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COMPARISON BETWEEN EMPIRICAL FORMULA AND INTEGRAL SIMULATION APPROACH FOR INVESTIGATION OF ENGINE IMPACT

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ABSTRACT

Empirical formulas are used since the 1960ies for assessing perforation capacity of civil structures with respect to the impact of projectiles as e.g. missiles respectively engines. These formulas were initially developed in order to study the impact of rigid projectiles. Today, these empirical methods can be used for assessing perforation capacity of reinforced concrete walls impacted by relatively deformable missiles, as aircraft engines are, providing margins in the calculation. In order to have a "best-estimate" approach, the original formulas can be adapted applying factors taking into account deformability of the engine. These "deformability factors" are defined in NEI 07-13 and were obtained thanks to impact tests carried out by Sugano. For the calibration of these factors typically test data are used as input.

The integral simulation approach can efficiently complete the experimental approach for the investigation of impact scenarios. A disadvantage of this method is the numerical complexity which increases the required effort but disappears step by step due to soft and hardware developments. An advantage is a realistic representation of the load scenario including all structural and geometric effects.

In the presented study the results using both approaches for different scenarios of an engine impact on a reinforced concrete wall are presented, confirming the good consistency between the simulation results and the results obtained with the empirical formulas, taking into account deformability of the engine or not.

INTRODUCTION

The impact of missiles and aircrafts is a relevant load case for the design of reactor buildings or auxiliary structures. For many scenarios, empirical formulas have been derived based on test data. They can easily be applied and enable a fast evaluation of the structure with respect to the impact. Nevertheless it must be mentioned that for most formulas the calibration of key parameters is based on specific test data.

These formulas were initially developed in order to study the impact of rigid projectiles. Today, these empirical methods can be used for assessing perforation capacity of reinforced concrete walls impacted by relatively deformable missiles, as aircraft engines are, providing margins in the calculation. In order to have a "best-estimate" approach, the original formulas can be adapted applying factors taking into account deformability of the engine. These "deformability factors" are defined in NEI 07-13 and were obtained thanks to impact tests carried out by Sugano. For the calibration of "deformability factors" typically test data are used as input. The integral simulation approach can efficiently complete the experimental approach for the investigation of impact scenarios.

Indeed, the numerical simulations using the FE method considering all influences within one model are getting more-and-more state of the art. Here the range of application is only limited to the realistic representation of the materials behaviour and the numerical method itself with respect to strain rates. A disadvantage of these computations is their complexity and the numerical effort.

The work can be separated into three parts. In the first step the finite element (FE) models of the two engines J79 GE (typical for military jets) and IAE V2500 (typical for commercial aircrafts) are generated for the solver ABAQUS, ABAQUS (2012). A model validation is carried out by comparing the load-time-function (Ft-function) for a crash onto a rigid wall with available test data, see Muto (1989).

In the second step an integral crash simulation onto a concrete wall is carried out. The simulation scenario is defined with respect to the Sugano engine test, see Sugano (1993), representing a full scale impact of the engine J79 GE. In this step the simulation approach consisting of the engine, the wall and their interaction is validated by the comparison with the real test.

Finally two different empirical formulas of the Nuclear Energy Institute (2011) are used for to defining an impact scenario, where the engine almost perforates the concrete wall. Both scenarios are investigated with the FE-approach. Thereby the calculated damage level of almost perforated walls confirms the good consistency between the simulation results and the results obtained with the empirical formulas, taking into account deformability of the engine or not.

ENGINE MODELS

Setup FE-Model

In the carried out study the two engines J79 GE, used primarily for Phantom F-4E, and IAE V2500, used primarily for smaller passenger aircrafts, are applied. The model setups are defined on published data and measurements of real hardware. The models consider the following parts from the front to the back: fan for the air inlet, compressor for packing the air, combustion chamber, turbine and exhaust nozzle. These are the key values for stiffness and mass distribution and therefore influencing the impact load for the final crash.

The modelling is carried out with HyperMesh, Altair (2012), using shell elements for all parts. The connection between different parts is generated by kinematic couplings. Figure 1 shows a cross section along the lateral axis for IAE V2500.

