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Validation of Integral Crash Simulation Method by Sandia Test Results for Phantom F4

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ABSTRACT

Within the last years commercial Finite Element (FE) software packages (ABAQUS 2013) and the performance of computational hardware have been improved steadily. This enables nowadays the investigation of aircraft impact on a nuclear power plant within one integral simulation (Arros 2007 and Kostov 2011), which offers advantages (Siefert 2011) compared to the existing decoupled approach where the load-time-function is computed in one simulation and then is applied as surface pressure in another simulation. At first the impact scenario with its three dimensional characteristics due to flight angle and surface geometry of the building can be considered in detail. And second the simulation accounts for local influences due to the structural setup of the aircraft.

On the contrary the engineer faces several challenges with respect to the model generation, property definition and simulation stability. Consequently it is very important to validate this new complex approach with experimental data. For the investigation of missile impacts this was already carried out within several studies as e.g. the IRIS 2010 benchmark (Rambach 2011). For the validation of an aircraft impact this is only possible by using the data of the Sandia Lab test of a Phantom F4 crashing on a concrete block (Riesemann 1989). In the work here presented all steps from model generation, simulation and finally evaluation and comparison with the measurement data are shown for this Sandia test with a F4 military jet.

INTRODUCTION

In Germany the impact of an aircraft has been a standard load case for the design of reactor buildings since the mid of the 1970 (Henkel 1984). Due to limited numerical capabilities a simplified decoupled procedure dividing the impact into two steps was used to compute the structural response. This included the following parts:

1. Computation of load-time-function by crash onto rigid wall (Riera 1968)
2. Application of load time function as surface pressure onto building and computation of structural response

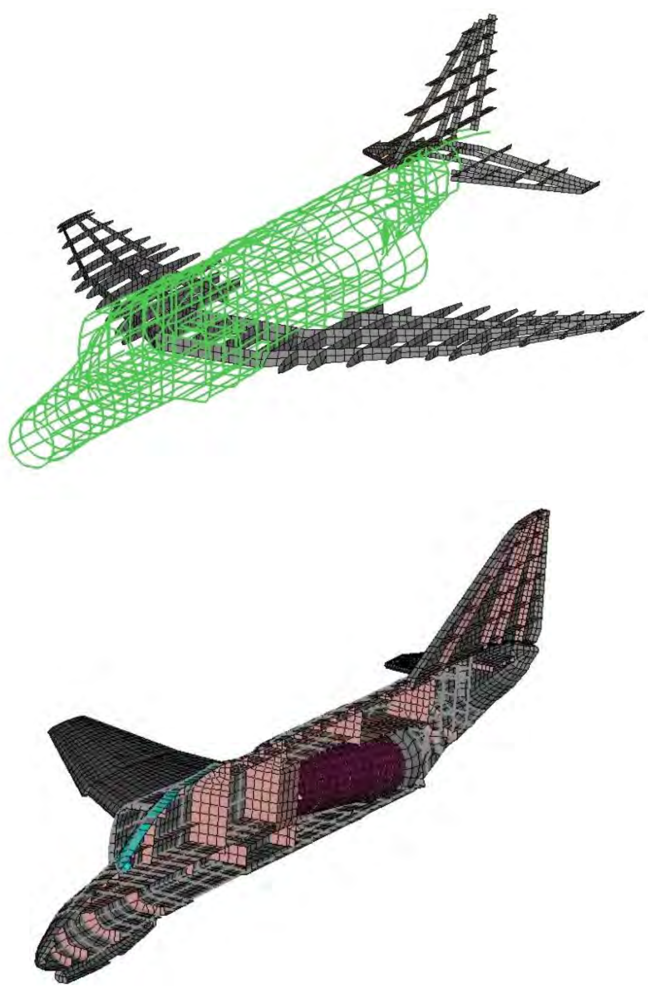
Using this approach the interaction between aircraft and building is not considered. Furthermore the load-time function is applied as a more or less equally distributed pressure, i.e. that the structural setup of the airplane which influences the local damage is missing. Finally geometrical effects due to flight angle and shape of the building are neglected.

