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INTERACTION OF BENDING AND PUNCHING IN REINFORCED CONCRETE SLABS SUBJECTED TO IMPACTS OF DEFORMABLE PROJECTILES IN IMPACT III PROJECT TESTS

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ABSTRACT

The research programme IMPACT, which includes reduced scale impact tests, is organised by the VTT Technical Research Centre of Finland in Espoo and funded by several institutions including the Swiss Federal Nuclear Safety Inspectorate ENSI. Phase III of this project comprised a series of experiments with reinforced concrete (RC) slabs subjected to impact by deformable missiles, which had the objective of investigating the combined effect of longitudinal and shear reinforcement. Corresponding to the response of a RC structure to the impact of an aircraft crash, the slab design and the loading parameters of the impacting missile aim to approach the ultimate load capacity of the slabs in both bending and shear. Subject to these conditions, the examinations include the influence of different combinations of reinforcement in terms of amount and constructive design.

The test specimens of this series are RC slabs with the dimensions 2.1 m × 2.1 m × 0.25 m, fixed by a steel frame with span widths 2 m by 2 m. The impacting missiles are steel pipes with a regular weight of 50 kg and different wall thicknesses. The impact velocities range up to 168 m/s. The variations of the test parameters concern the cross-sections of the longitudinal and shear reinforcement, the type of the shear reinforcement as well as mass, stiffness and dimensions of the projectiles.

Nonlinear dynamic analyses with different finite element programs for different model types are used to check current finite element techniques with regard to their suitability for the numerical simulation of the behaviour of RC structures when impacted by deformable missiles. The results of the aforementioned combined bending and punching tests are primarily used to show the performance of shell element models for the computational determination of stress states with nonlinear shear stresses in combination with nonlinear bending stresses. The paper gives a compact summary assessment based on comparisons of the measured forces, displacements and strains with the results of the performed numerical simulations.

INTRODUCTION

For the design and reassessment of new and existing structures of nuclear power plants for an airplane crash, reliable calculation methods are required that are suitable and sufficiently verified for simulating the specific nonlinear effects arising during this event. Impacting missiles are usually divided into rigid and deformable projectiles depending on their deformability compared to that of the target. Military and commercial aircraft can generally be considered deformable missiles with the exception of the massive engines.

Tests with deformable projectiles carried out in the past, e.g. the ballistic tests carried out in Meppen (cf. Borgerhoff et al. 2011), were used to validate and improve the capabilities of computer software for the computational investigation of extreme effects on RC components. The overall objective of the IMPACT research program, carried out at the VTT Technical Research Centre of Finland in Espoo, is to improve the understanding and methods for numerically simulating the mechanical behaviour of RC structures under the action of medium-velocity projectiles. Within the framework of the IMPACT project, small-scale impact tests are carried out primarily on square RC slabs with a side length of 2.1 m.

In phase III of the IMPACT project, the test series X called "Combined Bending and Punching Tests" was planned and carried out. In these tests, the combined effect of longitudinal and shear reinforcement on the load-bearing behaviour of RC slabs should be investigated. The slab design and the determination of the loading parameters of the impacting projectiles were aimed at reaching the ultimate load capacity in terms of both bending and shear. Taking this design requirement into account, the influence of different combinations of longitudinal and shear reinforcement on the structural behaviour was investigated. In addition, the type of the shear reinforcement and the size and mass of the missile were varied.

The authors have reported on individual aspects from the investigation of the combined bending and punching tests in the last SMiRT conferences (see e.g. Borgerhoff et al. 2019). This paper gives a compact summary assessment based on comparisons of the measured forces, displacements and strains with the results of the performed numerical simulations.

TEST DESCRIPTION

Test Facility

The test facility at VTT in Espoo (Finland) shown in Figure 1 consists of the firing system with a 13.5 m long pressure accumulator in the rear area and a subsequent 12 m long tube in which the projectile is accelerated. Furthermore, the test facility includes a steel frame, which is supported by four steel pipes against the rock of the cavern that includes the test hall. The test slabs are simply supported by the steel frame, see Figure 2. When using projectiles weighing 50 kg, a maximum impact speed of approx. 168 m/s can be achieved. The measuring instrumentation enables the recording of forces, displacements and strains.

