IASMiRT

SMiRT 26
50 Anniversary Berlin/Potsdam

Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Special Session: Impact Tests and Numerical Analyses

PUNCHING FAILURE OF REINFORCED CONCRETE SLABS SUBJECTED TO HARD MISSILE IMPACT, PART III: SIMULATION OF RECENT TESTS WITH THE RHT CONCRETE MODEL IN LS-DYNA

Christian Heckötter[1]

[1] Technical Expert, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Cologne, Germany (christian.heckoetter@grs.de)

ABSTRACT

Reinforced concrete structures protect safety relevant parts of nuclear facilities. Hard missile impact is a relevant loading case. Within the IMPACT project carried out at Technical Research Centre of Finland (VTT) several tests dealing with punching failure of reinforced concrete slabs subjected to hard missile impact were performed. These tests are used for validation purposes. This paper reports on validation studies using the RHT concrete model available in LS-DYNA. The goal is to assess the capability of the RHT model to reproduce effects of slab thickness, shear reinforcement, bending reinforcement ratio and missile inclination on the perforation resistance of the slabs. It is found, that the RHT model is in principle capable to reproduce test results regarding failure mode. With a slab thickness of 250 mm the effect of stirrups on perforation resistance is remarkably low in the numerical study, while a positive effect of stirrups is found for a slab thickness of 350 mm. Uncertainties occur regarding the predication of the residual velocity of the missile for impact velocities close to the just-perforation velocity.

INTRODUCTION

Analysis tools used to assess the consequences of hard missile impact on reinforced concrete (rc) structures have been validated based on impact tests carried out at the Technical Research Centre of Finland (VTT) in the so-called P-series (punching). Some of these tests without shear reinforcement and a slab thickness of 250 mm were subject of the OECD/NEA (2014) benchmark activities IRIS_2010 and IRIS_2012 (Improving Robustness Assessment Methodologies for Structures Impacted by Missiles). Because of IRIS, a substantial number of numerical studies regarding the corresponding tests has been published. Another test parameter of the P-series was shear reinforcement in form of either T-headed bars or conventional stirrups. It was concluded from test results by Orbovic and Blahoianu (2013) and Galan and Orbovic (2015), that stirrups have little or even negative effects on the perforation resistance of slabs with a thickness of 250 mm. A numerical study of Orbovic et al. (2015) came to the same conclusion for slab thicknesses of 250 mm as well as for 350 mm.

However, all tests performed in phases I-III of impact feature a slab thickness of 250 mm. Recently, additional tests dealing with a variation of slab thickness H were carried out in the frame of phase IV of the international project IMPACT, whose results are reported by Vepsä et al. (2022). The goal of these tests was to study the effect of slab thickness and in particular the effect of stirrups for an increased slab thickness on perforation resistance. Further, inclined impact tests have been studied and reported by Calonius et al. (2022). To the best of the author's knowledge, inclined hard missile impact on rc-slabs has not yet been experimentally studied for impact velocities relevant for aircraft impact assessment.

SUMMARY OF EXPERIMENTAL BACKGROUND

Parameters of selected P-series are summarised in Table 1. A substantial scattering in compressive strength of concrete f_c should be mentioned. In all cases despite ITP4R the slab is perforated with a nonzero residual velocity. In an approach of Kar (1979) based on energy conservation and simplified assumptions, residual velocity v_r, impact velocity v_0 , ballistic limit velocity v_{bl} at which transition from just-perforation to perforation occurs, projectile mass m_p (about 47.5 kg for all tests) and mass of spalled concrete m_c are related by Equation 1. It is used to calculate the ballistic limit velocity for selected tests. In IP1 and IP2 the missile strikes at angles of inclination of 20° and 30° relative to the surface normal of the target.

$$v_r = \sqrt{\frac{v_0^2 - v_{bl}^2}{1 + \frac{m_c}{m_p}}} \tag{1}$$

Table 1: Overview on punching test parameters and results and corresponding references (1. NEA (2014), 2. Galan and Orbovic (2015), 3. VTT (2019), 4. Vepsä et al. (2022), 5. Calonius (2022)).

Test	v_0 / m/s	Rebars	Stirrups	H / mm	f_c (cube) / MPa	Ref.	v_r / m/s	m_c / kg	v_{bl} / m/s
IRIS P1	136	Ø10/cc90	none	250	60.5	1.	34	N/A	-
IRIS P2	135	Ø10/cc90	none	250	58.3	1.	45	~120	105
IRIS P3	137	Ø10/cc90	none	250	60.5	1.	36	N/A	-
A12	110	Ø10/cc90	none	250	50.3	2.	20	N/A	-
P6	111	Ø10/cc90	Ø12	250	49.7	2.	5	~40	110
P3	140	Ø16/cc90	none	250	48.8	3.	45	125	111
P4	120	2*Ø10/cc90	none	250	51.2	3.	15	N/A	-
P11	127	Ø10/cc90	none	250	88.4	3.	38	122.6	105
P12	131	Ø10/cc45	none	250	88.4	3.	21	160.5	125
ITP1	138	Ø10/cc90	none	300	59.0	4.	25	129	126
ITP2R	162	Ø10/cc90	none	350	64.5	4.	48	136	132
ITP2RR	144	Ø10/cc90	none	350	47.5	4.	35	110	129
ITP4R	144	Ø10/cc90	Ø12	350	63.6	4.	p=15 cm	-	-
ITP4RR	156	Ø10/cc90	Ø12	350	47.5	4.	29	44	151
IP1	135	Ø10/cc90	none	250	66.5	5.	27	N/A	-
IP2	139	Ø10/cc90	none	250	63.2	5.	25	96	132