Consequently to overcome these disadvantages several approaches using the new numerical capabilities have been developed within the last 10 years (Arros 2007, Stepan 2005). The aim was an integral simulation approach which represents the impact of an aircraft more realistically than the decoupled procedure. Within this simulation procedure the engineer faces several challenges. First the model setup of the aircraft and the building where detailed information about geometry and nonlinear strain rate dependent material properties must be implemented. And second the complexity of the simulation itself including impact dynamics, contact and nonlinear behaviour due to geometry and material effects. Therefore it is very important to validate the procedure by experimental test data. There are several publications where this integral approach is validated for impact of a missile on a reinforced concrete wall as e.g. in the IRIS 2010 benchmark (Rambach 2011). For the impact of an aircraft only the experimental test data of the Sandia Lab test of a Phantom F4 crashing on a concrete block (Riesemann 1989) are available. This paper presents all steps from model creation, impact simulation and finally evaluation and comparison with the measurement data.

MODEL SETUP

Model Of F4 Phantom

Within the last years Woelfel has developed several models of passenger and military aircrafts. The model setup of Phantom F4 is based on available data about geometry and material. For a practical application with respect to the computational effort only the main components with respect to stiffness and mass are considered in detail. In the following figure 1 several states of the model setup are shown. On the top the basic framework which is modelled via beam elements and shell elements is represented. The second plot shows a cross section along the symmetry plane of the aircraft. It illustrates that all structural parts are modelled via shell elements. The connection to the framework is carried out via merged nodes.



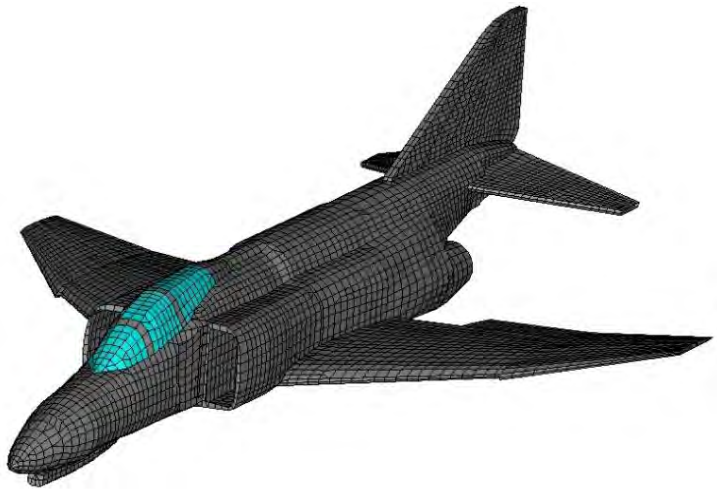


Figure 1: FE-model of Phantom F4: frame, cross section and isometric view.

In the model control equipment and other interior parts are not considered in detail, as no information is available and as their influence on the structural behaviour is negligible. Contrary thereto their mass must be considered as it is relevant for the impulse. The implementation is carried out via non-structural masses, which are distributed on the structural parts as the fuselage, the floor or the wings.

For the test setup at the Sandia Labs the fuel is replaced by water to avoid any secondary impact effects due to explosion. The modelling of the water is carried out via discrete mass elements which are equally distributed over the exterior wall of the tank. Nowadays a new approach is to model the fluid behaviour via particle elements. Within the study carried out a model variant using particle elements was generated. Thereby the tank volume is in the initial state filled with solid elements which are separated into particles after reaching a defined strain state. Background for this model variation was to evaluate the influence on the load-time function and the impact area.

The plot on the bottom shows an isometric view of the complete model. Altogether the setup has about 20,000 nodes and elements and about 83,000 degrees of freedom. The overall mass is 17.6 t and can be separated in 4.8 t for the fuel, 12.8 t for the structural parts. This value correlates with the test data.

