Assessment of the Capacity of a Reinforced Concrete Structure for Impact with Military Jet Aircraft

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1 Introduction

Aircraft impact has been considered in the design of nuclear facilities since the late 1960s under the assumption of accidental crash of a small military or small passenger airplane. Following the increased number of accidents with military jets, the nuclear power plant designers took seriously the risk of such event which would potentially lead to release of radioactive material in the atmosphere. Scientists and engineers started to work on analytical approaches for analysis of structures under aircraft impact. In 1968 Riera [1] proposed a formula for calculation of the load-time function of an aircraft based on the principle of momentum conservation. He assumes rigid-perfectly plastic model of the aircraft which impacts rigid target normally to the surface. Others, such as Zorn and Schuëller in [2], propose that the aircraft can be represented as series of lumped masses interconnected with axial and rotational springs with stiffness based on the stiffness properties of the aircraft material. The impact force is then obtained as the derivative of the momentum of the aircraft with respect to time. Based on different developments, the load-time function (LTF) of the F-4 Phantom II (shown in Fig. 1) has been set as a standard for the design of nuclear facilities. It is included in a number of regulatory documents such as [3].

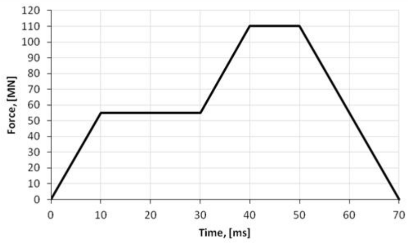

Fig.1: McDonnell Douglas F-4 Phantom II (left) and its LTF (right)

Two different approaches can be followed for the analyses of structures under aircraft impact loading. In the first one, the calculation can be performed as force time history analysis using a LTF like the one shown in Fig.1. The second, more advanced approach is the missile-target interaction analysis (MTI), i.e. impact simulation of the finite element (FE) model of the missile and the FE model of the target.

The current paper presents assessment of the structural capacity of reinforced concrete (RC) structure (target) in case of impact with F-4 Phantom II military jet by the MTI method. Detailed FE models of the missile (the airplane) and the target have been developed. The FE model of the airplane is validated by performing finite element impact analyses into rigid wall and moveable concrete block. The output results are compared with data, obtained from full-scale impact test performed at the SANDIA National Laboratory in Albuquerque, New Mexico, USA in 1988 [5]. The target structure is covered by a layer of asphalt. It is included in the model because it acts as an energy dissipation layer and increases the structural capacity in case of high velocity impact. A number of impact analyses are performed considering asphalt properties defined for different temperatures and strain rates. The parameter which is compared as a result from the analyses is the perforation area of the target. It is related to the amount of debris which can penetrate inside, as well as to the assessment of the possible fire effects.

2 Description of the SANDIA full-scale test

As mentioned above, the FE model of the airplane is validated with results from a full-scale impact test. It was performed at the SANDIA National Laboratory in Albuquerque, New Mexico, USA. The purpose of the test was to obtain the load-time function for impact of F-4 Phantom aircraft into an essentially rigid wall. For the purpose of the full-scale impact test, a flyable F-4D was used. The total mass of the test aircraft was 19 t including 4.8 t of water (to simulate fuel) and 1.5 t mass of the sleds and the solid rockets for propulsion. The plane was accelerated along a 600 meter-long rocket sled facility against the target, which was a reinforced concrete block with mass 469 t. The concrete block was placed on air bearings in order to avoid friction with the supporting structure. Various measuring devices were attached to the concrete block in order to record its response. The impact speed of the aircraft was 215 m/s and the impact direction was normal to the surface of the target. Detailed description of the experiment is given in [5]. The dimensions of the target concrete block and view of the aircraft during the impact are shown in Fig. 2.

