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KNOWLEDGE FROM FURTHER IMPACT III TESTS OF REINFORCED CONCRETE SLABS IN COMBINED BENDING AND PUNCHING

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ABSTRACT

The paper reports on a collaborative effort between the Swiss Federal Nuclear Safety Inspectorate (ENSI) and their consultants Principia and Stangenberg. As part of the IMPACT III project, impact tests were carried out on reinforced concrete structures. The paper deals with the simulation of tests X3 and X4, in which soft missiles impacted reinforced concrete slabs at different velocities, inducing phenomena such as bending and perforation. The object was to study the behaviour of the slabs under those impacts.

The missile is a steel tube with a mass of 50 kg, travelling at velocities above 140 m/s. The target is a reinforced concrete slab held in a stiff supporting frame. Calculations were conducted before and after the test with Abaqus (Principia) and SOFiSTiK (Stangenberg). With Abaqus concrete was modelled using solid elements and a damaged plasticity formulation, the rebars with embedded beam elements, and the missile with shell elements. In SOFiSTiK the target was modelled with non-linear, layered shell elements for the concrete reinforced on both sides; non-linear shear deformations of shell/plate elements are approximately included. The results indicate a good agreement between calculations and measurements.

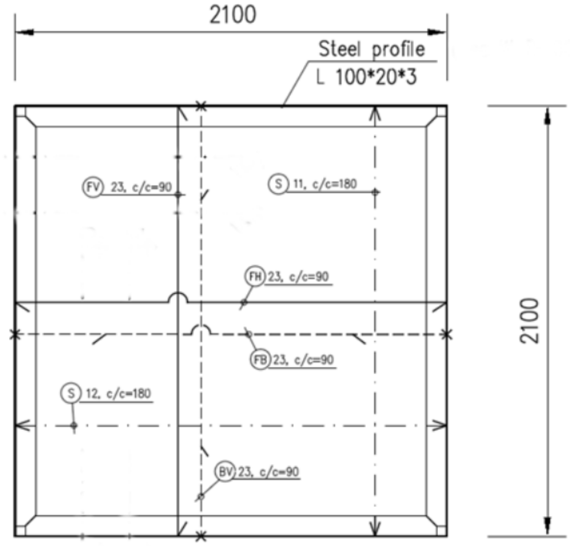
INTRODUCTION

The paper focuses on a collaborative effort between the Swiss Federal Nuclear Safety Inspectorate (ENSI) and their consultants Principia and Stangenberg. ENSI participates in the IMPACT III project organized by the Technical Research Center VTT (Finland) and funded by several institutions including ENSI. The series of impact tests on reinforced concrete structures are being carried out in Espoo (Finland), with the objective of investigating the influence of different combinations of longitudinal and transverse reinforcement on the structural behaviour, in situations in which the demands produced by the impact are very close to the ultimate load capacity of the slab in bending and shear.

The tests discussed are X3 and X4. The results of the various calculations are presented and compared with the tests. The general object of the exercise is to improve the safety of nuclear facilities against this type of impacts and, more specifically, to demonstrate the capabilities of current finite element techniques to reproduce the details of the behaviour of a reinforced concrete structure being impacted by a soft missile. Some of findings related with test X3 were already published by Zinn et al (2014), while the establishment of the ballistic limit of the structure and all aspects related with test X4 are entirely new.

DESCRIPTION OF THE TESTS

The target is a square, reinforced concrete slab with 250 mm thickness and 2100 mm sides, as shown in Figure 1. It is held in place by a stiff supporting frame and four steel back pipes.



Reinforcement bars:

Code	Diam.	Amount	a	b	c	d	L	Type
FV	10	23	2060				2060	
FH	10	23	2060				2060	
BV	10	23	2060	190	350		3140	
BH	10	23	2060	210	350		3180	
S	6	132	130	225		60	830	

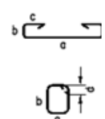


Figure 1. View of the slab and rebar quantities.

Reinforcement includes longitudinal rebars with 8.73 cm^2/m in each direction and face, and transverse reinforcement of 17.45 cm^2/m^2 with closed stirrups. The concrete is C40/50 and the reinforcing steel is A500HW. The bending reinforcement is made of 10 mm bars, with a yield strength of 559.0 MPa, tensile strength of 644.3 MPa, and ultimate elongation of 19.43%; the shear reinforcement is made of 6 mm bars and the corresponding properties are 629.0 MPa, 702.0 MPa and 12.37%. The slab was instrumented with displacement sensors, as well as with strain gauges on the front surface and in the reinforcing bars.

