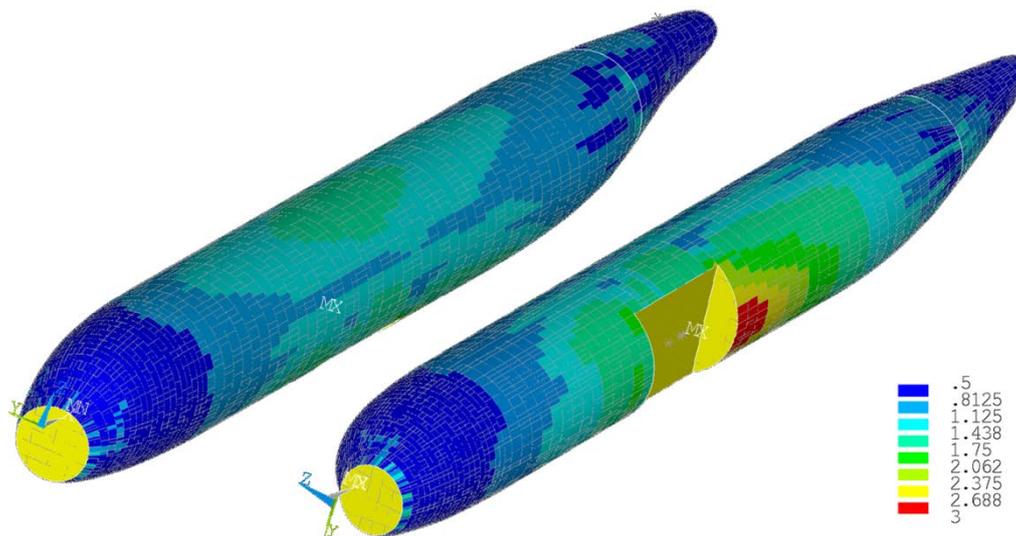


Figure 13: Exemplary distribution of material thicknesses after a static sizing run comprising five representative load cases

5: Crashworthiness Proof

In this section the analysis tool for crash computation – AC-CRASH - will be introduced. AC-CRASH consists of three different modules (see Figure 7):

- Modelling module
- FE solver
- Post Processor

With AC-CRASH it is possible to either conduct crash analyses of AC sections as well as full-scale aircraft (Figure 14 and Figure 19). Its modelling module

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

uses the APDL based PROSHAPE toolbox. The geometry and mesh of the aircraft or section respectively is modelled using ANSYS 13.0 (ANSYS, 2013).

The FE solver to be used in AC-CRASH can be specified by the user. Currently only PAMCRASH by ESI Group (ESI Group, 2013) is implemented but due to the departments expertise with different explicit codes the implementation of Abaqus by Dassault Systèmes (Dassault Systèmes, 2002 - 2013) and LS-DYNA by DYNAmore (DYNAmore, 2013) is being prepared.

Depending on the FE solver chosen for AC-CRASH the corresponding post-processing tool will be used. As only PAMCRASH is currently available as solver the post-processor is VISUAL-VIEWER V7.0 by ESI Group. Analogue to the planned implementation of additional solvers the implementation of the corresponding post-processing tools will be purposed.

As already mentioned does CPACS exhibit toolspecific nodes itself exhibiting several subnodes which will now be explained for AC-CRASH in detail:

- **Tool:** In this node the version of AC-CRASH can be defined. The current version is V3. V1 and V2 use the SECTMESH tool (Kohlgrueber, 2008) for model generation while V3 uses PROSHAPE which allows the modelling of complex shaped geometries (e.g. cockpit and tail section).
- **Model definitions:** Besides a link to the general element sizes to be used a subnode defines regions of the global model where a fine mesh using shell elements shall be used. Additionally each detailed region subnode has a link to its own mesh size definition (see element size definitions).
- **Job definition:** Here the general data to describe the computation job is stored, e.g. the aircraft model uID (unique IDentity), the fuselage uID, the cabin deck uID which describes the seats and seat row distribution.
- **Job control:** In this node all the boundary conditions for the computation are defined, e.g. the FE solver and version to be used, the number of processors, termination time, output intervals for time history and contour plot data.
- **Element size definitions:** This node has subnodes for each element size definition set available. Via an uID these element size sets are linked to the global model and the detailed regions defined. Thus it is possible to discretize several different areas of interest finer or coarser, depending on the intention of the user.

