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 VI: Numerical studies with the CDP model in ABAQUS and assessments with semi empirical methods

Arja Saarenheimo[1], Kim Calonius[2], Alexis Fedoroff[2], Markku Tuomala[3] and Ari Vepsä[2]

[1] Research Team Leader, VTT Technical Research Centre of Finland Ltd., Finland
[2] Senior Scientist, VTT Technical Research Centre of Finland Ltd., Finland
[3] Emeritus Professor, Tampere University, Finland

INTRODUCTION

Protective concrete barrier walls in nuclear power plants are required to withstand the effects of impacts by various kinds of projectiles ranging from aircraft crash to accident generated missiles. Missiles or projectiles can be roughly classified as hard, semi hard or soft, depending on the deformability of the missile with respect to the target deformability. E.g. aircraft fuselage, aircraft engine and aircraft engine shaft can be classified as soft, semi hard and hard, respectively.

During the previous Impact project phases (I-III), the thickness of the reinforced concrete wall for the hard missile tests was always 0.25 m. Within the ongoing Impact project (phase IV), the wall thickness was increased to the thicknesses of 0.3 m and 0.35 m. The first tests with these targets were carried out with the original missile design. This type missiles did deform more noticeably with higher velocities and thus the missile cannot be considered as entirely rigid. Therefore, a new, more rigid, missile type was designed to be used for the next tests.

TESTS

This paper considers hard missile impact tests carried out at VTT and described in detail in a parallel paper by (Vepsä, 2022). From series ITP2 and ITP4, tests named ITP2RR and ITP4RR are simulated with FE method. The thickness of the reinforced concrete target slab is 0.35 m and the span distance in both directions is 2 m. Both slabs were reinforced with D10 mm B500B rebars with spacing of 90 mm in both directions and on both faces with the concrete cover being 20 mm. Additionally, shear reinforcement in slab ITP4RR was realized in a form of D12 mm T-headed bars with spacing of 90 mm in both directions. An extensive set of material tests were carried out for this concrete batch. Stress-strain curves obtained from triaxial material tests are presented in Figure 1 with corresponding FE model material properties. The mass of the missile was about 47.5 kg and the diameter was 168.3 mm. The impact velocities in tests ITP2RR and ITP4RR were 144 m/s and 156 m/s, respectively. The missile perforated the slab in both tests and residual velocities were 35 m/s and 29 m/s, respectively. These and other related tests with plate thicknesses of 0.25 m and 0.3 m are analyzed also with simplified methods.

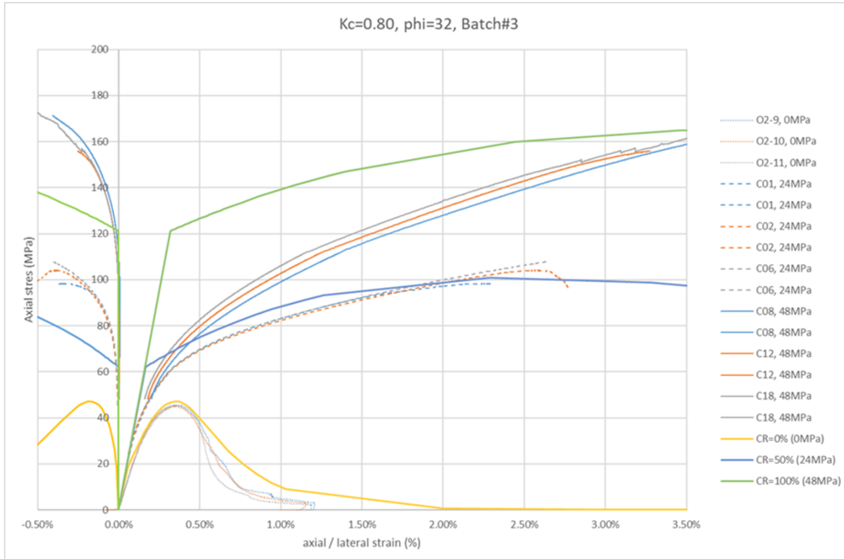


Figure 1. Triaxial material test results and corresponding FE model properties.

