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Analysis of combined bending and punching tests of reinforced concrete slabs within IMPACT III Project

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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, reduced scale impact tests of reinforced concrete structures were carried out. The simulation of test X3 is presented here and the numerical results are compared with those obtained in the test, carried out in August 2013. The general object is to improve the safety of nuclear facilities and, more specifically, to demonstrate the capabilities of current simulation techniques to reproduce the behaviour of a reinforced concrete structure impacted by a soft missile.
The missile is a steel tube with a mass of 50 kg and travelling at 140 m/s. The target is a 250 mm thick, 2,1 m by 2,1 m reinforced concrete wall, held in a stiff supporting frame. The reinforcement includes both longitudinal and transverse rebars. Calculations were carried out before and after the test with Abaqus (Principia) and SOFiSTiK (Stangenberg). In the Abaqus simulation the concrete is 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 is modelled with non-linear, layered shell elements for the reinforcement on both sides; non-linear shear deformations of shell/plate elements are approximately included. The results generally indicate a good agreement between calculations and measurements.

KEY WORDS: Impact; Soft missile; Reinforced concrete; Bending; Punching; Simulation.

1 INTRODUCTION

This paper focuses on outcomes of 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.

As part of the IMPACT III project, reduced scale impact tests of reinforced concrete structures are being carried out in Espoo (Finland). The series of combined bending and punching tests pursues the objective of investigating the influence of different combinations of longitudinal and transverse reinforcement on the structural behaviour, while the ultimate load capacity of the slab in bending and shear is not exceeded but is almost reached.

This paper concerns the simulation of test X3. The results produced in the various calculations are presented and compared with those obtained in the test, which was carried out in August 2013.

The general object of the exercise is to improve the safety of nuclear facilities and, more specifically, to demonstrate the capabilities of current finite element techniques to reproduce the details of the behaviour of a reinforced concrete structure impacted by a soft missile.

2 DESCRIPTION OF THE TEST

The target is a square, reinforced concrete slab with 250 mm thickness and 2100 mm sides, as shown in Figure 1 and Figure 2. It is held in place by a stiff supporting frame and four steel back pipes. The reinforcement includes longitudinal rebars with quantities 8.7 cm^2/m in each direction and face, and transverse reinforcement with quantity 17.45 cm^2/m^2 consisting of closed stirrups. The concrete quality is C40/50 and the reinforcing steel is A500HW steel. 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 values of the material 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.

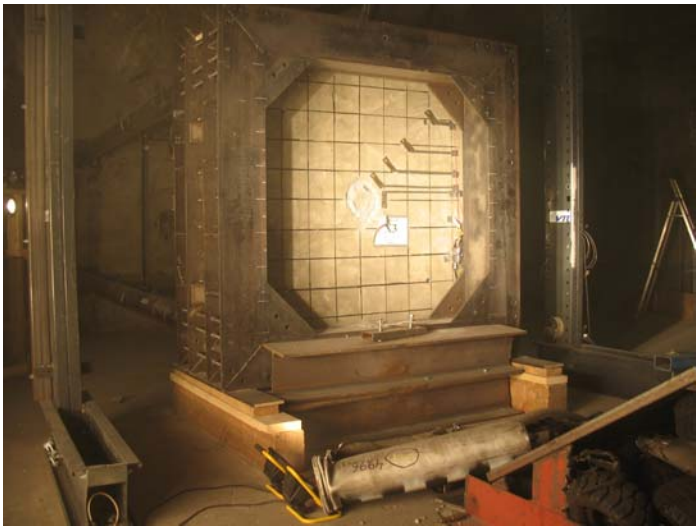
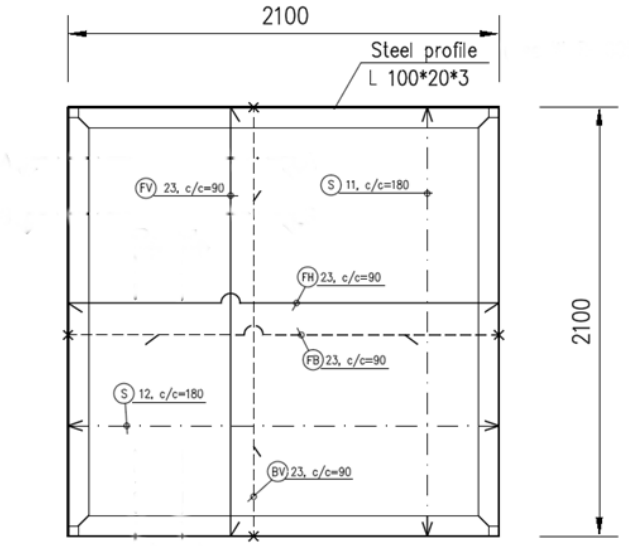


Figure 1. Test facility with slab X3

As shown in Figure 3, the missile is a capped steel tube with a length of 1304 mm, a representative 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 an impact velocity of 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%.