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

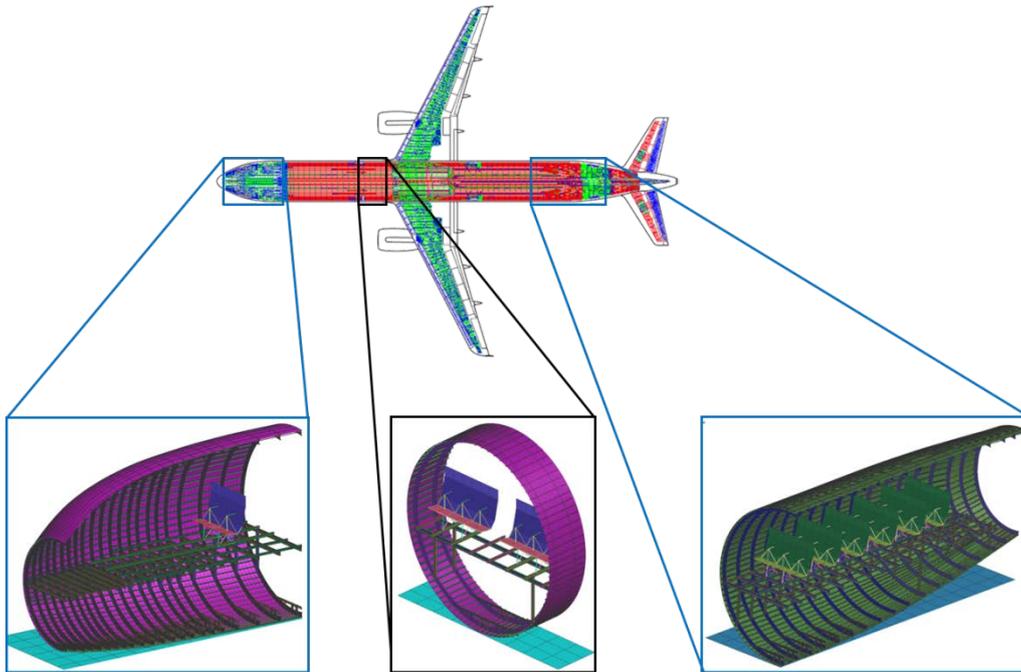


Figure 14: Section models created with AC-CRASH

As already indicated AC-CRASH offers two different types of modelling:

- Aircraft section
- Global aircraft

The aircraft section is used to compute drop tests which have been widely used to evaluate the crashworthiness of aircrafts (Fasanella & Alfaro-Bou, 1986; Fasanella, et al., 2004; Jackson & Fasanella, 1999; Logue, et al., 1995). The section drop load case is a drop of an aircraft barrel with a pure vertical velocity. More complex load cases like Nose Landing Gear failure or ditching cannot be adequately displayed by computing a vertical drop. By virtue of the growing computational power the latter load cases may be computed by means of full scale global models.

In case of using the global approach, the aircraft model is meshed using shell elements for the fuselage skin and elastic beam elements for structural components (e.g. frames, stringers, crossbeams) due to the high computational costs in case of using only shell elements for a complete aircraft.

Using elastic beam elements for the global model is justifiable due to the high amount of static load cases and the detail level of the preliminary design stage. In this period fast computations (results respectively) are desired to give a clear direction of result quality as the detailed design phase calls for a more precise investigation and therefore result quantity.

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

However, elastic beam elements do have the disadvantage of not being suited for displaying non-linear effects like plasticity (in case of metallic construction) or damage initiation (in case of composite construction).

These effects have to be taken into account when conducting crash computations as they play a key role in crash: For instance does the initial kinetic energy of the aircraft get transformed into internal (deformation) energy of the structure thus lowering the shock wave and the acceleration of the passengers which in turn reduces the risk of getting injured and increases the rate of survivability.

On the other hand modelling a complete aircraft using shell elements is very expensive regarding computation time. Therefore a global model (using elastic beam elements) with local refinements (using shell elements) was developed for AC-CRASH V3. Those local refinements are named *detailed regions*. By this approach the advantages of both discretization methods are unified:

- The global aircraft stiffness is mapped correctly by – computationally seen - cheap beam elements and
- Areas of interest can be computed using shell elements thus benefiting from their failure or damage models.

In Figure 15 and Figure 16 two exemplary detailed regions are shown. The first detailed region shows a Door Surround Structure (DSS) of a front PAX door. This structure was chosen as it must not deform plastically in case of a survivable crash landing to assure its function as an emergency exit. Therefore the detailed structural behaviour of the DSS is of high interest.