Figure 1. Test facility for impact tests of slabs at VTT in Espoo (Finland).

Figure 2. Experimental setup for test X1 (left) and projectile before the test (right).

Experimental Parameters

The test series X consists of 13 individual tests that were carried out between 2012 and 2018. The specimens are square RC slabs with a side length of 2.1 m and a thickness of 0.25 m. The slabs are simply supported on all sides by the steel frame shown in Figure 2 with a span of 2 m. The projectiles consist of a thin-walled stainless steel tube with a spherically shaped cap welded to the front and a carbon steel plate at the end of the pipe. The standard mass is 50 kg.

Table 1 gives an overview of the most important parameters of the two main test components. The information on the concrete slabs reinforced in both directions at both faces, and on the projectiles come from the research report by Calonius (2019). The first variations relate to the percentage of longitudinal and shear reinforcement as well as the type of the shear reinforcement of the RC slabs (tests X6 with closed stirrups, X7 with T-headed bars and X8 with hooked stirrups). In test X11, the mass of the projectile was increased to about 80 kg in order to achieve a higher impulse. A projectile with larger diameter was used in Test X12 to increase the ratio of projectile diameter to plate thickness. Beginning with Test X3, a significantly stiffer projectile with a smaller diameter ∅ and larger wall thickness t was used to produce the formation of a punching cone with plastic strains in both the longitudinal and shear reinforcements.

Table 1: Characteristic parameters of the test series X.

Test	Reinforced concrete slab					Projectile			
	f_{cm} [MPa]	f_{ctm} [MPa]	a_s [cm²/m	a_{sw} [cm²/m²	Type of shear reinforcement	m [kg]	Ø [mm]	t [mm]	v_{imp} [m/s]
X1	40.6	3.03	8.7	17.45	Closed stirrup	50.0	256.0	3.00	165.9
X2	44.1	2.98	8.7	11.67	Closed stirrup	50.1	256.0	3.00	164.5
X3	46.6	3.09	8.7	17.45	Closed stirrup	50.0	219.1	6.35	142.7
X4	41.7	2.26	8.7	17.45	Closed stirrup	50.0	219.1	6.35	168.6
X5	59.2	3.61	8.7	–	–	50.2	256.0	3.00	162.5
X6	57.8	3.19	8.7	34.90	Closed stirrup	50.0	219.1	6.35	166.7
X7	57.8	2.97	8.7	34.90	T-headed bar	50.0	219.1	6.35	166.5
X8	57.7	3.61	8.7	34.90	Hooked stirrup	50.0	219.1	6.35	166.7
X9	61.6	3.10	5.6	34.90	Hooked stirrup	50.0	219.1	6.35	165.1
X10	61.1	3.10	12.6	34.90	Hooked stirrup	50.1	219.1	6.35	165.7
X11	56.4	3.29	8.7	34.90	Hooked stirrup	79.2	219.1	6.35	131.6
X12	63.7	3.80	8.7	34.90	Hooked stirrup	51.2	355.6	4.78	164.8
X13	53.2	3.10	5.6	17.45	Closed stirrup	50.9	219.1	6.35	143.0

The following tests only differ in one parameter and are therefore directly comparable:

- X1 and X2 (cross-sectional area of shear reinforcement a_{sw}),
- X3 and X4 (impact velocity v_{imp}),
- X6, X7 and X8 (type of shear reinforcement),
- X8, X9 and X10 (cross-sectional area of longitudinal reinforcement a_s),
- X11 and X8 (impulse),
- X12 and X8 (projectile diameter) and
- X13 and X3 (also cross-sectional area of longitudinal reinforcement a_s).

TEST RESULTS

In test X1, cracks in the form of a punching cone had formed, but strains in the shear reinforcement only slightly exceeded the elastic limit. Therefore, this test was repeated as test X2 with only 2/3 of the stirrup percentage from test X1. Despite this weakening, crack formation and strains were largely the same, with linear behaviour of the shear reinforcement and a maximum strain of 4 ‰ in the longitudinal reinforcement. This observation led to the conclusion that the concrete resistance alone was high enough to withstand the impact loading in combination with the longitudinal reinforcement.