As material the aluminium alloy 2043-T3 is used for almost all structural parts. This represents a standard material for the structure of military and passenger aircrafts. With respect to the impact scenario the material definition must include nonlinear and strain rate dependent effects. Therefore the constitutive law of Johns-Cook for metal plasticity is chosen, see equation 1 (Johnson 1983). The test data to identify the free material parameters is taken from (Federal Aviation Administration 2000).

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

Equation 1: Constitutive law of Johns-Cook for metal plasticity.

For the failure of the material the *Damage Initiation* and *Damage Evolution* options which are available in ABAQUS are used (ABQUS 2013).

Model Of Concrete Wall

In the next step the model of the concrete wall for the final impact simulation is described. The dimensions are taken over from the real test, which are 7.0 x 7.0 x 3.66 m³ (width, height and thickness). The modeling is carried out by hexahedron elements. The element size varied over the thickness as only a local damage at the surface is expected.

The reinforcement is implemented by discrete beam elements. Beside the bending rebars at the front and the back side of the concrete block stirrups in impact direction are considered. The spacing between the discrete elements is 0.1 respectively 0.2 m. The interaction between discrete rebars and volume elements for the concrete is carried out via the *Embedded Element Formulation* (ABAQUS 2013), which generates automatically kinematic couplings in the preprocessing. This option of ABAQUS enables the use of not matching meshes for concrete and reinforcement. The following figure 2 illustrates the setup.

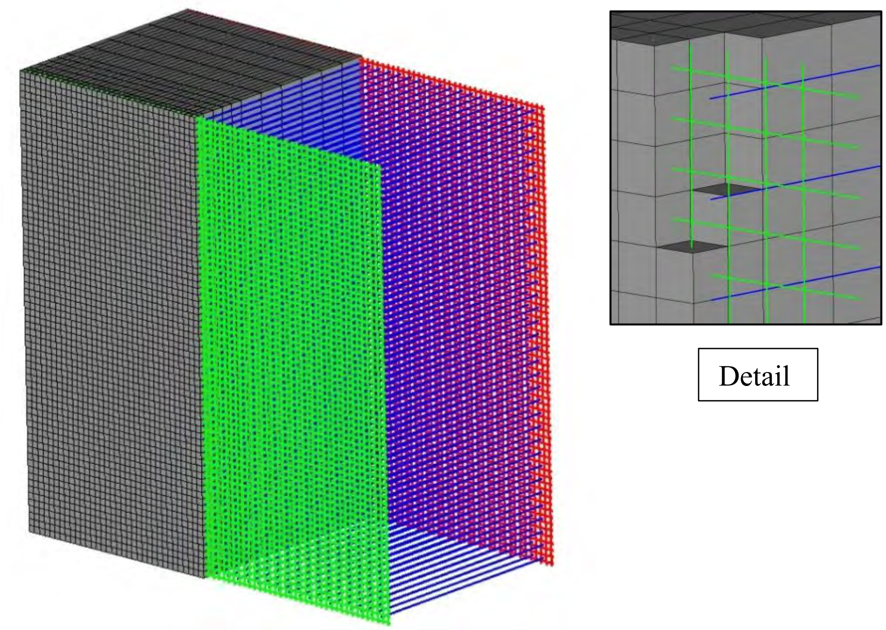


Figure 2: FE-model of reinforced concrete wall.

As for the setup of the aircraft the material definition of concrete and reinforcement steel must be nonlinear, strain rate dependent and must include a failure mechanism. For concrete the explicit solver of ABAQUS provides beside standard material models as e.g. the Drucker-Prager the Concrete Damage Plasticity model (Lubliner 1989). It is designed for simulations with monotonic or dynamic loading scenarios. Following the experimental setup a concrete with a compressive strength of 25 N/mm² is defined. As the standard approach of ABAQUS does not include failure a user-subroutine was developed deleting the elements with respect to plastic strain limits for compression and tension.