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 2. View of the slab and rebar quantities

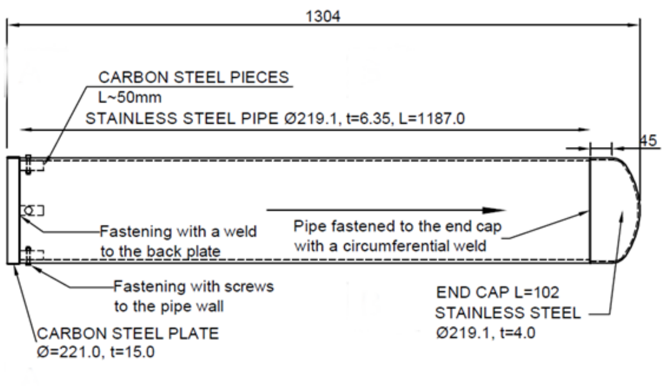


Figure 3. Drawing of the missile X3

3 ABAQUS SIMULATION

3.1 Idealisation

With Abaqus [1] 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.

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 a tensile strength of 3.01 MPa. In previous activities related to the IRIS_2012 impact benchmarks, Principia [2] had already introduced a modification in the damaged plasticity model, which consisted in making the compressive cohesion stress to depend also on the maximum principal stress. This modified model proved to be successful then, and it was kept in the present exercise.

It should be mentioned that the present calculations do not attempt to provide a conservative upper or lower bound, but are intended as a best estimate prediction. As a consequence, the parameters used for modelling the concrete represent best estimates of their average values.

For modelling the impact, advantage was taken of two of the symmetries displayed by the problem, which allowed reducing the model to one quarter of the actual configuration. The finite element model represented the concrete, the reinforcing bars, and the missile. The total number of elements employed is around 150,000.

In order to avoid excessive and unrealistic distortions, the elements are removed from the mesh when the equivalent plastic strain reaches 0.3; the removal is done with an Abaqus user's subroutine. 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.

For the reinforcing steel, an elastoplastic model was used, based on the properties given earlier, In the course of the impact a number of contacts take place between the various materials involved. The coefficient of friction was taken to be 0.3 at all such interfaces. The value of this parameter does not have a significant influence on the results.

3.2 Load function

The object of this first exercise is to determine the history of the contact reaction (load function) generated by the soft missile X3 while impacting a rigid wall. This information will 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 history of the reaction force is presented in Figure 4, with a peak of about 3.7 MN and a total duration of 5.2 ms. As can be seen in the figure, the averaged values correlate reasonably well with the estimates provided by the simplified method proposed by Riera [3], for highly deformable ("soft") missiles against a target reacting by relatively negligible deformations.

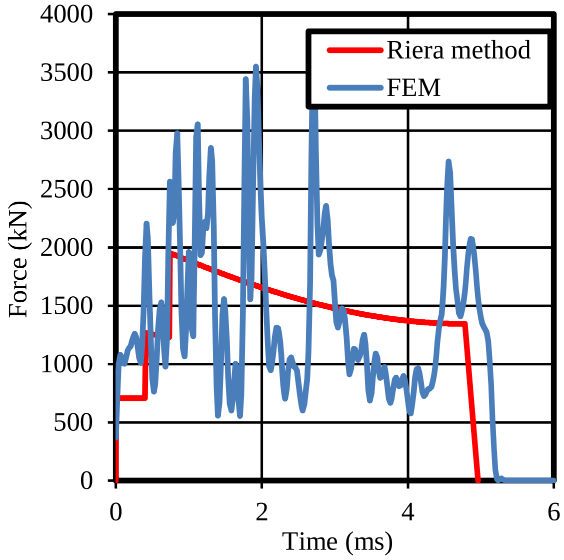


Figure 4. Load function for rigid wall

The deformed configuration of the missile after the impact is presented in Figure 5; the crushed length of the missile is around 430 mm, generating four folds in the shell of the missile.

Figure 5. Deformed missile after the impact

3.3 *Analysis of the impact*

As already mentioned the slab concrete is C40/50 with the basic properties given earlier. Since it is essentially identical to the concrete modelled for IRIS_2012 in [2], the constitutive description adopted here is the same one already employed in those analyses. In [2] a modification had been introduced in the damaged plasticity model, which consisted in making the compressive cohesion stress to depend also on the maximum signed principal stress. In that project the parameters of the modified model could be determined using information from triaxial tests provided. Since that type of information was not available in IMPACT III, the previous compressive cohesion stress curves were adapted based on uniaxial test data. This was done by scaling the stresses by a factor of 0.72 and the strains by a factor of 1.5. Besides the tensile fracture energy is taken a 150 J/m^2. The resulting curves, given in Figure 6 are again used in the present work.

