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RISK PROTEC CI – RESEARCH PROJECT FOR AIRCRAFT IMPACT FUNDED BY THE EU

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ABSTRACT

For the setup of critical infrastructures human-induced events and the related risk are relevant design scenarios. Therefor the EU started the research call CIPS 2010 II. Within this call the project Risk Protec CI under the leadership of Wölfel was realized Henkel (2014). The goal was to define a procedure for the vulnerability analysis of critical infrastructures as e.g. nuclear reactor buildings with respect to aircraft impacts by using the Finite Element (FE) method and to apply it exemplary.

In a first step the general procedure of the vulnerability analysis is described. Then in subsequence the used material approaches, the aircraft models and the simulation method itself are validated in comparison to available test data. Afterwards the method is applied for two idealized reactor building designs. Covering realistic scenarios the impacts of a B747 and an A320 with varying velocities are investigated. An evaluation of the structures is carried out via the structural behaviour of the outer containment. Based on these results a sensitivity study is performed with respect to the flight approach direction, the impact point and the effect of obstacles. Further local measures for increasing the resistance of the structure are assessed and optimized.

The paper will give a general overview of the research project. Nevertheless the main parts and results as the modelling, the numerical impact simulations and results of the sensitivity study with respect to flight approach direction and the effect to local measures is presented in detail.

INTRODUCTION

Since 9/11 human-induced events and the related risk are important in the management and design of critical infrastructures. Accordingly the EU started the call CIPS 2010 II supporting several research approaches in this area. Within this call the project Risk Protect CI under the leadership of Wölfel was realized, Henkel (2014). Its goal was to further develop an existing procedure for the vulnerability analysis of aircraft impacts on critical infrastructures.

Numerical approaches using the FE method are more and more state of the art for the investigation of aircraft impacts, see Arros (2007) and Siefert (2011). Nevertheless a standardized procedure describing the requirements and typical outcome is so far no defined and therefore was the goal of this research project.

The load case of aircraft impacts was initially defined in the 70ies in Germany. Due to the geopolitical situation the impact of a military jet was considered in the design of nuclear power plants. In these times only a decoupled investigation of this load case was realizable, i.e. the definition of the load is separated from its application on the structure.

The starting point for defining the load due to an aircraft impact was the publication of Riera (1968). Using a discrete model consisting of masses and springs the load-time-function (Ft-function) was defined for a straight impact on a rigid wall. Thereby the springs represent the crushing stiffness P_c and the masses the corresponding weight or the mass flow μ. Using both values the F can be defined as follows:

$$F = P_c + \mu \cdot v^2$$

Eq. 1: Load function of an aircraft impact on a rigid wall, Riera (1968)

The decoupled approach is very stable and easy to apply but is limited in the representation of the real scenario. First the effects due to the missile target interaction are not taken into account as the load is defined for a crash onto a rigid wall not considering the structural compliance. Second the procedure neglects the structural setup of the aircraft as the pressure is lumped over the complete impact area. For military jets this has a smaller influence as the structural setup is more or less a homogeneous. For passenger aircrafts this is not the case as the structure is inhomogeneous with respect to stiffness and mass, see Siefert (2011). Finally the approach cannot reflect geometric effects as the 3D shape of the building and the flight approach direction, which could influence the impact scenario.

The terrorist attacks of 9/11 have been starting point for detailed analysis of the load case aircraft impact. Using the constant improvements of hard- and software the development of an integral approach, including all effects in one simulation, was initiated. Nowadays an impact simulation including a detailed model of an aircraft and a structure and considering their interaction is more or less state of the art.

In Risk Protec CI an existing simulation method has been further developed and validated step by step in comparison to existing measurement data. Further a general procedure for a vulnerability analysis due to this load case was described. Finally the method was applied on idealized setups of nuclear power plants (NPP) and dams in Europe.

PROCEDURE FOR A VULNERABILITY ANALYSIS OF AN AIRCRAFT IMPACT

The first step of a vulnerability analysis for an aircraft impact on a NPP is a statistical study of the air traffic in the surrounding area. Thereby the appearance probability of the different types of aircrafts must be determined. Then the mass of the aircraft based on payload and fuel consumption must be defined. Further the topology around the structure has to be explored to define possible flight directions and angles to reach the structure based on the surrounding landscape and structures. Finally the impact velocity under consideration of realistic flight circumstances must be determined.

