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# COMPUTATION OF RESPONSE SPECTRA FOR LOAD CASE AIRCRAFT IMPACT - COMPARISON OF DECOUPLED AND INTEGRAL APPROACH

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## ABSTRACT

Due to the constant development for Finite Element (FE) simulations a crash analysis by an integral approach is nowadays possible, see Siefert (2011). Thereby all model parts, i.e. aircraft, structure and the contact in between, are considered in one model. This procedure provides the advantage to simulate the impact scenario, i.e. the structural setup of the aircraft, its flight direction, the shape of the building and possible obstacles realistically. Therefore it is state of the art for the analysis of local and global structural behaviour for the load case aircraft crash.

For the analysis of floor response spectra still the decoupled approach, i.e. separate load definition via load-time-function (LTF) and its application on the structure, is typically used. The work presented here shows the updated possibilities of the integral approach for the computation of floor response spectra. In a first step the impact of a military jet and a passenger aircraft on a rigid wall is shown defining the starting point for both approaches. In the second step the simulation of floor response spectra is carried out for a nuclear building using the decoupled and the integral approach.

Based on the result the general capabilities of the integral approach are shown for the computation of floor response spectra enabling a comprehensive analysis for all steps of the load case aircraft crash.

## INTRODUCTION

The constant improvement of software packages using the finite element method (FE-method) as e.g. ABAQUS or LS-DYNA and hardware setups for computational analysis enables nowadays the integral approach for the load case aircraft crash. Several papers as Kostov (2011) and Siefert (2013) have already discussed the benefits of the integral approach compared the usage of a decoupled analysis using (LTF).

Using the integral approach the computation of floor response spectra for buildings is still a challenge. A possible workaround was already presented by Siefert (2013). There the response spectra of the integral approach are post-processed using a low pass filter function, known for smoothing the LTF. Nevertheless the complexity of the integral approach leads to very high computational times. Accordingly the decoupled approach originally introduced by Riera (1968) is still applied very often for this kind of analysis. The presented work will show the updated capabilities of the integral approach and show a comparison between both procedures for the impact of a military aircraft on an exemplary containment structure.

## IMPACT RIGID WALL

In the first step the impact on a rigid wall is presented for a military jet Phantom F4 and the passenger aircraft B767. The computed LTF using a detailed FE-model of the planes is the starting point for all further steps.

### *Model Setup Phantom F4 and B767*-200ER

The setup of both aircraft models is based on published data about geometry and material from the manufacturer. Reducing the modelling effort and considering the influence on the final simulation only the main components with respect to stiffness and mass are considered in detail.

For both airplane models the setup can be separated in the structural frame, the outer surface, internal structural parts, the landing gears, the engines and loads (fuel and payload). With respect to the dimension of the real structure the modelling is carried out using beam, shell or discrete mass elements. The following figure 1 shows the general setup for the aircraft B767-200ER.