METHODS

The analysis method is based on LS-DYNA (LSTC (2020)). A sectional view of a typical model including basic dimensions is shown in Figure 1. Solid elements of concrete and beam elements of reinforcement are connected by means of common nodes. An average mesh size of 10 mm is chosen for the representation of the target. This relatively fine mesh size enables a detailed representation of reinforcement and avoids common nodes of stirrups, vertical reinforcement bars and horizontal reinforcement bars. These parts are separated by one layer of concrete elements. Tests with stirrups of the P-series mainly featured T-headed bars with a diameter of 12 mm. The models also include the heads of T-headed bars by means of shell elements. A simplified representation of the supporting frame was chosen. The boundary condition corresponds to a simply supported two-way slab, which is realised by cylindrical roller supports and contact of cylinders to frame and cover sheets. An eroding surface to surface contact is defined between missile and concrete. Material behaviour of reinforcement steel is simulated by the piecewise linear plasticity model of LS-DYNA, at which tabulated input provided by VTT for A500HW steel bars is used. Strain rate dependent hardening is considered by tabulated input based on results given by Amman et al. (1982). A failure criterion of 10 % effective plastic strain is supplied. Properties of the missile steel were represented with the Johnson-Cook (1983) model. The time-step is controlled by eroding elements with a time-step smaller than 10 % of the initial value.

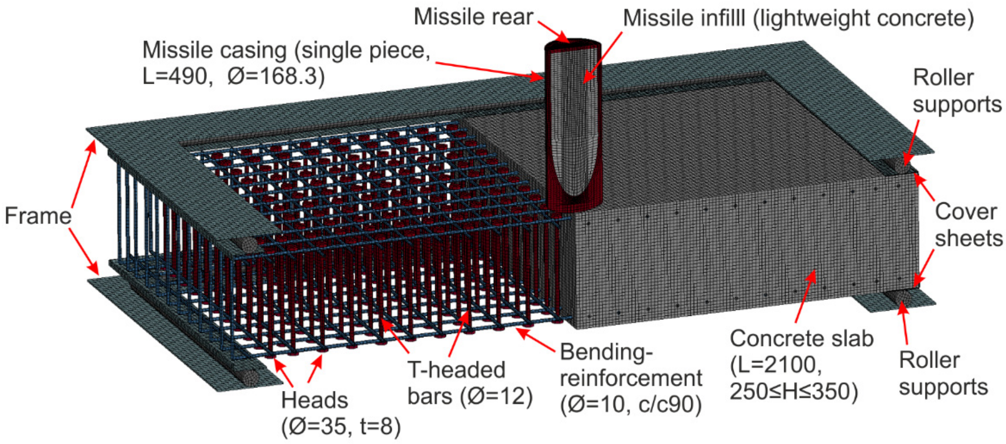

Figure 1. Typical numerical model of a hard missile impact tests for LS-DYNA.

The material behaviour of concrete is represented by the RHT concrete model, which was originally implemented in AUTODYN (Riedel (2004)) and is nowadays also available in LS-DYNA (Borrvall and Riedel (2011)). Comparisons of the implementations in the two analysis codes are given by Grunwald et al. (2017) as well as by Heckötter and Sievers (2017). Shear strength is described by three pressure dependent surfaces: the elastic limit surface, the failure surface, and the residual strength surface. Interpolation between failure surface and residual strength surface by means of a damage parameter considers damage. Totally damaged material has a certain strength in compression and may still transfer tensile forces by means of shear. The compressive meridian of the failure surface for hydrostatic pressures larger $f_c/3$ is given by Equation 2, while a piecewise linear form is used for lower pressures. Equation 3 defines the residual strength surface. The asterisk in Equation 2 and Equation 3 indicates, that stresses are normalised to the compressive strength. The model parameters were adjusted to test data on tri-axial compression given in NEA (2014) in the framework of the IRIS benchmark. Due to a lack of experimental data, it is a pragmatic choice to set B_{fail}=B_{fric} and n_{fail} and n_{fric}. Figure compares both forms for an input parameter set CONC-35 given by Riedel with the fit to the IRIS data.

$$Y^*_{triax}(p) = A_{fail} + B_{fail} \cdot (p^* - HTL^*)^{n_{fail}} \quad (2)$$
$$Y^*_{fric}(p) = B_{fric} \cdot (p^*)^{n_{fric}} \quad (3)$$

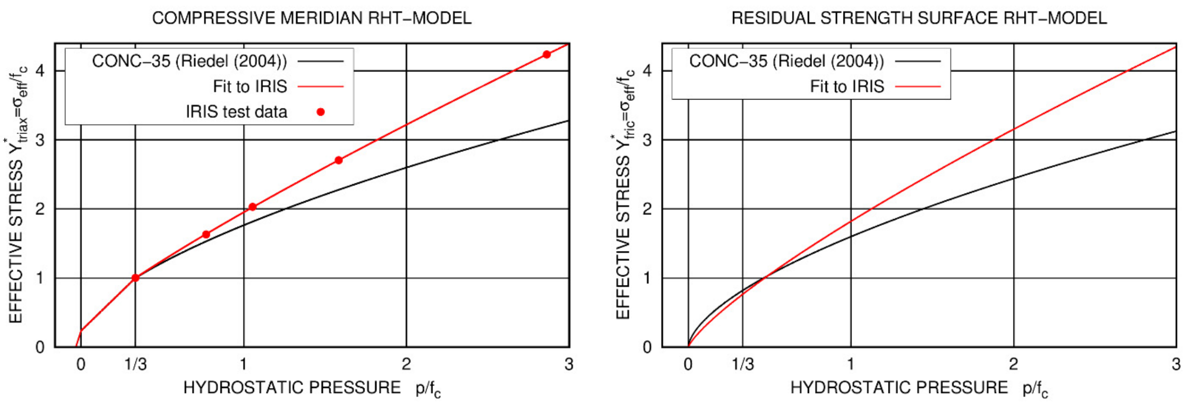

Figure 2. Compressive meridian and residual strength surface of RHT concrete model.