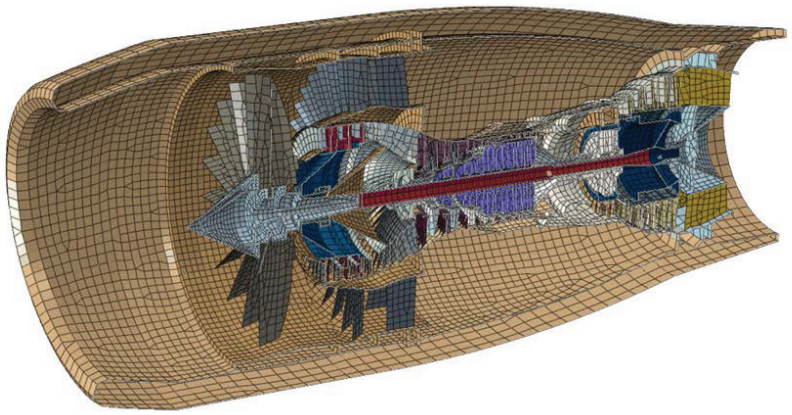

Figure 1. Model setup of IAE V2500

Beside steel several alloys are used. With respect to the impact scenario the material definition must include nonlinear and strain rate dependent effects and enable finally a failure after exceeding defined strain limits. This can be realized by the constitutive law of Johnson-Cook for metal plasticity, Johnson (1983), see Equation 1 below. The test data for identifying the material parameters is given by the literature.

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

Equation 1. Constitutive law for Johnson-Cook material approach

For the failure of the material the *Damage Initiation* and *Damage Evolution* options of ABAQUS are used.

Validation of FE-Model

The model validation of the J79 GE is carried out via the load-time-function (Ft-function) in comparison to real test results, see Muto (1989). The Ft-function is computed by a crash analysis on a rigid wall with a velocity of 215 m/s. The simulation covers the impact up to time of 20 ms. In figure 2 the deformed model is represented at 5 and 20 ms.

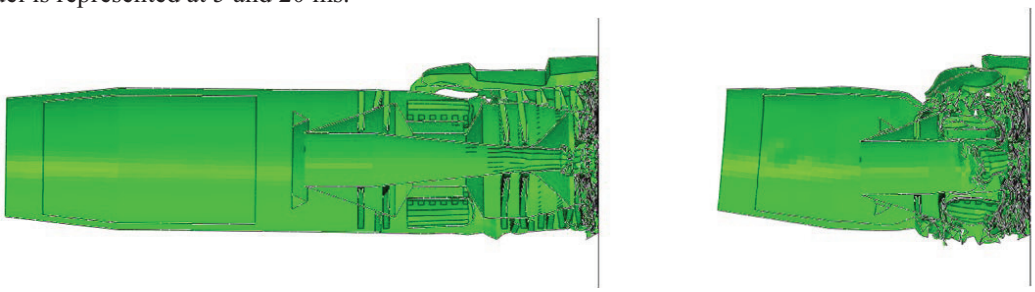

Figure 2. Model deformation of J79 GE at 5 and 20 ms

The Ft-function, presented in figure 3 is evaluated by the reaction forces of the reference node of the wall. The simulation result is compared with the real test data.

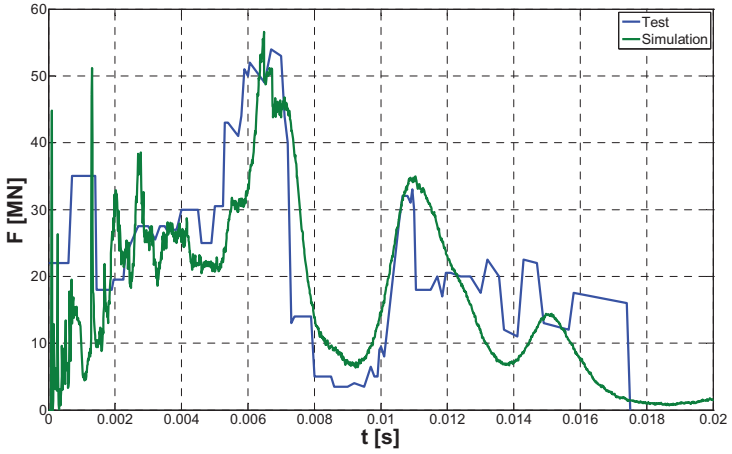

Figure 3. Impact J79 GE - Comparison of Ft-curve obtained by measurement and simulation