For the reinforcement the steel of Bst 420-500 is chosen. Similar to the aluminium alloy definition of the aircraft the Johnson-Cook plasticity approach is used as material law. For defining the strain rate dependence values from the literature are assumed (Brandes 1985). The following figure 3 shows the material behaviour for different strain rates.

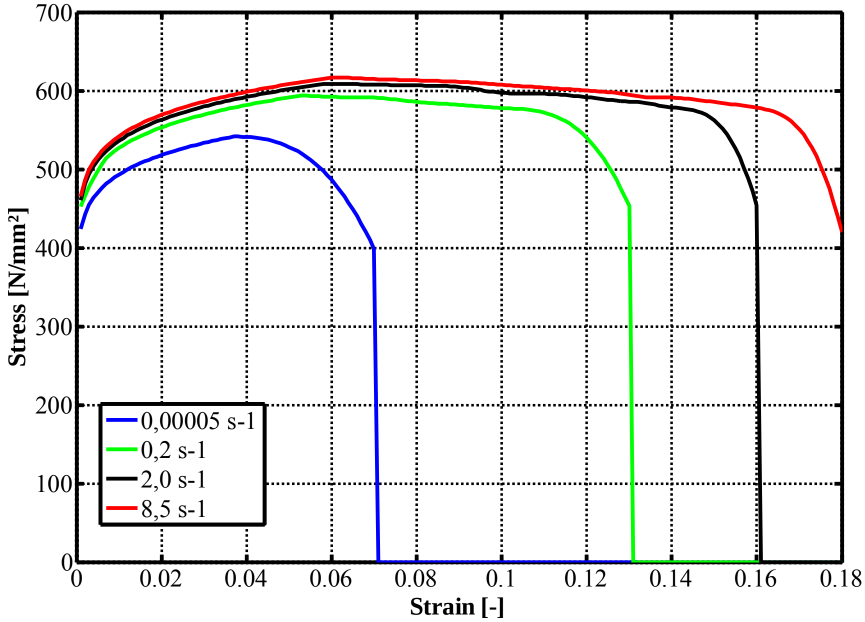


Figure 3: Defined material behavior of reinforcement steel Bst 420-500 for different strain rates.

Comparing the material behavior in the simulation with the experimental data a good correlation is achieved for all strain rates.

COMPUTATION AND RESULTS

Simulation Of The Impact On A Rigid Wall

The computation of the load-time function is carried out by simulating an impact on a rigid wall. Thereby a rigid body is used with the same dimensions in height and width as for the concrete wall. The wall is fixed for all degrees of freedom on its reference point. Reducing the computational time the aircraft is positioned in front of the wall and has an initial velocity of 215 m/s in flight direction.

In the model setup the rockets which are used to accelerate the aircraft and the sled which defines the flight direction are not considered. At the bottom of the aircraft some nodes are limited by boundary conditions in their vertical displacement to take into account the real connection between sled and aircraft.

The interaction between aircraft and the rigid wall is defined by a general contact algorithm. This includes also self-contact between the different structural components of the aircraft. For the contact the friction is assumed with a coefficient of 0.4. The computed impact time is 100 ms.

The validation of the simulation is carried out qualitatively and quantitatively. First the failure behavior of the military aircraft over time is compared visually with the observed real behavior. In figure 4 the initial undeformed and the deformed states for 25 ms, 50 ms, 75 ms and 100 ms are shown for the simulation via an isometric view. Thereby a correlation with the real behavior can be determined. Deviations are only appearing in the last part of the impact, where the destruction of the aircraft seems to be in the simulation smaller than in the real test. Additionally it can be observed that the rupture behavior for the outer part of the wings is different between computation and measurement. Finally the tail shows a vertical displacement which does not appear in the real test. Especially for this difference the missing modeling of the sled seems to be a plausible explanation.