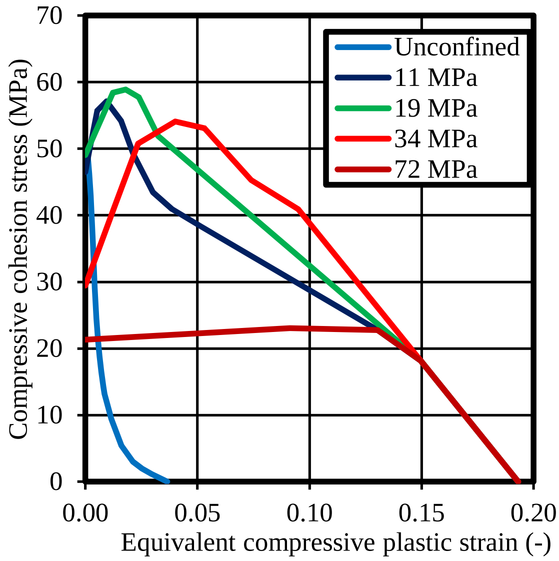


Figure 6. Compressive cohesive stress

When the impact was analysed with Abaqus using explicit integration, the calculations indicate that the missile does not perforate the slab. The resulting situation, as determined by the simulations 20 ms after the onset of impact, is presented in Figure 7.

Following the test, some minor modifications were incorporated in order to improve the simulation. The modifications consisted in increasing the fracture energy from 150 to 200 J/m^2, increasing the tensile strength from 3 to 4 MPa, and excluding the curve for unconfined compression in Figure 6. The new results are presented in Figure 8 and show that activating the erosion mechanism has little influence in the results; in either case the initially predicted cratering at the impact point disappears, as was the case in the test.

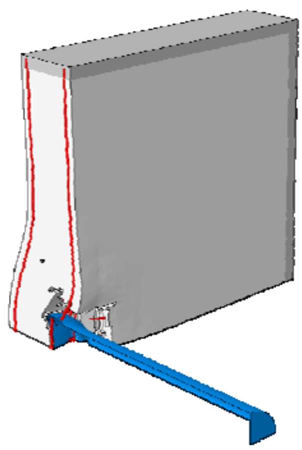


Figure 7. Deformation after the impact (initial model)

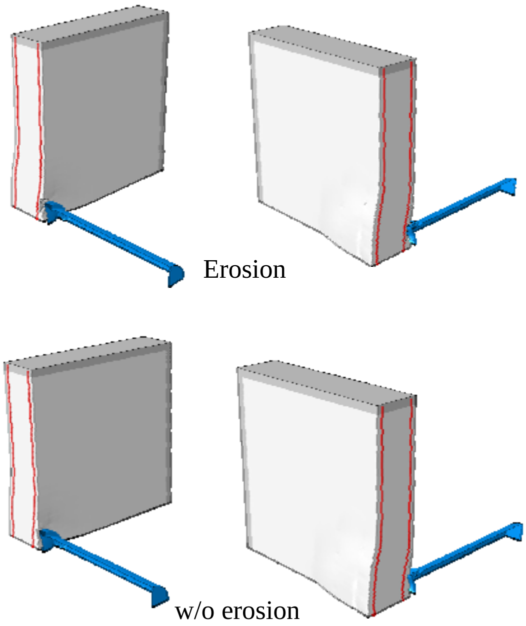


Figure 8. Deformation after the impact (modified model)

An outer view of the distribution of the crushing strains at 20 ms appears in Figure 9. For that same instant the distribution of equivalent tensile strains is presented in Figure 10, where the brown areas indicate values above 0.001. It can be seen that the missile was relatively close to perforating the slab.