The main characteristics of the Ft-function are two peaks at about 6 and 11 ms. The first peak results from the crash of the compressor and the second one from the impact of the combustion chamber on the wall.
It can be observed that the model result correlates well with the real data with respect to the curve characteristics and the amplitude level. Further the simulation fulfils the conservation principle of the momentum, as the simulation has a value of 0.36 MNs compared to 0.38 MNs using the analytical formula. Accordingly it is confirmed that the numerical model correlates well the real behaviour and it can be used for the impact studies on the concrete wall.

A similar crash simulation is carried out for the IAE V2500 but no measurement data for comparison is available. Considering a realistic scenario an impact velocity of 160 m/s is used. The simulation covers an impact time of 35 ms. The deformed model state at 25 ms is presented in figure 4. Compared to the results for J79 GE the deformation of the engine is much smaller, which is caused by differences in the structural setup. The IAE V2500 is due to smaller length and greater area compacter than the J79 GE.

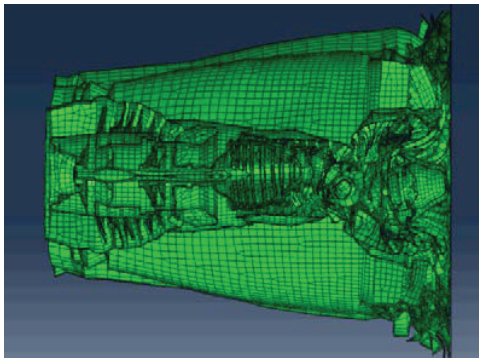

Figure 4. Model deformation of IAE V2500 at 25 ms

Evaluating the Ft-function for the IAE V2500, a similar curve characteristic as for the J79 GE is determined. Main difference is that the function for the J79 GE shows two peaks and the one of IAE V2500 one peak at about 6 ms and then a continuous decrease up to 22 ms. Regarding the peak values, the impact of both engines is with values of about 50 MN for the J79 GE and almost 60 MN for the IAE V2500, in the similar range.

CONCRETE WALL MODEL

Setup FE-Model

All simulation scenarios are more or less representing the impact on the concrete wall of the Sugano tests. Accordingly the geometry is derived by published data, see Muto (1989) and Sugano (1993). The dimensions of the concrete are 7.0 x 7.0 x 0.9 m³ and a bending reinforcement having a 34 mm diameter with a spacing of 200*200 mm, each way and each face, is embedded. The meshing of the concrete is carried out via 12 hexahedron elements over the thickness. The reinforcement is modelled by beam elements. For the interaction between concrete and steel, the *Embedded Element* Option of ABAQUS is used, defining automatically kinematic couplings between both kinds of Finite Elements. The fixation in the four corners is modelled by shells, where the nodes are merged to concrete. The two plates at the back and the front side are connected via beam elements, covering the real screw connection. In figure 5 an isometric view of the model is presented.