As shown in Figure 2, the missile is a capped steel tube with a length of 1304 mm, a diameter of 219.1 mm and a shell thickness 6.35 mm. It constitutes a fairly soft missile, with a mass of 50 kg and impact velocities that vary with the test but remain above 140 m/s. It is made of EN 1.4432 steel with a Young's modulus of 200 GPa, 0.2 proof strength of 352.0 MPa, tensile strength of 619.3 MPa, and ultimate elongation of 4.52%.

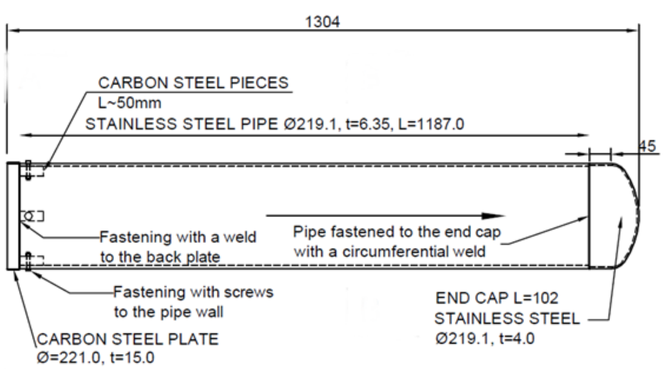


Figure 2. Drawing of the missile used in tests X3 and X4.

SIMULATION OF TEST X3 USING ABAQUS

Idealisation

With Abaqus (SIMULIA, 2014) the problem was solved by explicit integration. The concrete was modelled with solid elements and the reinforcement with embedded beam elements; the missile was represented using elastoplastic shell elements. Advantage was taken of the symmetries of the problem.

The constitutive description adopted for the concrete is the damaged plasticity model in Abaqus, which provides a general capability for analysis of concrete under various types of loading. It includes a scalar damage model with tensile cracking and compressive crushing modes. The model accounts for the stiffness degradation associated with the irreversible damage that occurs in the fracturing process. When unloading from a post-peak situation, the load path does not necessarily return to the origin, giving rise to some permanent strains; but the cyclic response is of only lesser importance in cases like the present one, which essentially consists of a single monotonic loading followed by the corresponding unloading.

The basic mechanical properties used are a density of 2237.4 kg/m^3, Young’s modulus of 26.1 GPa, Poisson’s ratio of 0.223, and tensile strength of 3.01 MPa. In previous work Rodríguez et al (2013) modified the damaged plasticity model to make the compressive cohesion stress to depend also on the maximum principal stress. This modified model proved to be successful then and was kept here. It should be noted that the present calculations do not attempt to provide a conservative upper or lower bound, but are intended as a prediction. Thus the parameters used represent best estimates.

For the steel, an elastoplastic model was used with the properties given earlier. A friction coefficient of 0.3 was used for the contacts that develop during the impact, though this parameter has little influence on the results. The model represents the concrete, reinforcing bars, and missile; the number of elements is around 150,000. To avoid unrealistic distortions, elements are removed from the mesh when the equivalent plastic strain reaches 0.3. Although the stiffness contribution of the concrete is already negligible when plastic strains exceed about 0.2, a premature deletion of elements may produce inadequate results.

Load Function

The object is to determine the history of the reaction generated by the soft missile while impacting a rigid wall, to be used later in the SOFiSTiK calculations. The missile was meshed with some 5700 shell elements and the analysis was conducted by explicit integration. The calculated history is presented in Figure 3, with a peak of about 3.7 MN and a total duration of 5.2 ms; the averaged values correlate reasonably well with the estimates proposed by Riera (1968). The deformed missile after the impact is presented in Figure 4; the crushed length is about 430 mm, generating four folds in the shell.

Analysis of the Impact

As mentioned the slab concrete is C40/50, essentially identical to that modelled for IRIS_2012 by Rodríguez et al (2013), the constitutive description adopted here is the same. A modification introduced there in the damaged plasticity model consisted in making the compressive cohesion stress to depend also on the maximum signed principal stress, with the parameters determined from triaxial tests. Since that type of information was not available in IMPACT III, the previous curves were adapted based on uniaxial test data, scaling the stresses by a factor of 0.72 and the strains by a factor of 1.5. Also, the tensile fracture energy is taken to be 150 J/m^2.