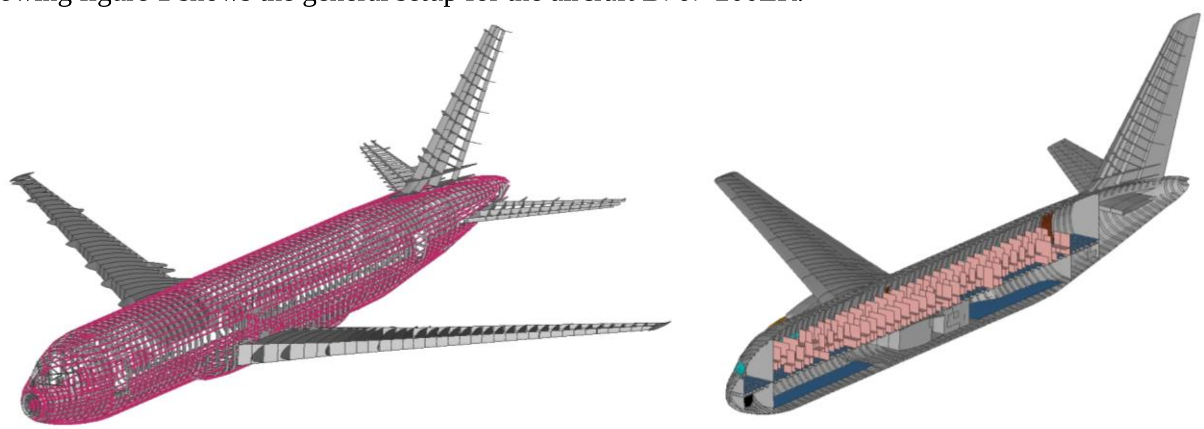

Figure 1. Model setup B767 – Frame and Cross Section

In the real setup different materials like aluminium, titanium, steel, rubber, glass and plastic are installed. Thereunder the aluminium represents the biggest part as it is used for the fuselage and the main frame. For the computation the behaviour of alloy 2043-T3 is used as it is a standard material for the structure of military and passenger aircrafts. For all materials nonlinear behaviour is assumed. Takin strain rate dependent effects into account the approach of Johns-Cook is used for all metallic parts. The material is defined following equation 1, Johnson (1983).

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

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

Finally the failure of the material is defined the Damage Initiation and Damage Evolution options are used which are available in ABAQUS (2014).

The weight of the B767 is defined with 179 t, what represent the Maximum Take Off Weight (MTOW) and for the Phantom F4 17.6 t are defined, reflecting the setup of the Sandia test, see Riesemann (1989).

***Computation of LTF via Impact on Rigid Wall***

The computation of the LTF is carried out by simulating an impact on a rigid wall. Thereby a wall defined as a rigid body covering the complete impact area is used. The wall is fixed for all degrees of freedom on its reference point.

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 impact velocity for the military jet representing the Sandia test is defined with 215 m/s. For the B767-200ER a speed of 160 m/s is assumed, which is used by several countries as maximum velocity. The duration of the simulation depends on the length of the aircraft and the defined speed. For the B767-200ER a time of 400 ms and for the Phantom F4 150 ms are simulated. The following figure 2 shows the deformed structure of B767-200ER at the state of 150 and 400 ms.

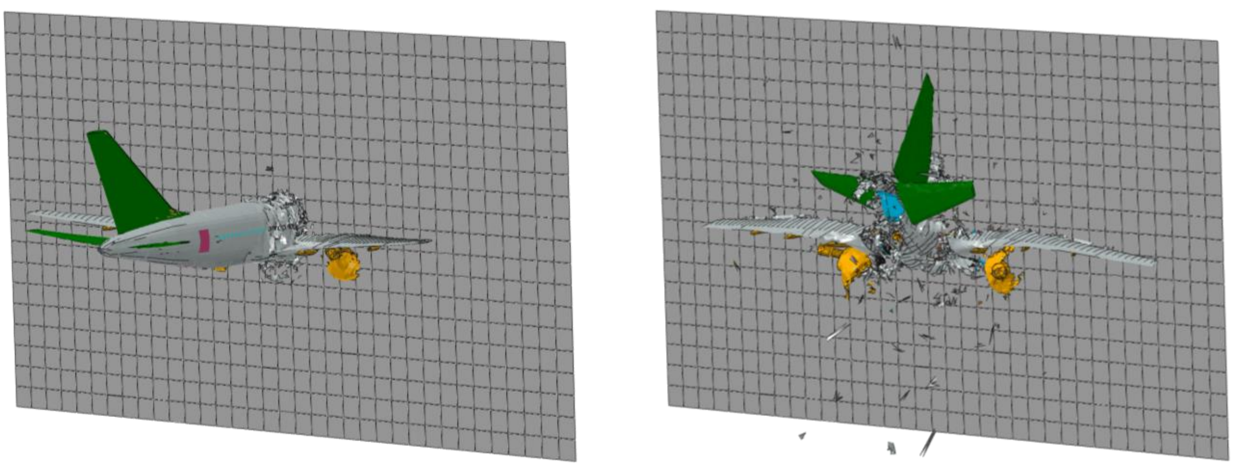

Figure 2. Impact of B767 on Rigid Wall – Deformed State at 150 and 400 ms

For both aircrafts a complete destruction can be observed at the end of the simulation. Further it can be observed that step by step the main parts are ruptured from each other, i.e. first the fixation of the turbines on the wing fails and the wings are ruptured from the fuselage.

