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SIMULATION OF IMPACT-LOADS ON REINFORCED CONCRETE STRUCTURAL ELEMENTS

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ABSTRACT

The article presents a comparison among experimental and numerical results for reinforced concrete slabs under short-term dynamic loads of deformable (soft) and non-deformable (hard) missiles. The comparison is based on the experimental results of impact test series carried out at the VTT (Technical Research Centre of Finland) within the framework of the international project IRIS 2010 (Improving Robustness Assessment Methodologies for Structures Impacted by Missiles). The numerical simulations are executed with three dimensional explicit short-term dynamic calculation models, in which the reinforced concrete slab and the missile are considered with their specific nonlinear material behavior. The conclusions are summarized based on a comprehensive comparison of simulation and experimental results taken the robustness and accuracy of the applied calculation methods into account.

INTRODUCTION

The design of safety relevant structures and facilities according to the current guidelines and standards requires the consideration of high dynamic loads as result of actions like explosions, air plane crashes or missile impacts. An adequate protective function against impact loads can usually be achieved with reinforced concrete structures, if an appropriate dimensioning and specific construction design is performed. The dimensioning of the structures can be carried out based on simplified methods with empirical formulas and analytical approaches or explicit short time dynamic calculations. In case of simplified methods, the impact type with its characteristics shall be taken into account. However, explicit short-term dynamic calculations using nonlinear three dimensional models have been established due to increased computing capacities, which enable the engineer a more realistic simulation of the complex nonlinear failure mechanism of reinforced concrete structures subjected to impact loads.

The studied impact loading on reinforced concrete structures with deformable (soft) and non-deformable (hard) missiles is one of the most complex short-term dynamic analysis because the highly concentrated impulsive loading leads to local failure mechanisms with penetration and spalling effects. Because of the simulation complexity, it is necessary to verify the robustness, the accuracy and the performance of the simulation models by the comparison with experimental results. This fact was the starting point of the international benchmark project IRIS 2010 (Vepsä et al., 2012), in which about 30 international teams participated with simulations using different material models and calculation methods of established software packages. A working group consisting of the Chair of Structural Statics and Dynamics, RWTH Aachen University, swissnuclear and SDA-engineering GmbH joined the benchmark project (Butenweg et al., 2012). The simulation results were compared among each other and with results from impact tests.. Because experimental data for missile impacts are quite limited and often insufficiently described in literature, two series of impact tests on reinforced concrete slabs have been prepared and executed by VTT in 2010. The testing program comprises bending tests with soft missiles and punching tests with hard missiles, which are used as reference tests within the benchmark project.

For both types of tests explicit short-term dynamic simulations models will be presented, in which the nonlinear behavior of the reinforced concrete slab and the missile are represented by rate-dependent constitutive laws. The reinforcement of the slab will be idealized by discrete elements and the concrete will be represented with different material models, in order to show the effect of the model selection on the calculation results. The determination of the material parameters is obtained from static compression and tension tests. The reinforced concrete slab and the missile are coupled by nonlinear adaptive contact algorithm, which allow the simulation of the progressive failure mechanism in the highly loaded contact zone between slab and missile. In addition a specific contact is defined to reproduce the contact situations during the folding process of the missile steel wall. The results of the explicit dynamic simulations will be compared with experimental tests and simplified calculations. Finally the sensitivity of the results with respect to changes of input parameter and program settings is discussed.

TEST SET-UP

The impact test set-up is illustrated in Figure 1. The left hand side shows the two-way reinforced concrete slab simply supported by a surrounding steel frame. The right hand side illustrates the schematic impact test set-up, consisting of the acceleration tube and the pressure tube, which are separated by a membrane. The test starts with a pressure generation in the pressure tube until the needed maximum operational pressure is reached. In the next step the membrane will be pierced and the pressure is directly transferred to the piston moving in the acceleration tube. In the following the moving piston picks up the missile by a mounted wing and both are accelerated. The piston will be stopped in front of the reinforced concrete slab by a piston catcher and the missile continues the flight with a previous defined speed against the slab.