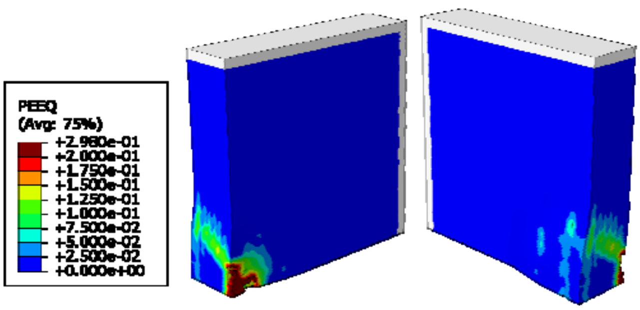
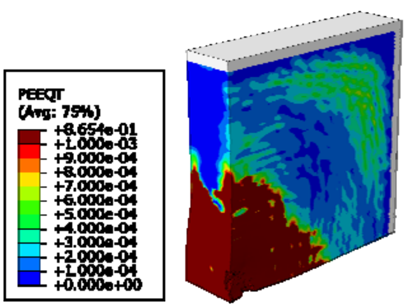
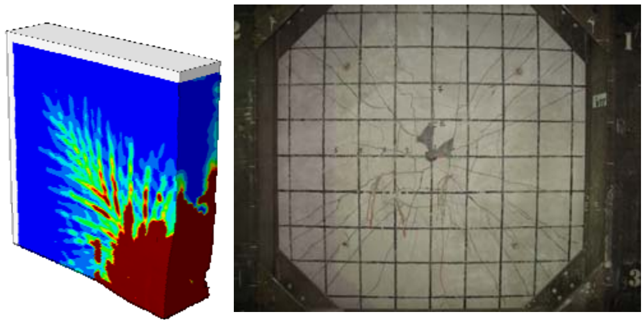


Figure 9. Crushing strains (-)



Front



Back

Figure 10. Eq. tensile strains and comparison of cracked areas

Another way of evaluating the effects of the missile impact on the slab is provided by the yielding and failure of the reinforcing bars. Figure 11 shows that information for both the bending and the shear reinforcement. The measured rebar strains matched very well the calculated values and, consistently with the test results, failure takes place in some of the stirrups.

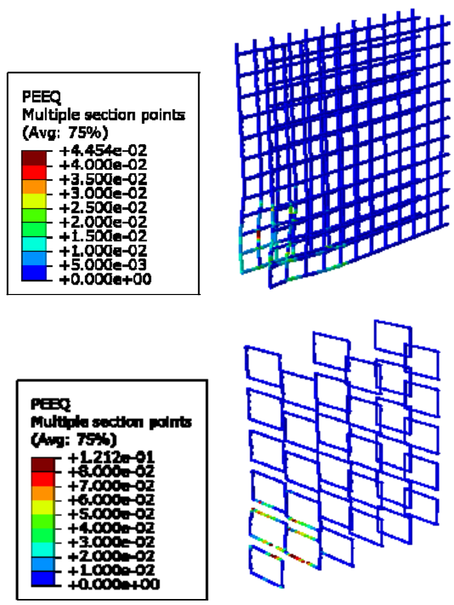


Figure 11. Equivalent plastic strains in rebars

The evolution of the kinetic energy of the missile is presented in Figure 12. This evolution indicates that practically all the relevant events caused by the impact take place in the first 5 ms. A similar conclusion arises from observing the evolution of a representative velocity of the missile, which has been plotted in Figure 13 together with the evolution that would be expected when applying Riera's approach.