***Result LTF and Evaluation***

The LTF is evaluated via the reaction force of the reference node from the rigid wall. Using the FE method for the analysis of an aircraft impact on a rigid body, numerical artefacts represented by high peak values at the LTF are known and also observed here. Eliminating these artefacts the computed LTFs are typically smoothed by the following options:

- Polygonal line
- Low pass filter 50 Hz
- Straight Average Approach (dt = 0.001 s)
- Polynomial 20$^{th}$ order

The influence of the smoothing algorithms is shown exemplary for the analysis of the Phantom F4 by the following figure 3.

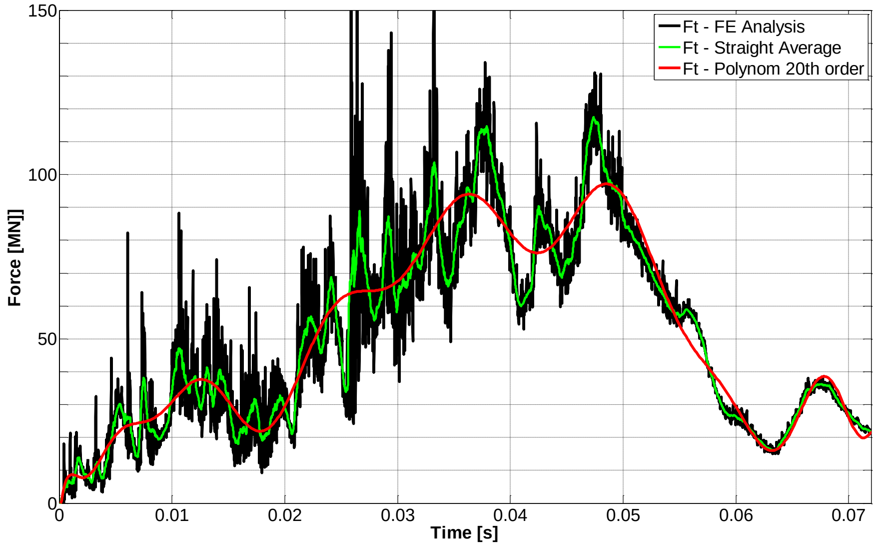


Figure 3. LTF Impact Phantom F4 with 215 m/s

First it can be seen that the general characteristics of the Sandia test results for the Phantom F4 crash with 215, i.e. a duration of about 70 ms for the impact and a peak load of 110 MN are fulfilled by the analysis. Comparing now the effects of the different smoothing approaches general differences can be observed. While the straight average approach only deletes significant outliers and keeps also minor characteristics, the polynomial eliminates everything beside the main characteristics. This can easily be visualized looking on the dynamic load factor (DLF) for all curves, see figure 4.