The evolution of the damage parameter in a simulation on test ITP2R is shown in Figure 3. During the first contact of missile nose and slab the concrete is damaged at the contact interface by material failure in compression. In the following a compressive wave is reflected at the rear face of the slab and gives rise to tensile failure. Further, secondary reflections at the nose of the missile give rise to further tensile damage. Within less than 0.5 ms the whole cross section is damaged. This outlines the relevance of the residual strength surface for the simulation of the subsequent tunnelling of the missile into the target and the possible ejection of concrete in the centre. Damaged concrete which is confined by reinforcement may have still a substantial residual strength. It is supposed to be more relevant for thicker slabs and for slabs with stirrups.

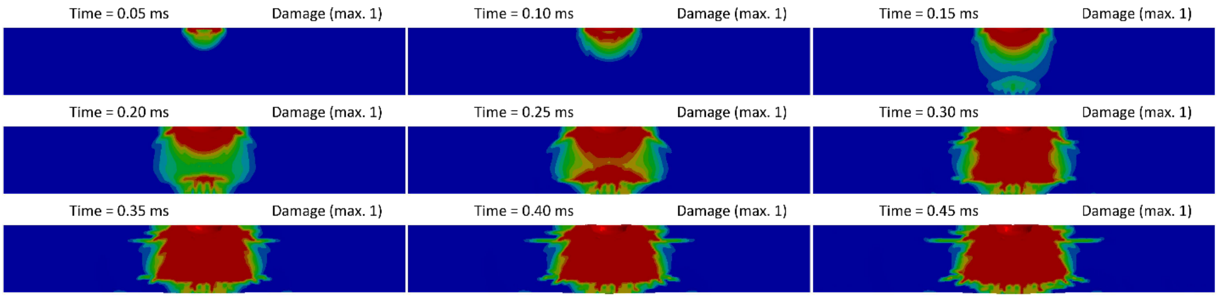

Figure 3. Simulated initial evolution of concrete damage of the section of a 350 mm thick slab (ITP2R).

RESULTS ON NORMAL IMPACT

Figure 3 shows exemplarily calculated time histories of the rear of the missile for two different parameter sets for the residual strength surface for a simulation of ITP2R. Apparently, there is a substantial effect on residual velocity and target penetration. However, both models correctly predict the failure mode perforation. Shear failure occurs at low hydrostatic pressures. In this pressure regime the residual strength of the IRIS fit is larger than that of the CONC-35 set (see Figure 1). Hence, the IRIS fit predicts larger residual velocities. Similar findings on the sensitivity of residual velocity on residual strength were reported by van Dorsselaer et al. (2011) for simulation on IRIS tests using the Karagozian&Case (K&C) concrete model. Like the RHT model, the K&C model features three limit surfaces. Since test data on residual strength are usually not available, a sensitivity study should be carried out in analyses of similar problems.

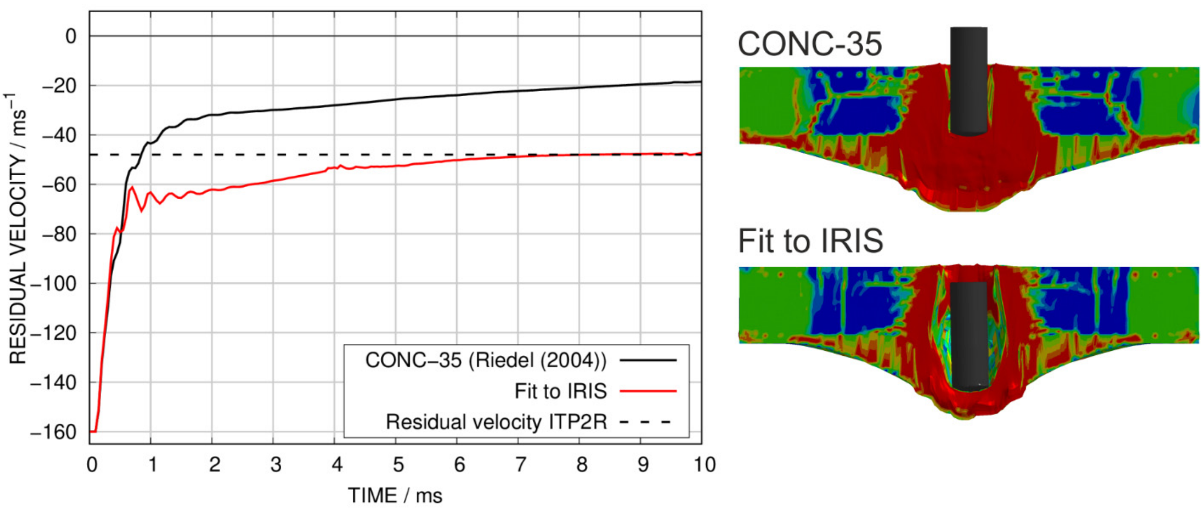

Figure 3. Velocity of the rear of the missile and damaged sections after 10 ms in ITP2R simulations.

A numerical study regarding impact velocity was carried out for different configurations of the slab. Relations of impact velocity and calculated residual velocity are compared in Figure 4 with test data. The residual velocity depends on residual strength of concrete. Another relevant parameter is failure of reinforcement, but even after failure of rear face reinforcement some residual shear strength may unrealistically slow down the missile. Hence, a certain penetration depth (p=H+50 mm) of the nose of the missile is considered as criterion for penetration. However, for thicker slabs the residual velocities are underestimated. For selected tests the diagrams include estimations according to Equation 1 with input data given in Table 1. It is astonishing, how well the test results are matched by the estimation for the case of H=250 mm without stirrups.