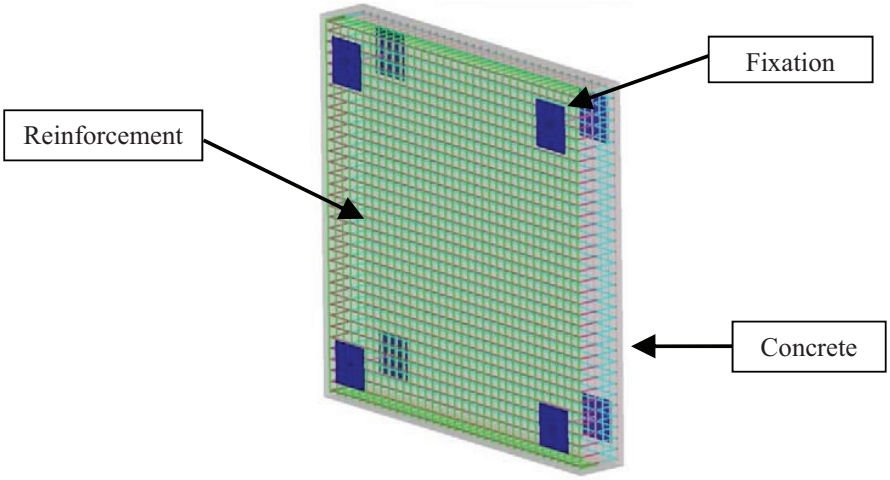

Figure 5. Model setup of the concrete wall

Material Properties

ABAQUS Explicit provides the Concrete Damage Plasticity model Lubliner (1989), which enables the modelling of concrete or other brittle materials including reinforcements. It is designed for setups with monotonic and dynamic loading scenarios. The material definition is separated in tension and compression. For each of these material performances the plasticity and damage behaviour must be described. The damaged part specifies thereby the reduction of Young's modulus. The properties are defined for a compressive strength of 23.5 MPa given by the test data. The strain rate dependent stress strain curve is defined following the CEB-FIP Model Code (1993), see figure 6.

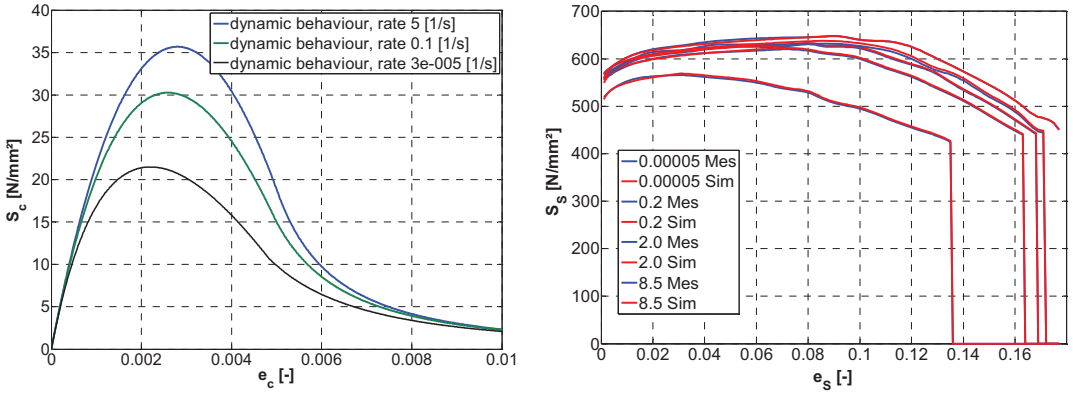

Figure 6. Stress Strain curves for compression behaviour of concrete and steel, at various strain rates

Additionally the material behaviour of the reinforcement steel must be defined. In the tests, the material was similar to a BSt 500-550 with respect to the yield and ultimate strength. As published data related to the stress-strain-curve under different strain rates exists for this material (Brandes (1985)), it is used in the simulations. Also here the Johnson-Cook plasticity approach, Johnson (1983), is implemented for describing the reinforcement.

VALIDATION OF SIMULATION APPROACH

In the first step the integral simulation approach considering engine, slab and their interaction simultaneously is validated by the Sugano full scale test L1, Sugano (1993). The interaction between all model parts is defined by the *General Contact* algorithm of ABAQUS. The initial missile velocity in front of the wall is defined with 215 m/s and an overall impact time of 75 ms is investigated. As a first result, the final engine velocity is evaluated, see figure 7, enabling a general assessment of the impact and damage state of the slab. It can be observed that the engine almost perforates the wall. Further a rotation about the lateral axis and a rebounding can be determined what correlates with test observations.

