NUMERICAL SIMULATION OF IMPACT TESTS OF REINFORCED CONCRETE SLABS WITH DOMINATING PUNCHING

M.Borgerhoff[1], F.Stangenberg[1], R.Zinn[1]
[1]Stangenberg und Partner Ingenieur-GmbH, Bochum, GERMANY
E-mail of corresponding author: borgerhoff@stangenberg.de

ABSTRACT

Within the IRIS-2010 benchmark project numerical simulations have been performed by the authors as blind pre-calculations of *VTT-CNSC-IRSN* punching missile impact tests. In addition to the IRIS project, a number of large-scale impact tests, which primarily have shown punching behaviour, carried out in Meppen (Germany) in the late 70ies and the early 80ies have been used for recalculations by means of non-linear dynamic analysis. The program utilized for the Finite Element (FE) analyses is *SOFiSTiK*. As finite elements for modelling the r/c plates, shell elements are used based on a layered concrete model regarding the reinforcement at both sides; shear deformations of shell/plate elements are approximately included. The analyses of impact tests of reinforced concrete slabs with dominating punching behaviour confirm that the program *SOFiSTiK* 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. If this restriction is not fulfilled, empirical perforation formulae or analyses by use of simple two-mass vibration models are applicable.

INTRODUCTION

The benchmark project "Improving Robustness Assessment Methodologies for Structures Impacted by Missiles (IRIS)" includes three *VTT-CNSC-IRSN* punching missile impact tests carried out in 2010 by the *Technical Research Centre of Finland (VTT)* in collaboration with the *Institut de Radioprotection et de Sûreté Nucléaire (IRSN)* and partly with the *Canadian Nuclear Safety Commission (CNSC)* within the *Subgroup on Concrete of the Working Group on the Integrity and Ageing of Components and Structures (IAGE)* of the *Nuclear Energy Agency (NEA)* of *OECD*.

The test specimens were 2.1 m x 2.1 m x 0.25 m reinforced concrete slabs, which have been subjected to impacts of missiles with 47 kg weight and 136 m/s velocity consisting of steel pipes with a filling of lightweight concrete. The slabs were fixed by a steel frame supported itself by four steel backpipes. The test slabs were designed in order to fail in a punching mode and therefore did not contain any transverse reinforcement besides their longitudinal reinforcement.

In addition to the IRIS project, the large-scale impact tests performed in Meppen (Germany) sponsored by the former *Federal Ministry of Research and Technology* in the late 70ies and the early 80ies are an excellent opportunity to validate and improve the possibilities of computer software for computations of extreme impacts on r/c targets. The authors have been involved in planning and analyzing the second test phase (tests II/11 through II/22) together with *Hochtief AG* and *GRS (Gesellschaft für Anlagen- und Reaktorsicherheit)*. Results of these and of later performed analyses have been reported at different occasions; e. g. Schwarzkopp et al. [1], Zinn et al. [2]. The test specimens of the treated Meppen tests were 6.5 m x 6.0 m x 0.7 m resp. 0.5 m reinforced concrete slabs, which have been impacted by steel pipe missiles of approximately 1000 kg weight and 172 to 258 m/s velocity.

COMPUTATIONAL APPROACH AND FE MODELS

The program utilized for the non-linear dynamic Finite Element (FE) analyses is *SOFiSTiK*; cf. *SOFiSTiK AG* [3]. The analysis of non-linear effects in *SOFiSTiK* is done by iterations using a modified Newton method; i.e. an implicit integration scheme is used. The calculation code *SOFiSTiK* is well-suited for the analysis of r/c targets subjected to extreme impact loads, cf. Chauvel et al. [4] and Zinn et al. [2].

As finite element for modelling the r/c plates, a shell element is used based on a layered concrete model 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. However, it is thought that an increase of concrete and steel strength values of up to some 10 % would be justified for the impact tests, but the influence should be small with regard to the overall uncertainties of the computations.

The FE models are shown in Fig. 1. The total system of r/c plate, steel frame and back pipes of the *VTT* punching behaviour tests has been considered in a coupled model. For the Meppen tests, the support of the plate has been modelled by non-linear gap elements for the load cells and blind cylinders as well as non-linear spring elements for the anchoring tie rods considering the pre-stressing of these elements according to the reported data, cf. *Hochtief* [5]. The used mesh size for the FE model is 50 x 50 mm for the VTT punching behaviour tests and 112.5 x 112.5 mm for the Meppen tests, respectively. The constitutive laws for reinforcing steel and concrete are plotted for the *VTT* punching behaviour tests and by way of example for Meppen test II/4 in Fig. 2.