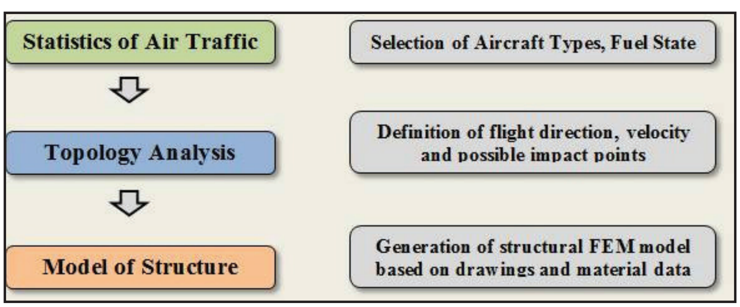

Figure 1. Definition for load scenario of vulnerability analysis

After defining the load case scenario the FE model of the structure must be generated. Reducing computational effort the model must be separated in sections with higher level on detail as e.g. the impact area and in sections with lower level as e.g. the basement. Instead of generating new models existing setups of studies as e.g. earthquake investigations can be used and adapted.

Then the material properties are determined. While elastic properties are sufficient for components in a greater distance of the impact point, nonlinear characteristics have to be considered for the impact area and the surrounding field. This includes nonlinear elasticity, plasticity, strain rate dependence and failure.

In the last step the load must be defined using Ft-curves or FE models of aircrafts. Within the last years Wölfel has developed several models of passenger and military aircrafts (A320, A340, A380, B747, B767, B787, F4 and Cessna 210). As the goal of the computation is an evaluation of the structure only the main components with respect to stiffness and mass are taking into account. A validation of the model setups was carried out e.g. by a comparison to the Sandia test, von Riesemann (1989), already presented in Siefert (2013).

Finally the simulation is carried out using the decoupled or the integral approach. The final goal of the computation is the evaluation of the structural integrity for the outer containment. The following top down menu illustrates all steps required for a detailed vulnerability analysis of an aircraft impact.

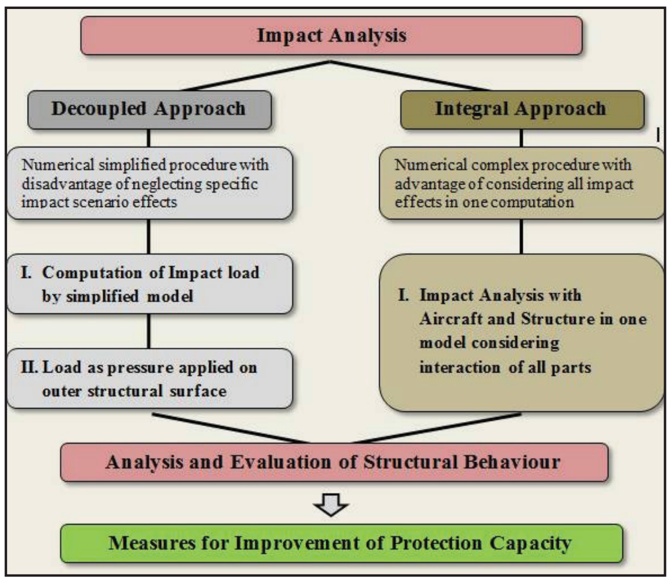

Figure 2. Procedure for vulnerability analysis with respect to aircraft impact

In the following chapters this procedure is applied for the impact analysis of a passenger aircraft on an exemplarily structure of a reactor building. Thereby the integral approach is applied using the FE solver ABAQUS (2012).

MODEL GENERATION

Concrete

Beside standard FE-simulation requirements as choice of element type, discretization, boundary definition and stability controlling effects, an important task is the accurate representation of the material behaviour. This includes on the one side the choice of an adequate continuum mechanical approach and on the other side a correct identification of the material parameters. Thereby concrete represents a challenge due to its structural inhomogeneity. Riedel (2000) shows an overview about existing modelling approaches, where the *Concrete Damaged Plasticity* model based on Lubliner (1989) is chosen. It is designed for setups with monotonic and dynamic loading scenarios and covers the nonlinear behaviour under tension and compression, see figure 3.