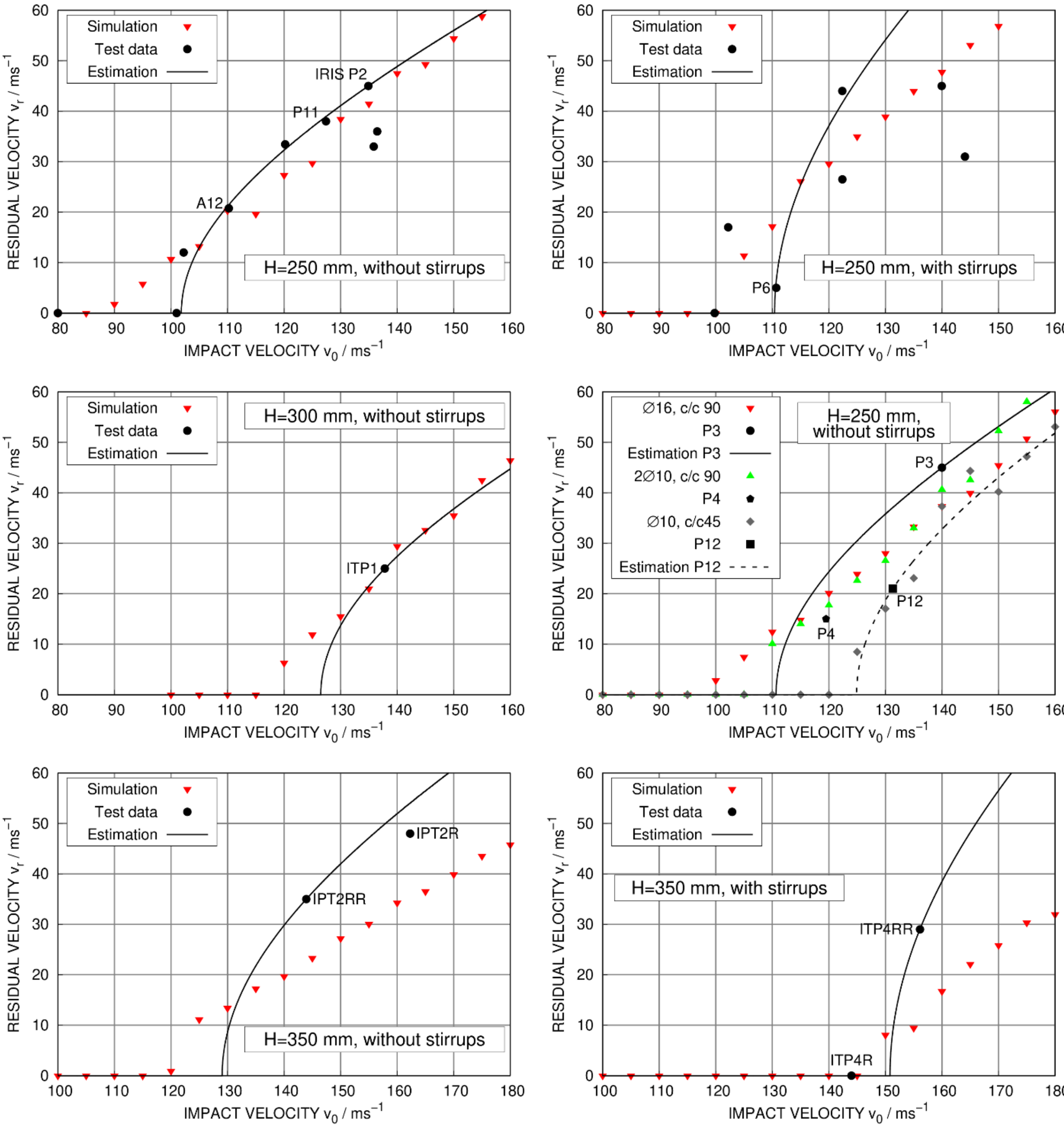

Figure 4. Tests and results of numerical study on influence of slab parameters on perforation resistance.

In Figure 5 to Figure 9 simulated slab damage of front and rear face are compared with photographs taken after the tests. The simulations correctly predicted the failure modes. The measured penetration depth of about 15 cm in ITP4R was correctly calculated. Perforation occurred in all other cases. The horizontal reinforcement bars are close to the surface. Hence, the scabbed area is more extent in horizontal direction. Due to the refined modelling of reinforcement, the models are capable to reproduce this effect. Some effect of H on v_{bl} can be concluded from the comparison of IRIS and ITP1. The additional positive effect of further increased H in ITP2R/ITP2RR seems to be small. This may be attributed to the strengthened missile. The shape of the scabbed area in ITP2R (see Figure 7) deviates from the related tests, which may be due to the specifics of the concrete mixture (see Vepsä et al. (2022)). Stirrups basically reduce the scabbed area (see Figure 6). However, for H=250 mm the effect of stirrups on v_{bl} is relatively low, which is also concluded from simulations. Scattering of tests seems to be larger compared to tests without stirrups (see Figure 4).