For the next test, the already mentioned significantly stiffer projectile with a smaller diameter and larger wall thickness was used. In test X3, according to the photos of the test slab shown in Figure 3, there was a more pronounced punching cone formation with wide cracks and limited concrete spalling. The objective of approaching the ultimate load capacity with regard to both bending and shear force was achieved with large plastic strains in the longitudinal reinforcement (max. 5.5%) and the stirrups (max. 6.5%).

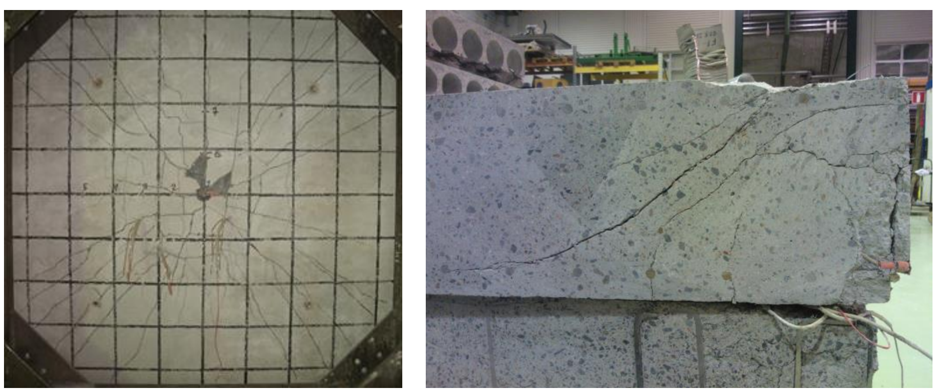

Figure 1. Test X3: Rear side (left) und vertical section of test slab (right).

In the follow-up test X4, it should be examined whether an increase to the maximum possible impact velocity of approx. 168 m/s could cause a perforation of the test slab, while the other test parameters are the same as in test X3. As can be seen from Figure 4, the projectile has completely penetrated the slab. In contrast to the predominantly tunnel-shaped perforation of a hard body, a conical concrete breakout occurred in test X4. This behaviour is due to the energy dissipation as a result of the plastic deformation of the longitudinal reinforcement in combination with the confining stirrups. It is reflected in the number and distribution of cracked bars and stirrups, see Figure 4.

The test X5 without shear reinforcement was carried out in order to gain more detailed knowledge about the contribution of concrete to the punching resistance when impacted by a deformable projectile. The plastic deformation resistance of the projectile, which is significantly determined by the pipe wall thickness, and the impact velocity were correctly calculated based on empirical formulas. As a result, the envisaged formation of a punching cone with activation of the dowelling effect and the cable-net supporting effect of the longitudinal reinforcement was achieved without perforation of the slab.

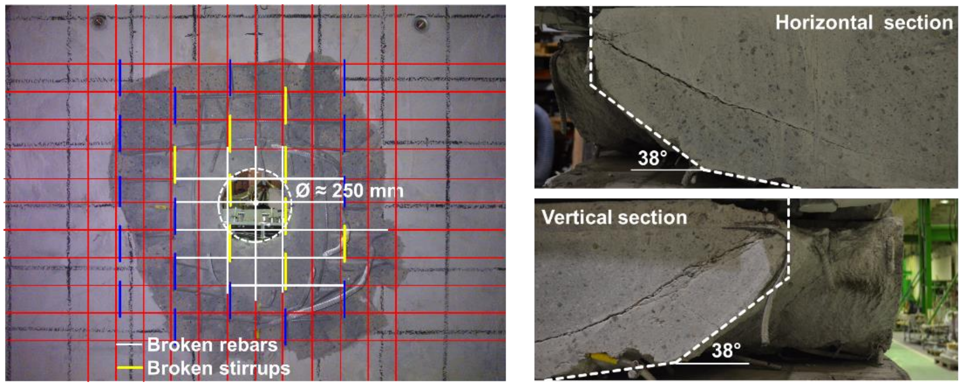

Figure 4. Test X4: Rear side (left) und sections of test slab (right).