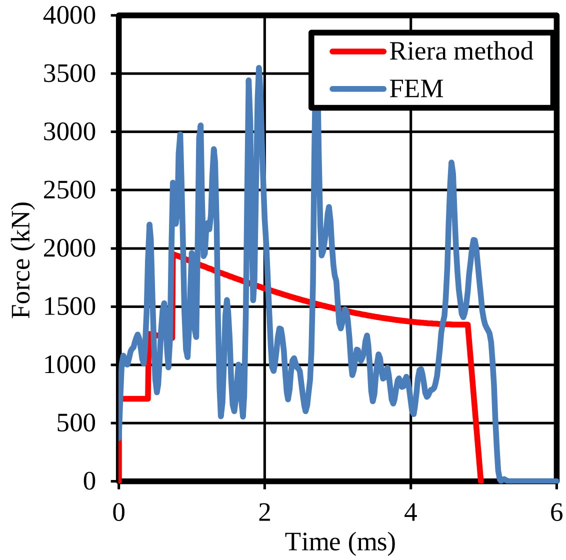


Figure 3. Load function for rigid wall

Figure 4. Deformed missile after the impact

The explicit calculations with Abaqus indicate that the missile does not perforate the slab. The resulting situation, 20 ms after the onset of impact, is presented in Figure 5.

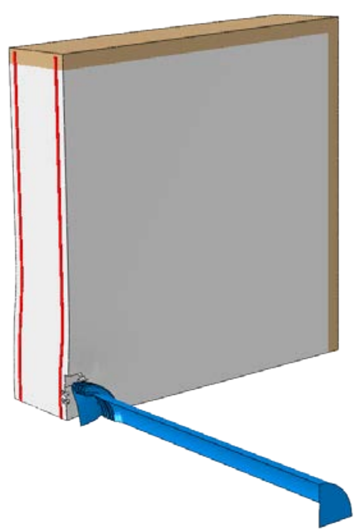


Figure 5. Deformation after the X3 test

The evolution of the velocity of the missile is consistent with the approximate approach proposed by Riera (1968); and all the relevant events caused by the impact occur in the first 5 ms. The slab displacements were being monitored at a number of locations. Figure 6 provides the locations of the sensors and a comparison of histories for a representative location. Also of interest are the effects on the reinforcing bars, some of which appear in Figure 7.

It is also instructive to compare the missile shortening caused by the impact. When the impact occurs against a rigid plane, the calculations indicate that the collapsed length would be 430 mm. When the impact takes place against the actual concrete slab, the collapsed length reduces to 330 mm; this figure is perfectly consistent with the test observations, which recorded a collapsed length of 328 mm, with the same four concertina folds predicted by the calculations, see Figure 4.