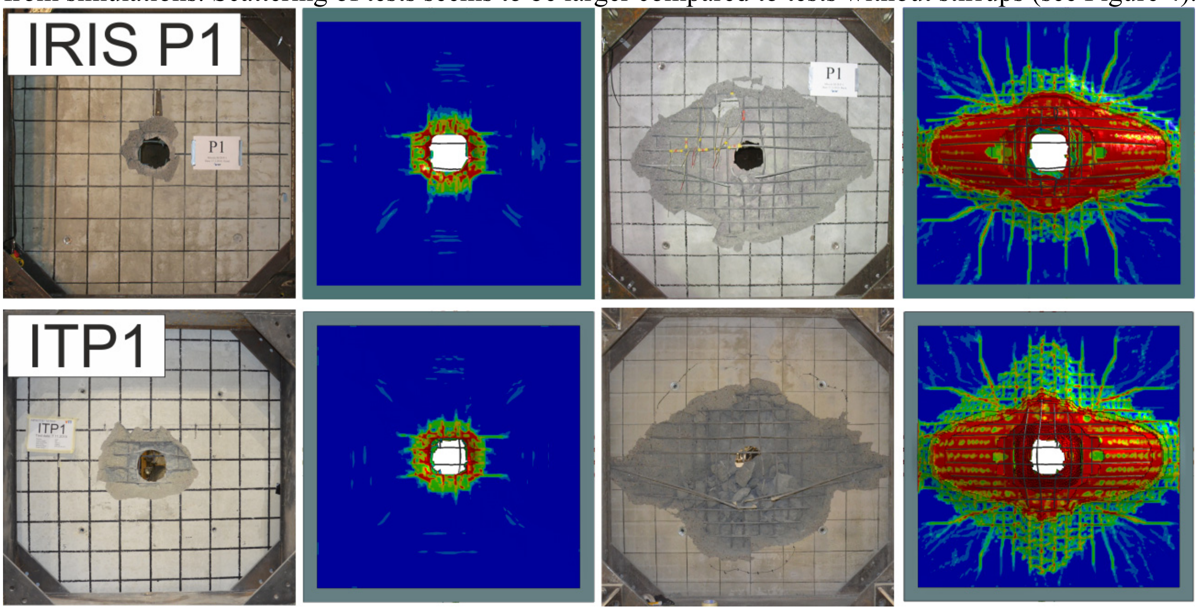

Figure 5. Comparison of slab damage of front and back face in tests IRIS P1 and ITP1.

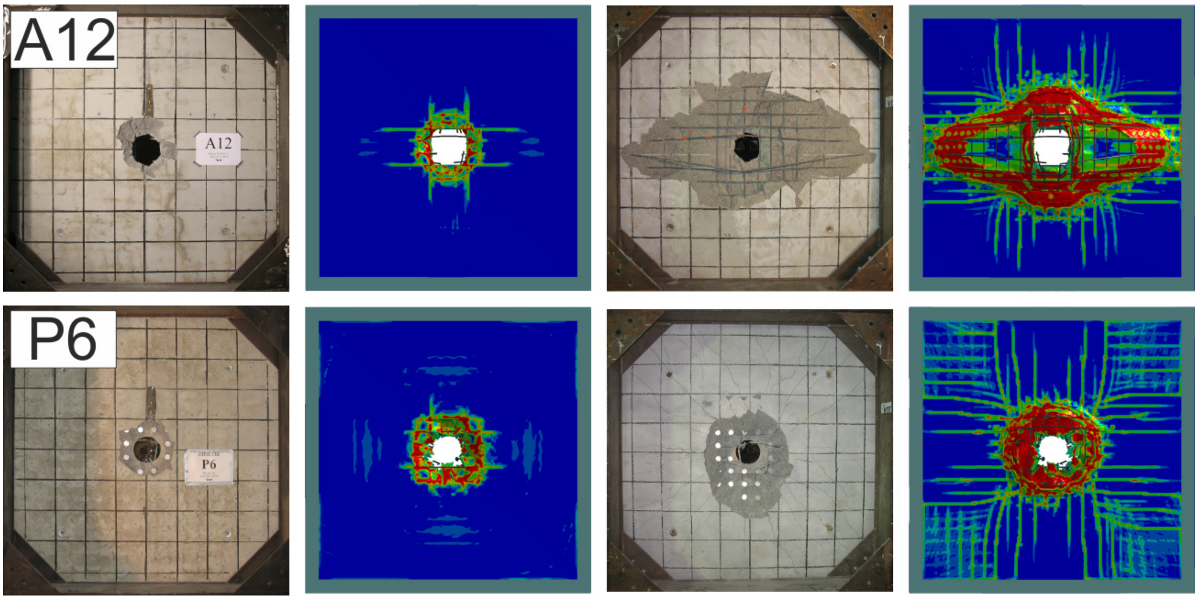

Figure 6. Comparison of slab damage of front and back face in tests A12 and P6.

For H=350 mm the effect of stirrups on v_{bl} seems to be more relevant than for H=250. The comparison of ITP2R and ITP4RR (see Figures 4 and 7) indicates, that residual missile velocity and mass of spalled concrete are both reduced by stirrups. Therefore, stirrups are supposed to result in a larger energy absorption of the slab. The comparison of ITP2RR and ITP4R (see Figures 4 and 8) shows, that stirrups may have a positive effect regarding failure mode. One limitation of these comparisons is the fact, that the concrete properties deviate (see Table 1). According to Vepsä et al. (2022) the perforation resistance is remarkably low for ITP2R. Since the slab of ITP4R is casted from the same batch of concrete, the comparison of ITP2RR and ITP4R indicates a positive effect of stirrups on v_{bl}. This is also concluded from the numerical study. Therefore, the conclusions from the numerical study presented in this paper are consistent for H=250 mm but deviate for H=350 compared to numerical results of Orbovic et al. (2015).