RESIDUAL VELOCITY STUDIES WITH ABAQUS

A commercial finite element (FE) code Abaqus/Explicit (Abaqus, 2019) was used for numerical simulations on the tests described above. The main purpose of these simulations was to validate the used modelling methods, especially the concrete material model, against empirical results. For the FE model of the target wall, the Concrete Damaged Plasticity material model of Abaqus with in-house developed enhancements (Fedoroff et al., 2020) was applied. Obtained numerical results are compared with the corresponding experimental findings. Figure 2 shows the FE model of IPT4RR slab reinforcement where the concrete elements are hidden. The shear reinforcement close to the impact area is modelled in detail. There are 37 solid elements through the thickness of the slab. The same finite element model, but of course without shear reinforcement, was used for slab ITP2RR.

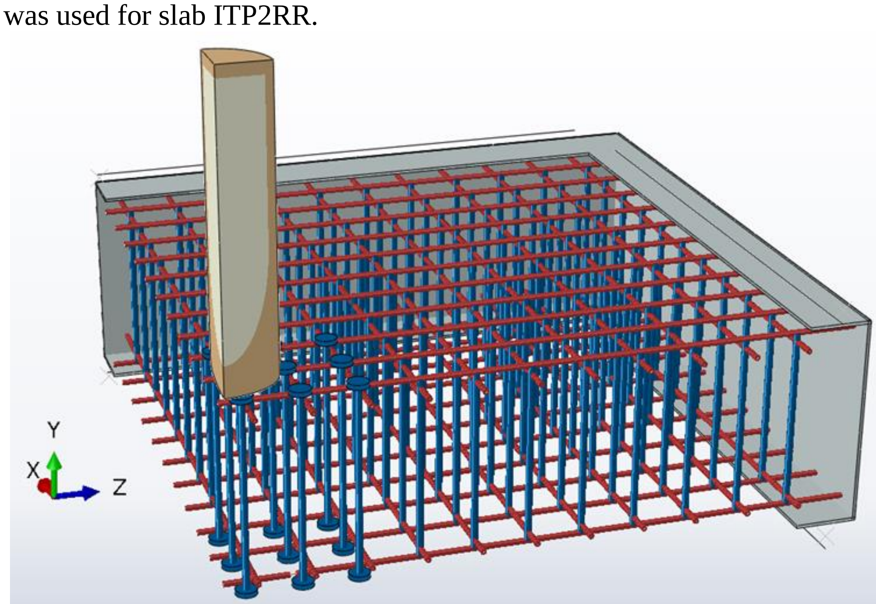


Figure 2. FE quarter model of test IPT4RR showing steel reinforcement.