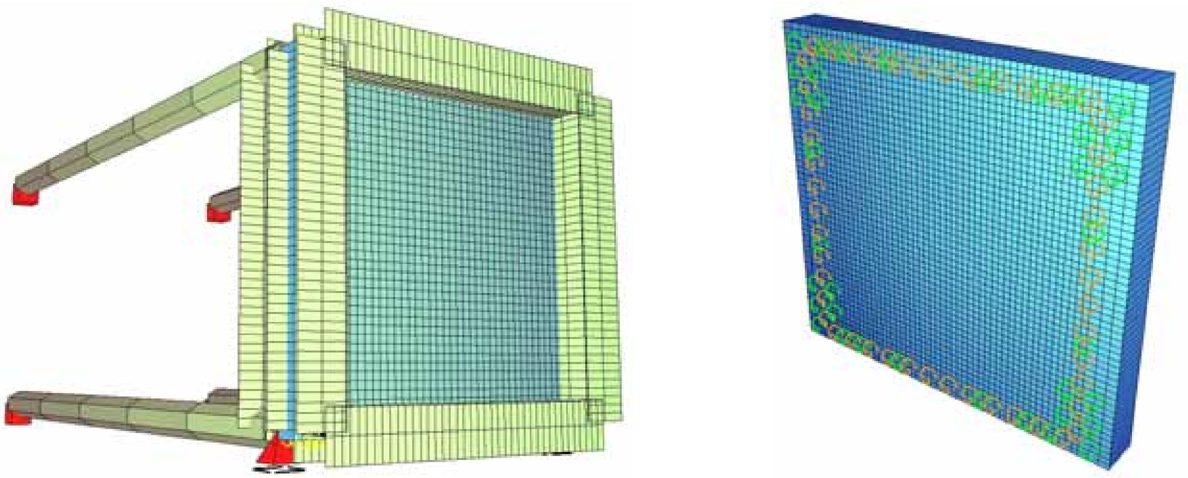


Fig. 1 FE models for *VTT* punching behaviour tests (left) and for Meppen tests (right)

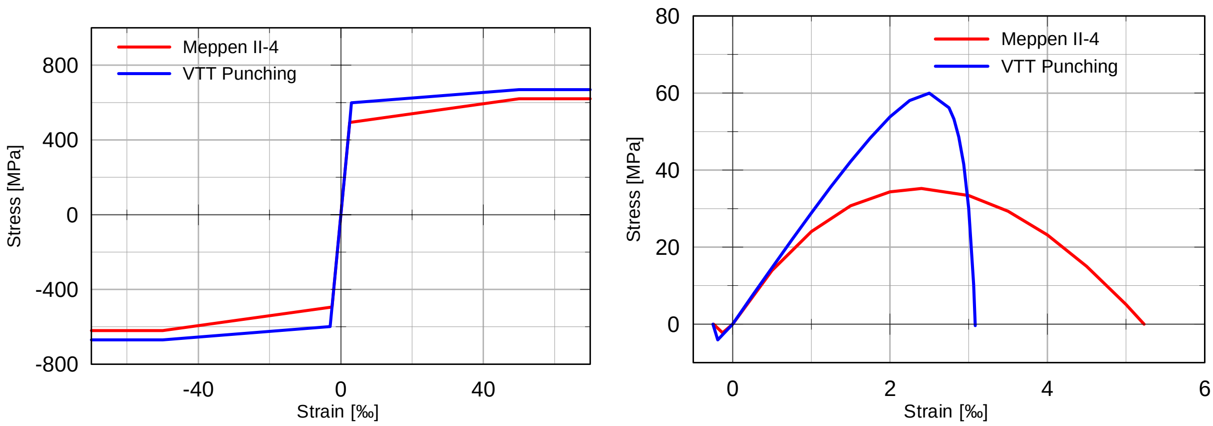


Fig. 2 Constitutive laws of reinforcing steel (left) und concrete (right)

For the impact by the hard missiles used in the *VTT-CNSC-IRSN* punching behaviour tests, a loading function is implicitly obtained, which takes into account the missile-target coupling and the momentum balance for the introduced impact. Due to the short time duration of these impacts, there is no need for a high precision of the load-time function, since the integral momentum is the dominating influence.

Also the missiles of the Meppen tests have not been modelled explicitly. Instead, the loading functions have been derived by an improved version of the approach by Riera [6]. The so-called "Riera method" originally was developed for impacts of deformable missiles on rigid targets. This assumption does apply approximately for the Meppen tests.

CALCULATION AND NUMERICAL RESULTS FOR VTT PUNCHING BEHAVIOUR TESTS

The time step of the blind pre-calculation performed by use of the SOFiSTiK FE slab model shown in Fig. 1 on the left is 0.025 ms; duration of calculation is 50 ms. This FE analysis indicates that by use of shell elements no high degree of reliability can be achieved for r/c plates without transverse reinforcement failing due to perforation of the impacting missile; cf. Fig. 3. Although a perforation of the r/c plate could not clearly be concluded from the computation, the obtained results, e. g. shear distortions in the range of the punching zone, crack patterns and hand-estimations of the punching resistance lead to the conclusion of a punching failure of the r/c plate.