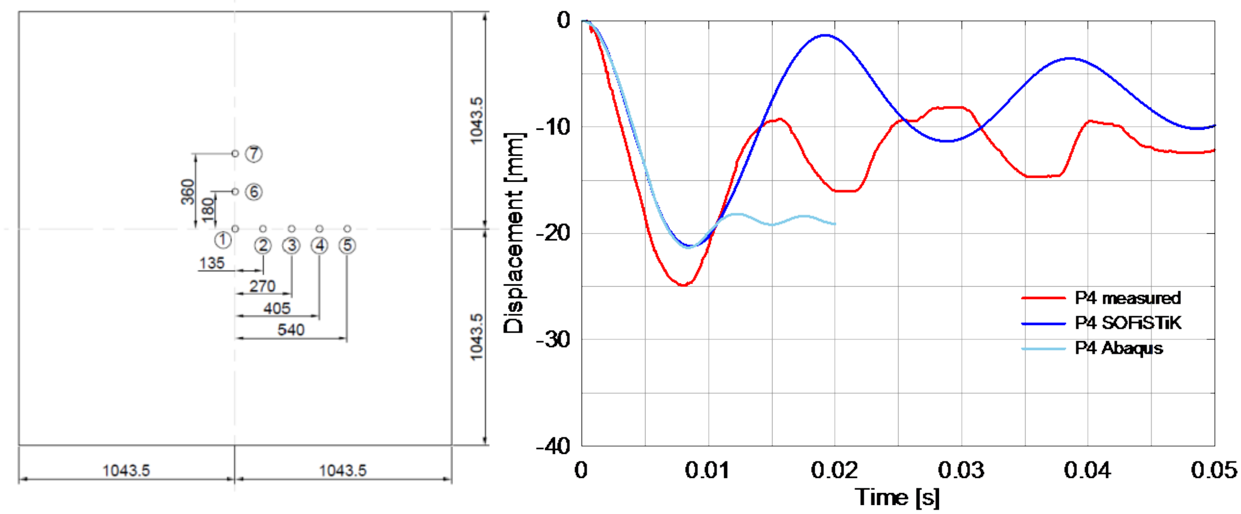


Figure 6. Comparison of displacements for the X3 experiment

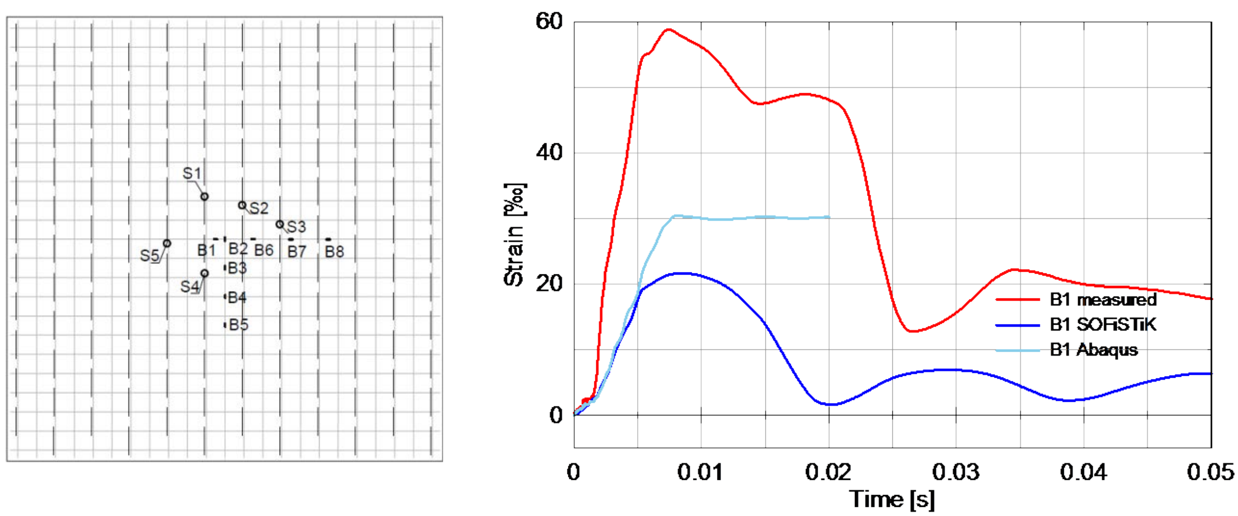


Figure 7. Comparison of reinforcing steel strains for the X3 experiment

SIMULATION OF TEST X3 WITH SOFiSTiK

The Finite Element (FE) program SOFiSTiK (2010) applied for the non-linear dynamic analyses by use of a shell element model is verified by a lot of simulations of extreme impact tests of reinforced concrete (r/c) targets, i. e. documented by Zinn et al (2014). The test slab is modelled with non-linear, layered shell elements regarding the crosswise reinforcement at both sides. The damping was introduced by Rayleigh parameters adjusted to 1 % of critical damping for the relevant frequency range (30 - 80 Hz). Strain-rate effects have not been taken into account.

The total system of r/c slab, supporting steel frame and back pipes has been considered in the coupled model depicted in Figure 8. The concrete and reinforcing steel material properties of test X3 measured prior to the test and used in the computations are compiled in Table 1.

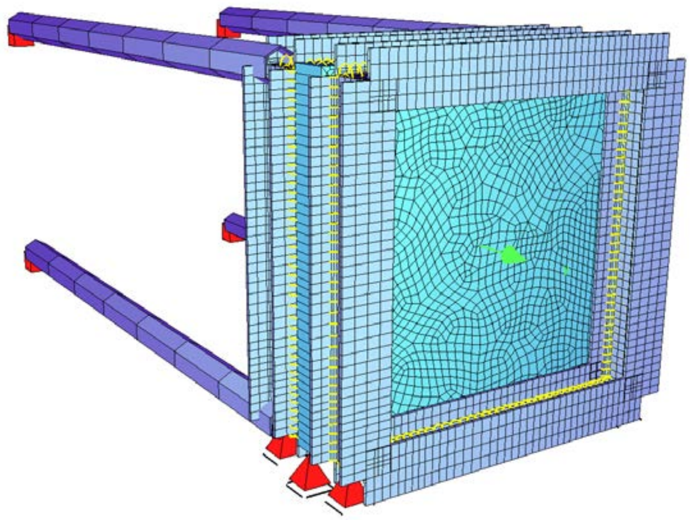


Figure 8. FE model of test facility

Table 1: Material properties of test X3

Concrete compressive strength f_c [MPa]	46.6
Concrete splitting tensile strength f_{ct} [MPa]	3.09
Concrete Young's modulus E_c [MPa]	27,989
Reinforcing steel (longitudinal / transverse reinforcement)	
Yield strength R_{eH} [MPa]	559 / 629
Tensile strength R_m [MPa]	644.3 / 702
Total elongation under maximum load A_{gt} [%]	11.2 / 5.83

Shear deformations of shell/plate elements are approximately included by SOFiSTiK. The elements shear forces are limited by the ultimate punching shear resistance of the concerning r/c structure to be specified by the program user. One main characteristic value affecting this resistance is the size of the punching cone angle, because it governs the activation of stirrups in its sphere of influence. The angle of a punching cone caused by an impact for its part depends on a lot of influencing parameters. In particular the utilisation rate of the punching shear resistance, the ratio of concrete and stirrup contribution, the ratio of longitudinal and transverse reinforcement, the deformability of the missile and the layout of transverse reinforcement should be mentioned.