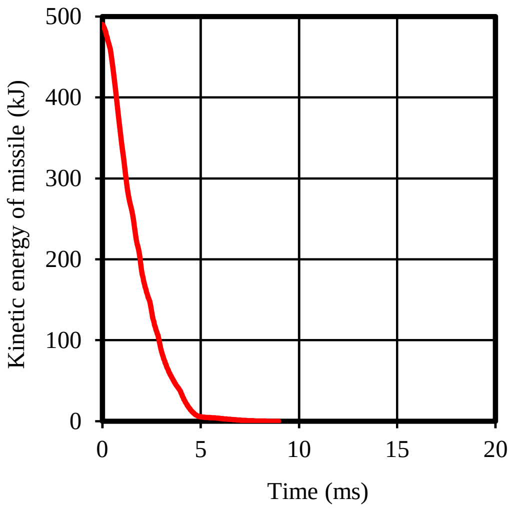


Figure 12. Kinetic energy of the missile

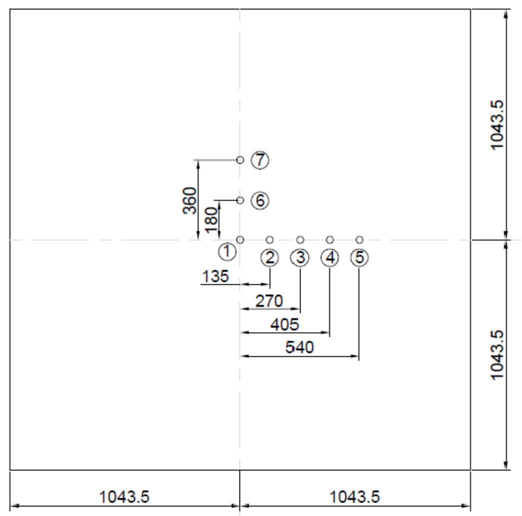


Figure 14. Displacement sensors

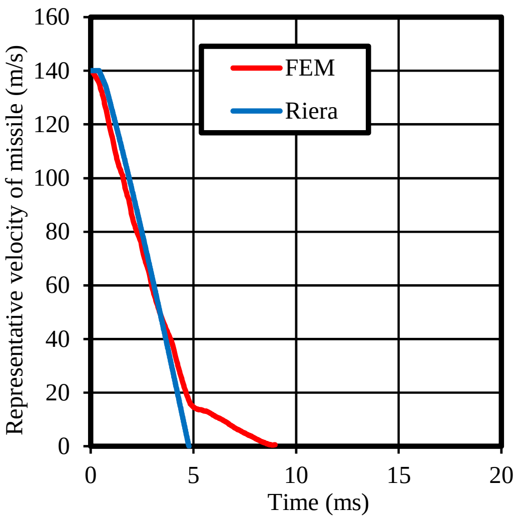


Figure 13. Representative missile velocities

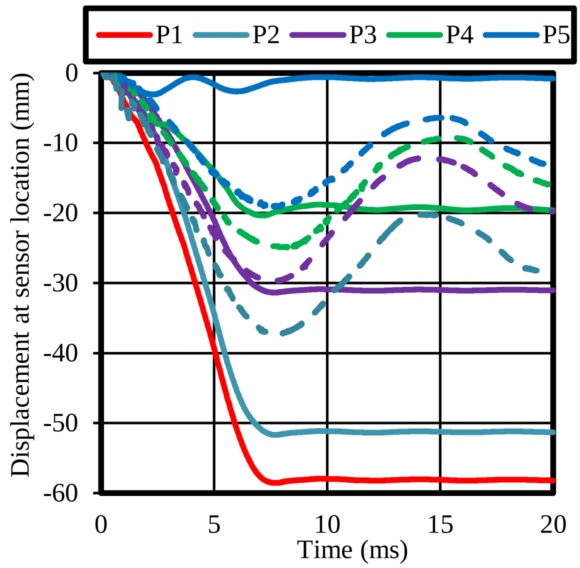


Figure 15. Computed *vs* measured slab displacements (Solid lines are computed, dashed lines are measured values)

It was already mentioned that the slab displacements were being monitored in the course of the test at a number of locations. Figure 14 provides the locations of the displacement sensors placed in the slab.

The computed displacement histories are compared with those obtained in the test in Figure 15. The comparison can be considered quite reasonable, though no comparisons are possible at locations P1 because the corresponding sensor failed during the test. Also, the parallel evolution of the displacements at locations P2, P3, P4 and P5 suggest that the complete slab may be oscillating on its supports, while that boundary condition had been assumed to be infinitely rigid in the calculations.

It is also worth comparing the lengths of the missile that collapse in the course of 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, that 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 5.

Finally, it should be stressed that the parameters of the present impact test were selected such that the energy and other characteristics of the missile are very near those strictly required to perforate the slab. As a consequence, relatively minor differences in approach or modelling strategy may alter the conclusions of the analysis, i.e.: perforation *vs* non perforation, which makes the simulation particularly challenging.

4 SOFISTIK SIMULATION

The program used for the non-linear dynamic Finite Element (FE) analyses is SOFiSTiK [4]. The calculation code SOFiSTiK is well-suited for the analysis of r/c targets subjected to extreme impact loads, see Borgerhoff et al. [5].

The reinforced concrete target is modelled with non-linear, layered shell elements regarding the reinforcement at both sides. Shear deformations of shell/plate elements are approximately included in SOFiSTiK. The elements shear forces are limited by the ultimate shear resistance specified with respect to the punching resistance of the concerning r/c structure. 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 FE model of the combined bending and punching tests is shown in Figure 16. The total system of r/c plate, supporting steel frame and back pipes has been considered in a coupled model. The used mesh size for the FE model of the slab is 50 x 50 mm.

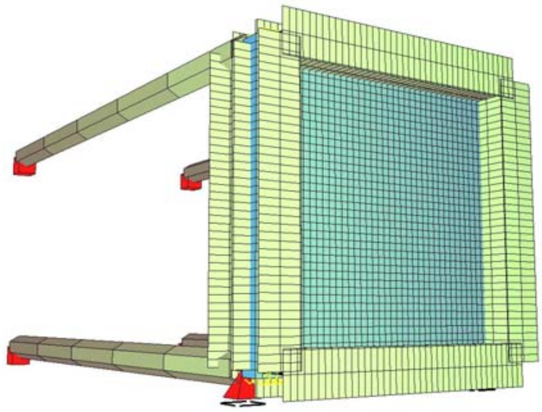


Figure 16. FE model of test facility

All computations documented hereafter are blind pre-computations. The concrete and reinforcing steel material properties of test X3 used in the computations and measured prior to the test are compiled in Table 1.