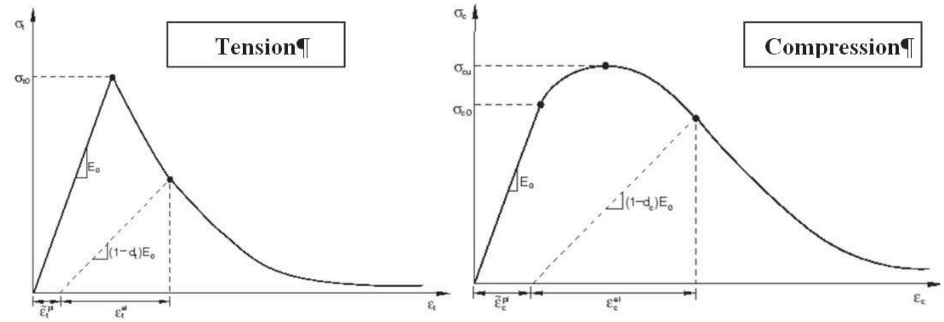

Figure 3. Qualitative concrete behaviour defined by *Concrete Damaged Plasticity* model

The definition is separated in tension and compression and for each state the plasticity and the damage behavior must be described. The damage part specifies thereby the reduction of Young's modulus, see figure 3. The required input for the identification of the material parameters is the stress-strain-curve (S-E-curve). Using the CEB-FIP Model Code 90 (1993) the S-E-curve can be derived from the compressive material strength. Further the standard is used for definition the strain rate dependence, which must be considered for this high speed dynamic load case.

A challenge is the definition of the erosion criterion, after exceeding that elements are deleted. Erosion is a virtual parameter and is not related to any physical quantity. Therefore it has been adjusted iteratively in comparison to the test data as e.g. from the IRIS benchmark 2012, see Orbovic (2013).

Reinforcement Steel

Beside the concrete the behavior of the reinforcement steel bars has to be defined for the structure. For considering the nonlinearity, the strain rate dependence and the failure the Johnson-Cook [13] plasticity model is used, which is represented by the following equation.

$$\bar{\sigma} = \left[A + B\left(\bar{\varepsilon}^{pl}\right)^n\right]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0}\right)\right]\left(1 - \hat{\theta}^m\right)$$

Eq. 2: Formulation of Johnson Cook plasticity, Johnson (1983)

Here A, B, C and m are free material parameters which are identified via an optimization algorithm using Matlab (2007). In the described case the influence of the temperature ϴ is neglected. For including the failure behavior the formulation is enhanced by a damage model of ABAQUS.

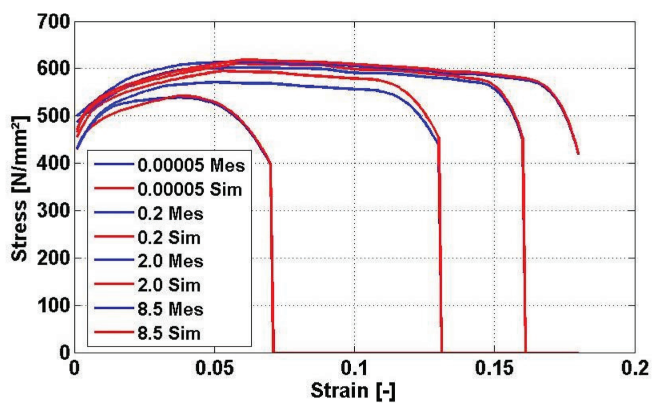

Figure 4. Comparison of measurement and simulation of steel BSt 420/500

As input measured S-E-curves for different loading rates are used, see Brandes (1985). In figure 4 the comparison of test data and the behavior simulated in ABAQUS is presented for the typical reinforcement material BSt 420/500, showing a good correlation for all strain rates.

Structural Model

Within the project the investigations are carried out on idealized structures for the outer containment of NPPs. The modelling of the outer concrete shell is separated in very detailed setup around the impact area and a less detailed setup for the rest, see figure 5 (left). For both parts volume elements are used and generated with the pre-processor using HyperMesh ,Altair (2012).