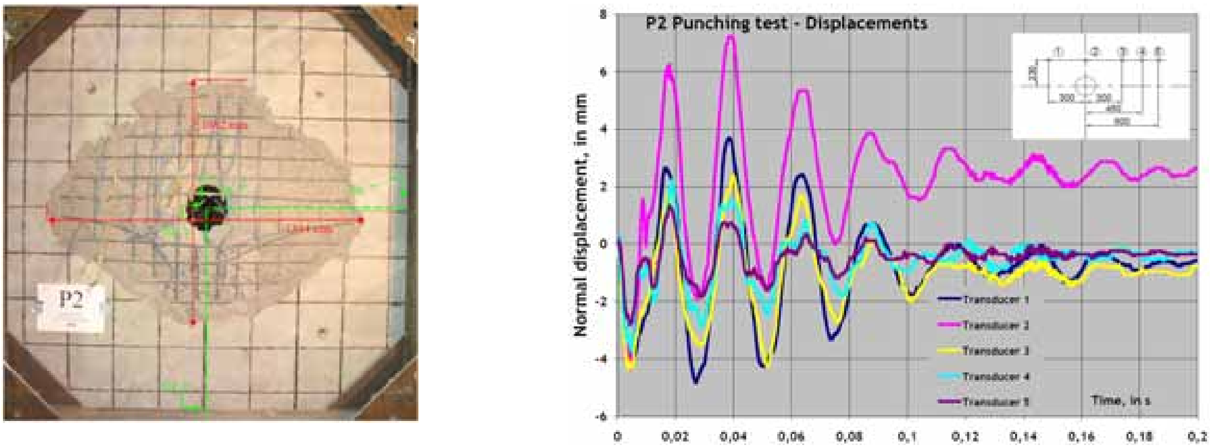


Fig. 3 *VTT* punching behaviour test P2, back side of slab after the test (left) and measured displacements (right)

For the purpose of comparison, an analysis with a non-linear two-mass vibration model directly coupled with the load determination regarding the target contact face displacements including penetration has been performed. This improved version of the so-called *CEB* model defined in CEB-Bulletin No. 187 [8] is predominantly suited for an approximate non-linear impact analysis of flat walls. The basis of the improved process is derived from that of the CEB code model which consists of a spring-mass model with simplified non-linear behaviour laws for the concerned structural elements. The two-mass model which is shown in principle in Fig. 4 on the left covers the local response – punching – as well as the global response – overall bending.

The characteristic curve of the punching spring R2 is shown in Fig. 4 in the middle. It is defined by a first part resulting from the punching resistance of the concrete determined according to *SRD* [9] and a second part representing the bending reinforcement acting as a wire mesh until failure when the characteristic ultimate steel strain is reached. The resulting load-time function is shown in Fig. 4 on the right.

The calculated displacements and velocities according to the diagrams in Fig. 5 show a much better correlation with the test results than those from the FE analysis in Fig. 3. Particularly, the perforation of the r/c plate is clearly predicted by the large displacements and velocities of the punching cone after reaching the failure criterion. According to *VTT* [7] the residual velocity was 45.3 m/s in test P2 and 35.8 m/s in test P3.

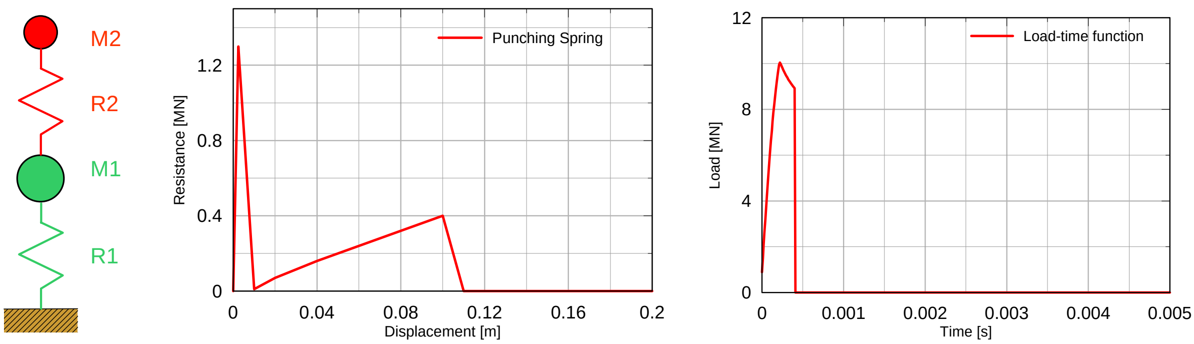
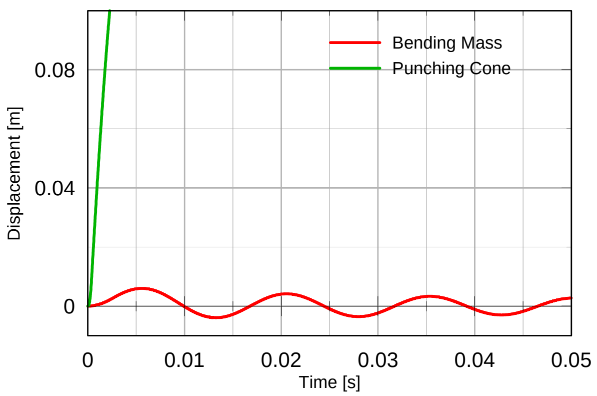


Fig. 4 VTT punching behaviour test, CEB two-mass model (left), non-linear characteristic curve of punching spring R2 (middle) and load-time function (right)