Based on the Abaqus computations the punching cone angle was expected in the range of 35° and 50°, see Figure 9. A photo of the cut surface of a quarter of the test slab X3 sawn-up after the test in comparison with the stirrup distribution is demonstrating that the angles of the cracks have been induced by the positions of the stirrups. Based on these findings, the further documented SOFiSTiK results are related to limitations of the ultimate punching shear resistance assuming a mean punching cone angle of 45°.

The impact analysis has been performed using the detailed load function according to Figure 3. Computed and measured displacements showing a good correlation have been presented already in Figure 6. In contrast, especially in the slab centre the correspondence of reinforcing steel strains measured near positions of discrete cracks is not as good due to the smeared crack approach in the numerical analysis. The measured concrete strains at the front surface indicate that the recorded values are not highly precise, see Figure 10. In this respect, the correlation with the calculated results is acceptable.

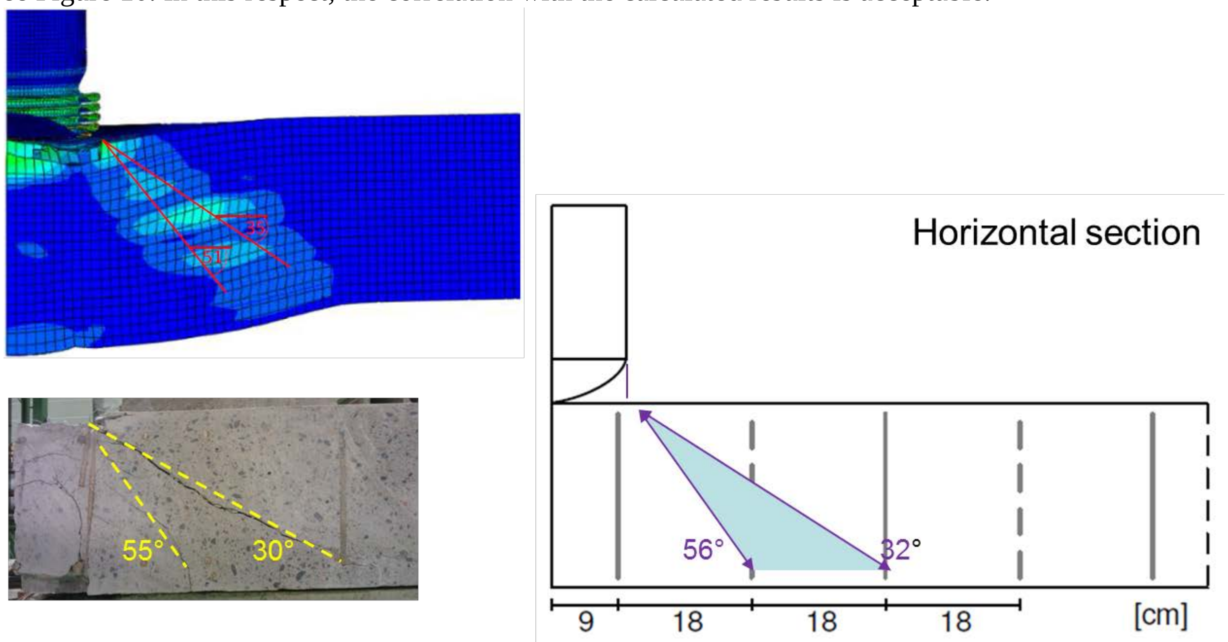


Figure 9. Computed and observed crack development related to stirrup distribution