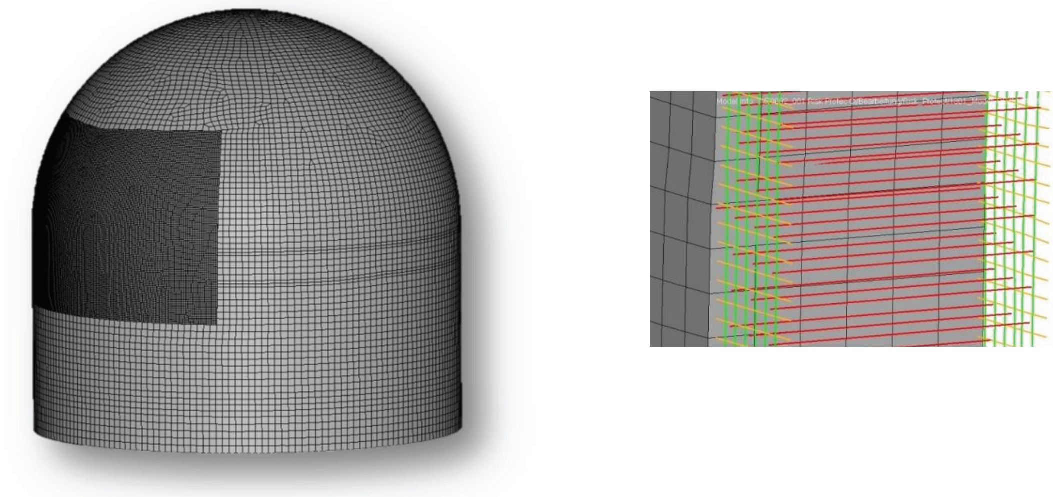

Figure 5. FE-model of outer concrete shell: global (left) and local setup (right)

The reinforcement is represented by discrete beam elements, see figure 5 (right), including vertical and horizontal bending bars and stirrups for the shear loading. These elements are embedded in the concrete volume. The coupling is defined automatically by using the *Embedded Element* Option of ABAQUS. Accordingly the displacement of nodes from the reinforcement is defined by the surrounding nodes of the concrete. Within the study two thickness variants with 1.2 and 1.8 are investigated.

Aircraft Model

For the study two types of aircrafts are chosen. First the A320-200 as it is very common for short-range flights. Consequently the probability of human induced event with this passenger aircraft is very high due to its availability. Second the B747-400 will be applied as an aircraft for long-range flights. The B747-400 is beside the A380 the biggest passenger aircraft at the moment. The B747-400 is preferred in this study as already several hundreds of this aircraft are in operation compared to about 100 for A380, respectively the probability for an accident with the B747-400 is higher than for an A380.

For both models the geometric and material information are taken from public data and checked via information of the manufacturer. The goal for the modelling of the aircraft is to represent the load case realistically. Consequently only the main parts with respect to stiffness and mass are considered in the model setup, what includes the fuselage, the wings, the tails, the turbines with rips and stringers, the fuel and the payload. The model setup consists of shell, beam and discrete mass elements and is represented for the B747-400 in figure 6.

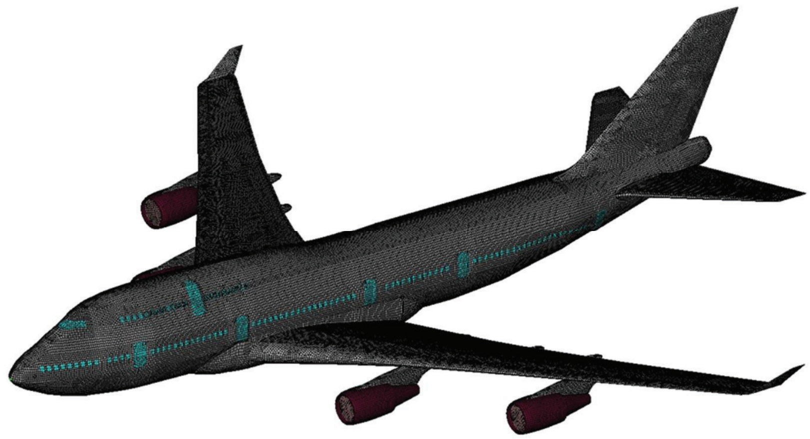

Figure 6. Isometric view of FE-model for aircraft of type B747-400

A validation of the modelling procedure was carried out for a crash of a Phantom F4 on to a concrete slab in comparison to the data for the Sandia test, see von Riesemann (1989) and Siefert (2013). In table 1 a comparison for both aircraft types with respect to the general key values is presented.