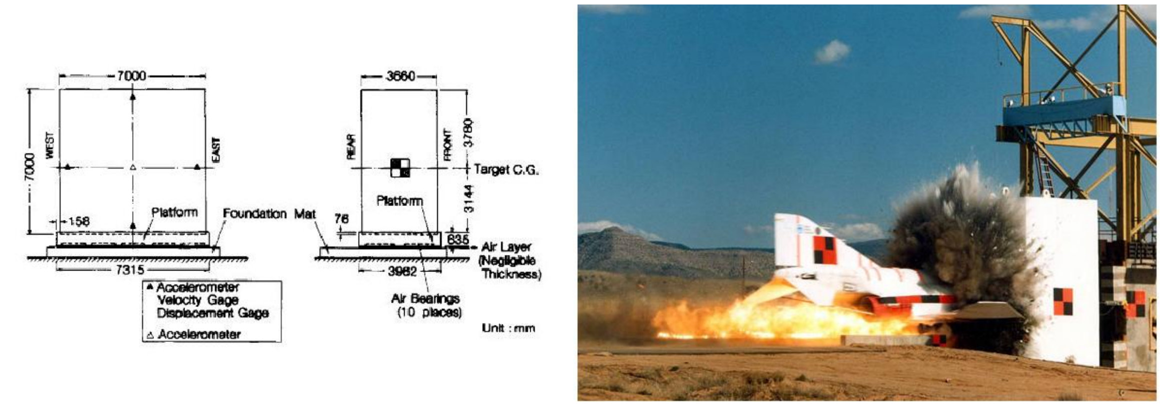

Fig.2: Dimensions of the target concrete block (left) and view of the impact (right) [5]

3 Description and validation of the FE model of the airplane

Two FE models of the aircraft are created, whereas two fuel models are considered – rigid fuel model and Smooth Particle Hydrodynamics (SPH, [4]). The approch for modeling aircraft fuel using SPH is described in [6] and [7]. The rigid fuel model refers to the case where the mass of the fuel is taken into account by increasing the mass density of the structural parts of the fuel tanks. Both models are shown in Fig. 3.

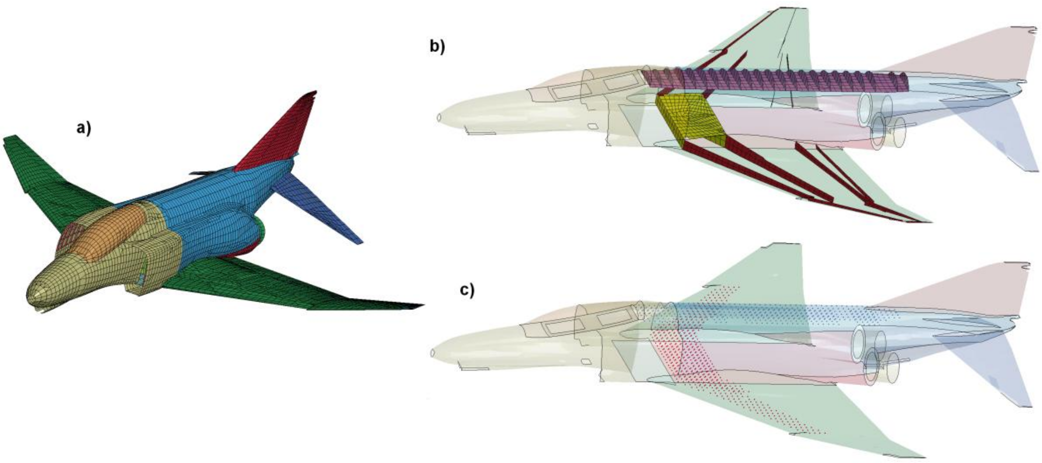

Fig.3: FE model of the airpane a), structural elements with lumped fuel mass b) and SPH fuel particles c)

Apart from the fuel, both FE models are the same and are built entirely by shell elements. The material which is used is ***MAT_PLASTIC_KINEMATIC** [8] with material properties typical for aluminium. The dynamic increase of the material strength due to strain rate effects is considered. The material properties of the SPH correspond to water. The mass of the FE models is 19 t, including 12.7 t structural mass, 1.5 t mass of the propulsion rockets and 4.8 t of fuel mass. The model mass and mass distribution complies with the SANDIA test conditions.