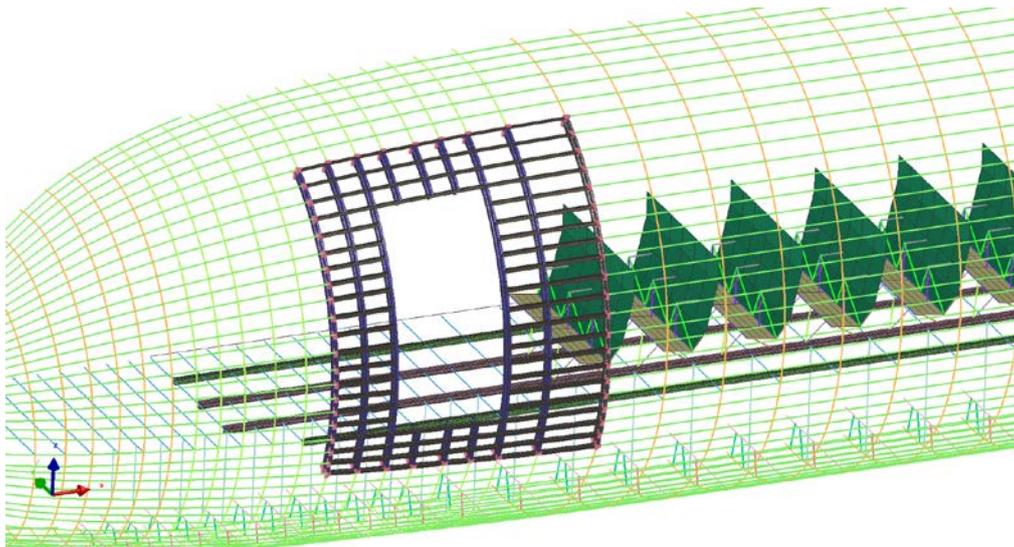


Figure 15: Detailed region “DSS”

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

The second detailed region chosen in this paper is the ditching impact area. In case of ditching this region is the first zone getting in contact with the water. Therefore high forces are locally introduced into the aircraft structure which leads to either damage initiation or high structural deformation, depending on the material model used.

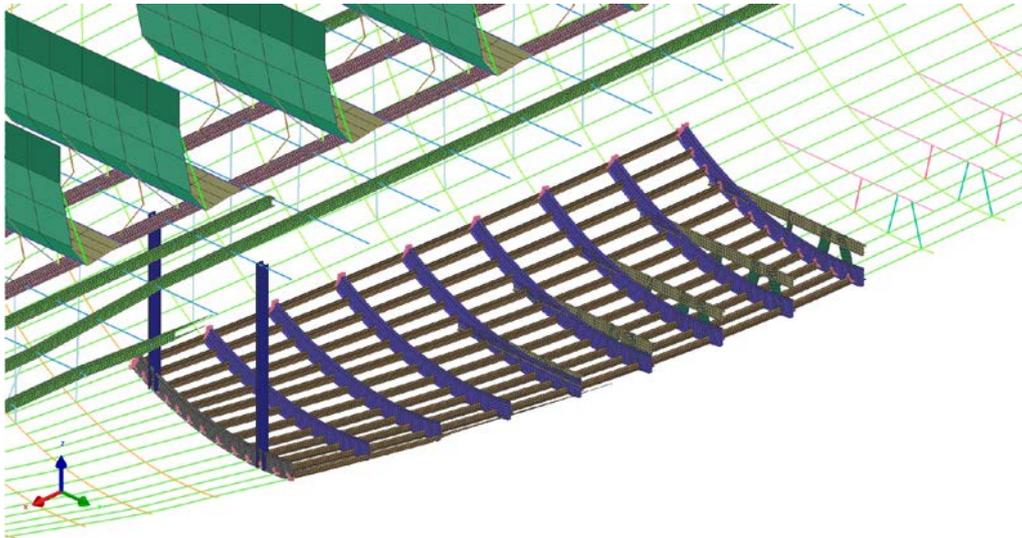


Figure 16: Detailed region “Ditching impact area”

This mixed discretization method in turn requires the adaption of the mesh at the common interfaces, e.g. the interfaces between shell and beam mesh as well as, for the fuselage skin, the mesh size adaption from detailed regions to the global mesh size. The second item is not necessarily required as it is possible to mesh the complete fuselage skin with one single mesh size. As certain structural behaviours, e.g. bending, are not able to be displayed when using a too big mesh size it is highly recommended to mesh the fuselage skin in detailed regions finer than in the global region.

For the transition between beams and shells AC-CRASH uses Multi-Point-Constraints (MPCs) connecting the beam node with the corresponding shell nodes at its common interface by coupling translational and rotational degrees of freedom. The AC-CRASH modelling algorithm automatically detects all existent interfaces and the corresponding node numbers to write the constraint definitions for the FE computation. Such a constraint is exemplarily shown in Figure 17 using the PAMCRASH solver and definition. In PAMCRASH this MPC is named MTOCO. Further information about the MTOCO feature can be found in the corresponding manual (ESI Group, 2011).