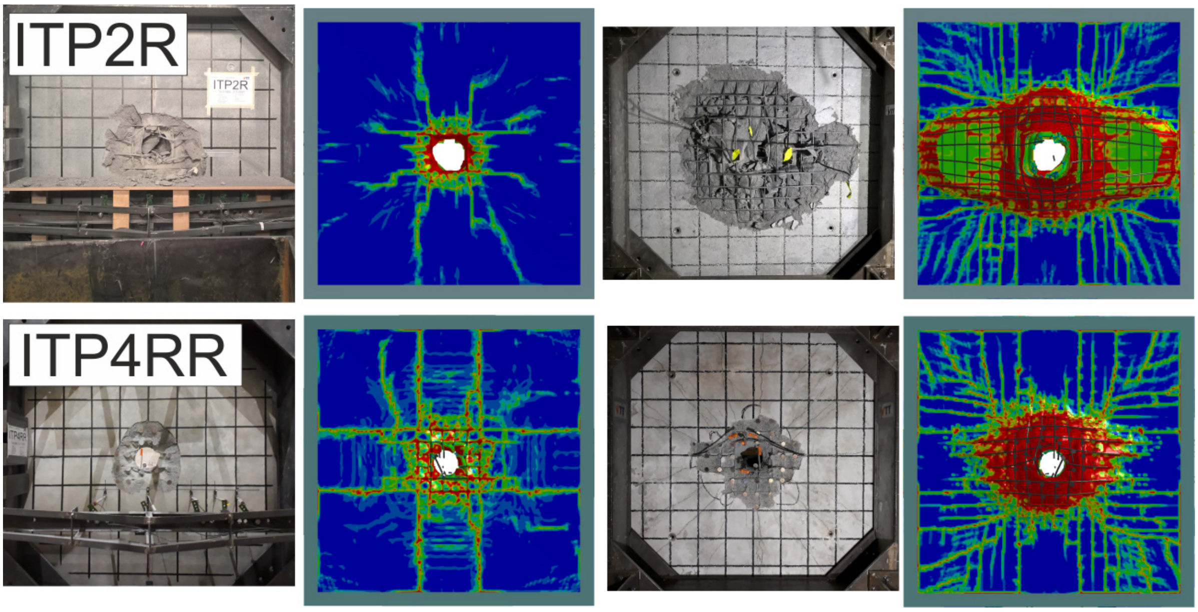

Figure 7. Comparison of slab damage of front and back face in tests ITP2R and ITP4RR.

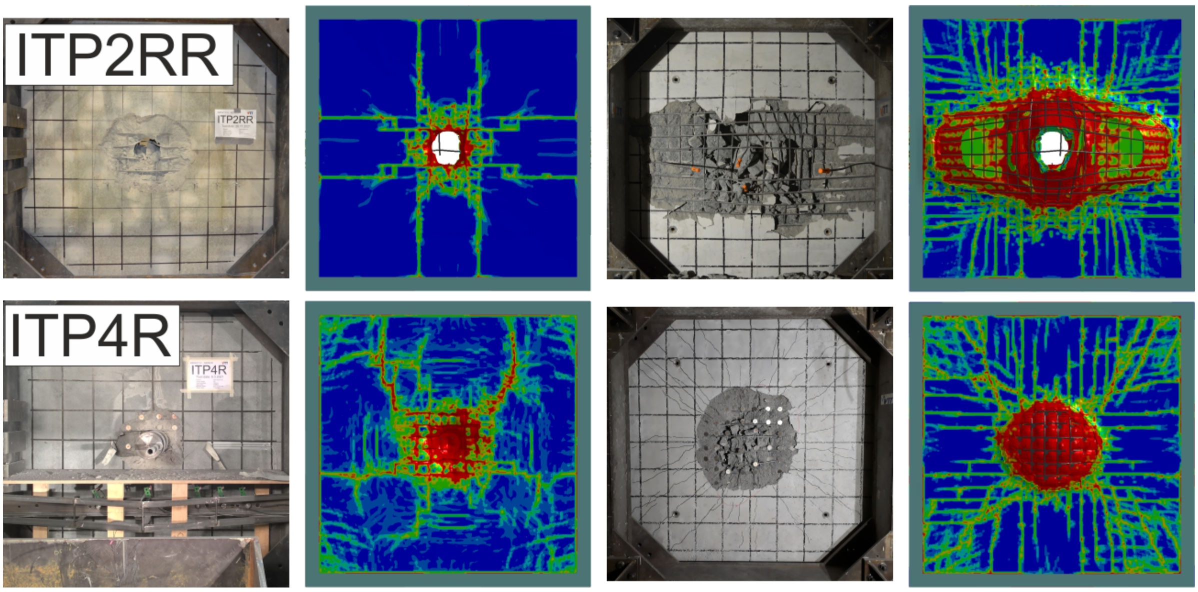

Figure 8. Comparison of slab damage of front and back face in tests ITP2RR and ITP4R.

Figure 9 indicates that a reduction of bending reinforcement bar spacing increases the scabbed area. As expected, more reinforcement bars are activated compared to test P4 with the same reinforcement density but a spacing of 90 mm of pairs of two close bars. Compared to IRIS tests or A12, the perforation resistance in P3 seems to be only slightly increased by Ø16 bars. The comparison of P11 and P12 (see Figure 4) indicates, that the effect of additional bending reinforcement on v_{bl} seems to be more beneficial than adding stirrups for H=250.