The airplane models are validated by performing impact analyses into rigid wall and concrete block. The latter is not supported in direction of impact in order to match the experiment set-up. Pictures from the impact analyses are shown in Fig. 4.

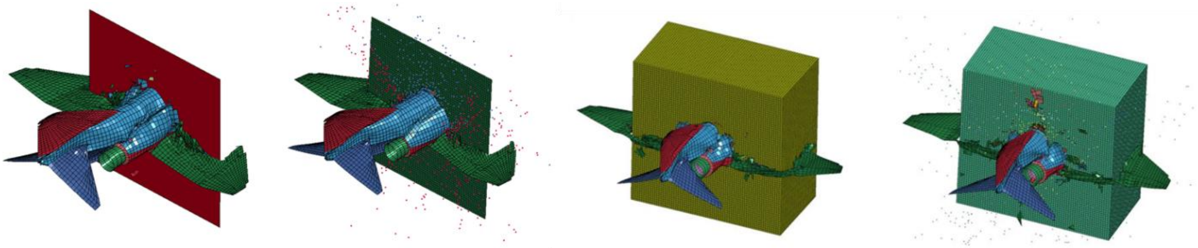

Fig.4: Impact of the FE airplane models into rigid wall and concrete block

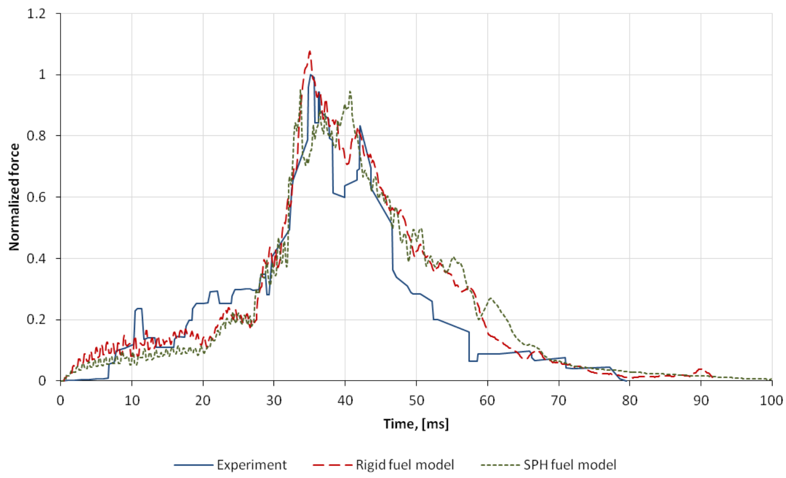

Fig.5: LTFs from analyses into rigid wall

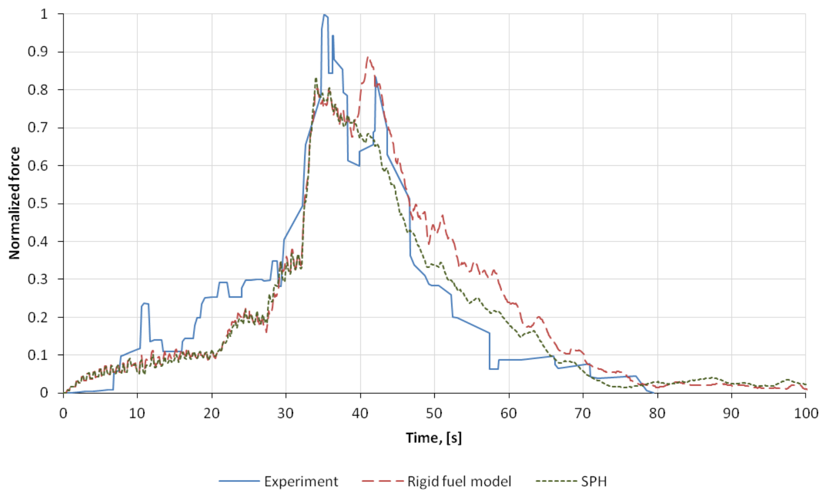

Fig.6: LTFs from analyses into concrete block

The normalized load-time functions, obtained from the FE analyses into rigid wall are compared to the load-time function obtained from the SANDIA experiment in Fig. 5. Very good match between the load curves from the experiment and from the FEA with rigid fuel model is observed, especially at the peak force values. The load curve calculated by the FE analysis with SPH fuel model slightly differs from the experimental one in the peak values but the overall shape is similar. The deviations at the peak values are attributed to the interaction between the SPH particles and the aircraft structure and the rigid wall. The normalized impact forces resulting from the analysis of F-4 with rigid fuel model and SPH fuel model into the concrete block are shown in Fig. 6. The force functions differ in their peak values however there is a good overall fit. Both impact force functions (with rigid fuel model and SPH) capture well the overall shape of the impact force obtained by the experiment. Table 1 shows comparison of the momentum change and the impulse of the impact force. The differences are within 10 % which implies that the impulse-momentum theorem is fulfilled.

Fuel model	Normalized change of momentum	Normalized impulse of the impact forces	Difference, [%]
Impact into rigid wall			
Rigid	0.94	1	6
SPH	0.98	1	2
Impact into concrete block			
Rigid	0.99	1	1
SPH	1.06	1	6