Table 1. Comparison of model setup for A320-200 and B747-400

Aircraft	MTOW	Width / Length	Fuselage Area	Nodes	Elements
A320-200	78 t	34.0 / 37.5 m	12.5 m²	25,000	27,000
B747-400	397 t	64.4 / 76.6 m	39.0 m²	200,000	300,000

The big difference in the Maximal Take Of Weight (MTOW) is the reason that the load level for an impact of the B747-400 is much higher than for A320-200. Computing the Ft-function for a crash with a velocity of 160 m/s onto a rigid wall the maximal peak load for B747-400 is three times the value of the A320-200, see figure 7.

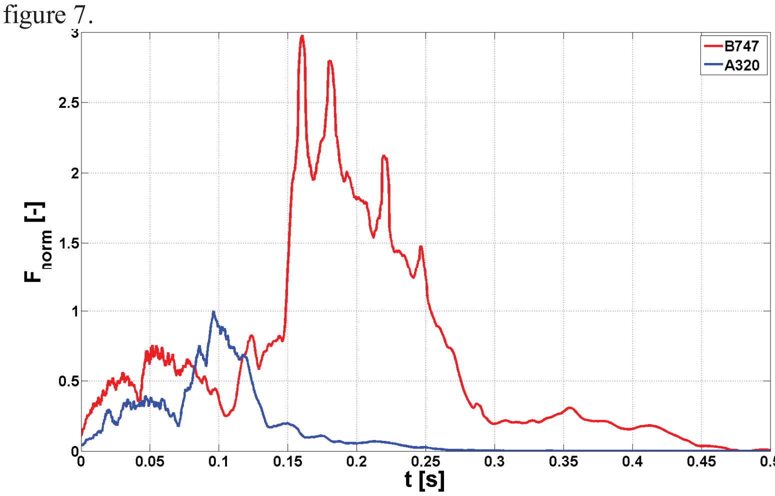

Figure 7. Normalized Ft-functions for A320-200 and B747-400 for 160m/s

Beside the load level also the duration of the impact is different. While the crash for the A320-200 ends after 250 ms it lasts for B747-400 almost 500 ms.

IMPACT SIMULATION

The preload in the containment due to gravity is neglected as the stress level is much lower as for the crash scenario. The impact location is positioned in the transition zone from the cylindrical to the spherical part of the outer shell. The interaction between aircraft and the containment is defined by a general contact algorithm using the penalty approach including self-contact. In the simulations impacts with the velocities of 100 and 160 m/s are investigated. While 100 m/s represents the typical range for landing 160 m/s is in the international community accepted as a limit value to reach a target with a big aircraft but is due its low probability a conservative scenario. Accordingly the following scenarios are investigated:

- Impact of A320 with 160 m/s on structure with thickness of 1.80 m;
- Impact of B747 with 160 m/s on structure with thickness of 1.80 m;
- Impact of B747 with 160 m/s on structure with thickness of 1.20 m;
- Impact of B747 with 100 m/s on structure with thickness of 1.20 m;

At the start of the simulation the aircraft is positioned in front of the containment. The simulation time is defined with 0.4 s for the A320 and with 0.5 s for the B747. Figure 8 shows the model behaviour for the impact of the B747 on the structural setup with 1.8 m for an isometric view and a section cut.