In total, three soft impact tests (B1 - B3) and two hard impact tests (P1, P2) were performed, from which only the tests B1 and P1 will be selected for the comparison of the simulation results. Table 1 summarizes the dimensions and total weights of slab and missile, the reinforcement arrangement and the velocities of the missiles for both types of tests. The bending tests are executed with soft missiles whereas the punching tests are carried out with hard missiles, filled with lightweight concrete. In order to produce the punching, only bending reinforcement was placed at the top and bottom of the slabs.

Table 1: Dimensions, reinforcement and properties of the missiles (VTT, 2010a, 2010b)

Component	Bending	Punching
Concrete slab		
Dimensions	2,082 x 2,082 m	2,1 x 2,1 m
Thickness	0,15 m	0,25 m
Concrete cover	15 mm	20 mm
Reinforcement		
Bending reinforcement (top/bottom)	Ø6/55, 5,1 cm²/m²	Ø10/90, 8,7 cm²/m
Shear reinforcement	Ø6/44, 50 cm²/m²	nonexistent
Missile		
Properties	soft, without filling	rigid, lightweight concrete filling
Length	2,11 m	0,64 m
Diameter	0,25 m	0,168 m
Wall thickness	2 – 12 mm	10 mm
Total mass	50 kg	47 kg
Velocity	110 m/s	135 m/s

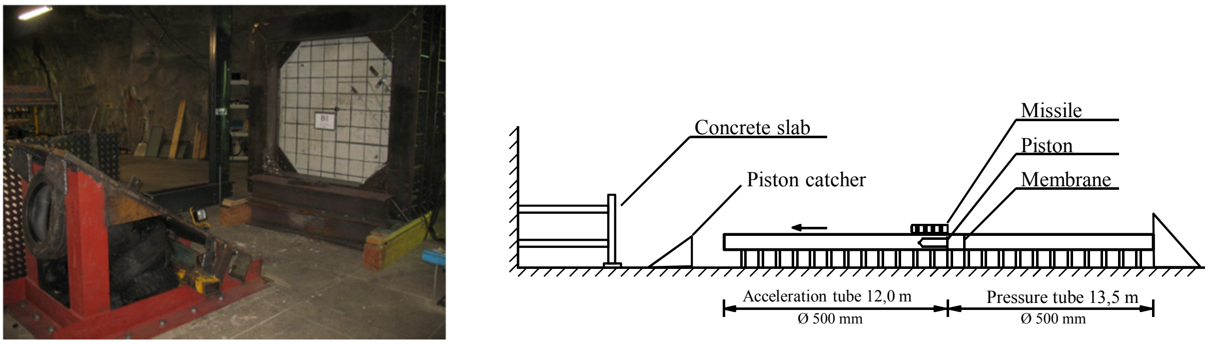

Figure 1. Schematic impact test set-up (left) and reinforced concrete slab (right) (Vepsä et al., 2012)

SIMULATION MODELS

The simulations are executed with LS-DYNA (2013) using steel and concrete models with rate-dependent material laws. The simulation models for both types of impact tests are quarter models with appropriate symmetry conditions along the cut faces of the slab and the missile. In doing so, the calculation time can be significantly reduced. Figure 2 shows the quarter models for bending (right) and punching (left) with all relevant model entities, which will be described in the following sections.

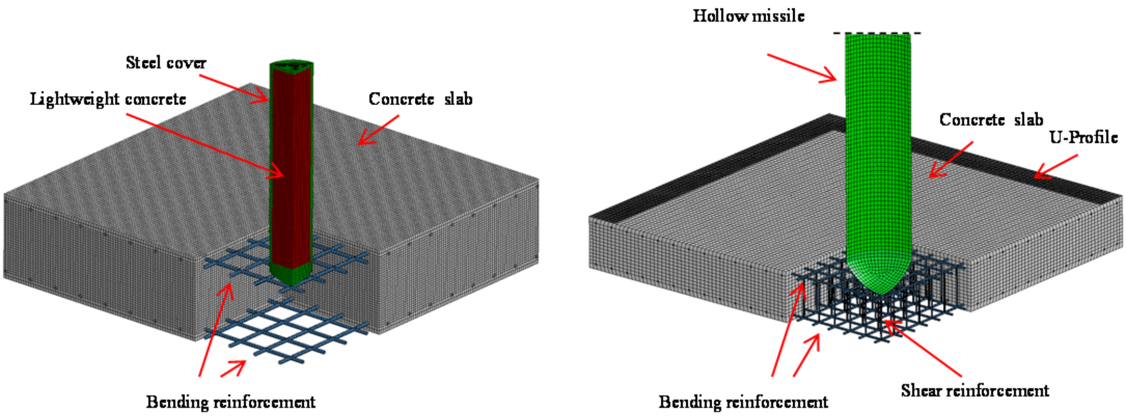

Figure 2. Quarter model of the punching (left) and bending (right) calculation model