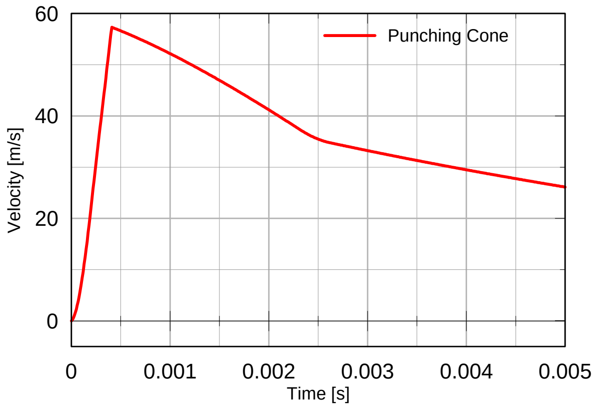


Fig. 5 *VTT* punching behaviour test, displacements of bending mass (slab outside the punching cone) and punching cone (left) and velocity of punching cone (right)

CALCULATION AND NUMERICAL RESULTS FOR MEPPEN TESTS

A number of the large-scale impact tests performed in Meppen (Germany) with varying transverse reinforcement as well as impact velocity, which primarily have shown punching behaviour, has been chosen for an additional investigation on the capabilities of the program *SOFiSTiK* for the numerical simulation of this type of non-linear mechanical behaviour by use of shell elements. In Table 1, the punching resistances of the recalculated tests according to German codes DIN 25449 and draft of KTA 2203 as well as *SRD* [9] are compared with the maximum loads from the calculated load-time functions; cf. *Hochtief* [5], [10]. It is obvious from this comparison that all tests are in the range of the ultimate load capacity. The tests II/5 and II/15 resulted in perforation due to a considerable exceedance of the ultimate limit state with respect to punching.

Table 1 Data of Meppen tests with predominating punching and associated punching resistances

Test No.	Mass	Velocity	Target Slab								Maximum load (calculated)	Maximum displacement
			Thickness	Lower reinforcement	Stirrups	DIN 25449			KTA 2203	SRD		
						Vrdc	stirrups	Vrdsy	Vrdsy	FP		
	kg	m/s	m	cm²/m	cm²/m²	MN	MN	MN	MN	MN	MN	mm
II/4	1016	247,7	0,70	53,6	50,2	5,85	7,36	13,21	14,33	12,00	13,12	45
II/5	974	234,8	0,70	53,6	12,6	5,97	1,66	7,64	3,64	11,75	11,60	Perforation
II/6	956	257,9	0,70	53,6	50,2	5,73	6,63	12,36	13,31	12,19	13,74	163
II/7	940	225,3	0,70	53,6	24,6	5,82	3,71	9,53	7,33	12,27	11,16	137
II/8	990	235,9	0,70	53,6	37,7	6,04	7,26	13,30	10,94	12,39	11,93	41
II/15	1000	236,3	0,50	56,0	64,9	3,80	4,60	8,40	9,63	7,94	14,40	Perforation
II/17	954	178,4	0,50	56,0	64,9	3,68	4,58	8,25	9,43	7,59	8,60	68

The tests enlisted in Table 1 divide into two groups. In the first group of 0.70 m thick slabs with constant bending reinforcement and impact velocities in the same order of magnitude, the amount of stirrups varies between the percentages 100 % and 25 %. Moreover, two slabs of this group with the same amount of stirrups (50.2 cm²/m²) have been tested with different impact velocities. In the second group of 0.50 m thick slabs with constant amounts of reinforcement, the impact velocities vary, too.

A suitable representation of the punching behaviour of the slabs by use of the layered shell element implemented in *SOFiSTiK* can be achieved by an appropriate specification of the ultimate shear resistance, which is dependent on the amount of transverse reinforcement and on the angle of the punching cone. According to the tests, the mean angles of the decisive shear cracks in the range of the ultimate limit state vary between some 40° and 50° related to the slab surface; cf. Fig. 6.

Subsequently, the recalculations of the Meppen tests according to Table 1 are described in detail. Further recalculations by the authors of Meppen tests (II/12, II/20 and II/21) are documented in [4].