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

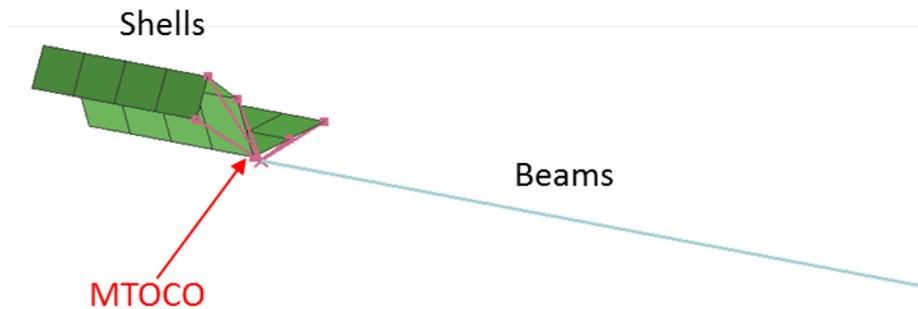


Figure 17: MTOCO coupling a stringer modelled using beam and shell elements respectively

Regarding the second mesh transition item so-called transition zones were implemented in AC-CRASH. A transition zone is basically a ring around the detailed region giving space to stepwise adopt the mesh sizes avoiding high gradients. The more transition zones are defined the smaller is the increase of element size between the finer and the coarser mesh, i.e. the smoother is the mesh.

Exemplarily the mesh transition is shown in Figure 18 by the use of the ditching impact area (as shown in Figure 16).

The detailed region, where the structure is meshed fine by shell elements, is limited by frames C57 and C65 and stringers St-34 and St+34, highlighted by the four red corner circles. This detailed region is surrounded by two transition areas stepwise increasing the element size to the global one.

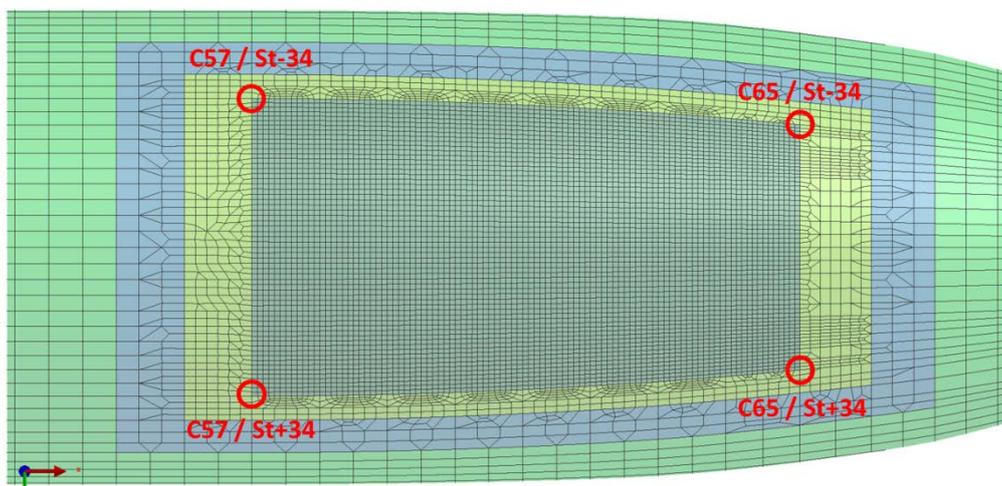


Figure 18: Mesh transition in the fuselage skin in the ditching impact zone

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

Another feature of AC-CRASH is the generation of cut-outs (see Figure 19). It was already mentioned that modelling door cut-outs is of essential importance concerning emergency evacuation of passengers. Another reason for implementing door cut-outs is the alternation of stiffness and adoption of the changed load path. The generation of cut-outs is independent from the definition of detailed regions, i.e. a detailed region does not have to be necessarily defined for modelling a cut-out.

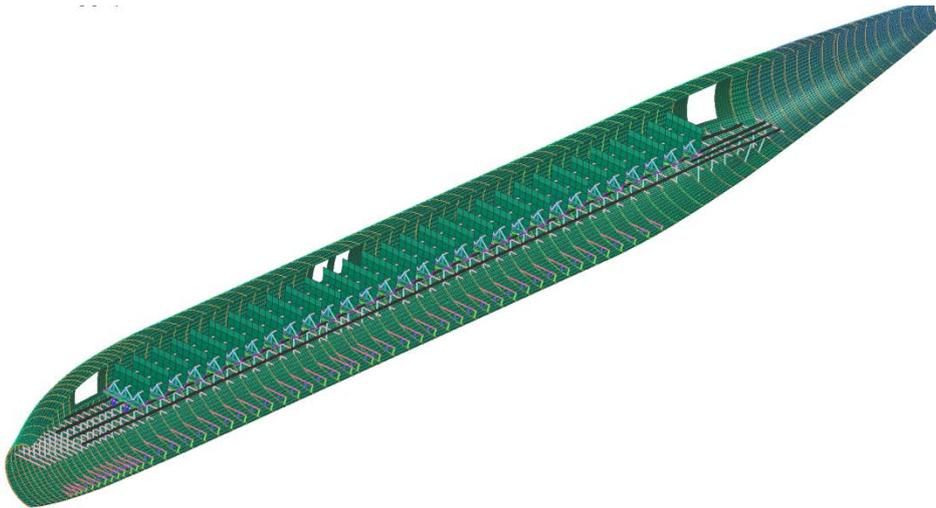


Figure 19: Generic door cut-outs without the use of detailed regions (to display the interior structure only half of the model is shown)