The concrete slab is discretized with 8-node volume elements and the efficiency is increased by using a reduced one point integration. Due to the simplified integration technique hourglass modes may appear and lead to a worse solution quality. In order to prevent this effect appropriate hourglass control types are activated, which avoid the occurrence of incorrect deformation states. Furthermore the hourglass energy is calculated and checked to be small enough in comparison to the kinetic and internal energy of the overall structure. The reinforced concrete slab is enclosed by a steel U-profile, which is substituted by supports in the punching model (Figure 2, left) to reduce the computation time. The influence of this simplification on the final results was found to be negligible in sensitivity studies. The bending model includes the profile, idealized with shell elements and connected to the volume elements of the slab by contact elements (Figure 2, right). The bending and shear reinforcement are discretized by standard Hughes-Liu beam elements LS-DYNA (2013), fully coupled in all crossing points of the reinforcement bars. In addition the beams are coupled to the volume elements of the concrete with coincident nodes, hence a rigid connection between concrete and reinforcement bars is assumed. This idealization allows the simulation of the complex failure mechanism with local yielding of the reinforcement as well as penetration and spalling effects of the concrete. The missile in the bending tests is modelled with shell elements due to the thin-walled steel cover. For the punching test, the steel cover of the missile and the lightweight concrete filling is idealized with volume elements for taking the stiffness of both components into account.

The already introduced model components have to be completed by contact formulations to represent the load transfer between the single components and to mirror the specific failure modes of the used materials. The soft missile used in the bending tests is supplemented by a self-contact to detect contact situations occurring during the folding of the thin-wall steel cover. Furthermore a surface to surface contact is applied between the missile and the slab as well as between the enclosing steel U-profile and the concrete slab. With these contact formulations the bending test can be simulated properly. However, the standard contact formulation between the concrete slab and the missile for the simulation of the punching test is insufficient, because a contact participation of the reinforcement and an update of the contact surface are needed to simulate the progressive penetration of the missile into the reinforced concrete slab. Therefore, a combination of an adaptive contact algorithm with simultaneously deletion of highly distorted elements (erosion) in the contact front is applied. Because of the missile penetration into the slab, an additional contact between missile and reinforcement is added for taking the direct interaction into account. The necessity of the additional contacts for punching is also confirmed by the experimental test results.

CONCRETE MODELLING

The numerical simulations are carried out with the material models MAT_072R3, MAT_084 and MAT_159, all provided in the standard LS-DYNA material library (LS-DYNA, 2012a, 2012b, 2013). The choice of the model input parameter for reinforcement and concrete is based on uniaxial tension and compression tests as well as triaxial tests with different degrees of confinement. Wu et al. (2012) already compared and proved the correctness and efficiency of the three chosen models for different standard tests and concluded that triaxial tests with higher degrees of confinement can only be well simulated with the model MAT_072R3. Based on this conclusion a model calibration using the triaxial test results is only applied for this model. The other two material models are applied with predefined material parameter for the purpose of comparison. In the following the applied material models are briefly described and supplemented by references to the relevant literature. The formulation of the model MAT_072R3 is based on the decoupling of the volumetric and deviatoric parts and it works with three invariants and three failure surfaces (Malvar and Simons, 1996). The volumetric part is described mathematically by constitutive equations, which calculate the actual pressure as a function of the volumetric strain and the internal energy. The basis of this function is the input of a series of pairs of values of volume strain and hydrostatic pressure. Intermediate values between the pairs of values will be linearly interpolated. Once the hydrostatic pressure is calculated using the constitutive equation, the determination of the shear failure surface, described by three failure surfaces on the basis of the second invariant of the deviatoric stress tensor, is carried out. The failure surfaces are defined by eight parameters a_i, which are assigned to the maximum failure surface, the yield failure surface and the residual failure surface:

Maximum failure surface:
$$\Delta\sigma_m = a_0 + \frac{p}{a_1 + a_2 p} \tag{1}$$

Yield failure surface:
$$\Delta\sigma_y = a_{0y} + \frac{p}{a_{1y} + a_{2y} p} \tag{2}$$

Residual failure surface:
$$\Delta\sigma_r = \frac{p}{a_{1f} + a_{2f} p} \tag{3}$$

Herein p is the hydrostatic pressure and $\Delta\sigma$ the failure surface of the deviatoric stress part:

$$\Delta\sigma = \sqrt{3J_2} = \sqrt{\frac{3}{2}(s_1^2 + s_2^2 + s_3^2)} \tag{4}$$

The active failure surface results from the interpolation among the three failure surfaces:

$$\Delta\sigma_y \leq \Delta\sigma \leq \Delta\sigma_m\colon \Delta\sigma = \eta\left(\Delta\sigma_m - \Delta\sigma_y\right) + \Delta\sigma_y \tag{5}$$

$$\Delta\sigma \geq \Delta\sigma_m\colon \Delta\sigma = \eta(\Delta\sigma_m - \Delta\sigma_r) + \Delta\sigma_r \tag{6}$$

Herein, η describes the damage function depending on the effective plastic strain λ. The damage function takes values between 0 and 1 and the maximum damage of 1 corresponds to the maximum failure surface. The damage function can be defined user-specific by 13 pairs of values. Figure 3 illustrates the theoretical basis of the model, in which the stress is positive in the compression range, following the conventions for geotechnical problems. Figure 3 shows on the left hand side the three failure surfaces in tension and compression and on the right hand side a uniaxial stress-strain relationship for compression with locations of the points A, B, C, which can be assigned to the specific failure surfaces.

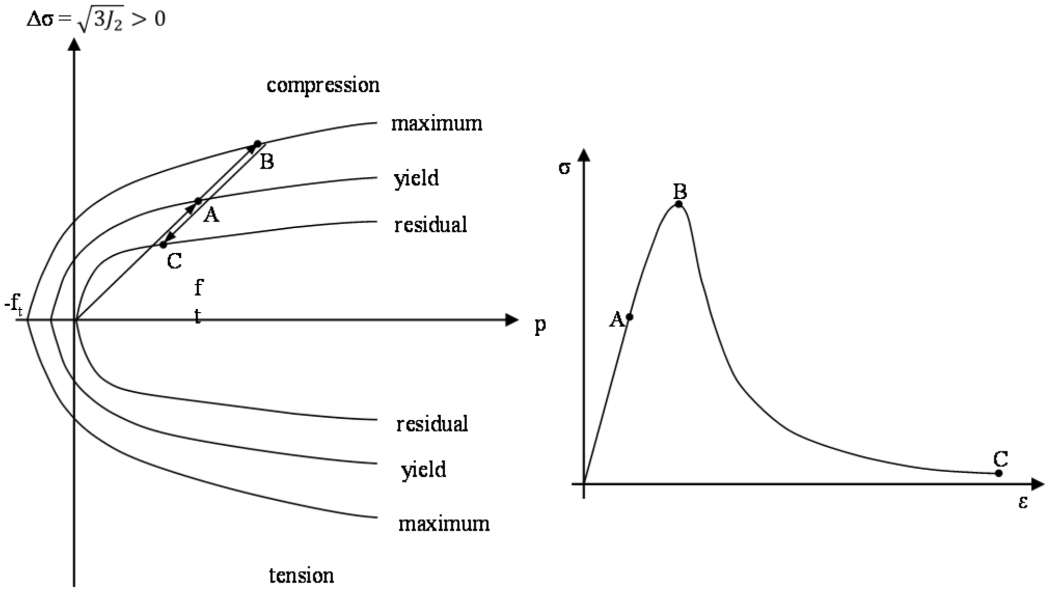

Figure 3. Failure surfaces (left) and uniaxial stress-strain relationship for compression (right) (Markovich et al., 2011; Malvar et al, 1997; Crawfort et al., 2012)

The specification of the softening parameters b_1, b_2 and b_3 has a significant influence on the softening behavior. The parameter b_1 describes the softening behavior in compression, the parameter b_2 represents the softening behavior for uniaxial tension loading and the parameter b_3 specifies the softening due to tension and simultaneously acting further stress components. The parameters are calculated iteratively, so that the area under the softening curves corresponds to the fracture energy. If no triaxial test results are available, the calculation can be executed with internally generated standard input parameters based on the axial compression strength as input value.