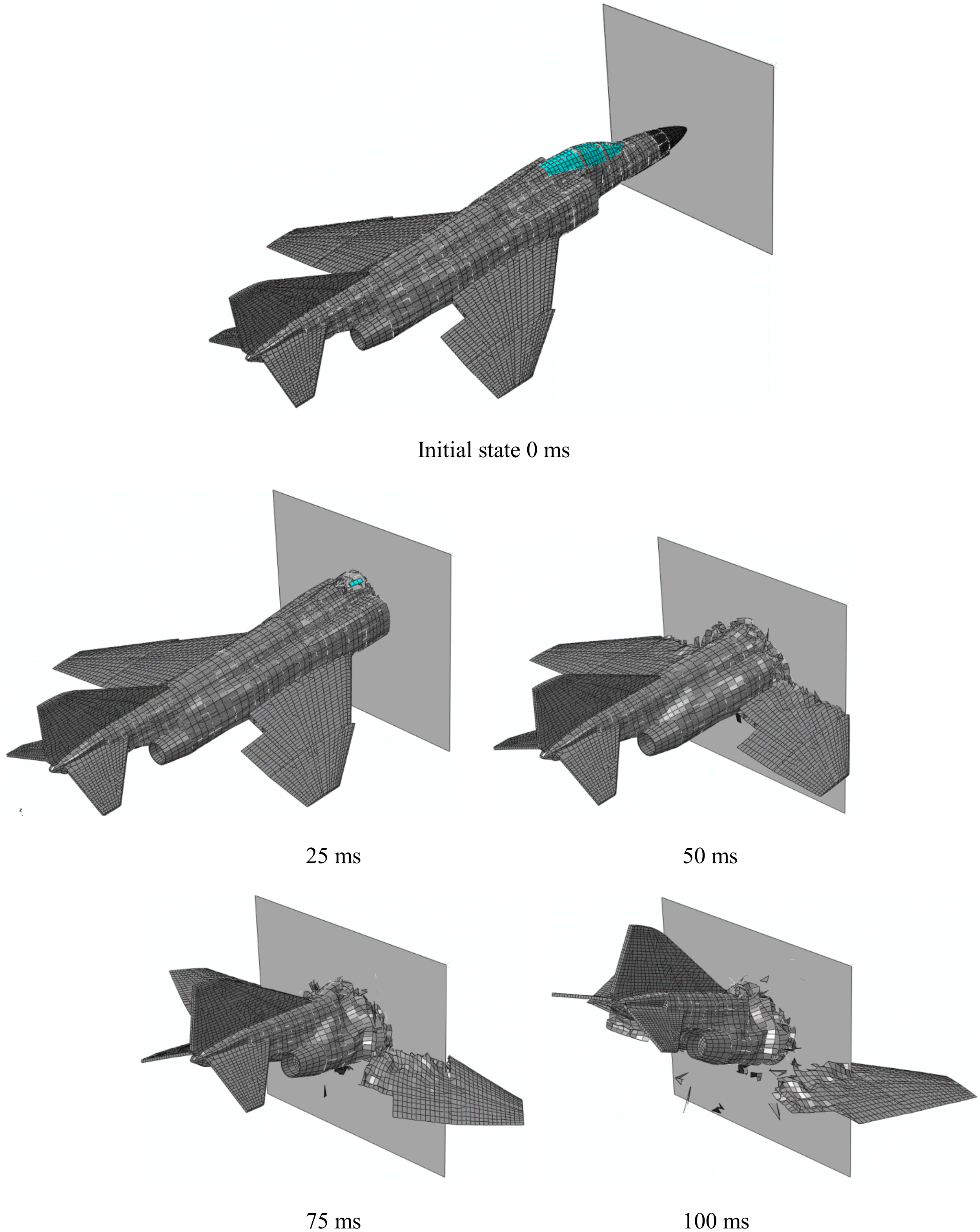
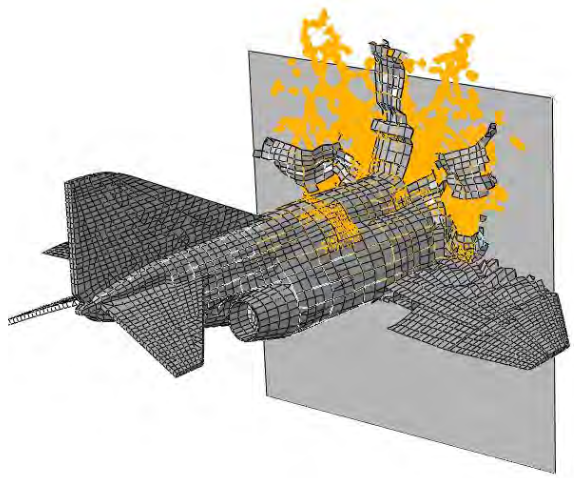
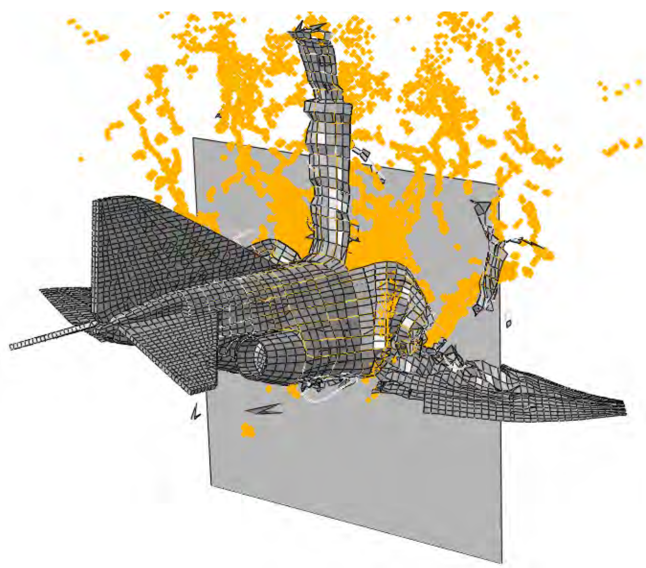