Table 1: Change of momentum compared to the impulse of the impact force

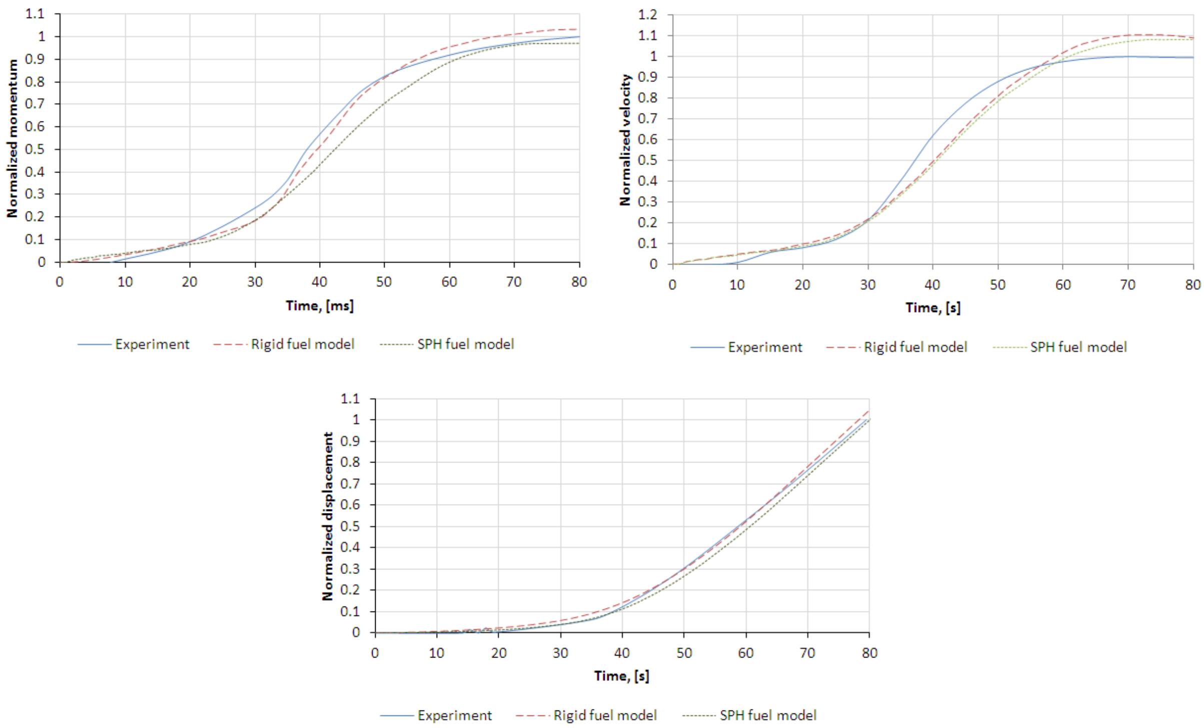

Fig.7: Normalized momentum, velocity and displacement of the concrete block

Comparison of the momentum, velocity and displacement histories of the concrete block computed by the FEA and the ones measured during the experiment is presented in Fig. 7. All of the three parameters, obtained by the numerical calculation demonstrate good match with the experiment.

4 Description the FE model of the RC structure

The model of the target structure is shown in Fig. 8. It represents a RC plate which is built of brick elements. The concrete material used is Continuous Surface Cap Model (CSCM, [8]). The reinforcement in the plate is modeled with beam elements. The rebar material model is Plastic Kinematic [8]. It is constrained into the concrete by the **`*CONSTRAINED_LAGRANGE_IN_SOLID`** option [4]. As mentioned in the introduction, the plate is covered with asphalt. It is modeled also with brick elements. The material model used is Drucker-Prager (DP, MAT193 is LS-Dyna [8]). The use of this material model