Table 1: Material properties and reinforcement.

	Blind Pre-Computation	Test X3
Concrete		
Compressive strength f_c [MPa]	44.1	46.6
Splitting tensile strength f_{ct} [MPa]	2.98	3.09
Young's modulus E_c [MPa]	26,341	27,989
Reinforcing steel (longitudinal / transverse reinforcement)		
Yield strength R_{eH} [MPa]	536.7	559/629
Tensile strength R_m [MPa]	629	644.3/702
Total elongation under maximum load A_{gt} [%]	11.2	11.2/5.83
Longitudinal reinforcement (∅ 10, s = 90 mm e.w.e.f.), [cm²/m]	8.73	8.73
Transverse reinforcement (closed stirrups ∅ 6 mm) [cm²/m²]	17.45	17.45

The two load functions as shown in Figure 4 have been used leading to very similar results, see displacements at the slab centre in Figure 17. This is due to the fact that the higher oscillations in the FEM load function only affect frequencies > 300 Hz, see Figure 18 (the fundamental plate frequency is approximately 50 Hz). Another studied parameter was the effect of the punching cone angle, which was expected in the range 32° - 45°. A pronounced formation of a punching cone becomes apparent from the displacement distribution over the mid-section of the test slab at the time of maximum displacements, see Figure 19. Figure 20 shows the total reaction force time histories from the four backpipes. The reduced load transmission by formation of steeper punching cone angles can be identified from the force amplitudes in Figure 20. A photo of the cut surface of a quarter of the test slab X3 sawn-up after the test is shown in Figure 21 demonstrating that the assumption concerning the punching cone angle was satisfactory.

The further documented results are related to the Riera load function and the punching cone angle 45°. Computed and measured displacements are presented in Figure 22. The numerical results show a good correlation with the measured results of test X3.