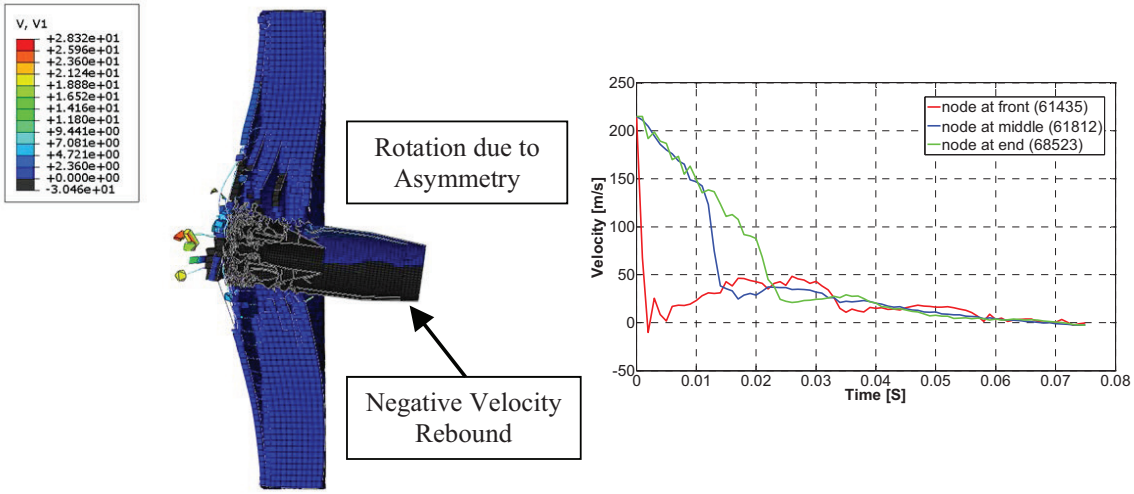

Figure 7. Velocity of the symmetry plane at the end of the simulation and Velocity-Time curve for nodes at the front, the middle and the back part of the engine

A detailed comparison to the real test is carried out via the damage of the concrete and the reinforcement plastic strains. In general the simulation is quite consistent with test behaviour, see figure 8. Main difference is observed at the back side of the wall. Indeed, a greater area of concrete is ejected due to scabbing in the test in comparison to the numerical analysis. Thereby it must be considered that due to the element size of about 80 mm, a fine representation of scabbing is not covered by the model setup.

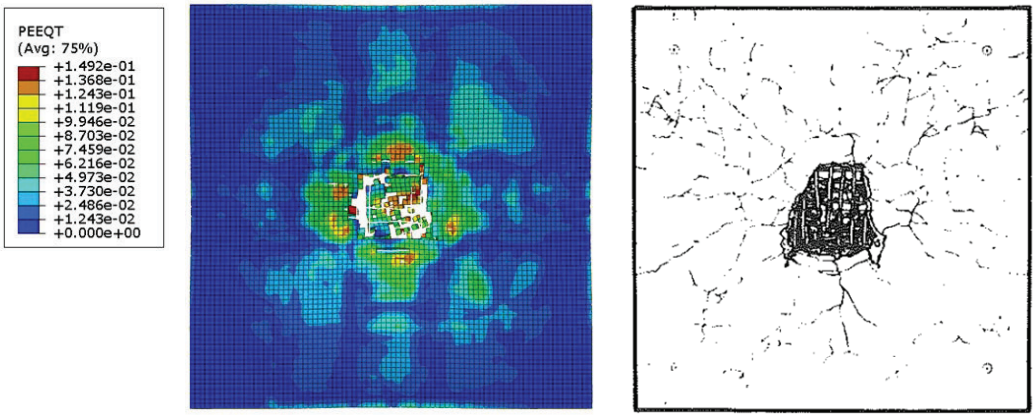

Figure 8. Comparison of simulation and test for damage at the front side of the wall

Further differences can also be observed between test and calculation results. While the maximum displacement value in the simulation is about 80 cm, the test shows a 60 cm maximum displacement. In the test, 4 vertical and 4 horizontal rebars were broken. The simulation differs slightly as at the front side, 5 vertical and 6 horizontal are broken and at the back side, 1 vertical and 3 horizontal rebars are broken.

Summarizing all results, it can be determined that the simulation is quite consistent with test results Accordingly the simulation approach, the model setup and the material definitions are validated and can be applied for further investigations.