6: Crash Model Generation Benchmarking

This section provides a benchmarking of the crash model generation giving a good understanding of how fast and efficiently the model generation routine works. The sections consisted of the following structural components:

- Fuselage skin
- Stringers
- Frames
- Crossbeams (PAX and cargo)
- Crossbeam struts (PAX and cargo)
- Longitudinal floor beams
- Seats (including PAX masses)

The model generation was conducted locally on a Fujitsu Celsius W280 PC with following properties:

- Windows 7 (64 bit), Enterprise Edition, Service Pack 1
- Intel® Core™ i7 CPU 870@2.93GHz
- 8 GB RAM

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

- 4 processor cores
- NVIDIA Quadro 2000 graphic card with 1024 MB memory

The attended time for model generation includes:

- Initialization of CPACS
- Geometry generation
- Meshing
- Converting *.cdb to *.pc

In order to be able to compare the results the following two mesh size configurations were used for all generated models (see Table 1):

Table 1: Mesh configurations

Structural Component	Mesh #1	Mesh #2
Fuselage Skin	100	50
Frames	25	10
Stringers	25	15
Cargo Crossbeams	25	15
Cargo Support Struts	25	15
PAX Crossbeams	20	10
PAX Beam Struts	20	10
Long Floor Beams	25	15

One can see that the mesh size configuration #2 conforms to approximately half the mesh size from configuration #1. It shall be noted that the given values for the mesh sizes cannot always be met by ANSYS, e.g. an area having the dimensions 25 x 25 [mm] meshed with elements having an edge length of 15 [mm] will result in 4 elements with an edge size of each 12.5 [mm]. Thus the given mesh sizes are only a guideline value which ANSYS tries to cover.

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

The required time for model generation is the time between the initialization of the process chain and the generation of the converted structure *.pc file which is the point where the crash computation starts.

Ten different model configurations were generated, ranging from sections in the cockpit area to sections in the rear part of the aircraft covering different section lengths. Some example configurations are presented in Figure 20. For visibility of the interior structure only half of the model is shown.

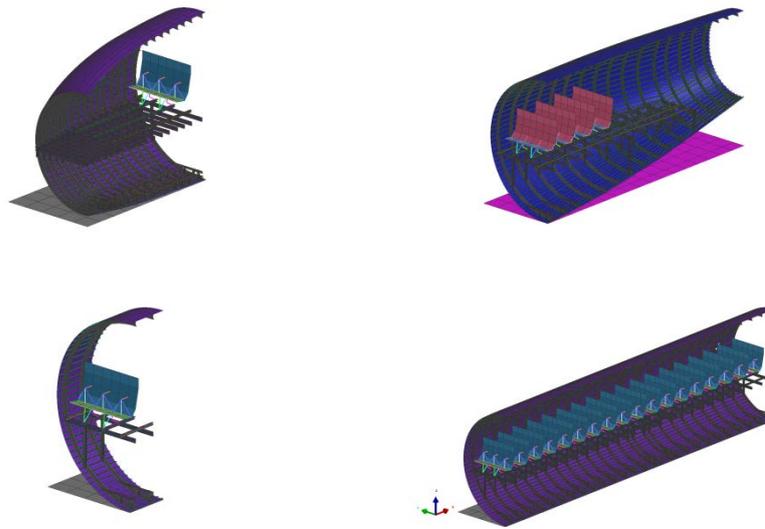


Figure 20: Exemplary sections (2), (6), (4), (1) (clockwise, starting top left)

Table 2 presents the results giving an overview of the boundary conditions of the benchmarking runs.