MAT_084 is the Winfrith concrete model, based on the well-known four parameter plasticity model of Ottosen. The parameters are functions of the ratio between tension and compression strength and must be defined with experimental data. For the following simulations the model is applied with standard input parameters, calculated from the following input values: Tensile strength, compression strength, Poisson ratio, initial stiffness, crack energy, density and dimension of the concrete aggregate. The specialty of the model is the possibility to simulate the crack propagation. Detailed information about the model can be found in the following references: Schwer, 2010 and Schwer, 2011. MAT_159 is a continuous surface cap model (CSCM), it allows a continuous transition between yielding and hardening. In total 37 material parameters must be defined based on experimental data. For the following simulations, the model is applied with standard input parameters, calculated from the following input values: density, compression strength and dimension of the concrete aggregate. Further information about the model can be found in the following references: LS-DYNA, 2007a and LS-DYNA, 2007b.

SIMPLIFIED APPROACH

In addition to the introduced simulation models a simplified approach for impact loads on reinforced concrete slabs will be applied. The approach is based on a two mass model according to the report CEB-187 (1988), in which the model with its mass and stiffness represent the global bending of the concrete slab and the local damage of the punching cone. A detailed model description is omitted here but can be found in Butenweg et al. (2013).

SIMULATION OF THE TRIAXIAL TESTS

At VTT a total number of five triaxial tests with different degrees of confining pressures f_r were carried out. The confining pressures, geometry parameters and strength values of the test specimens are summarized in Table 2 (VTT 2010a, 2010b).

Table 2: Confining pressure, geometry and material strength of the concrete cylinders for the triaxial tests

Nb.	f_r [Mpa)]	H [mm]	D [mm]	f_c [MPa]	E [GPa]	ν [–]	f_t [MPa]
1	0	138,70	69,86	69,00	29,66	0,22	4,04
2	15,5	139,62	69,86	66,93	29,67	0,22	4,04
3	26	139,26	70,15	66,93	29,67	0,22	4,04
4	47	139,10	69,96	66,93	29,67	0,22	4,04
5	100	140,72	69,94	66,93	29,67	0,22	4,04

The simulations of the triaxial tests are carried out with the model MAT_072R3. The concrete cylinder is idealized with volume elements and fixed at the top and the bottom with a pair of rigid plates, attached to the cylinder with contact elements. The contact elements transfer the compression load in vertical direction and the lateral strain restraint at the cylinders top and bottom is estimated with a coefficient of friction of 0,4. The compression load is applied with a velocity of 0.07 mm/s. The determination of the necessary material parameter is carried out using the calibration results of Malkovich et al. (2011) for the failure surfaces, the damage function as well as the pair of values of the constitutive equations. Due to the absence of sufficient experimental data for the determination of the softening parameter, they are optimized starting with the automatically generated standard values by LS-DYNA (2013). The optimization with variation of the softening parameter is repeated until a satisfactory agreement between tests and simulations is reached. Figure 4 shows the comparison between the simulation results and the triaxial tests for different confining pressures. Overall, up to a confining pressure of 47 MPa a good agreement can be observed. Acceptable deviations result for the high confining pressure of 100 MPa, for which no improvement can be achieved even with further variation.