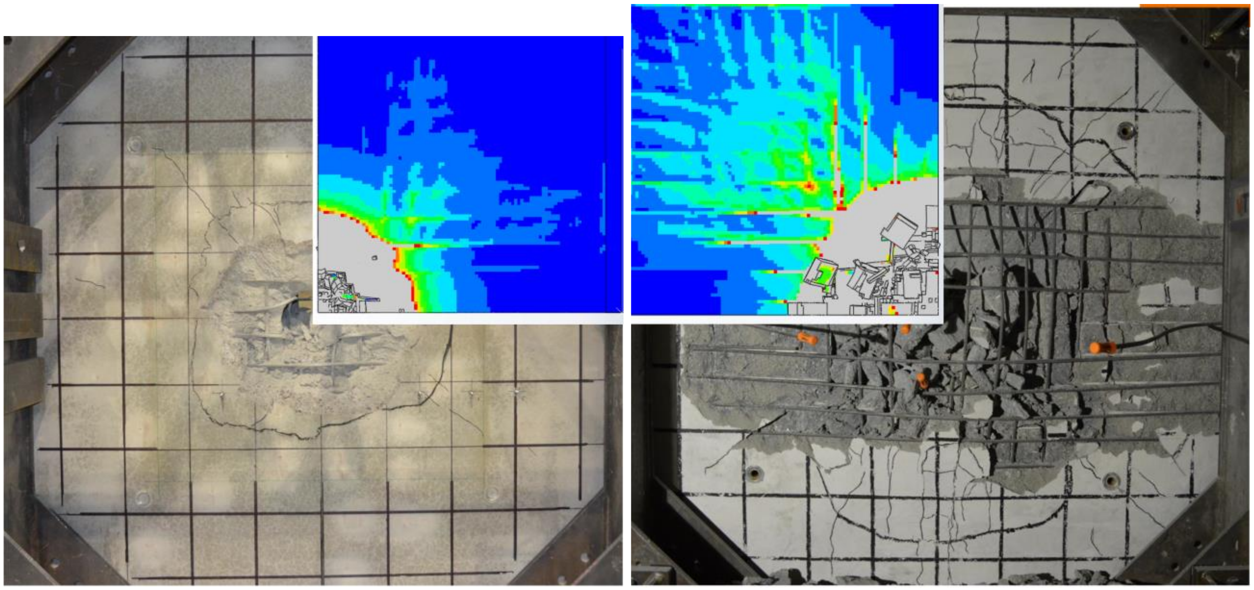


Figure 3. Front and rear faces of slab IPT2RR after test with FE result (maximum principal strain).

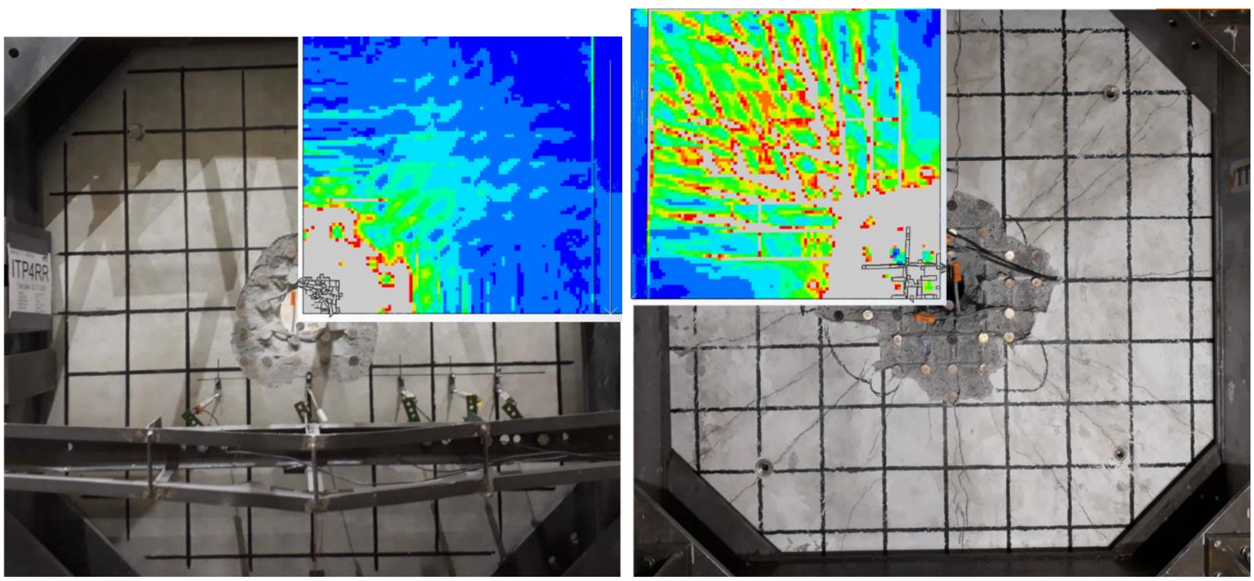
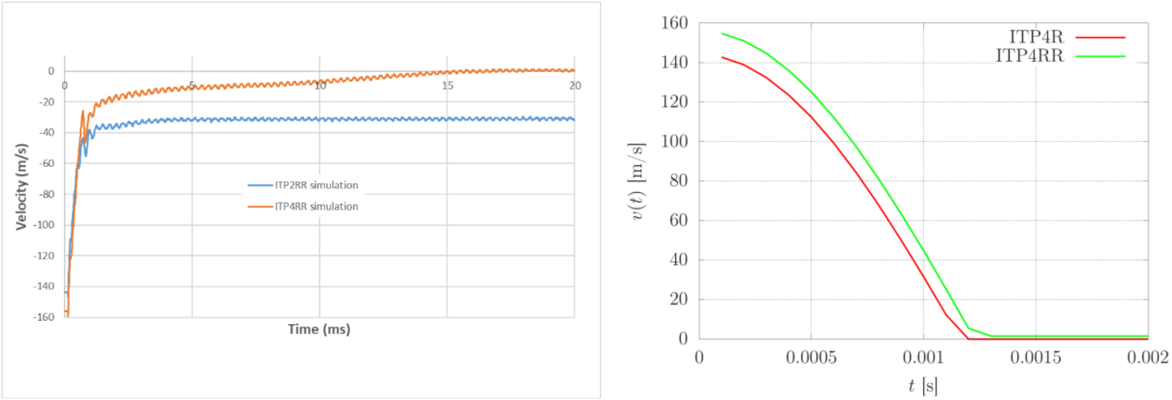