for asphalt is reported in [9] and [10]. The main parameters of the DP material are the internal friction angle ϕ, the cohesion c and the shear modulus G. These parameters are defined considering literature resources. Additionally, the asphalt is modeled with the Karagozian & Case concrete model (KCC, MAT072R3 in LS-Dyna [8]) in an attempt to capture its contribution to the structural behavior.

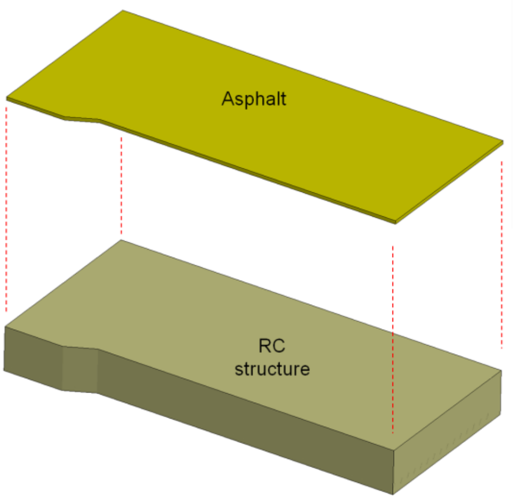

Fig.8: FE model of the target structure

4.1 Parameters of the DP model

The material properties of asphalt depend on the temperature and the strain rate, i.e. the speed of loading. A relation between the asphalt compression strength, the temperature and the strain rate is determined in [11] and can be expressed by the formula:

$$f_c = -108\left(1 - \frac{1}{1 + \left(\dot{\varepsilon}.e^{-86.3+\frac{24260}{T}}\right)^{0.32}}\right) \tag{1}$$

In formula (1) $\dot{\varepsilon}$ is the strain rate and T is the tempertaure in Kelvin. Plots of the compressive strength of asphalt as function of strain rate for different temperatures, computed using formula is (1) shown in Fig. 9.