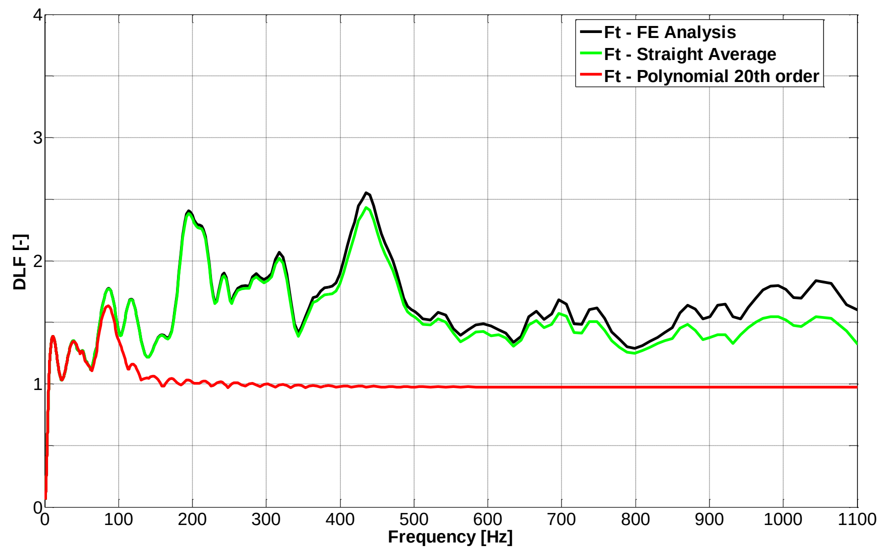


Figure 4. DLF-Function Impact Phantom F4 with 215 m/s

The main characteristics of the impact are included in the frequency range up to 100 Hz. Here the DLF values are almost the same for all three curves. Due to the smoothing effect of the polynomial any content

above 100 Hz is eliminated. This is not the case for the straight average approach, as the curve is up to 1000 Hz very similar to the initial computational result.
As mentioned before the content of above 100 Hz is due to numerical effects while computing the LTF. Further it is known that displacements caused by accelerations in this frequency range are very small and therefore would not have an effect on the component behaviour. Therefore the application of smoothing algorithms, like the polynomial or the low pass filter, is approved and state of the art. For the integral approach this intermediate step is not possible and as a consequence of this the computation of floor response spectra shows typically higher amplitude in the upper frequency range.
Nevertheless it has to be mentioned that this conclusion is mainly based on the experience of the impact analysis on a rigid body. Taking into account nonlinear and damping effects of the material in a complete building analysis could reduce this effect. Therefore the second step presented here is the computation of floor response spectra for a nuclear building for all three curves, i.e. decoupled approach using polynomial and straight average curve and the integral analysis with the direct impact analysis of the aircraft.

## IMPACT NUCLEAR BUILDING – COMPUTATION RESPONSE SPECTRA

In the following chapter only the results for the impact and floor response spectra of the Phantom F4 are presented. Similar observations are made for the analysis of the B767-200ER, but are not presented here due to limitations of the publication.

### *Modell Setup Nuclear Building*

The used nuclear building is a virtual design, i.e. it does not represent any real structure. Nevertheless some parameters are chosen realistically. In figure 5 the general setup of the building with its dimensions of 50 x 20 x 20 m (length, width, height) is shown. Internally the building has several walls in length and width direction (not shown completely in figure 5). Beside the ground level a second floor is modelled about 12 m. All internal walls are connected to the foundation plate only and decoupled from the outer wall and the roof.