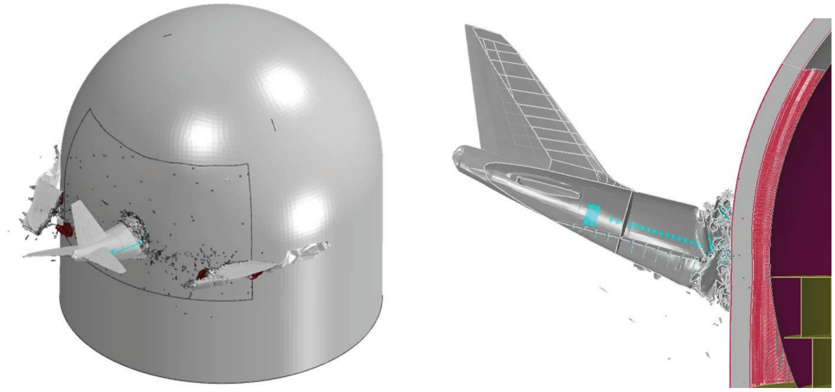

Figure 8. Result B747-400 impact with 160 m/s on outer shell with d = 1.80 m, simulation time 500 ms

The evaluation of the structural integrity is carried out via the displacement respectively a potential damage over the thickness of the outer concrete shell in the area of the impact. The following table 2 shows the summary of the results for the carried out simulations.

Table 2. Overview of simulation results

No.	Thickness [m]	Aircraft	Velocity [m/s]	Structural Integrity
1	1.80	A320-200	160	No Damage
2	1.80	B747-400	160	No Damage
3	1.20	B747-400	160	Damage
4	1.20	B747-400	100	No Damage

Only for the impact of B747-400 on the shell with a thickness of 1.2 m a relevant damage is observed. Accordingly the following sensitivity studies and the investigation about a concept to improve the protection capacity locally are carried out for this scenario.

SENSITIVITY STUDY OF FLIGHT DIRECTION AND OBSTACLES

There are several effects which can influence the flight approach direction respectively the impact location. First the topology of the landscape and the surrounding infrastructure must be considered. Further limitations in the handling of aircrafts have to be taken into account. Based on impact studies on rigid walls it is known that only a rotation about the vertical axis has an influence on the load scenario. Further a translation of the impact location is relevant for structures with a three dimensional outer shape. Following this a sensitivity study with the 5 variations, shown in table 3, is carried out.

Table 3. Overview of variants for the sensitivity study

Change	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
Rotation	0°	10°	10°	20°	30°
Translation	5 m	0 m	5 m	10 m	0 m

In addition a variation is investigated, where the aircraft hits a rigid obstacle before the impact, what leads to a partial rupture of the wing. A visual impression of this scenario is presented in figure 9.

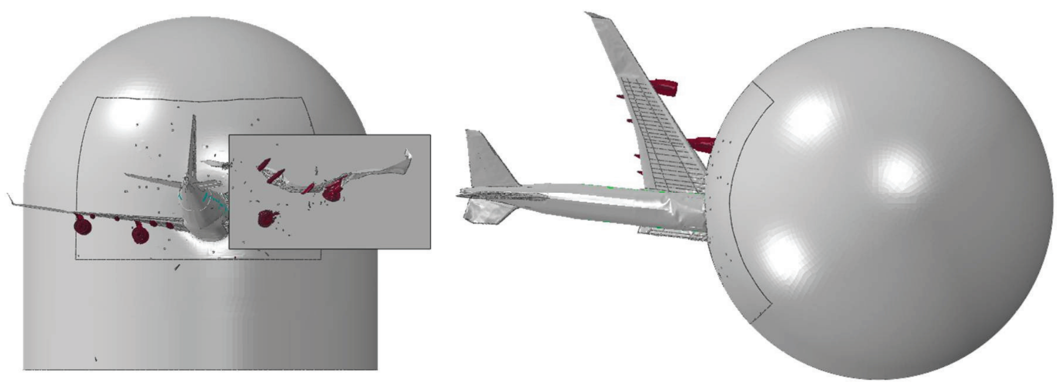

Figure 9. Effect of partial impact of outer wing on flight approach direction

Summarizing all simulations leads to the following conclusions:

- Translations of several meters for the impact location without rotations of the aircraft has only minor influence on the scenario. The reason is that a translation of several meters goes only along with a small change of the curvature of the outer shell.

- A rotation of the flight direction approach about the vertical effects has especially for values above 10 ° degree a significant effect. Accordingly investigations of specific sites should take into account any changes due to the surrounding landscape and structures.