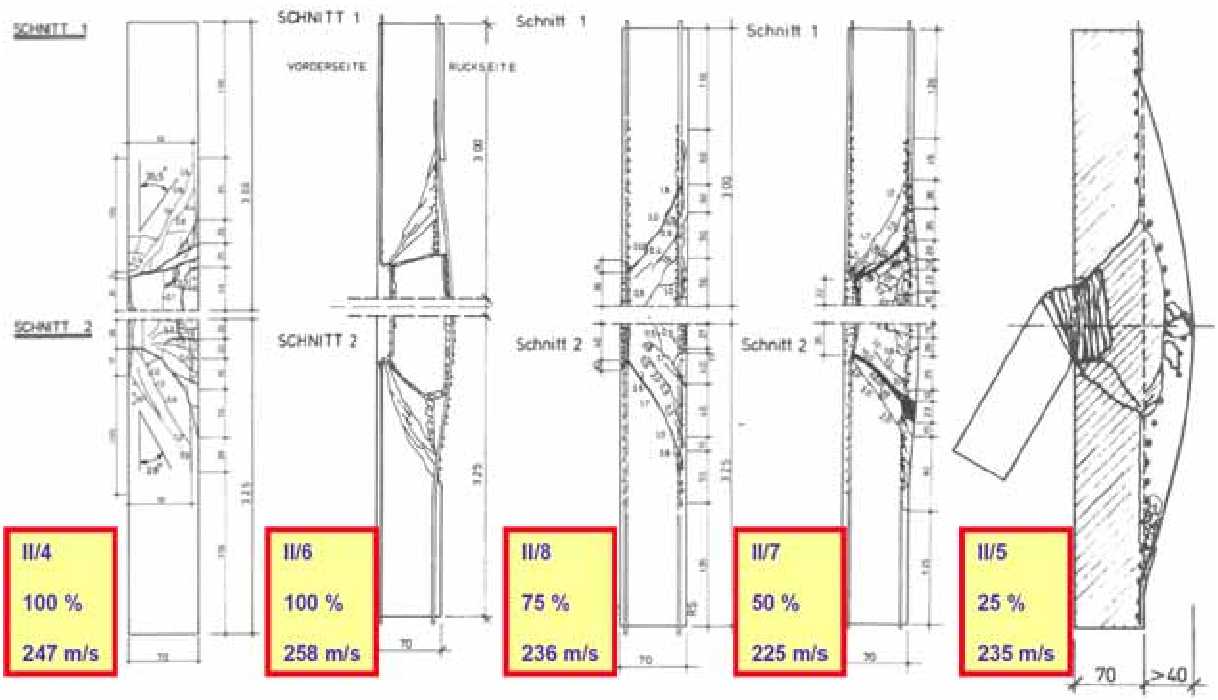


Fig. 6 Meppen tests with different percentages of stirrups, sections through plates after the tests according to [5]

The time steps of the recalculations of the Meppen tests according to Table 1, performed by use of the SOFiSTiK FE slab model shown in Fig. 1 on the right, is 0.05 ms; duration of calculation is 100 ms. Fig. 7 shows the location of displacement gauges, load cells and prestressed tie rods.

Time histories of the displacements of test II/4 are presented in Fig. 8. Although the displacement gauges W3, W4, W5 and W6 are situated symmetrically related to the axes of symmetry of the slab, the displacements are not equal due to possible unsymmetrical behaviour of the impacting missile and due to the heterogeneity of the reinforced concrete composite structure. The computed results necessarily are identical. They show a good correlation of period and amplitude of the maximum displacements. In contrast, the oscillations of the measured displacements after the impact phase point to an even stronger damping than the computed curves.

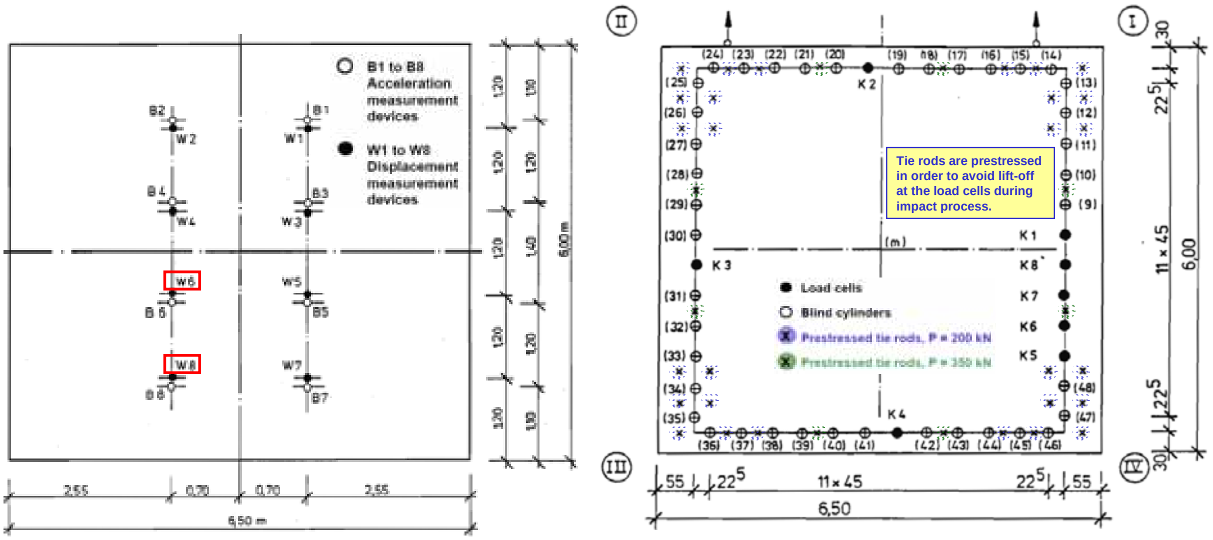


Fig. 7 Meppen tests, location of displacement gauges (left), load cells, blind cylinders and tie rods (right)