The objective for the three tests X6 to X8 was to investigate the influence of different types of shear reinforcement on the punching shear capacity. The otherwise uniform test parameters were selected in such a way that the ultimate limit state was almost reached in all tests, see Figure 5. The types of shear reinforcement used were closed stirrups in test X6, T-headed bars in test X7, and hooked stirrups in test X8. Significant differences with regard to the effect of the different types of reinforcement on the measurement results could not be determined.

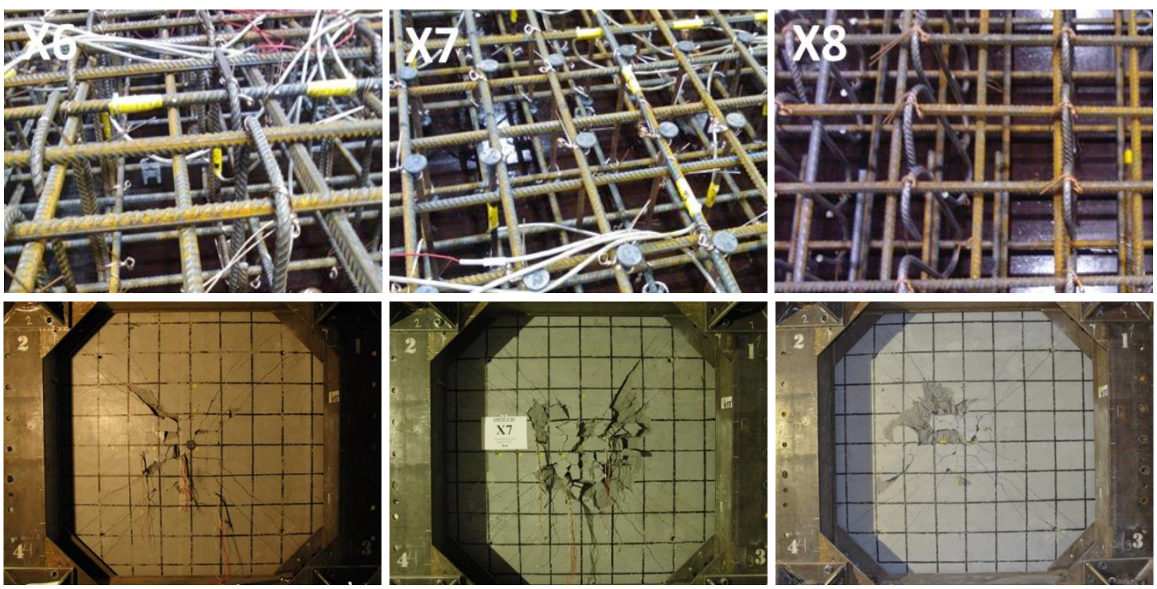

Figure 5. Tests X6 to X8: Different types of shear reinforcement (top), crack patterns and spalling on the rear side of the slabs (bottom).

The tests X9 and X10 were carried out in comparison to the reference test X8 with the aim of investigating the influence of different longitudinal reinforcement percentages on the combined bending and punching behaviour. While the other test parameters were identical (including a_{sw} = 34.9 cm²/m²), reinforcing bars with Ø 8 mm were selected for test X9 and Ø 12 mm for test X10 (X8: Ø 10 mm), see

Table 1. In the same way, in test X13 the effect of a reduced longitudinal reinforcement with only half the shear reinforcement (a_{sw} = 17.45 cm²/m²) was examined in comparison with the reference test X3, see Table 1. These variations mainly affect the maximum size and the plastic portion of the deflections. A quantification of the load capacities is not possible due to the small number of tests.

The difference between test X11 and the reference test X8 is the higher projectile mass in test X11, which results in a 26% larger impulse in combination with the chosen impact velocity, see Table 1. Unfortunately, the results of this test were not usable due to an unintended different projectile behaviour.