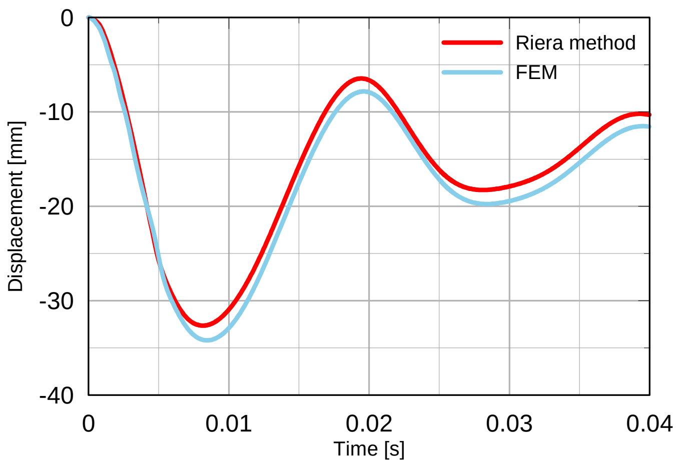


Figure 17. Displacements of slab centre

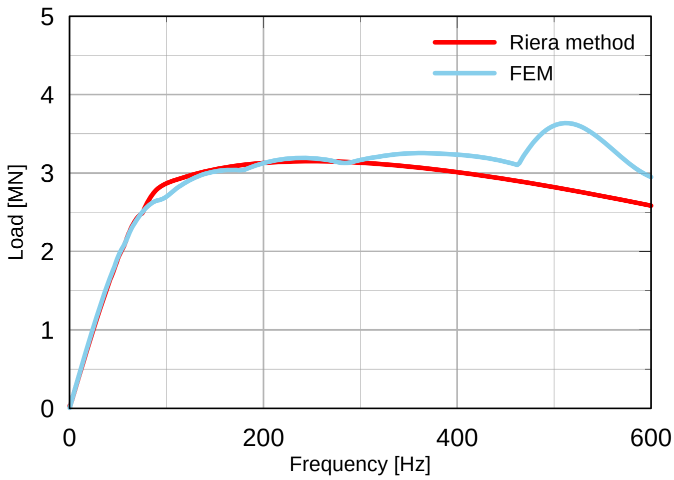


Figure 18. Comparison of response spectra of load functions

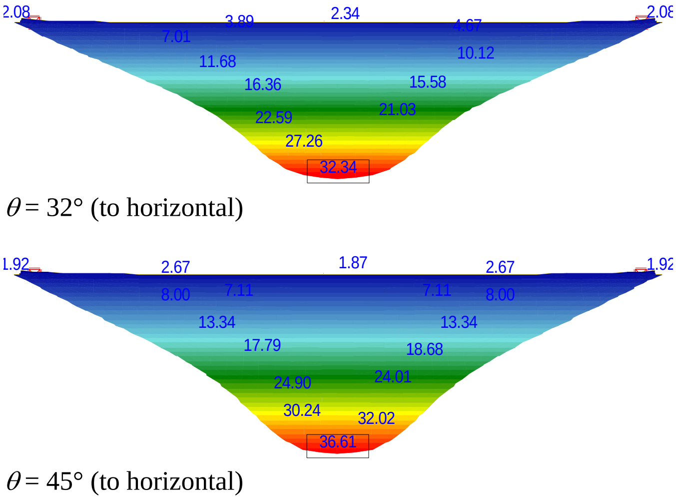


Figure 19. Effect of punching cone angle on displacements

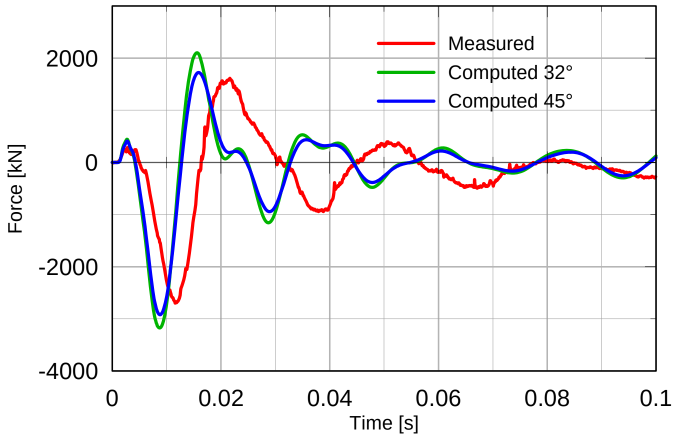


Figure 20. Measured *vs* computed sum of support forces

Figure 21. Vertical section of sawn slab

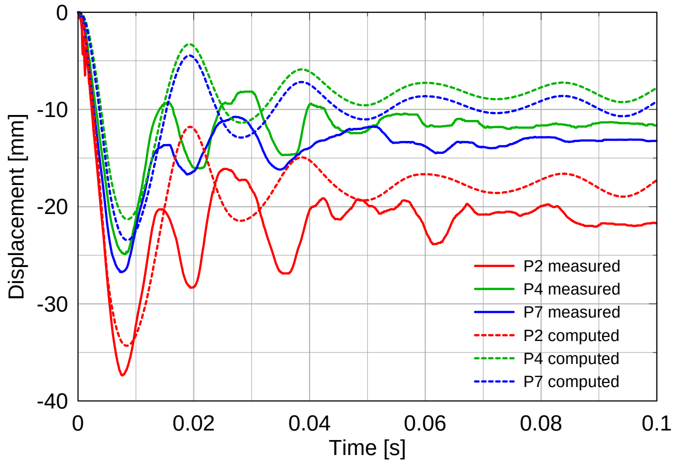


Figure 22. Measured *vs* computed slab displacements

The measured concrete strains at the front surface (location of gauges see Figure 23) indicate that the recorded values are not highly precise, see Figure 24. In this respect, the correlation with the calculated results is acceptable.

The steel strains measured at the back reinforcement (location of gauges see Figure 25) are compared to the computed values in Figure 26. While the correlation at the locations of gauges B3 and B5 is acceptable with respect to the measurement uncertainties, there is a large deviation for gauge B4. Besides the possibility of an error, the reason for this difference can be the observed formation of a discrete crack in the distance of 270 mm from the slab centre (location of gauge B4) visible in Figure 21.