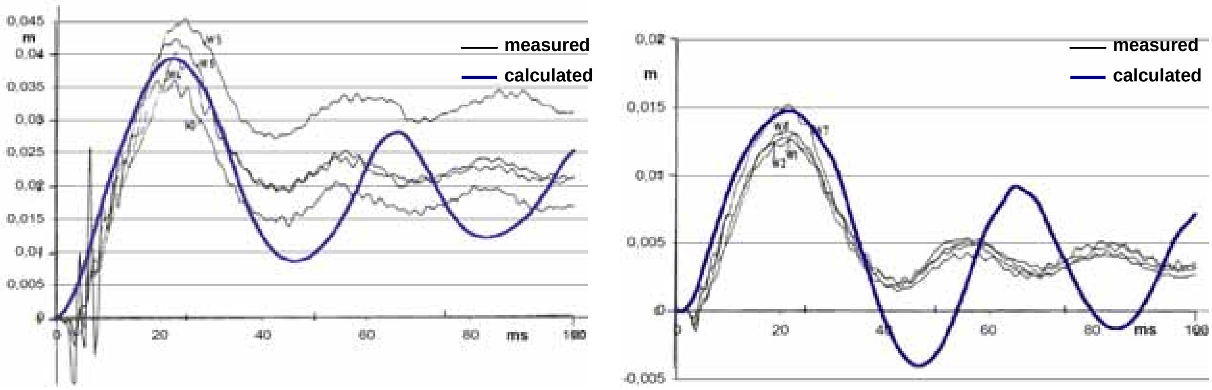


Fig. 8 Meppen test II/4, time histories of computed and measured displacements W6 (left) and W8 (right)

Test II/6 with the same shear reinforcement as test II/4, but impacted with velocity 258 m/s resulted in a deep penetration due to punching of a cone with steep angles of the decisive shear cracks. The calculated displacements match the measured values only in the period until formation of the brittle fracture, which cannot be realized by the elastoplastic shear stress approach implemented in the used program *SOFiSTiK*; cf. Fig. 9.

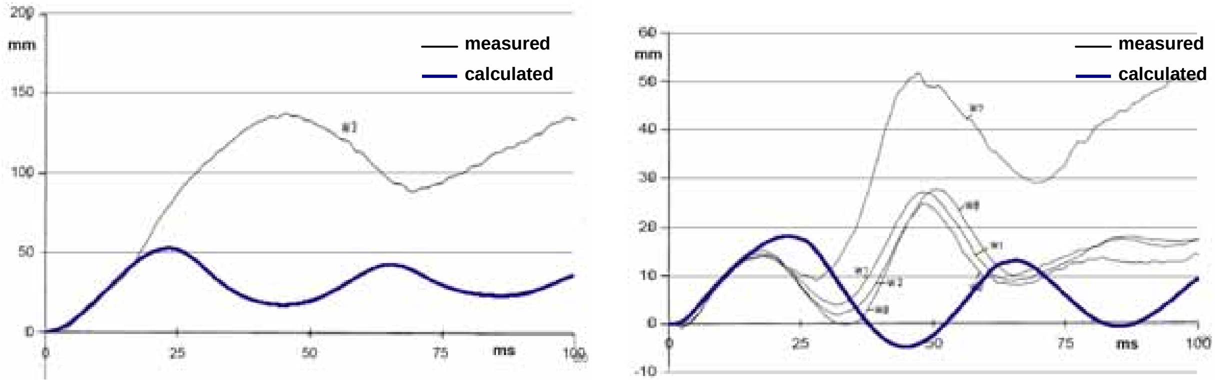


Fig. 9 Meppen test II/6, time histories of computed and measured displacements W3 (left) and W8 (right)

In test II/8, which is reinforced with 75 % of the transverse reinforcement of test II/4, the ultimate load capacity is not exceeded. Therefore, the non-linear shell element analysis produced results in good agreement with the test. Indeed, the oscillations of the calculated displacements after the impact phase are larger than the measured values. But the mean residual deformations do not deviate strongly from each other.

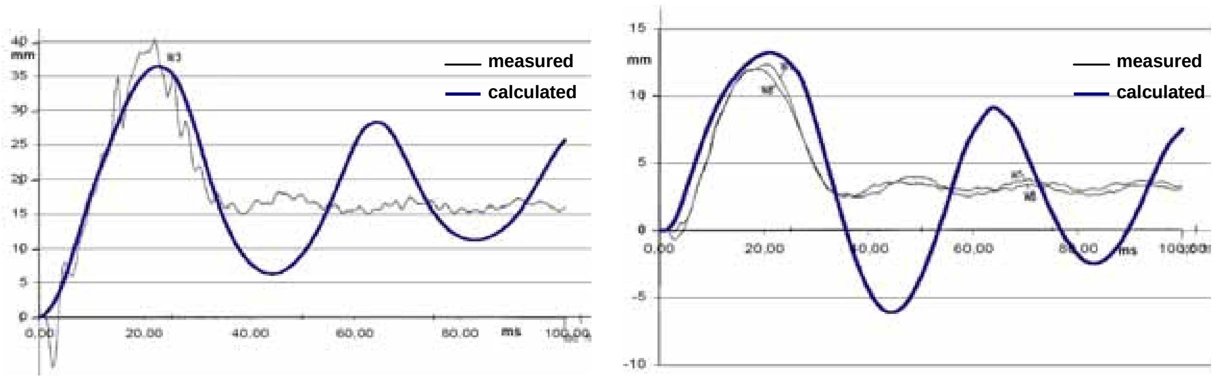


Fig. 10 Meppen test II/8, time histories of computed and measured displacements W3 (left) and W8 (right)