SCENARIO 1: IMPACT OF RIGID MILITARY ENGINE J79 GE

In this simulation, the Degen empirical formula for a rigid missile is applied to calculate the minimum wall thickness to reach just-perforation of the slab. In a first step the deformable engine model of the J79 GE is converted into a rigid missile by assigning all model parts as rigid bodies. The masses and the rotary inertias are implemented via discrete elements at the defined reference nodes. The impact velocity is still defined with a value of 215 m/s. Using the empirical formula of the NEI (2011), see equation 2, a thickness of 1.6 m is calculated to reach a just-perforation damage state of the slab, impacted by the rigid missile. This value is obtained without taking into account safety factors usually used in design.

$$t_p = \alpha_p D \{2.2 (x_c/\{\alpha_c D\}) - 0.3 (x_c/\{\alpha_c D\})^2\} \text{ , for } x_c/\{\alpha_c D\} \leq 1.52.$$

Equation 2. Reduced Degen formula calculating thickness for almost perforated, NEI (2011) – US units

In the formula x_c represents the penetration depth of the missile into the concrete, D is the outer casing diameter of the projectile and α_p represents a "reduction factor" depending on missile deformability, with a value of 0.6 for the investigated setup. For this scenario only the wall thickness is scaled from 0.9 to 1.6 m. The material properties and the percentage of the reinforcement are not modified.

In a first step, the plastic strains in the concrete are evaluated in the cross section of the symmetry plane, see figure 9. The result shows that the engine penetrates the wall up to the first three element rows, representing an almost 40 cm depth. Further the development of a punching cone can be identified, leading to the conclusion that the state of almost perforated is not far away.

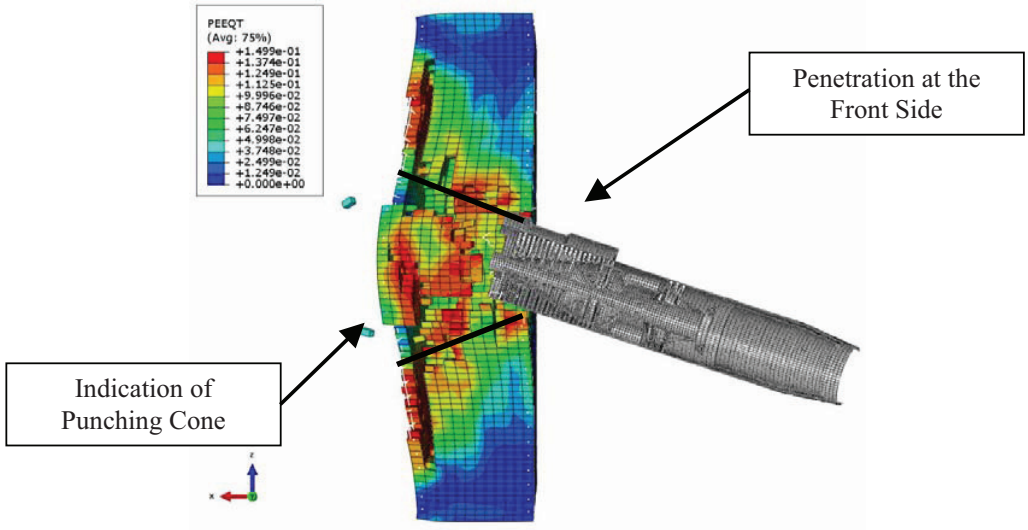

Figure 9. Maximum plastic strains in the concrete - cross section of the symmetry plane

A maximum displacement of about 60 cm is determined at the back side of the concrete wall. At the front side a cracking can be observed with an approximate 1.8 m radius around the impact centre. At the back side almost the complete surface shows cracks and scabbing of the rear concrete cover. Even if the damage of the concrete wall is significant, the just-perforation damage state of the slab is not completely reached, as the plastic strains of the bending reinforcement do not reach the ultimate strain of steel at the back side. Here, the maximal plastic strain values of about 3 % are reached, i.e. that the wall still covers some resistances for a further increase of the impact load, see figure 10.