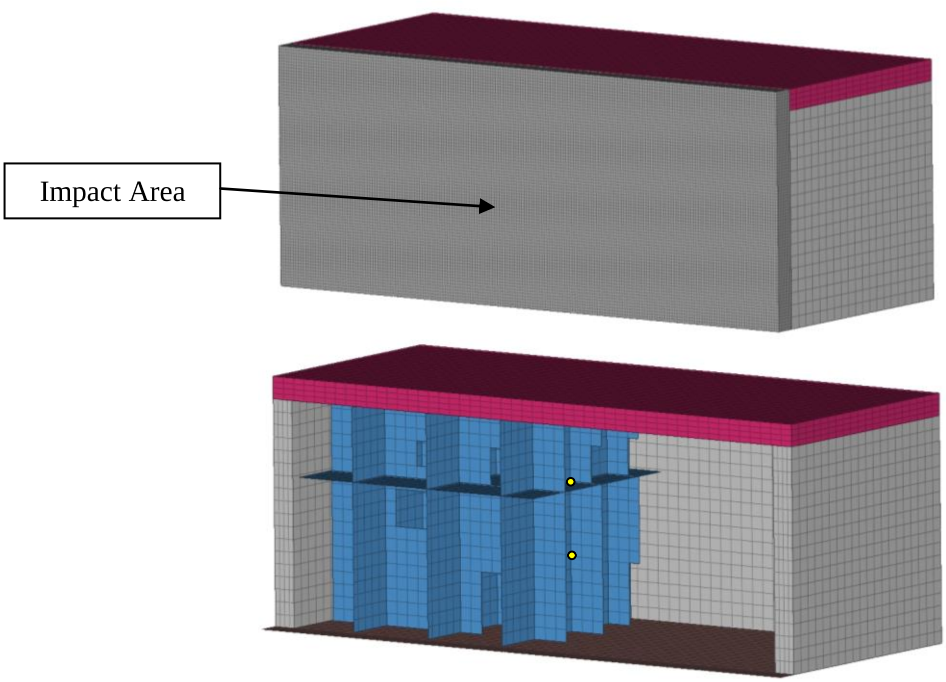


Figure 5. Building for impact analysis – frontal view with and without outer wall

The outer wall has a thickness of 1.80 m and includes bending and shear reinforcement. The wall impacted by the aircraft is modelled via solid elements, while for the rest shell elements are used. The reinforcement is modelled with truss elements and is embedded in the outer wall and interacts with kinematic couplings. The basement is modelled via rigid body which is supported by a connector element considering typical stiffness and damping values for the ground supporting the building.

For the impacted wall nonlinear material behaviour and a failure criteria leading to erosion are assumed for the concrete and reinforcement. For the rest of the building a linear behaviour is defined as no damage can be expected. The damping is assumed via the Rayleigh approach with 4 % at 10 and 50 Hz for the not impacted structural parts. The overall weight of the building is about 22,000 t. In an eigenfrequency analysis the following values are computed for the main modes of the building:

- Tilting over short axis 5.1 Hz
- Tilting over long axis 6.0 Hz
- 1st mode of the roof 7.9 Hz

***Simulation Impact – Local Damage Behaviour***

For the integral approach the aircraft position in front of the outer wall centre at a height of about 10 m. Then the computation is started with an initial velocity of 215 m/s. The interaction between all model parts is defined by the general contact algorithm. For the decoupled analysis the LTF of the straight average approach and the polynomial are applied via a varying pressure over time. Following the state of the art the pressure is applied onto a surface of 7 m². In figure 6 the initial setup for both approaches are presented.

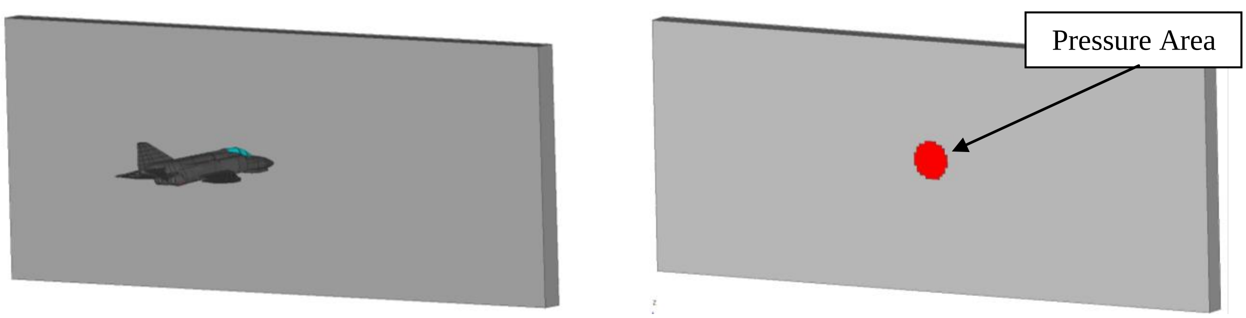


Figure 6. Model setup integral and decoupled approach

For both procedures the computation is carried out up to 0.7 s using the explicit solver scheme of ABAQUS. Only a minor difference can be observed for the computation time, i.e. the integral simulation was about 25 % slower than applying the LTF.