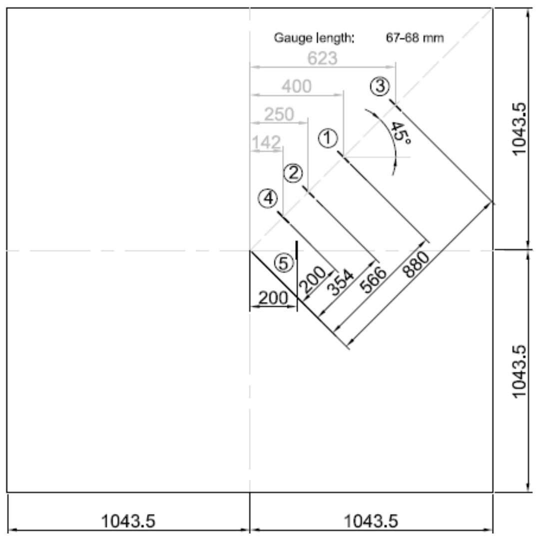


Figure 23. Strain gauges on the front surface

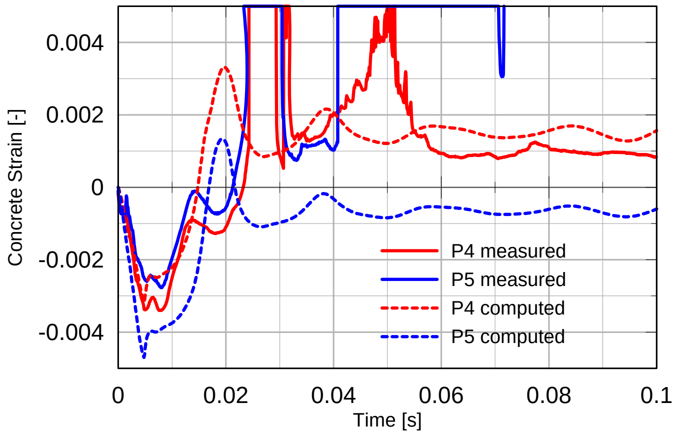


Figure 24. Measured *vs* computed concrete strains

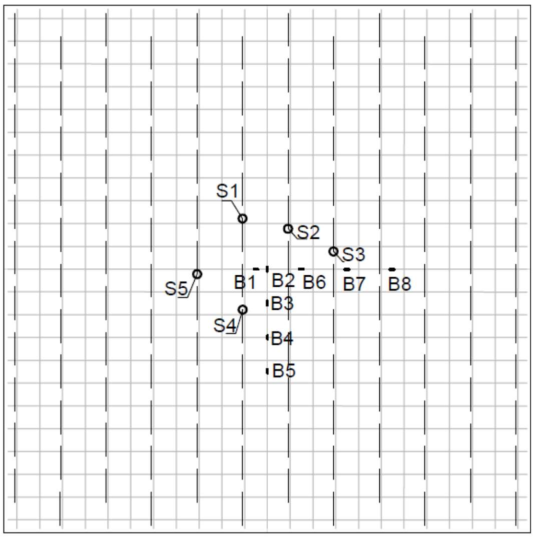


Figure 25. Strain gauges on the reinforcement

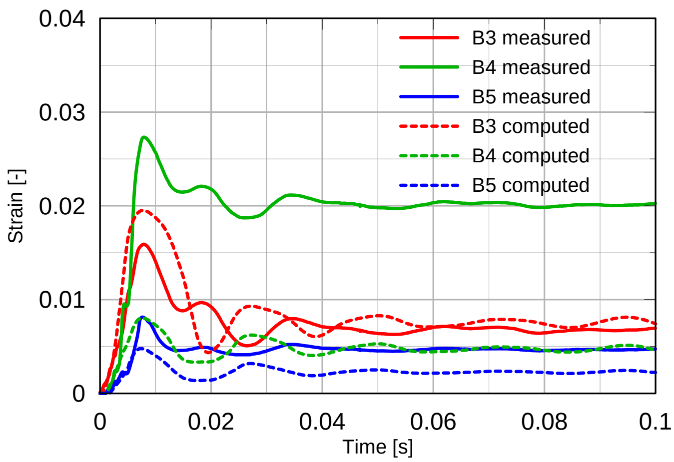


Figure 26. Measured *vs* computed steel strains

The non-linear dynamic analyses of extreme impact tests of reinforced concrete slabs with combined bending and punching deformation behaviour carried out within the IMPACT III project demonstrate that scenarios like aircraft impact on r/c structures can realistically be solved by numerical simulation. Also in the combined bending and punching tests performed so far, the layered shell element of the program SOFiSTiK has demonstrated that it is suitable for a reliable numerical simulation of this problem, provided that the slabs have a minimum of transverse reinforcement, which is sufficient to assure that the ultimate limit state with respect to punching is not exceeded.

5 CONCLUSIONS

Analyses have been carried out of the effects of the impact at 140 m/s of a soft missile against a reinforced concrete slab. The calculations have been performed in the context of the IMPACT III project. Based on the work performed, several conclusions can be extracted.

First of all, the calculations indicated that the missile would not perforate the slab, a conclusion confirmed by the test; the conditions however are relatively close to achieving perforation.

The collapsed length of the missile is predicted to be 430 mm in the case of impact against a rigid plane and 330 mm in the case of impact against the concrete slab. The length reduction measured in the test was 328 mm with the same four concertina folds predicted by the calculations.

For the locations where the sensors survived, the comparison of calculated and measured slab displacements is reasonable, though there seems to be a global motion of the slab on its supports that was not incorporated in the model. Rebar strains also compare well.

Overall therefore it must be concluded that the capabilities exist for making realistic predictions of impact events such the one 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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