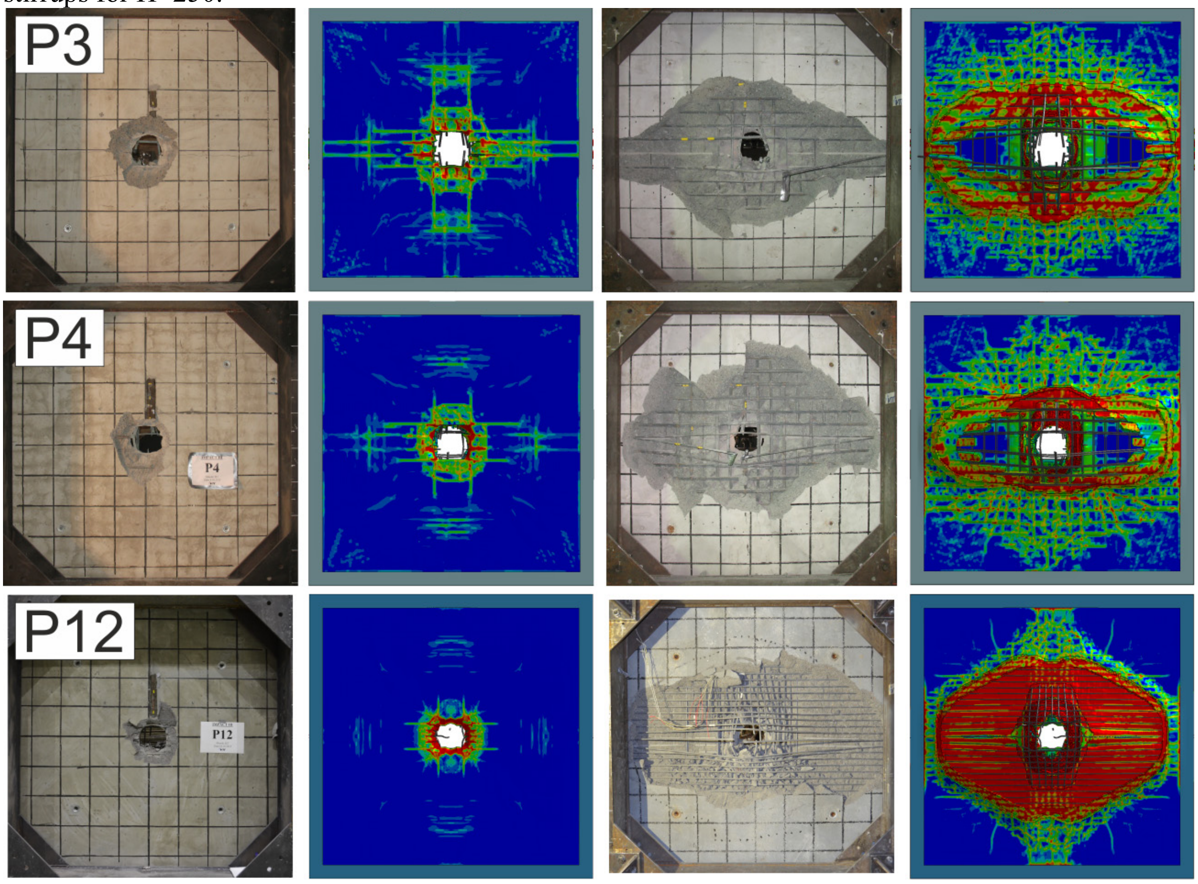

Figure 9. Comparison of slab damage of front and back face in tests P3, P4 and P12.

RESULTS ON INCLINED IMPACT

IRIS tests are baseline cases with normal impact (see Table 1) for tests IP1 (20° inclination) and IP2 (30° inclination). In this context the angle of inclination is measured between initial velocity of the missile and surface normal of the target. Figure 10 compares simulated front and rear face slab damage with photographs taken after tests IP1 and IP2. In IP1 the slab is obviously perforated, which is also predicted by simulations. As expected, the residual velocity is decreased compared to IRIS tests due to inclination. In test IP2 perforation occurred as well, at which the residual velocity is close to the value measured in IP1. This is not reproduced by the simulation, even though slicing of back face bending reinforcement is predicted. The reason is an overestimation of rotation of the missile. A comparison of time histories of missile velocities in Figure 11 indicates, that the inclination of the missile in IP2 simulations suddenly increases after about 9 ms. Because of this, the missile is embedded in the slab and retained by the unbroken reinforcement bars. This is further illustrated by results on a numerical study dealing with variation of inclination angle shown in Figure 11. Up to an angle of inclination of about 26° simulations predict perforation. Above a critical inclination of about 27° pronounced rotation and embedding of the missile occurs. It is therefore concluded, that test IP2 was performed with an inclination close to a critical value.

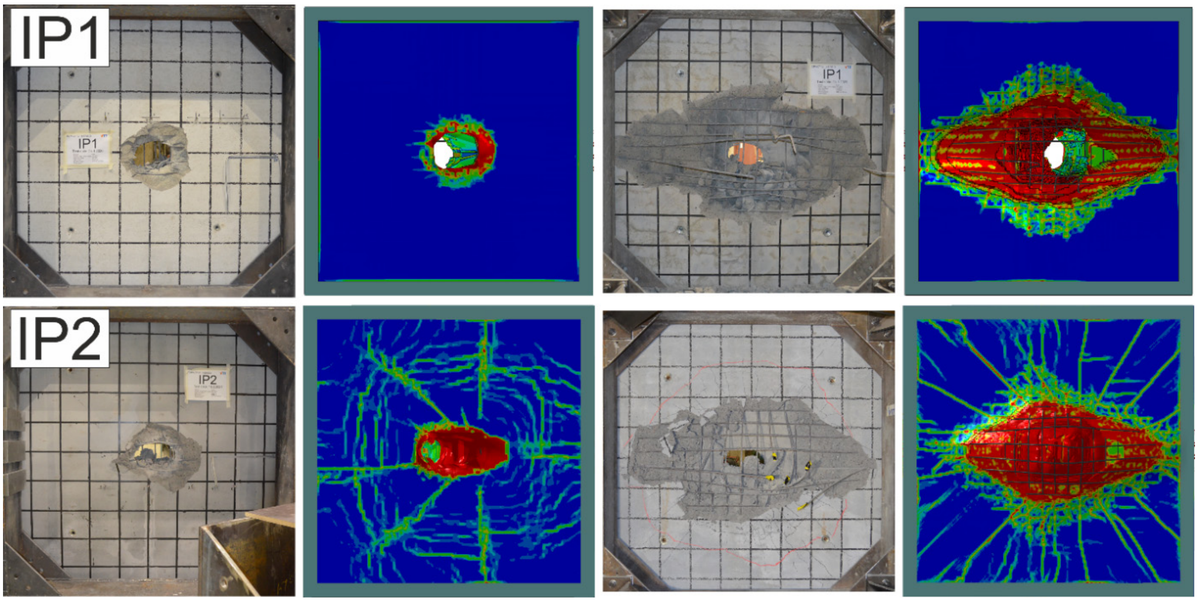

Figure 10. Comparison of slab damage of front and back face in tests IP1 and IP2.