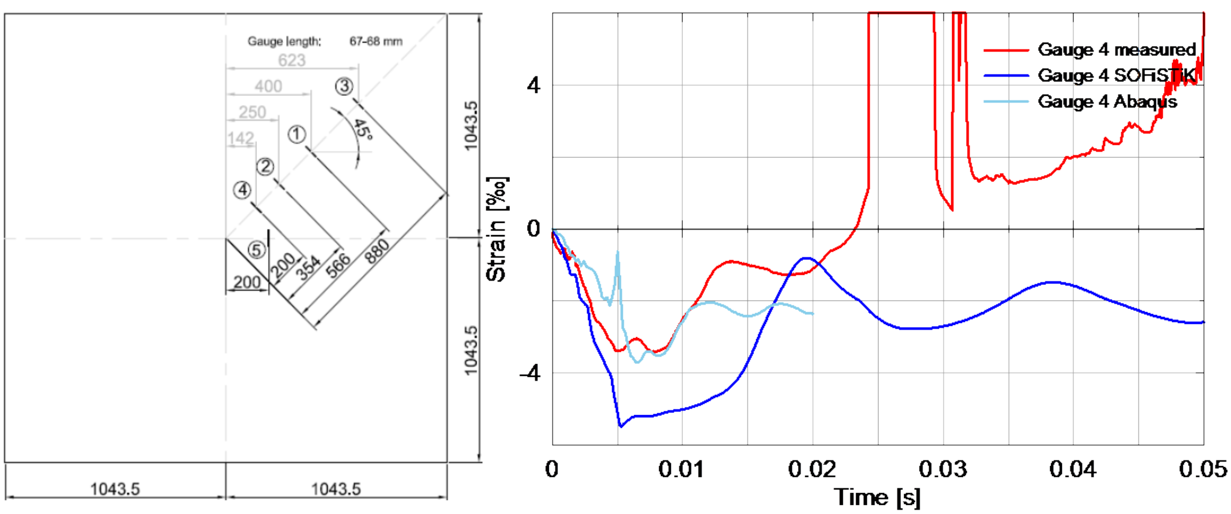


Figure 10. Comparison of concrete strains for the X3 experiment

STUDY OF THE BALLISTIC LIMIT

Having modelled fairly successfully the X3 impact test, in which the missile had been barely arrested by the target, it seemed desirable to investigate situations closer to the perforation limit of the slab. Since the missile had a velocity of 140 m/s in X3, new calculations were conducted for increasing missile velocities, in increments of 10 m/s, up to 200 m/s. The results appear in Figure 11; perforation is still not expected at 160 m/s but will occur with a velocity of 170 m/s.

In this situation it was decided to conduct the X4 test at 165 m/s, a velocity for which an additional calculation was performed. Figure 12 shows the residual kinetic energy in the model after the impact, which evinces that, for the missile being used, the ballistic limit of the plate is very close to 165 m/s.