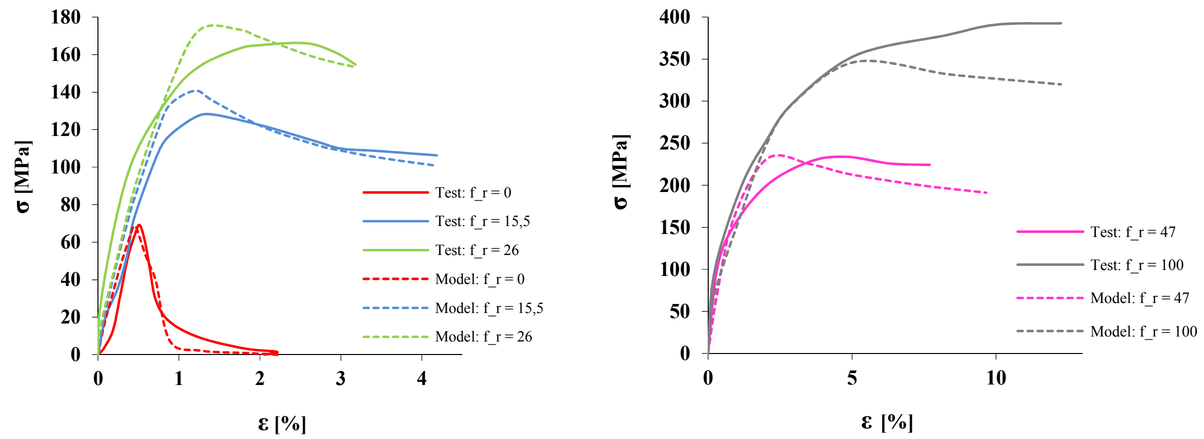

Figure 4. Comparison of simulation and triaxial test results

SIMULATION OF THE IMPACT TESTS

Bending test

The impact bending test is simulated with the material models presented before. First of all the global bending deformation of the slab and the deformation behavior of the missile will be evaluated. Figure 5 shows the crack pattern on both sides of the reinforced concrete slab and the deformed missile after 100 ms, obtained with the material model MAT_084. The crack distribution with radial orientation is qualitatively understandable and agrees well with the experimental crack distribution. Furthermore the simulation results show the missile shortening of 1.15 m due to the folding of the thin-walled steel cover, which corresponds to the experimental results.

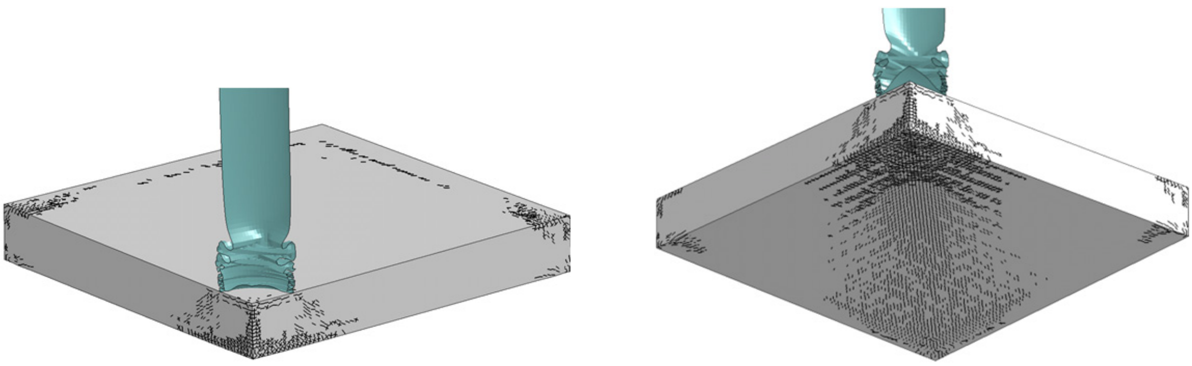

Figure 5. Crack pattern (left: top, right: bottom) with deformed missile after 100 ms (Kleemann , 2012)

A comparison of displacements and steel strains is carried out exemplarily for the selected measuring point W1, located exactly in the center of the slab (Butenweg et al., 2012). Figure 6 shows the time histories of the experimental and simulated displacements for the measuring point W1 up to 100 ms. The comparison shows a good agreement of the measured maximum displacement and the simulated maximum displacements using the simplified model and the presented material models. The free oscillation after the impact can be satisfactory simulated by the simplified two mass model, the material model MAT_084 and the calibrated model MAT_072R3 including strain rate effects. The neglect of strain rate effects leads to a considerable different residual displacement and oscillation frequency. A quite similar oscillation behavior shows MAT_159.