The diameter of the projectile was increased by 62% to approx. 356 mm in test X12, see Table 1. Compared to the reference test X8, the test results consist in smaller deflections and a finer crack distribution, which indicates that bending behaviour prevails, see Figure 6.

Figure 6. Test X12: Rear side (left) und vertical section of test slab (right).

NONLINEAR DYNAMIC ANALYSES

The experiments were numerically simulated by nonlinear dynamic analyses using different finite element (FE) programs for different types of models with the objective of verifying the capabilities of current finite element techniques to reproduce the details of the behaviour of a reinforced concrete structure under soft impact (Borgerhoff et al. 2019, and Ghadimi Khasraghy et al. 2019). The results of the combined bending and punching tests are primarily used to demonstrate the performance of shell element models for the computational determination of load conditions with non-linear shear stresses.

The FE model shown in Figure 7, created with the program SOFiSTiK (2014), was used for the numerical simulation of the mechanical behaviour of the test slabs. The test slab is represented in this model, which also includes the steel frame and its supports, by multi-layered shell elements.

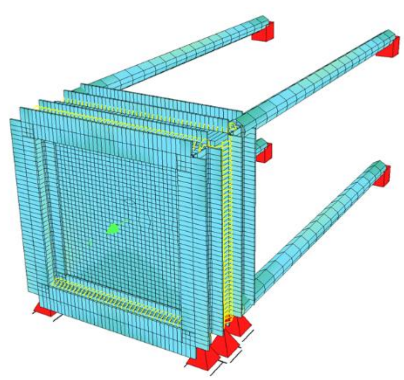

Figure 7. Finite element model of experimental setup.

The SOFiSTiK layer model simulates the interaction of concrete and longitudinal reinforcement taking into account the non-linear material properties. The shear reinforcement that cannot be explicitly included in a shell element model is taken into account in a simplified manner using an elastic-perfectly plastic shear stress distortion law. To quantify the plastic limit shear stress, the angle of a fictitious punching cone has to be specified in addition to the percentage of the shear reinforcement. Depending on the load proportion that can be transferred by the shear reinforcement in the ultimate limit state, the punching cone angle lies between approx. 45° (without shear reinforcement) and approx. 30° (total load transferable by the shear reinforcement). As part of comparative calculations for the test X3, parametric analyses were carried out for punching cone angles in the specified range. The best fit to the experiment was achieved with the fictitious value of 45°.

The load-time function due to the impact in test X3 was determined in a separate nonlinear FE calculation of an Abaqus shell element model of the projectile, cf. Borgerhoff et al. (2015). Figure 8 shows the resulting load function in comparison to a load-time function derived using the Riera method, see Riera (1968). Parametric analyses show that despite the strong oscillations of the (realistic) load profile from the FE calculation compared to the simple load-time function according to the Riera method, the two calculations yielded almost the same results. The reason for this is that the strong oscillations of the load function from the FE calculation only have an effect in the higher frequency range from about 300 Hz, but the decisive slab frequency is only 50 Hz.

The displacements shown in Figure 8 as an example of the computed results, which have been determined using the Riera load function and assuming a 45° punching cone angle, show good agreement with the measured values. Individual deviations between the calculated and measured steel strains are due to discrete cracks that the FE model used cannot simulate, see Figure 3.

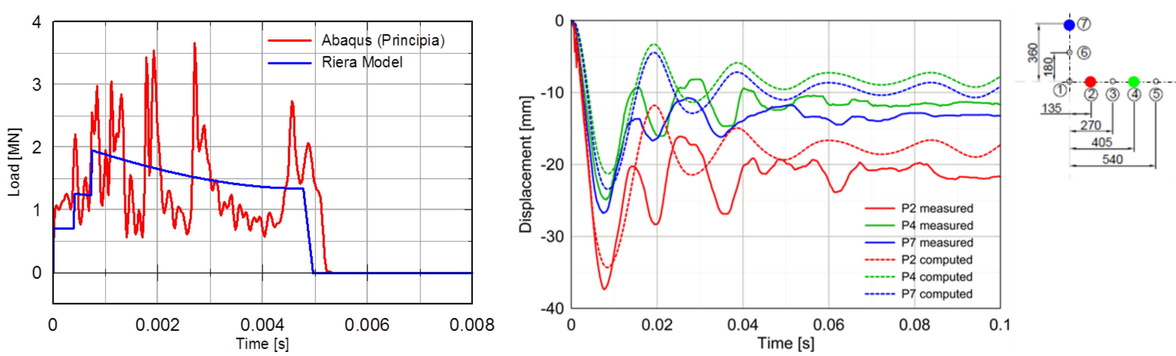

Figure 8. Test X3: Load functions for 140 m/s (left) and displacements (right).