Table 2: Model generation benchmarking

Run No.	X _{Start} [m]	X _{End} [m]	Mesh	Structural Components	Seatrows	Nodes	Elements	Time
1	10.0	11.0	#1	116	1	49,734	42,981	00:02:16
2	2.0	6.0	#1	236	1	266,030	234,680	00:05:21
3	6.0	10.0	#1	161	5	183,441	160,108	00:03:55

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

4	6.0	20.0	#1	341	18	667,879	585,591	00:20:55
5	20.0	25.0	#1	179	5	231,644	202,391	00:04:42
6	25.0	33.0	#1	240	4	328,109	286,505	00:06:31
7	20.0	33.0	#1	321	10	558,967	488,929	00:13:25
8	10.0	12.0	#1	134	2	97,912	85,280	00:02:47
9	1,5	12,0	#1	339	8	569,646	500,998	00:14:31
10	5.0	33.0	#1	600	30	1,295,627	1,136,206	01:17:56
11	10.0	11.0	#2	116	1	137,479	125,757	00:02:44
12	2.0	6.0	#2	236	1	809,705	752,196	00:10:33
13	6.0	10.0	#2	161	5	503,507	462,116	00:06:00
14	6.0	20.0	#2	341	18	816,702	718,035	00:24:37
15	20.0	25.0	#2	179	5	639,562	587,430	00:07:29
16	25.0	33.0	#2	240	4	922,473	848,145	00:11:10
17	20.0	33.0	#2	321	10	686,518	602,863	00:18:21
18	10.0	12.0	#2	134	2	272,610	250,291	00:03:19
19	1.5	12.0	#2	339	8	1,654,232	1,529,694	00:32:01
20	5,0	33,0	#2	600	30	1,583,789	1,394,312	01:26:33

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

The benchmarking resulted in 20 runs with generated structural components ranging from 116 to 600. The amount of nodes and elements ranges from 49,734 nodes and 42,981 elements to 1,654,232 nodes and 1,529,694 elements. The shortest time was 02:16 minutes while the longest run needed 01:26:33 hours. A graph for better visualization is presented in Figure 21.

It shall be noted at this point that not only the structural mesh but also all required input cards for the Crash computation have been generated completely without any user interaction.

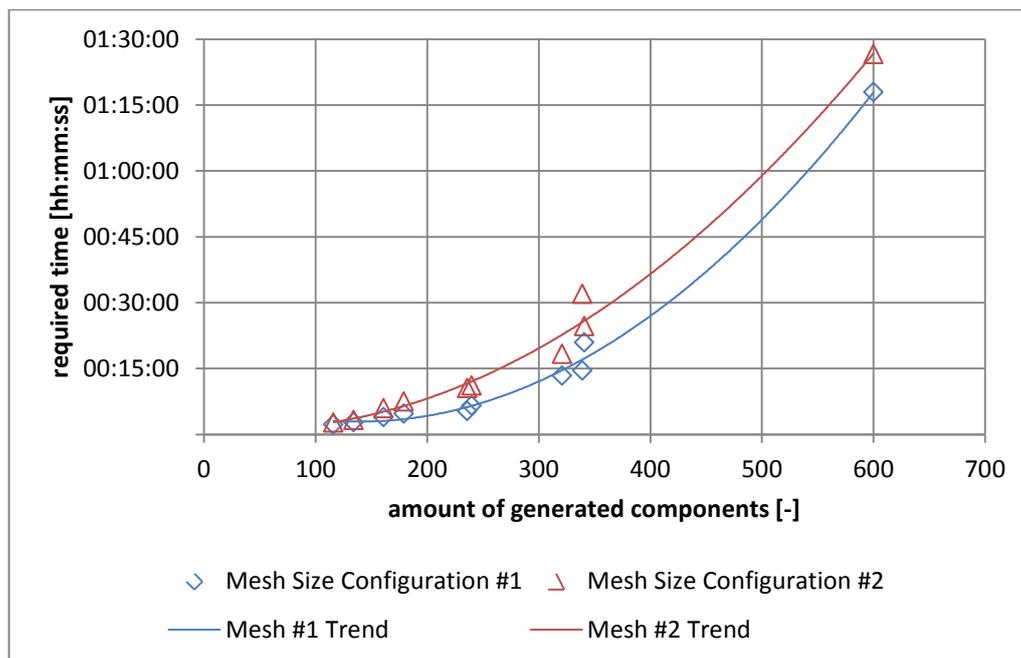


Figure 21: Required time versus generated components

In Figure 21 mesh configuration #1 is presented in blue while configuration #2 is shown in red. Obviously, the model generation requires more time when using the finer discretization, as a finer mesh means more nodes and elements to create but also more nodes and elements to be converted from the *.cdb to the *.pc file. The benchmark tests also show that the influence of the structural components to be generated is greater than the influence of the finer discretization.

7: Conclusion and Outlook

A fully parameterized multidisciplinary process chain for AC sizing under static as well as crashworthiness aspects was presented. Based on initial values the structure is optimized and the resulting configuration is investigated subsequently regarding its energy absorption abilities.

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

The required tools TRAFUMO, S-BOT and AC-CRASH were introduced as well as the interfacing CPACS data schema.

Benchmark tests showed that, depending on the amount of generated components and mesh size, the mesh generation for AC sections up to 28 m of length with approximately 1,6 million nodes requires less than 90 minutes predestining the chain for the use in parametrical studies. The benchmark tests also showed that the influence of the amount of structural components to be generated is greater than the influence of meshing.