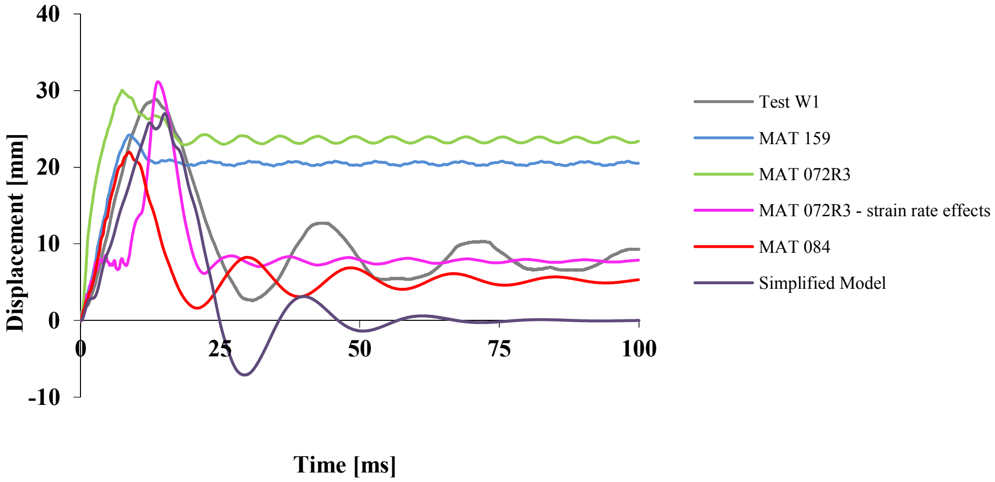

Figure 6. Time history of displacements in the center of the slab in measuring point W1

Punching test

The simulation of the punching test is much more complex and time consuming, because the rigid missile moves through the concrete slab and exits at the back side. Figure 7 shows the penetration process of the missile simulated with material model MAT_159 on the example of the plastic strain distribution for two discrete time steps.

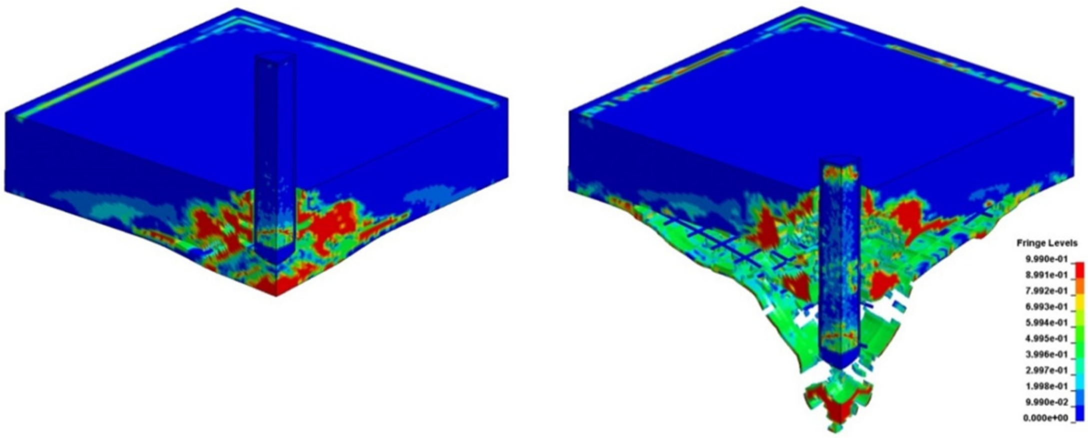

Figure 7. Plastic strain distribution after 0.0026 s (left) and 0.0147 s (right)

At time step t = 0.0026 ms (Figure 7, left) the missile is penetrating into the slab and the plastic strains are locally concentrated around the missile contact. At time step t = 0.0147 ms (Figure 7, right) the rigid missile leaves the slab on the back side with accompanied spalling effects. Figure 8 shows the good correlation of the spalling effects and reinforcement damages on the back side of the slab between simulation after 100 ms (Figure 8, left) and test (Figure 8, right).