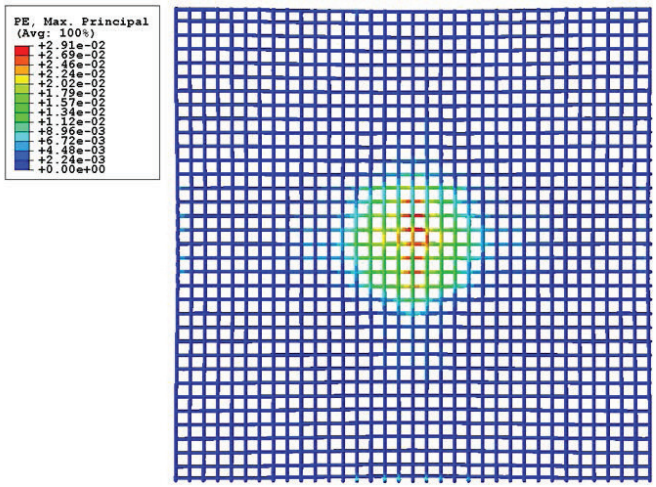

Figure 10. Plastic strains of reinforcement at the back side of the wall

Summarizing the results, it can be determined that the empirical formula slightly overestimates the effect of this impact on the specified wall, in comparison with the calculation results. Nevertheless the difference between the predicated state of the empirical formula and the result of the numerical simulation is not significant, meaning that both methodologies are in a good agreement.

SCENARIO 2: IMPACT OF DEFORMABLE PASSENGER ENGINE IAE V2500

Finally the reduced Degen formula, see equation 2, is used in combination with the equation for the penetration depth x_c, see equation 3, to calculate the impact velocity necessary to reach just-perforation of the slab in a defined scenario:

$$x_c = \alpha_c \{4\ K\ W\ N\ D\ (V / (1000\ D))^{1.8}\}^{1/2}, \text{ for } x_c / \{\alpha_c\ D\} < 2$$

Equation 3. Formula for calculating the penetration depth x_c, NEI (2011) – US units

Here K represents the strength of the concrete material and W stands for the weight of the engine. N covers the geometry of the projectile and is determined with 0.72 for a flat-noise engine.

Using both equations for the impact of the passenger engine IAE V2500 on the concrete wall of the Sugano test L1, thickness 0.9 m, the velocity V is calculated with a value of 150 m/s. The setup of the concrete wall corresponds to the simulation used for the validation of the numerical approach.

As a first result the equivalent plastic strain in the concrete are presented in the cross section of the wall and at the back side, see figure 11. The simulation shows a strong penetration of the engine into the concrete (more than half the slab thickness, in the center part only) and the beginning of scabbing process

of rear concrete cover. In the centre a hole appears due to the impact of the shaft, but the outer case is still at the front side of the plate. This observation is very similar to a conclusion from the NEI (2011):
A turbofan engine is distinguished by a large diameter (approximately 6-inch) hollow shaft, which acted as a hardened penetrator in the wall test using a turbofan engine as a missile. While the shaft can punch through a wall similar to a pipe missile, it cannot exit the wall independent from the casing since the turbine discs attached to the shaft are trapped within the crushed casing. Thus, the engine cannot completely perforate and exit a wall until the casing has completed crushing and the combined crushed casing and shaft perforates a wall.