Figure 4: Simulation result for crash of Phantom F4 on a rigid wall with velocity of 215 m/s.

In figure 5 the simulation result for the variation using particles instead of discrete elements to model the fuel is presented. It can be observed, that after the destruction of the tanks the fluid distributes in radial direction to the impact area, which seems to be plausible with respect to the reported real behavior.



50 ms



75 ms

Figure 5: Simulation result (50 and 75 ms) of model variant using particles to represent fuel for crash of Phantom F4 on a rigid wall.

For the final application this variant seems to be more realistic than representing the fuel by discrete elements. As the computational effort increases considerably for using the particle elements it is very important to assess the difference also quantitatively. Therefore the computed load-time function is finally compared with the results of the measurement, see figure 6. Thus of using a rigid wall with an infinite stiffness numerical artifacts in form of unrealistic force peaks occur. For eliminating these effects the simulation results are smoothed by the straight-average method using a time increment of dt = 2 ms.

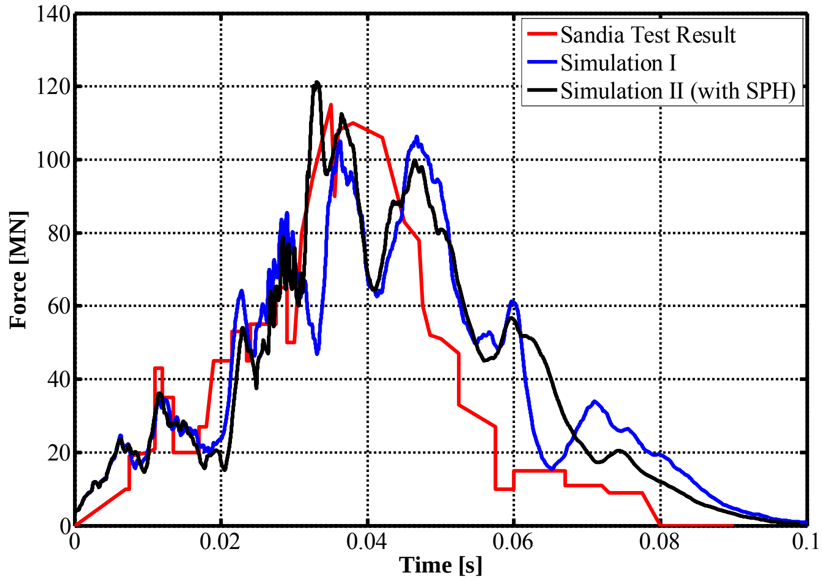


Figure 6: Comparison of load-time-function for Measurement and Simulation (Variant I – Discrete elements, Variant II – Particle elements).

Comparing the load-time-function for both variants it must be determined that the differences between them are rather small, i.e. the modeling by using particle instead of discrete elements shows with respect to the load-time function no relevant advantage. Comparing the simulations with the real measurement data a good correlation is observed for the main characteristics as maximum value and curve progression. Differences are determined after the impact time of 50 ms as the simulation shows then a delay of about 5 ms with respect to the real data. Possible reasons are the missing modeling for the rockets and the sled and the related boundary conditions.

Simulation Of The Impact On A Reinforced Concrete Wall

The first studies here presented are with the aircraft model using particle elements. The simulation procedure of the impact on the concrete wall is similar as for the crash on the rigid wall. The aircraft is positioned in front of the wall with an initial velocity of 215 m/s. As boundary condition the lower part of the wall is fixed. Compared to the real setup this represents a simplified assumption as there the concrete wall was vertically supported by a basement and in flight direction only restraint by the friction due to gravity preloading. The interaction between aircraft and concrete wall is defined by a general contact algorithm including friction with a coefficient of 0.4. The computed impact time is 100 ms. Figure 7 shows first the overall behavior of the simulation at the impact time of 60 ms. As for the crash on the rigid wall the radial expansion of the fuel can be observed.

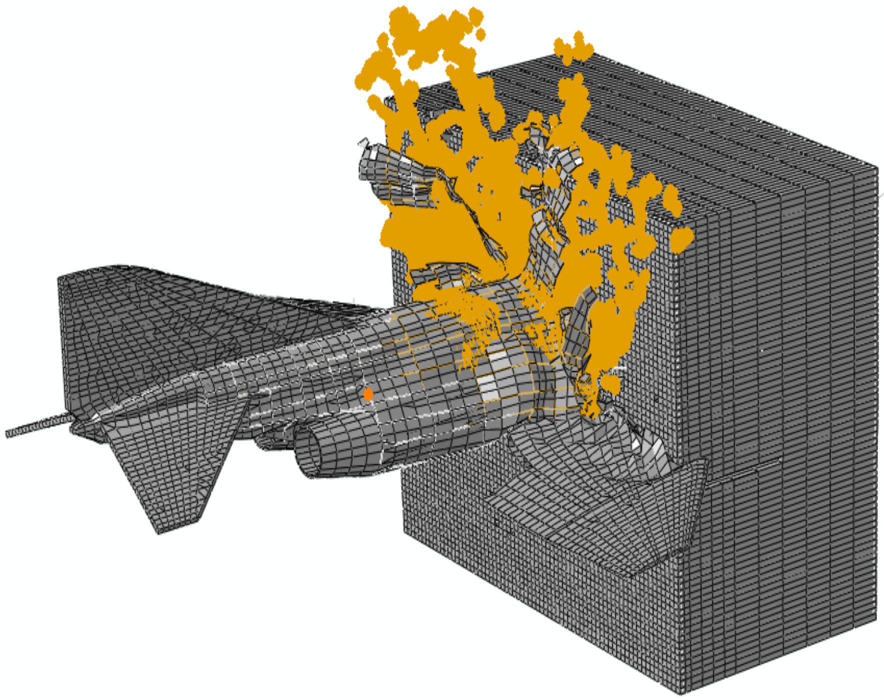


Figure 7: Overall model behavior at impact time of 60 ms – isometric view.