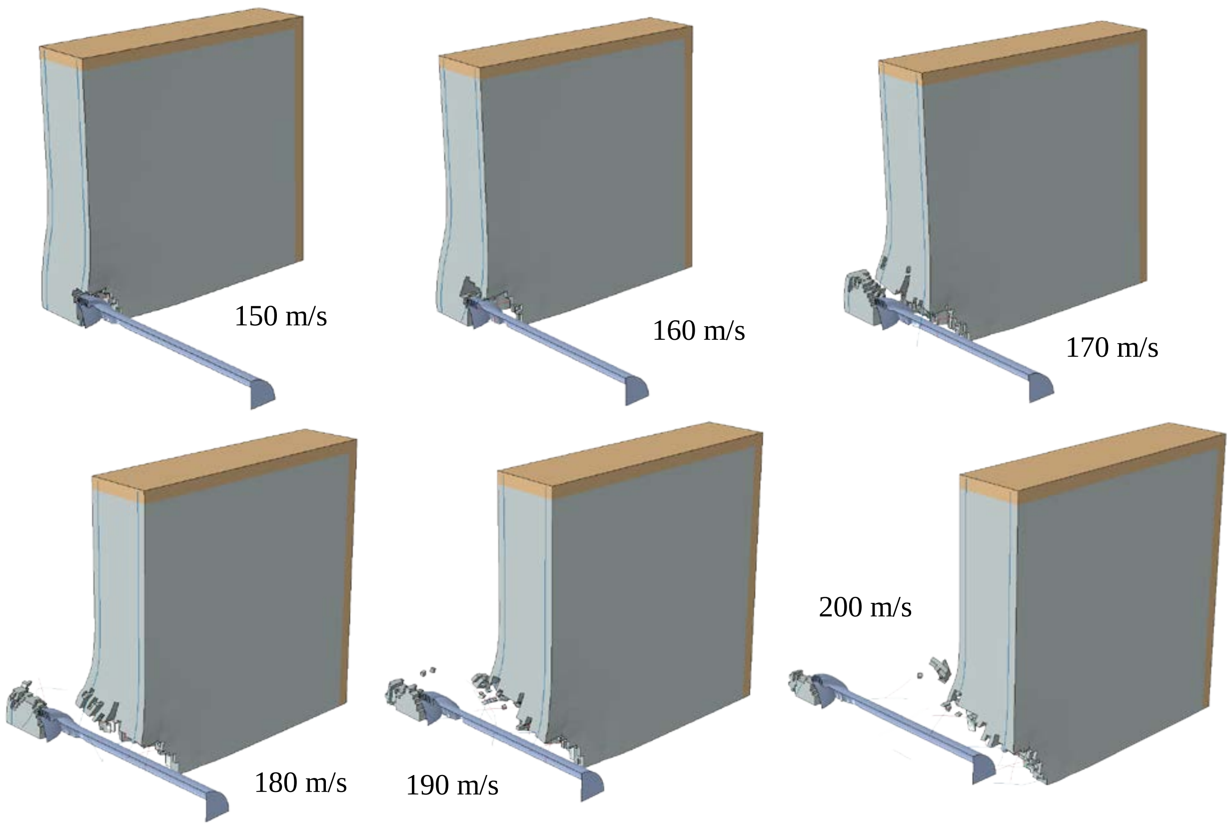


Figure 11. Deformation after 20 ms for different impact velocities

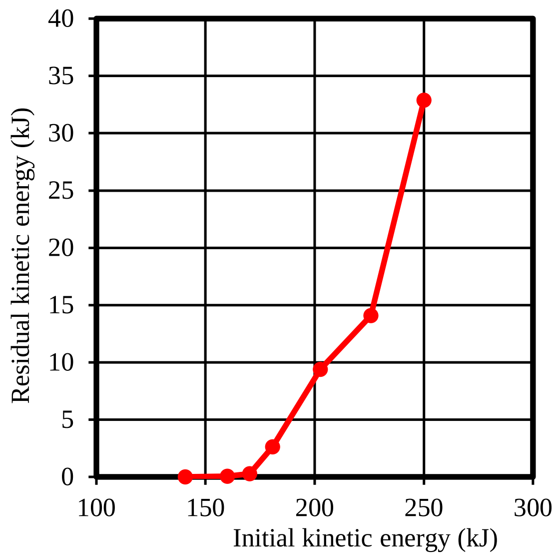


Figure 12. Residual kinetic energy in the model

SIMULATION OF TEST X4 WITH ABAQUS

The simulation of test X4 is of particular interest because the missile velocity adopted, which was actually measured to be 168.6 m/s, is very near the ballistic limit of the slab. As it turned out, the blind calculations predicted correctly that the missile would barely manage to perforate the slab. Figure 13 depicts the results obtained in the test and in the calculations.

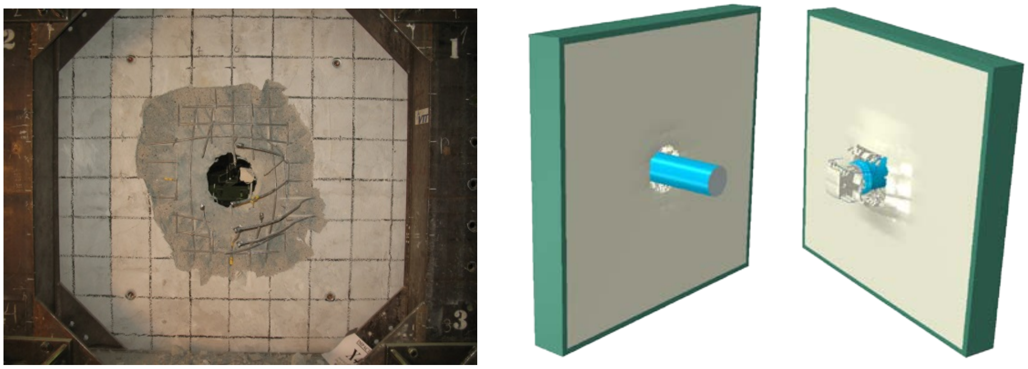


Figure 13. Rear view of plate after X4 test (photograph and FEM after 20 ms)

As shown in Figure 14, the computed residual velocity of the missile matches very well the test observations. Also the calculated and measured plastic strains of the stirrups in the vicinity of the perforation hole (cf. Figure 7) agree very well until failure of the strain gauge S2, see Figure 14