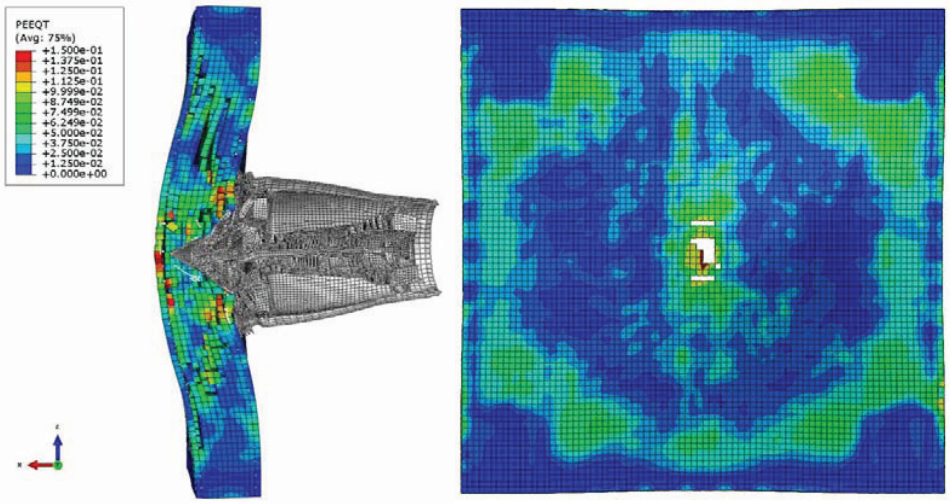

Figure 11. Plastic strains of the symmetry plane and at the back side at the end of the simulation

The damage of the concrete wall is significant. Due to the impact of the shaft, a strong penetration is observed into the concrete and some rebars of the front bending reinforcement layers are completely broken in the centre. This damage state can be considered as close to the just-perforation state of the slab without being completely reached, as the plastic strains of the bending reinforcement do not reach the ultimate strain of steel at the back side (the maximum calculated plastic strain value is 9% at the rear side), see figure 12.

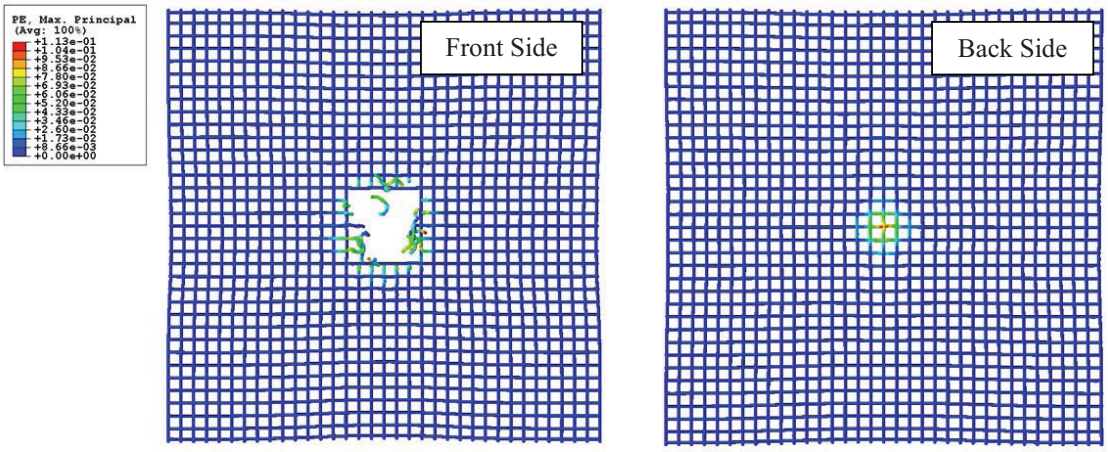

Figure 12. Plastic strain for the reinforcement at the front and back side

The prediction of the empirical formula is very close to the calculated behaviour for this impact case, confirming for another kind of aircraft engine, the good consistency between the formulas and calculations.

CONCLUSION

The work presented in this paper showed that the numerical simulation using FE method is capable to provide results which are consistent with the results of engines impact tests on reinforced concrete slabs. Only minor differences are observed in comparison to the results of experimental setups.

Further it could be observed that the damage state predicted by the numerical simulation is very close to the results provided by the empirical formulas. This conclusion is valid for both deformable and rigid projectiles and for two kinds of engines related to military and commercial aircrafts. The numerical results confirmed the consistency of the 0.6 "deformability factor" defined in NEI 07-13 for aircraft engines impact on reinforced concrete structures.

Accordingly the application of these formulas in the investigated range seems to be appropriate. These results showed that the integral simulation approach can efficiently complete the experimental approach for the investigation of impact scenarios, regarding other parameters like slab geometry, concrete compression strength and percentage of reinforcement. Therefore additional scenarios where these parameters are changed can be investigated in further research work, for example to contribute to an extension of validity domain of empirical formulas.

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