One of the main benefits for the integral approach is a more realistic analysis of the local damage as the load is not lumped over the complete impact area. Local effects due to the structural setup as e.g. the fuel tank or the turbines are taking into account more detailed. Therefore the analyses are compared first with respect to the displacement and the damage in the impact area.

The above mentioned consideration of local effects for the integral analysis leads to an erosion of some elements at the front side of the outer wall, which is not observed for both decoupled analysis. In figure 7 the area of the eroded elements and the displacements at the end of the simulation are shown.

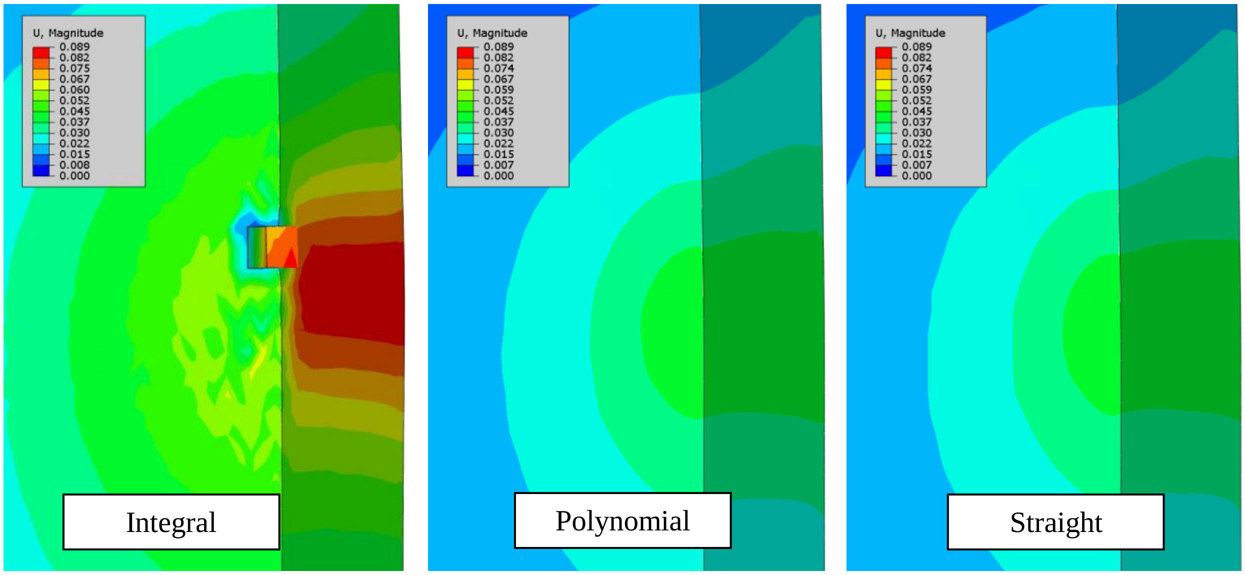


Figure 7. Displacement [m] at the end of the simulation

It can be observed that the integral analysis leads to the highest displacement results with a maximum value of 0.13 m at 80 ms and 0.089 m at the end of the simulation. Both decoupled approaches show similar values with a maximum displacement of 0.07 m at 70 ms and a final value of 0.045 m.

A similar result can be observed for the cracking of the concrete, displayed via the maximum plastic strains in the impact area. While the decoupled analyses show only a cracking at the back side, the integral analysis shows a cracking over the complete thickness. A more general difference is that the applied pressure of the decoupled approach results in no damage at the front side of the wall.