In the calculations with the SOFiSTiK shell element model according to Figure 7 for the tests X6, X7 and X8, no distinction was possible with regard to the shear reinforcement type (closed stirrups, T-headed bars or hooked stirrups); cf. Figure 5. When determining the plastic limit shear stress assumed in the elastic-perfectly plastic shear stress distortion law, the decisive punching cone angle was set at an average of 48° based on photos of the cut surfaces of a quarter of the tested test panels. The load-time function determined in a separate FE calculation as a result of the projectile impact is shown in Figure 9 on the left, cf. Borgerhoff et al. (2017).

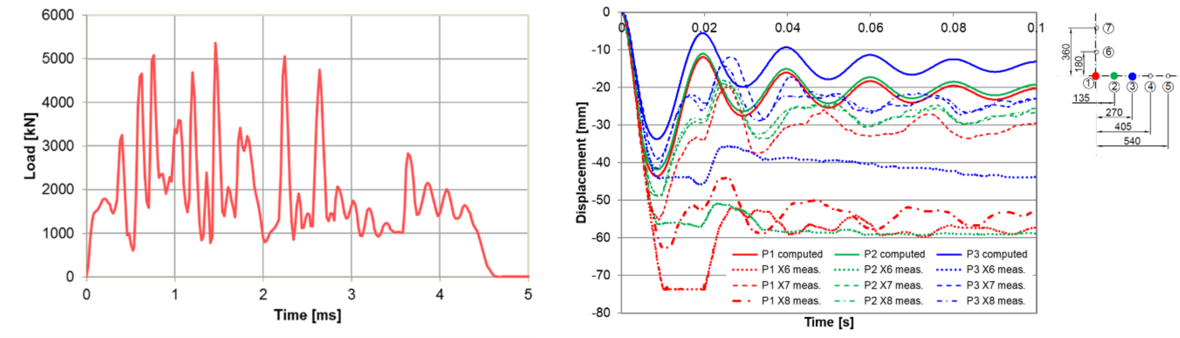

Figure 9. Tests X6 to X8: Load function for 167 m/s (left) and displacements (right).

In order to assess the influence of the different types of shear reinforcement, the displacements measured in the tests X6 to X8 in the centre of the slab and at two other equidistant points to the side of it are plotted over time in Figure 9 on the right. The measurements in test X6 (dotted lines) are obviously erroneous, since the measured values are significantly larger than the permanent deformations recorded after the test, which are largely the same in all three tests. In contrast, the displacement histories of the tests X7 and X8 are largely congruent and therefore plausible. In comparison, the calculated displacements underestimate the experimental observations. Overall, the test results indicate that the types of shear reinforcement used had no significant influence on the punching shear behaviour of the test slabs X6 to X8.

The load-time function according to Figure 9 on the left was also used for the calculations with the SOFiSTiK shell element model according to Figure 7 for the tests X9 and X10 with different percentages of longitudinal reinforcement. In the Figures 10 and 11, displacements and vertical reinforcement strains are compared with each other and with the reference test X8. The calculated and measured values deviate only slightly from each other, both in the maximum values and the permanent strains. The large discrepancies between the calculated and measured displacements and strains in test X8 are probably due to incorrect measurements.

The tests X8 to X10 indicate that a decreasing percentage of longitudinal reinforcement with the same load leads to larger shear deformations, which are caused by the formation of a punching cone with a steeper angle. The punching cone angle to be specified was selected as a uniform 48° based on test X8 without taking into account the described dependency in the blind precalculations. This assumption explains the deviations of the calculated displacements in test X9 from the measured values, see Figure 10.