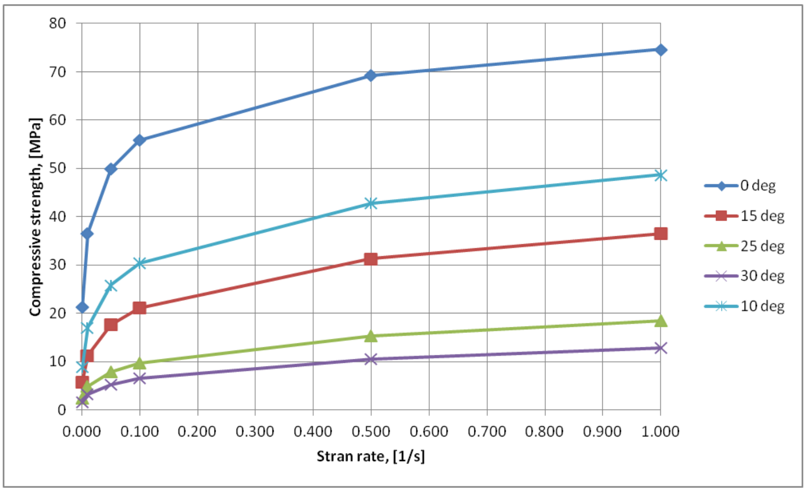

Fig.9: Asphalt compressive strength vs. strain rate

Formula (2) relates the asphalt compressive strength, the cohesion and the angle of internal friction (see [12]):

$$f_c = \frac{2.c.\cos\phi}{1-\sin\phi} \tag{2}$$

By using formula (2) one can compute the cohesion c for given angle of internal friction ϕ and compressive strength which, in turn, can be defined for given strain rate and temperature using formula (1). The material properties of the asphalt are defined for three temperatures – 10^{O}C, 25^{O}C and 30^{O}C. The angles of internal friction which correspond to these temperatures are taken from literature resources ([13] and [14]) as follows: ϕ = 26^{0} (for T=10^{0}C and T=25^{0}C) and 35^{0} (for T=30^{0}C). Plots of the cohesion as function of strain rate for the temperatures of interest are shown in Fig. 10.

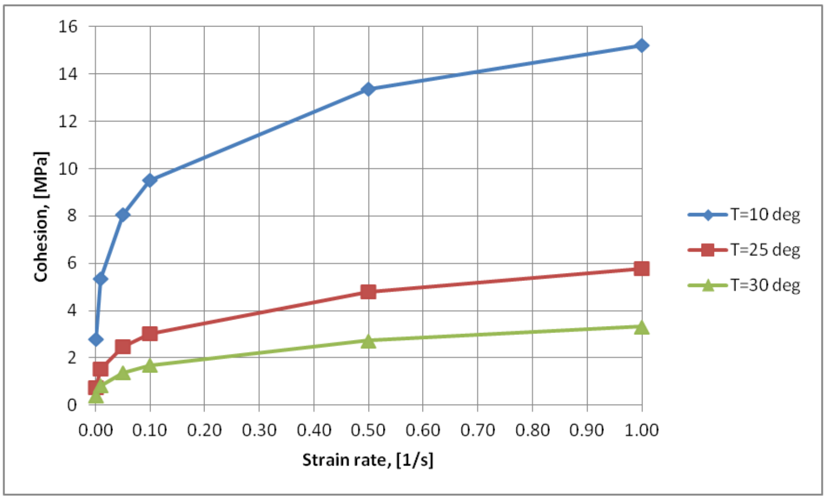

Fig.10: Cohesion vs. strain rate

The shear moduli of the asphalt required for the input of the Drucker-Prager material are calculated from the moduli of elasticity. The latter are adopted from reference [11] which contains stress-strain curves in compression, experimentaly obtained from testing asphalt specimens under different strain rates and temperatures. The elasticity and shear moduli for the three temperatures of interest and strain rate 1 s^{-1} are given in Table 2.

	T=10^{0}C	T=25^{0}C	T=30^{0}C
E, [MPa]	16320.74	5160.5	1479.6
G, [MPa]	6277.208	1984.808	569.0769

Table 2: Computed elasticity and shear moduli

4.2 Parameters of KCC model

The KCC model is used as an alternative for the asphalt concrete with the intention to account for its tension strength. Using the KCC model, the asphalt layer is modelled as concrete with compressive strength 48 MPa. This compressive strength corresponds to strain rate $\dot{\varepsilon}$ = 1 and temperature 10^{0}C as seen in Fig. 9. The KCC model is chosen for the asphalt concrete model because it allows direct input of the tensile strength, i.e. it is not computed from the compressive strength through the material model relations. The static tensile strength is assumed to be 2.4 MPa [15]. The increase of the tensile strength due to strain rate effects is considered by dynamic increase factor (DIF), computed according to formula (3) [16].

$$DIF = 1.86 + 0.1432\log_{10}\dot{\varepsilon} \text{ for } \dot{\varepsilon} \le 15s^{-1} \tag{3}$$

For strain rate $\dot{\varepsilon}$=1 the DIF is obtained to be 1.86. The values of the tensile and compressive strength are defined for strain rate $\dot{\varepsilon}$=1 and no further dynamic increase is considered by the material model.