- The effect due to a partial impact with an obstacle has only an effect on the global load level due to the ruptured part. An influence on the flight approach direction is not observed as the impact velocity is too high.

STUDY OF LOCAL PROTECTION MEASURES

In the final step the design of a local measure is investigated to increase the protection capacity. Thereby the focus is on steel-concrete-steel (SCS) sandwich structures. Therefore the containment is locally enhanced by a steel plate at the outer and the inner surface. The connection to the existing structure is created via anchors. They are also used to bond the additional steel plates with each other. The general setup of this local measure is presented in figure 10.

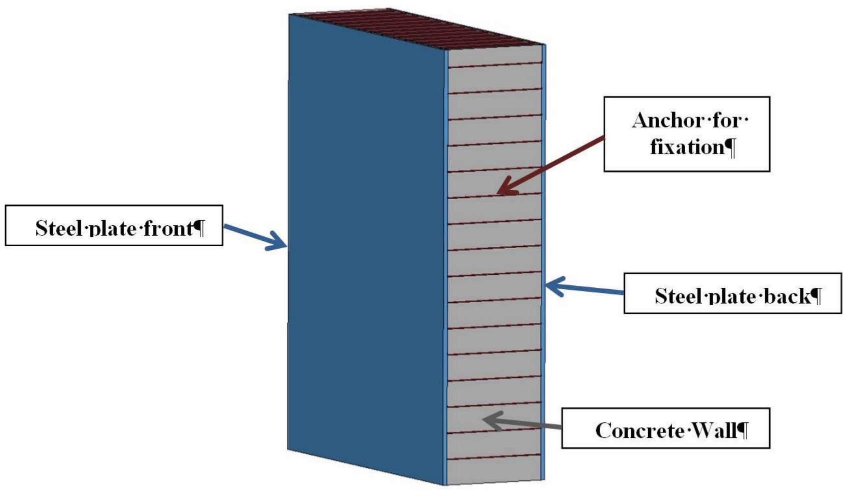

Figure 10. SCS structure as local measure to increase the protection capacity

The original concrete wall and the steel plates are only interacting via contact. The outer nodes of the anchor elements are merged with the steel plate. The inner nodes are connected to the concrete via the Embedded Element Option of ABAQUS. The modelling of the steel plates is carried out with shell elements and the anchors are implemented via beams. In the study the thickness of the plates and the anchor diameter is varied. Finally with optimized values the initially determined damage disappears, see figure 11.

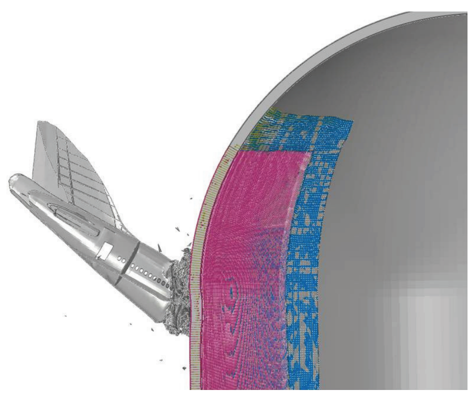

Figure 11. Simulation result for SCS structure with optimized design values

The simulation result shows that local measures are capable to improve the protection capacity significantly. Compared to global protection concepts as e.g. an additional second outer shell they are very time and cost effective. Further its installation is much easier and space problems due to surrounding buildings are rather improbable.

SUMMARY

In the research project Risk Protec CI a procedure for a vulnerability analysis of a critical structure with respect to an impact of an aircraft is described. The procedure is based on a method using the FEM for the assessment of the structural integrity.

In a first step the method was validated step by step in comparison to measurements. Then the approach is applied on two idealized outer containments of a reactor building. Further a sensitivity study with respect to the flight approach direction and the impact location was carried out. Finally a concept to improve the protection capacity by a local measure was investigated and evaluated.

By the simulation results it was shown that the designed procedure for a vulnerability analysis is capable to assess structural designs with respect to the load case aircraft impact. The benefit of the applied integral approach was shown by the investigation of changes for flight approach direction or the impact location.

ACKNOWLEDGEMENTS

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