In test II/7, the amount of stirrups has been reduced further to 50 % of the transverse reinforcement of test II/4. As illustrated in Fig. 6, the residual deformations increased due to punching in combination with rupture of the inclined concrete compression struts. The computed deformations of the slab centre on average are consistent with the measured values; cf. Fig 11 on the left. In contrast, the observed displacements outside the punching area are overestimated by the analysis in consequence of the reduced load transmission from the punching zone to the surrounding slab area; cf. Fig. 11 on the right.

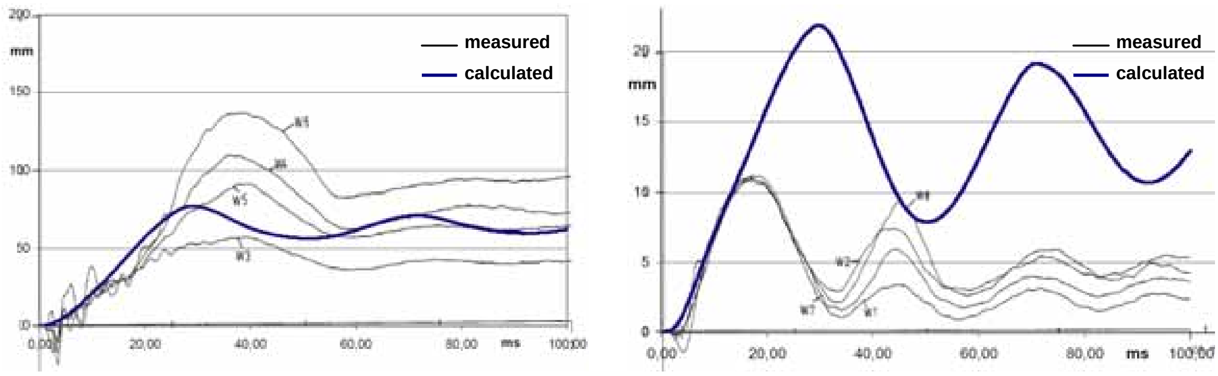


Fig. 11 Meppen test II/7, time histories of computed and measured displacements W6 (left) and W8 (right)

Finally, the slab of test II/5 is only reinforced with 25 % of the transverse reinforcement of test II/4. As shown in Fig. 6, it has been almost perforated by the missile, which was stuck in the plate after the test. Fig. 12 shows comparative presentations of the measured and calculated displacements. As the case in the recalculation of test II/6, the correlation in the period of deformation increase is excellent. But also in this test exceeding the punching resistance, the further deformation behaviour cannot be realized by *SOFiSTiK*'s elastoplastic shear stress approach.

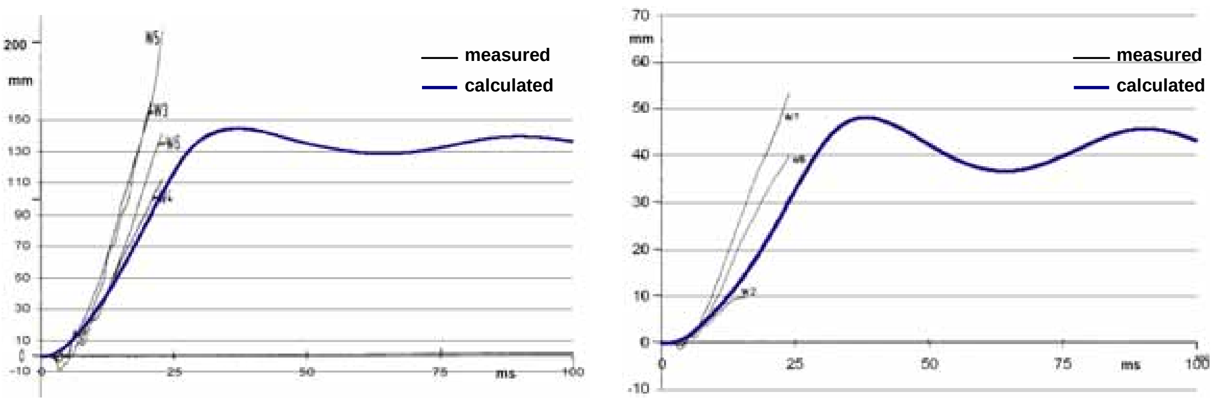


Fig. 12 Meppen test II/5, time histories of computed and measured displacements W6 (left) and W8 (right)

It is plausible according to the characteristic punching resistance of the 0.50 m thick slab of test II/15 that it has been perforated by the missile (600 mm diameter), which has produced a hole with only 950 mm to 1150 mm diameter. Such a case is not suitable for a calculation by use of a shell element model. The test with the same slab type but lower impact velocity II/17 (178 m/s instead of 236 m/s) resulted in the measured displacements, which are compared to the calculated time history in Fig. 13 on the left. In the analyses, the punching cone angle assumed for specification of the ultimate shear resistance in *SOFiSTiK* has been varied between 31° and 50° related to the slab surface; cf. Fig 13 on the right. Although the maximum of the calculated displacements is too large in this case, the variant with 50° provides the more realistic results with respect to residual deformations.