To achieve a more realistic wing load introduction into the fuselage and thus a more realistic distribution of material thicknesses, an improved structural representation of the centre fuselage region is currently under development comprising all major structural subcomponents. This centre fuselage definition requires additional inputs to define main frames, pressure floor, side box, lateral panels and the keel beam. As the geometric shape of some subcomponents is strongly related to the geometric wing shape, a working wing model integration is required that is currently under development with other DLR partners. The actual coupling of the refined centre fuselage and the wing is done by constraint equations.

First steps in coupling a single aisle fuselage generated by TRAFUMO and a corresponding wing generated by the ELWIS wing modelling tool (Dorbath, et al., 2012) have already been performed (see Figure 22). A first evaluation of results confirms the importance of a detailed centre fuselage definition relating to realistic introduction of aerodynamic wing loads into the pressurized fuselage.

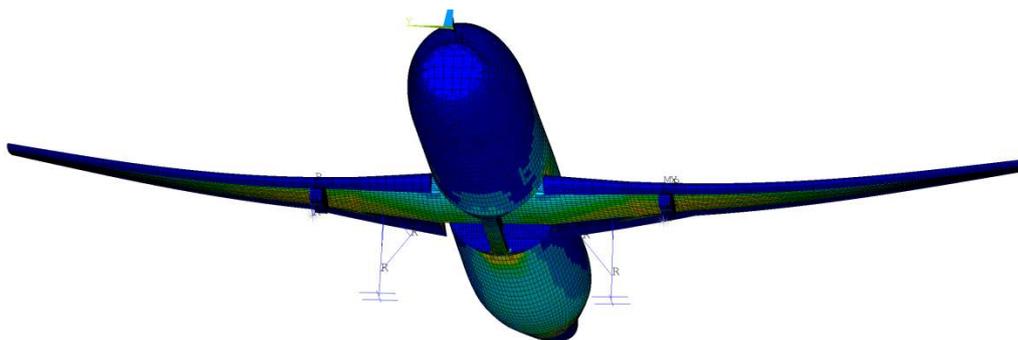


Figure 22: Exemplary distribution of van Mises stresses of a coupled TRAFUMO generated fuselage and an ELWIS generated wing in a +2.5g manoeuvre load case

Regarding S-BOT currently emphasis is put on the validation of sizing results with analytic tools, the extension of the stability criterions for shells and beams in particular, the implementation of anisotropic material models and the sizing of models containing wing and empennage structures.

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

Future work on AC-CRASH focusses on the integration of other structural components (e.g. landing gear bays) and secondary masses. Another aim is the substitution of PAX nodal masses by crash dummies to improve the PAX-structure interaction and to investigate potential PAX injuries. Furthermore investigations of DSS under crash loads that may influence door sizes and therefore PAX boarding times is of high interest.

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

REFERENCES

ANSYS, 2013. [Online]

Available at: <http://www.ansys.com>

[Accessed 25 January 2013].

Apache Software Foundation, 2012. [Online]

Available at: <http://www.apache.org>

[Accessed 25 January 2013].

Apache Subversion, 2013. [Online]

Available at: http://en.wikipedia.org/wiki/Apache_Subversion

[Accessed 25 January 2013].

Bachmann, A., Kunde, M., Litz, M. & Schreiber, A., 2009. A dynamic data integration approach to build scientific workflow systems. In: *4th International Conference on Grid and Pervasive Computing*. The institute of electrical and electronics engineers, Inc., pp. 27-33.

Bachmann, A., Kunde, M., Litz, M. & Schreiber, A., 2010. *Advances in Generalization and Decoupling of Software Parts in a Scientific Simulation Workflow System*. Florence, Italy, The Fourth International Conference on Advanced Engineering Computing and Applications in Sciences - ADVCOMP.

Bruhn, E. F., 1973. *Analysis & Design of Flight Vehicle Structures*. Jacobs Publishing Inc.

CPACS, 2013. [Online]

Available at: <http://code.google.com/p/cpacs/>

[Accessed 25 January 2013].

Dassault Systèmes, 2002 - 2013. [Online]

Available at: <http://www.3ds.com>

[Accessed 25 January 2013].

Distributed Revision Control, 2013. [Online]

Available at: http://en.wikipedia.org/wiki/Distributed_revision_control

[Accessed 25 January 2013].

Dorbath, F., Nagel, B. & Gollnick, V., 2012. *Implementation of a Tool Chain for Extended Physics-Based Wing Mass Estimation in Early Design Stages*. Bad Gögging and Manching, Germany, 71th Annual Conference of Society of Allied Weight Engineers (SAWE).