5 Analysis results

Four analyses are performed using material parameters of asphalt DP model for temperatures 10^{O}C,25^{O}C and 30^{O}C, as well as the KCC model. The approach for computing the parameters is described above. Strain rate $\dot{\varepsilon}$=1 is considered although higher values are reached during high velocity impact. The reason is that the investigations in the literature resources which are reviewd assume the use of asphalt concrete for transportation purposes where the strain rates in general are much lower and the extrapolation of the results may not be accurate.

The analysis result which is compared is the area of the perforation of the RC plate. This parameter is important for assessment of the fire consequences inside the structure, as well as for assessment of the ammount of debris which could penetrate and cause damage to the internals of the building. The perforation area is computed by projecting the contour of the perforation onto a horizontal plane as shown in Fig. 11. The normalised perforation areas are summarised in Table 3. In all analysis cases the airplane gets stuck into the plate, it does not completely penetrate through it.

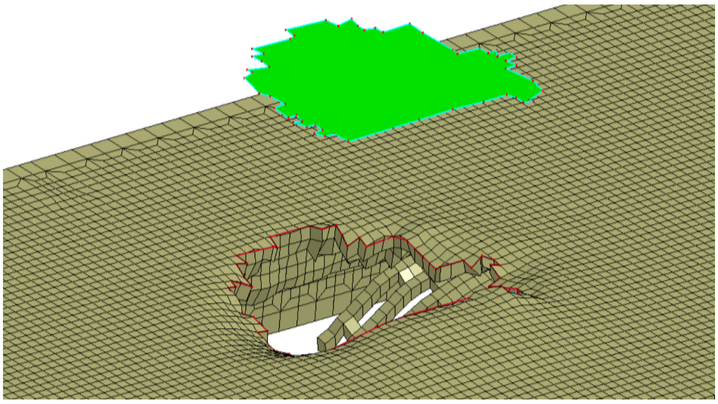

Fig.11: Perforation area

	DP asphalt model at T=10^{0}C	DP asphalt model at T=25^{0}C	DP asphalt model at T=30^{0}C	KCC asphalt model
Perforation area	0.93	0.98	1	0.84

Table 3: Summary of the considered analysis results

6 Conclusion

The presented study describes assessment of the structural capacity of a RC structure in case of impact with F-4 Phantom military jet. The FE model of the airplane which is created for the purposes of the MTI analyses is validated by comparison of numerical impact simulations to available test data. The impact force, impact momentum, velocity and displacement of the target demonstrate very good match with the experimental results as described in Section 3. Conclusion can be drawn that the mass and stiffness distribution of the missile are well captured by the FE model and it is suitable for performing MTI analyses. The impact analyses of the RC target are performed considering different models of the asphalt layer (Drucker-Prager and KCC model) which is laid over it. The asphalt is introduced as an energy dissipation layer during the high velocity impact. As presented in Section 4.1, the asphalt compressive strength and cohesion increase with increase of strain rate and decrease with increase of temperature. The results summarized in Table 2 show similar perforation areas obtained from the analyses whereas the smallest perforation area corresponds to the setup with KCC model for the asphalt. A tendency is observed, that the perforation area increases with increase of the temperature, which corresponds to decrease of the cohesion of asphalt. In other words, a correlation between the asphalt properties and the damage is established. The fact that the aircraft does not fully penetrate into the structure implies that the internals will be subjected only to impact of small structural debris.

7 Literature

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