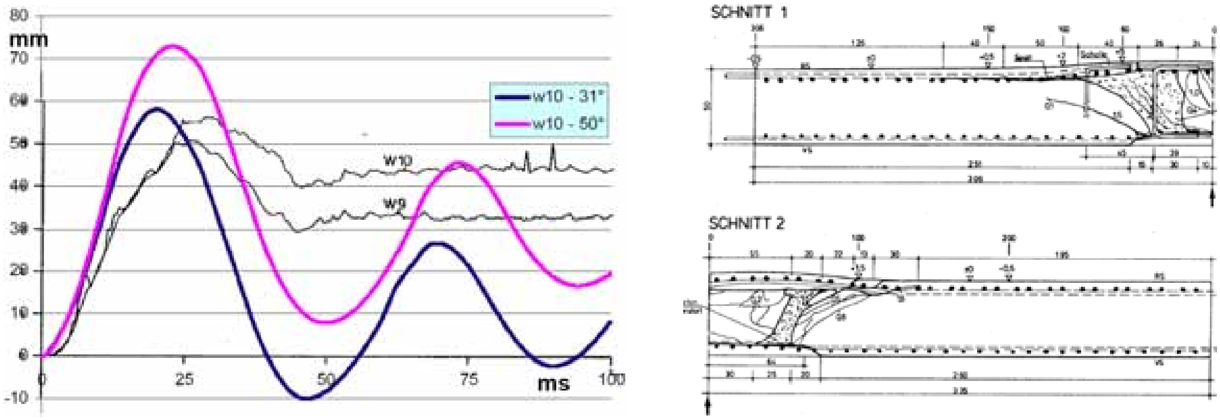


Fig. 13 Meppen test II/17, time history of computed and measured displacements W10 (left; location 0.70 m distance to plate centre) and sections through plate after the test (right) according to [10]

CONCLUSION

The analyses of impact tests of reinforced concrete slabs with dominating punching behaviour confirm that the layered shell element of the program *SOFiSTiK* 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. This limitation is due to the elastoplastic shear stress approach implemented in *SOFiSTiK*, which is only valid in case of formation of a punching cone with not too steep angles of the decisive shear cracks so that enough stirrups cross this area. The requirement is implicitly fulfilled in the design of a structure which has to resist a specified impact load.

In the case of checking r/c plates without shear reinforcement (or with significant exceedance of punching resistance), empirical perforation formulae or analyses by use of simple two-mass vibration models are applicable.

REFERENCES

[1] Schwarzkopp, D., Zinn, R.: Simplified Nonlinear Analysis of Reinforced Concrete Structures under Projectile Impact Including Penetration and Projectile Deformation Effects. *Proc. 1st Int. Conf. on Concrete for Hazard Protection, Edinburgh, Scotland, 1987.*

[2] Zinn, R., Stangenberg, F., Borgerhoff, M., Chauvel, D., Touret, J.-P.: Non-Linear Behaviour of Concrete Structures under Severe Impact, *CONSEC'07, Tours, France, 2007.*

[3] SOFiSTiK AG: SOFiSTiK, Analysis Programs, Version 25.0, Oberschleissheim, 2010.

[4] Chauvel, D., Touret, J.-P., Stangenberg, F., Borgerhoff, M., Zinn, R.: Non-Linear Impact Analysis of a Concrete Building. *18th Int. Conf. on Structural Mechanics in Reactor Technology (SMiRT 18), Beijing, China, 2005.*

[5] Hochtief AG: Ultimate Kinetic Bearing Capacity of Reinforced Concrete Slabs, RS 165, IV. Technical Report, Meppen Tests II/1 to II/10, 1983.

[6] Riera, J.D.: On the Stress Analysis of Structures subjected to Aircraft Impact Forces, Nuclear Engineering & Design 8,415 – 426, 1968.

[7] VTT: Experimental Tests for Bending and Punching Behaviour of Reinforced Concrete Walls under Impact Loading. Research Report VTT-R-05587 -10, 2010.

[8] CEB, Comité Euro-International du Beton: Concrete Structures under Impact and Impulsive Loading, Synthesis Report, Bulletin d'Information No. 187, 1988.

[9] SRD, Safety and Reliability Directorate: Guidelines for the Design and Assessment of Concrete Structures Subjected to Impact, 1888 Edition. SRD R 439 Issue 2, 1988.

[10] Hochtief AG: Results of the Meppen Tests II/11 to II/22, RS 467, II. Technical Report, 1984.