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

DYNAmore, 2013. [Online]

Available at: <http://www.dynamore.de>

[Accessed 25 January 2013].

EASA, 2013. *Certification Specifications - Part 25*.

ESI Group, 2011. *VPSolution 2011.0 - Solver Reference Manual*.

ESI Group, 2013. [Online]

Available at: <http://www.esi-group.com>

[Accessed 25 January 2013].

FAA, 2013. *Federal Aviation Regulations - Part 25*.

Fasanella, E. & Alfaro-Bou, E., 1986. *Vertical Drop Test of a Transport Fuselage Section Located Aft of the Wing*. NASA-TM-89025: NASA.

Fasanella, E. et al., 2004. *Crash Simulation of a Boeing 737 Fuselage Section Vertical Drop Test*. NASA: Document ID: 20040086069.

Fredericks, W. et al., 2010. *Aircraft Conceptual Design Using Vehicle Sketch Pad*. Orlando, USA, 48th AIAA Aerospace Sciences Meeting.

Hahn, A., 2010. *Vehicle Sketch Pad: A Parametric Geometry Modeler for Conceptual Aircraft Design*. Orlando, USA, 48th AIAA Aerospace Sciences Meeting.

Harbig, K., 2010. *Entwicklung eines parametrisierten Netzgenerators zur automatisierten Crashsimulation von Flugzeugrumpfstrukturen*. DLR-IB 435-2010/22: DLR.

Howe, D., 2000. *Aircraft Conceptual Design Synthesis*. London and Bury St Edmunds, UK: Professional Engineering Publishing Limited.

Hürlimann, F. et al., 2011. Mass Estimation of Transport Aircraft Wingbox Structures with a CAD/CAE-based Multidisciplinary Process. *Aerospace Science and Technology* 15, pp. 323-333.

Jackson, K. & Fasanella, E., 1999. *Crashworthy Evaluation of a 1/5-Scale Model Composite Fuselage Concept*, NASA/TM-1999-209132: NASA.

Kohlgrueber, D., 2008. *SECTMESH V5 - Description of a Tool to Automatically Generate Finite Element Meshes of Transport Aircraft Sections*. DLR-IB 435-2008/18: DLR.

Liersch, C. & Hepperle, M., 2011. A distributed toolbox for multidisciplinary preliminary aircraft design. *CEAS Aeronaut J* 2, pp. 57-68.

DEVELOPMENT OF A MULTIDISCIPLINARY PROCESS CHAIN FOR THE PRELIMINARY DESIGN OF AIRCRAFT STRUCTURES

Logue, T., McGuire, R., Reinhardt, J. & Vu, T., 1995. *Vertical Drop Test of a Narrow-Body Fuselage Section with Overhead Stowage Bins and Auxiliary Fuel Tank System on Board*, DOT/FAA/CT-94/116: FAA.

Nagel, B. & et al., 2006. *An Alternative Procedure for FE-Wing Modeling*. Braunschweig, Germany, Deutscher Luft- und Raumfahrtkongress.

Nagel, B., Kintscher, M. & Streit, T., 2008. *Active and Passive Structural Measure for Aeroelastic Winglet Design*. Anchorage, USA, ICAS - International Council of the Aeronautical Sciences.

OpenVSP, 2012. [Online]
Available at: <http://www.openvsp.org>
[Accessed 25 January 2013].

Raymer, D. P., 1992. *Aircraft Design: A Conceptual Approach*, Washington, D.C.: AIAA.

Repository, 2013. [Online]
Available at: [http://en.wikipedia.org/wiki/Repository_\(version_control\)](http://en.wikipedia.org/wiki/Repository_(version_control))
[Accessed 25 January 2013].

Rizzi, A. et al., 2012. *Towards a Unified Framework using CPACS for Geometry Management in Aircraft Design*. Nashville, USA, AIAA Aerospace Sciences Meeting.

Scherer, J., 2011. *Koppelung der Modellgenerierung und der statischen Dimensionierung von Flugzeugrümpfen im Vorentwurf*. DLR-IB 435-2011/33: DLR.

von Mises, R., 1913. *Mechanik der festen Körper im plastisch-deformablen Zustand*. In: *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen.*, pp. 582-592.

XML, 1996 - 2003. [Online]
Available at: <http://www.w3.org/xml>
[Accessed 25 January 2013].

Zill, T., Böhnke, D. & Nagel, B., 2011. *Preliminary Aircraft Design in a Collaborative Multidisciplinary Design Environment*. Virginia Beach, USA, AIAA Aviation Technology, Integration, and Operations (ATIO) 2011.

Zill, T., Ciampa, P. & Nagel, B., 2012. *Multidisciplinary Design Optimization in a Collaborative Distributed Aircraft Design System*. Nashville, USA, 50th AIAA Aerospace Sciences Meeting.