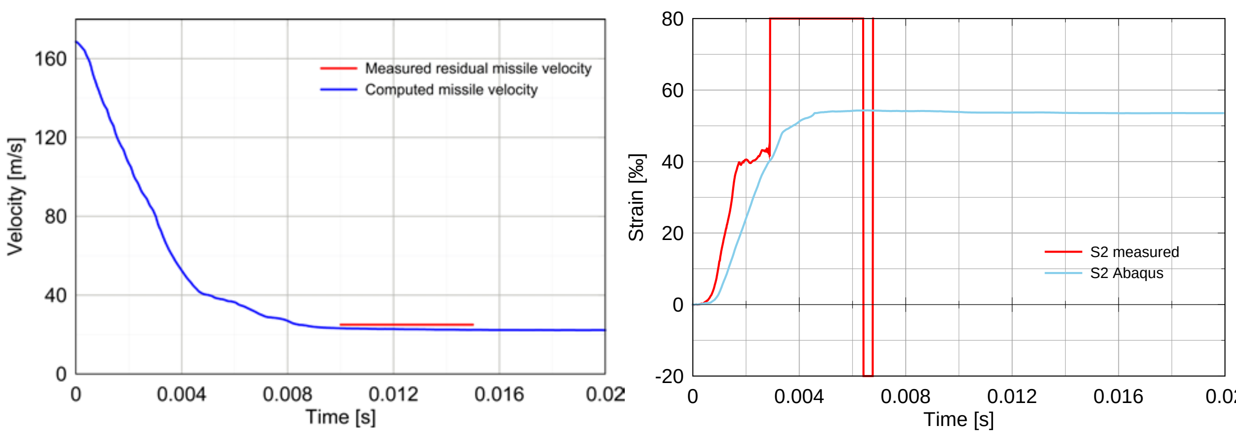


Figure 14. Residual velocity of the X4 test (left) and strains of stirrup S2 (right)

SIMULATION OF TEST X4 WITH SOFiSTiK

In spite of the limited significance of shell/plate element modelling with respect to punching and particularly perforation, an analysis of test X4 has been performed also by use of the SOFiSTiK model. With the expectation of a steep punching cone angle the ultimate resistance has been specified under the assumption of an angle of 60°.

The displacement results shown in Figure 15 indicate that no perforation is predicted by the SOFiSTiK analysis despite concentrated plastic reinforcing steel strains near fracture elongation. Due to the continued computational transfer of the residual kinetic energy until complete stop of the missile the displacements calculated by SOFiSTiK are much higher than the Abaqus results, which match the observations very well.

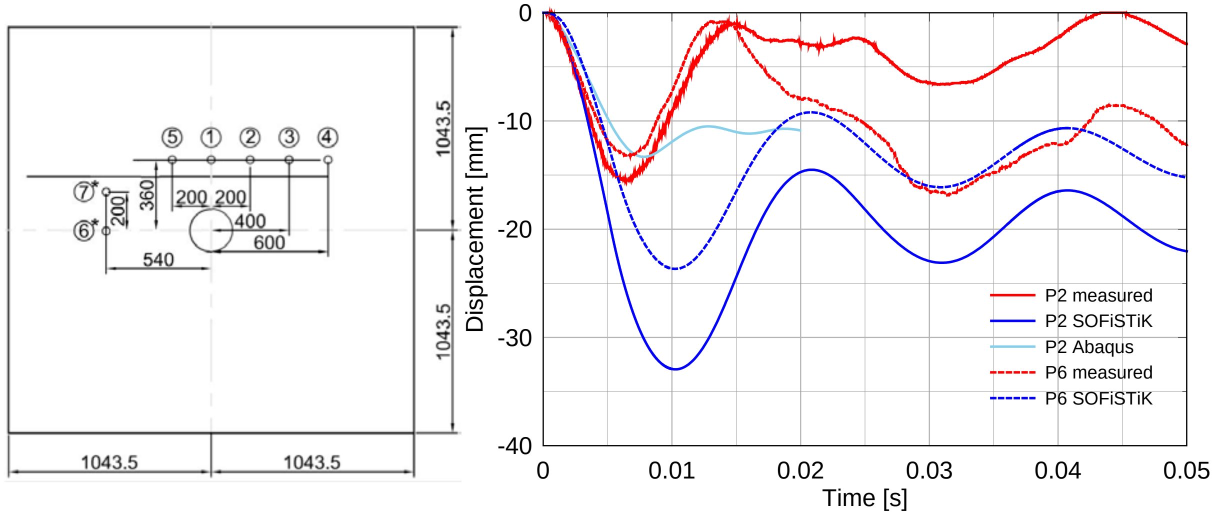


Figure 15. Comparison of displacements for the X4 experiment (front side)

CONCLUSION

Analyses were conducted of the effects of impacts of a soft missile against a reinforced concrete slab in the context of the IMPACT III project, which achieve a high utilisation of ultimate strength with respect to bending as well as punching. Several conclusions can be extracted from these further investigations:

- The calculated history of the reaction force correlates reasonably well with that proposed by Riera (1968) for highly deformable missiles against relatively rigid targets.
- The final shape of the missile is well reproduced in the calculations.
- In case that perforation is prevented, both simulation models prove to be equally well suited for the analysis of the mechanical behaviour of the slab. The calculations by use of a volume element model predict accurately whether the missile will perforate the slab or not.
- The calculated peak displacements compare well with the measurements but, since the unloading stiffness is not well represented in the constitutive model adopted, permanent displacements are not accurately captured. Strains in the rebars (and stirrups in the Abaqus model) also correlate well with the actual measurements.

Overall therefore it must be concluded that the capabilities exist for making realistic predictions of impact events such as the ones analysed here, but the simulation must be carefully performed and special attention must be paid to the constitutive description used to represent the concrete behaviour.

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