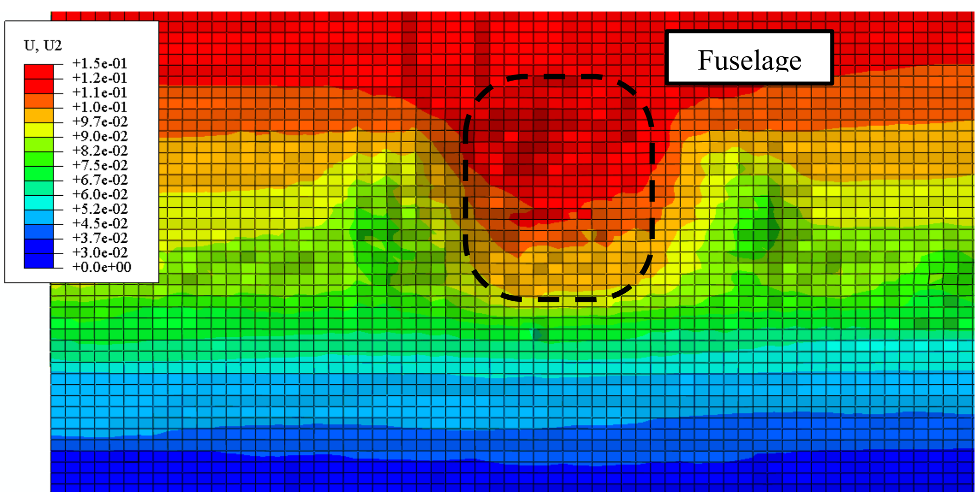


Figure 8: Displacement in flight direction at impact time of 60 ms.

In figure 8 the displacement in flight direction is shown for the impact time of 60 ms. Comparing the local damage of the concrete with the real test differences are observed. While the simulation shows almost for the complete fuselage a constant displacement of about 10 cm the real damage in this area is very small and occurs only at the edge of the fuselage, i.e. the damage looks like an apple cutter. A possible reason for this difference is the simplified assumption of the boundary condition in the simulation. Therefore further studies will be carried out including the preload due to gravity. Further a mesh refinement at the surface of the concrete wall should be considered.

CONCLUSION

The presented work shows the validation of an integral simulation approach for the impact of the Phantom F4 on a reinforced concrete wall reflecting the real test setup of the Sandia test. In a first step the model setup of the used aircraft was validated by the crash on a rigid wall. Comparing the damage of the aircraft with the real behaviour a good correlation is achieved till a simulation time of 50 ms. Thereafter smaller differences occur in the rupture of the wings and in the vertical displacement of the tail. A scalar comparison was carried out by computing the load time function. Thereby the computation reflects the main characteristics of the experiment. The visual and scalar differences could be explained by the fact that the model setup does not include the rocket and sled which are used in the real test to accelerate the aircraft. Summarizing this first step the applied model setup of the aircraft reflects the reality and therefore could be used for an integral simulation.

The second step of the presented work shows first simulations of the impact on the reinforced concrete wall. Thereby the main characteristics of the local damage are reflected by the simulation. Differences are observed in the displacement which requires for further studies. Therefore a possible reason is the simplified assumption of the boundary conditions of the concrete wall. To overcome this problem the preloading of the wall due to gravity should be included within the process. In spite of these differences the simulation reflects the real behaviour and therefore is a possible approach to investigate the impact of an aircraft on structural building. Compared to the existing decoupled approach this integral procedure enables the reflection of the real impact scenario more realistically which is a benefit for the assessment of existing and new structures. A disadvantage of the procedure is its complexity, which requires an appropriate simulation knowhow to apply the method for the assessment of structural behaviour of nuclear power plants.

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