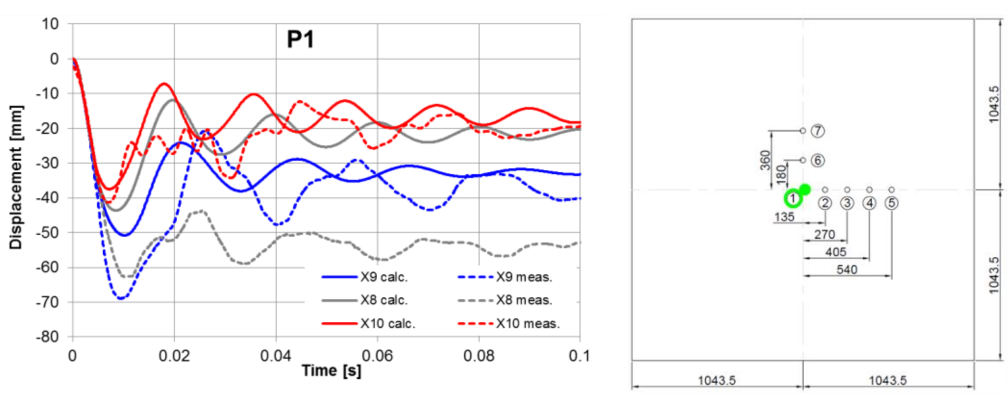

Figure 10. Tests X8 to X10: Displacements of the slab centre.

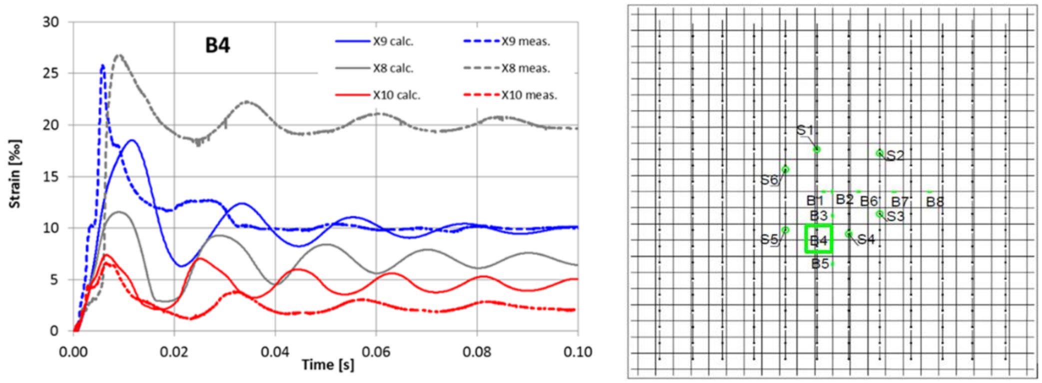

Figure 11. Tests X8 to X10: Strains of the vertical reinforcement.

CONCLUSIONS

Various influencing parameters were varied in the series of tests to investigate the interaction of longitudinal and shear reinforcement in impact-loaded reinforced concrete slabs, which is part of phase III of the research program IMPACT. In this paper, the numerical simulations for those tests are discussed in more detail, in which the amount and type of the shear reinforcement and the percentage of longitudinal reinforcement were varied. The comparison of test results with calculation results obtained with a SOFiSTiK shell element model shows that the nonlinear mechanical behaviour of reinforced concrete components under the action of deformable projectiles can be predicted with reasonable accuracy using the described calculation methods.

In the SOFiSTiK shell element calculations, the shear reinforcement, which cannot be explicitly discretised in a shell element model, is taken into account in a simplified manner by means of an elastic-perfectly plastic shear stress distortion law. The investigations into the tests with different types of shear reinforcement show that the numerical simulation with such a shell element model allows a reliable prediction of the integral load-bearing capacity of the modelled reinforced concrete structure. The stresses of the shear reinforcement embedded in the concrete matrix in the punching shear area are difficult to reproduce in detail even with a three-dimensional FE model due to local discontinuities.

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