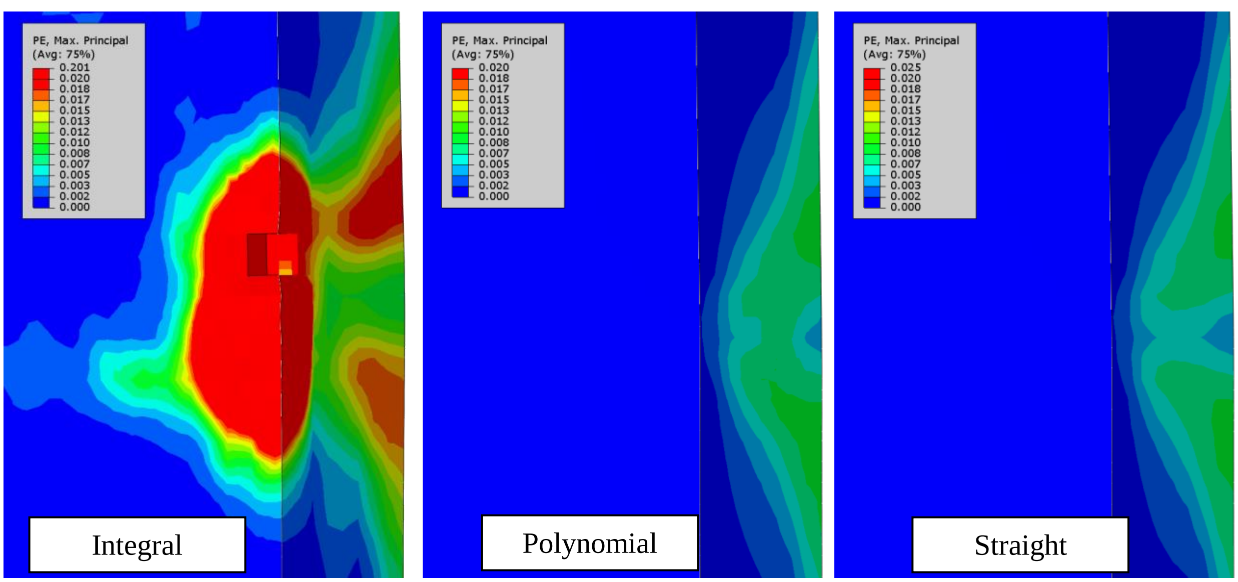


Figure 8. Maximum plastic strain [-] at the end of the simulation

The here presented results show that the general observations between the analysis types is similar, but the integral analysis results in higher damage values of the impacted wall. The main reason for this difference is that the load is not lumped via criteria area, accordingly stress hot spots appear leading to a greater local damage.

### *Analysis and Evaluation of Floor Response Spectra*

In the final step the floor response spectra in x, y and z direction has been computed for several locations in the building. The sampling rate of the results is 1000 Hz. In the following figure 9 and 10 the exemplary result of the acceleration response spectra (horizontal direction) are shown for two locations (see figure 5) in the centre of the building. For the computation of the response spectra a damping coefficient of 4 % is applied.