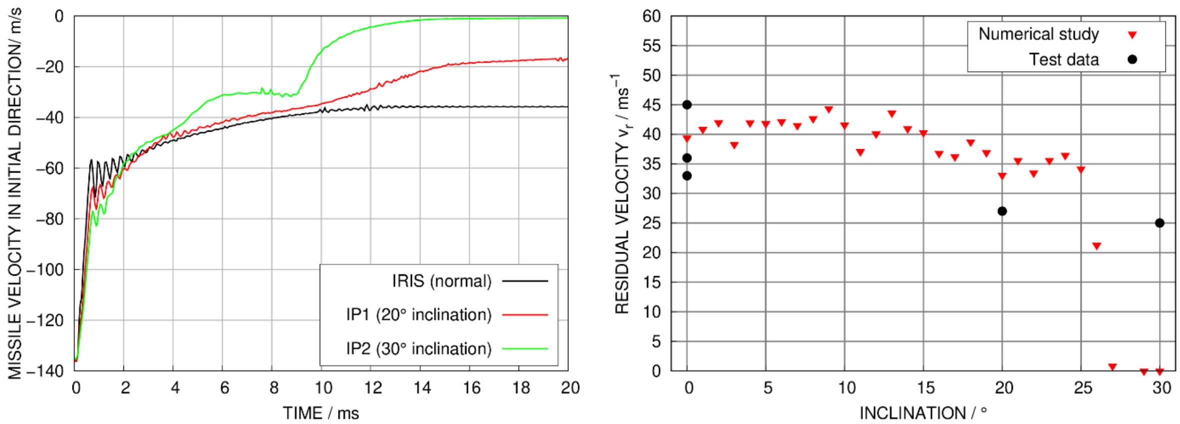

Figure 11. Simulated missile velocities in IRIS P1, IP1 and IP2 and numerical study on inclination angle.

CONCLUSIONS

In principle results of numerical simulations with the RHT concrete model in LS-DYNA are in good agreement with test results regarding failure mode and extension of scabbed area. The residual missile velocity depends on the shape of the residual strength surface, for which usually no test data are available. Hence, sensitivity studies regarding residual strength should be carried out. For impact velocities close to the ballistic limit velocity and for thicker slabs uncertainties regarding residual velocity are by trend larger.

The modelling approach correctly reproduced the effect of rc-slab thickness and stirrups on perforation resistance and reduction of scabbed area. For a slab thickness of 250 mm the positive effect of stirrups on perforation resistance seems to be small, while it is quite substantial for a slab thickness of 350 mm. The effect of the diameter of bending reinforcement on perforation resistance is small, while some effect of spacing of bending reinforcement could be observed.

Residual velocities are somewhat lower in cases with non-normal impact. The simulations overestimated the effect of rotation of the missile for an inclination of 30°. Further testing is needed to quantify a critical inclination, at which rotation of the missile may occur.

ACKNOWLEDGEMENT

The work of GRS was carried out in the frame of the German reactor safety research program funded by the German Federal Ministries for Economic Affairs and Climate Action (BMWK) and for Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV).

REFERENCES

Amman, W., Mühlematter, M., Bachmann, H. (1982): "Zugversuche an Bewehrungs- und Spannstahl mit erhöhter Dehngeschwindigkeit," ETH Zürich, ISBN 3-7643-1396-2

Borrvall, T., Riedel, W. (2011). "The RHT Concrete Model in LS-DYNA," *8th European LS-DYNA Conference*, Strasbourg, France

Calonius, K. et al. (2022). "Punching Failure of Reinforced Concrete Slabs Subjected to Hard Missile Impact, Part II: Recent tests and Analyses on Inclined Impact," *Transactions of SMiRT 26*, Potsdam/Berlin, Germany

van Dorsselelaer, N., Lapoujade, V., Nahas, G., Tarallo, F., Rambach, J.-M. (2011): "Impact Simulations on Concrete Slabs: LS-OPT® Fitting Approach," *9th European LS-DYNA Conference*, Strasbourg, France

Galan, M., Orbovic, N. (2015). "Quantification of Perforation Resistance of Pre-Stressed Walls with Transverse Reinforcement and Liner under Hard Missile Impact based on Test Results," *Transactions of SMiRT 23*, Manchester, United Kingdom

Grunwald, C., Schaufelberger, B., Stolz, A., Riedel, W., Borrvall, T. (2017): "A General Concrete Model in Hydrocodes: Verification and Validation of the RHT model in LS-DYNA," *International Journal of Protective Structures 8*, 58-85.

Heckötter, C., Sievers, J. (2017): "Comparison of the RHT Concrete Material Model in LS-DYNA and ANSYS AUTODYN," *11th European LS-DYNA Conference*, Salzburg, Austria

Johnson, G.R., Cook, W. H. (1983). "A constitutive model and data for materials subjected to large strains, high strain rates, and high temperatures," *Proceedings 7th International Symposium on Ballistics*, The Hague, Netherlands.

Kar A.K. (1979). "Residual velocity for projectiles." *Nuclear Engineering and Design 53(1)*, 87-95.

LSTC (2020). "LS-DYNA, A Program for Nonlinear Dynamic Analysis of Structures in Three Dimensions," Version R12.0., Livermore Software Technology Corporation.

NEA (2014). "Improving Robustness Assessment Methodologies for Structures Impacted by Missiles (IRIS_2012)". Final Report NEA/CSNI/R(2014)5, Nuclear Energy Agency.

Orbovic, N., Blahoianu, A. (2013). "Tests to Determine the Influence of Transverse Reinforcement on Perforation Resistance of RC Slabs under Hard Missile Impact," *Transactions of SMiRT 22*, San Francisco, USA

Orbovic, N., Sagals, G. and Blahoianu, A. (2015). "Influence of transverse reinforcement on penetration resistance of reinforced concrete slabs under hard missile impacts," *Nuclear Engineering and Design*. 295, 716-729.

Riedel, W. (2004): "Beton unter dynamischen Lasten. Meso- und makromechanische Modelle und ihre Parameter," Fraunhofer-Verlag, ISBN: 3-8167-6340-5, Freiburg im Breisgau.

Vepsä, A. et al. (2022). "Punching Failure of Reinforced Concrete Slabs Subjected to Hard Missile Impact, Part I: Recent tests on Influence of Slab Thickness and Shear Reinforcement," *Transactions of SMiRT 26*, Potsdam/Berlin, Germany

VTT (2019). "IMPACT III: Punching behaviour tests for simply supported reinforced concrete walls," Research report VTT-R-04293-17, confidential