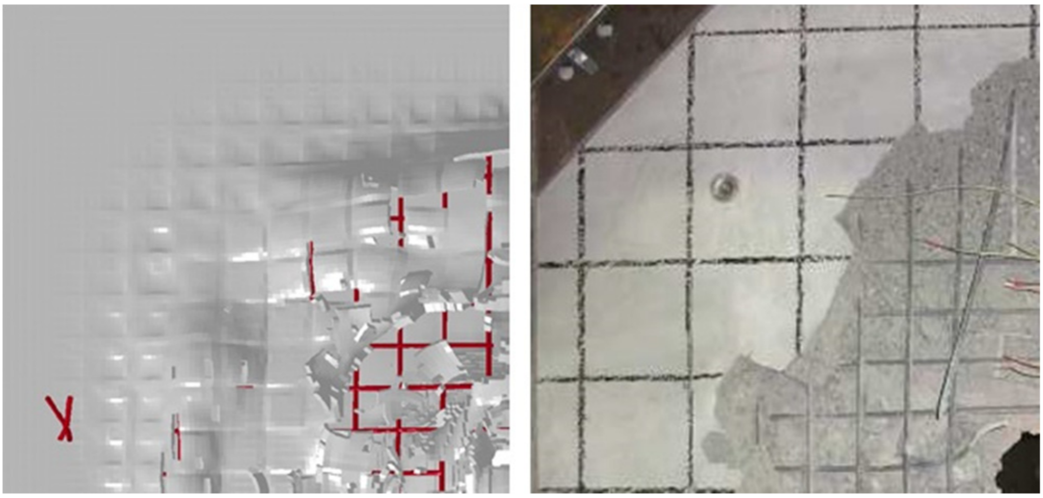

Figure 8. Damage distribution on the back side: Simulation after 100 ms (left) and test (right)

Figure 9, left shows the time history of the bottom reinforcement strain of the measuring point D4, located 405 mm and 110 mm from the center of the slab (Figure 9, right). The time histories show that the maximum strain of the test is very well reproduced for both numerical simulations, however the strain decrease and the residual strain differs from the test results.

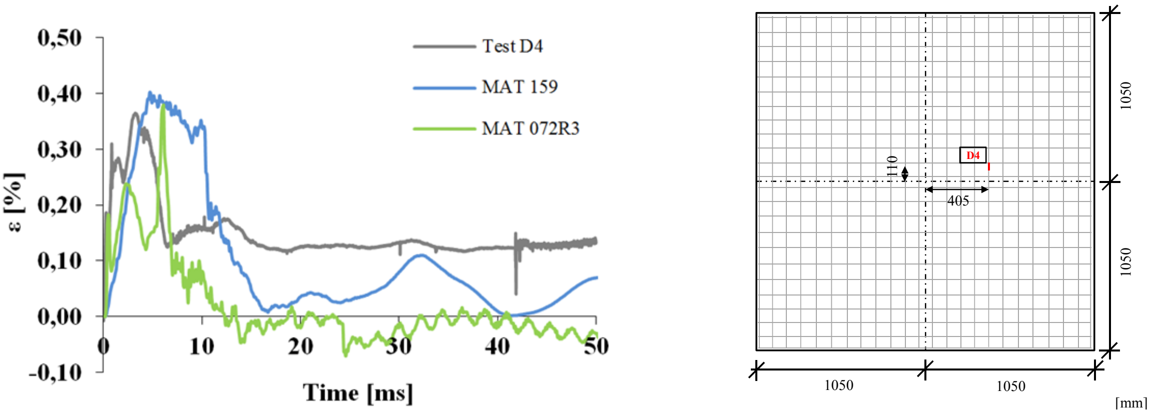

Figure 9. Test and simulation time histories of the bottom reinforcement strain in measuring point D4

CONCLUSION

Short-term dynamic analyses with nonlinear strain-rate dependent material models allow the simulation of impact load on reinforce concrete structural elements. For this purpose sufficient material input data and material tests must be available, in order to define appropriate material model parameter. Furthermore, the performed analyses have shown that it is necessary to test the sensitivity of the model parameters and in parallel to proof the plausibility of numerical results with simplified calculations. The authors gratefully acknowledge financial support from swissnuclear.

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