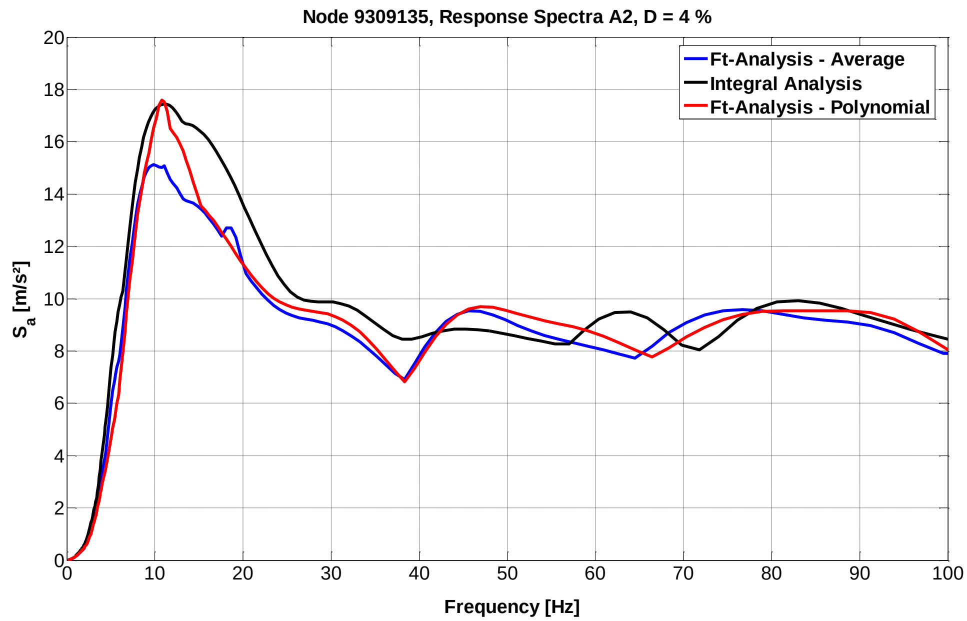


Figure 9. Response Spectra A2 for the upper node 9309135

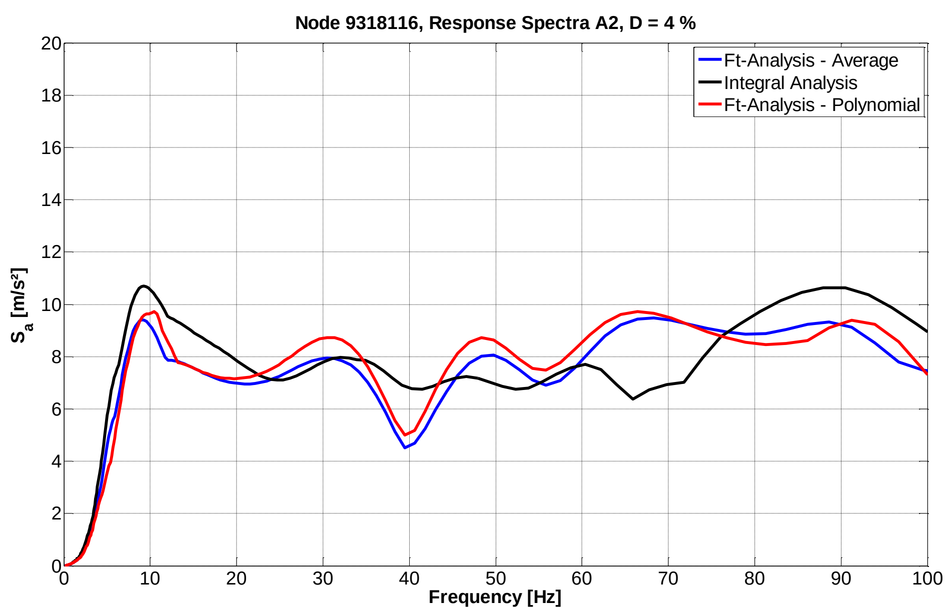


Figure 10. Response Spectra A2 for the lower node 9318116

In general a consistency between the decoupled approach using the polynomial and the straight average function and the integral analysis can be observed for the computed response spectra. All computations show similar results with respect to the characteristics (peak locations) and the amplitudes of the response spectra. Accordingly it can be concluded that the integral analysis can also be used for the computation of response spectra. This enables a comprehensive analysis including relevant effects as 3D shape of the structure, pre-impacts with obstacles or the influence of a partial impact.

## CONCLUSION

The work here presented showed a comparison between the decoupled and the integral simulation approach for the computation of the response spectra due to the crash of a military aircraft on a nuclear building. First the general differences with respect to the frequency content of both simulations were shown for the impact analysis on a rigid wall.

Second the impact of Phantom F4 on nuclear building was computed for all three approaches. Evaluating first the local behaviour of the outer wall it was observed that the detailed consideration of the structural setup of the aircraft leads for the integral approach to higher damages. Especially the determined damage on the impacted front wall in the integral seems to be more realistic then no damage in the decoupled analysis. Finally the response spectra have been presented computed for several locations in the building in the horizontal direction. Thereby a good correlation was achieved between the decoupled and the integral analysis.

Based on the presented results it can be concluded that integral approach is a comprehensive procedure which enables a realistic representation of local impact effects as structural setups of the aircraft are considered in detail. Further it can also be used for the computation of response spectra. Accordingly a separation of the analysis in local behaviour via the integral procedure and response spectra behaviour via the decoupled procedure is not necessary anymore.

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