Figure 4. Front and rear faces of slab IPT4RR after test with FE result (maximum principal strain).

The target slab was perforated in both tests. Front and rear faces of the slab after the test ITP2RR are shown in Figure 3 with corresponding calculation results in terms of maximum principal strain distribution. The effect of shear reinforcement can be seen in Figure 4 where the experimental and calculation results on test ITP4RR are shown. Calculated velocities of the missile are presented in Figure 5a as a function of time. According to these simulations, the residual velocity in test ITP2RR is 32 m/s and this is very close to the measured value. In test ITP4RR the measured residual velocity is 29 m/s but according to the simulation no perforation occurs and the calculated residual velocity is zero. In Figure 5b are shown residual velocities computed by a simplified model in tests ITP4R and ITP4RR in which just perforation mode is predicted.



(a) (b)

Figure 5. Calculated residual velocities. a) FE model, b) simplified model.

PENETRATION AND PERFORATION FORMULAE

Degen's perforation thickness formulae

Based on experimental results in Reference (Degen, 1980) are derived new coefficients for the NDRC/ACE perforation thickness equations

$$\frac{e}{d} = 2.2\left(\frac{p}{d}\right) - 0.3\left(\frac{p}{d}\right)^2, \quad \frac{p}{d} < 1.52 \quad \text{or} \tag{1}$$

$$\frac{e}{d} = 0.69 + 1.29\left(\frac{p}{d}\right), \quad 1.52 \le \left(\frac{p}{d}\right) \le 13.42, \tag{2}$$

where the penetration depth p [m] is obtained from the NDRC formulae. By definition e is the smallest plate thickness to prevent perforation. The NDRC equation for penetration depth is

$$\frac{p}{d} = 2G^{0.5}, \quad G \le 1 \text{ or } \frac{p}{d} = G + 1, \quad G > 1, \tag{3}$$

where d is the projectile diameter [m], $G = 3.8 \times 10^{-5} \frac{N m v_0^{1.8}}{\sqrt{f_c} d^{2.8}}$, m is the mass of the projectile [kg], v_0 is the impact velocity [m/s], f_c is the ultimate compressive strength of concrete [Pa], N is a nose shape factor: 0.72 for a flat nose, 0.84 for a blunt nose, 1.0 for a hemispherical nose (bullet nose) and 1.14 for a sharp nose.

The formulae are valid in the following range: $28.4 < f_c < 43.1$ MPa, $25 < v_0 < 318$ m/s, $0.15 < h < 0.61$ m and $0.1 < d < 0.31$ m, (Li, 2005).

In (Degen, 1980) for (1) are given application limits: amount of reinforcement larger than 160 kg/m^3, impact velocity in the range from 20 m/s to 230 m/s, for higher velocity perforation thickness tends to be overestimated, $h/d > 0.5$, and if $d < 0.15$ m, then the nose factor N should be continuously augmented from 0.72 to 1.14 even for flat nose.

CEA-EDF perforation velocity and perforation thickness formulae

In Reference (Fullard, 1991) is given a perforation velocity equation

$$v_p = 1.3\rho_c^{1/6} f_c^{1/2} \left(\frac{dh^2}{m}\right)^{2/3} \left(\rho_p + 0.3\right)^{\frac{1}{2}}, \quad (4)$$

where ρ_c is the density of concrete [kg/m^3], ρ_p is the amount of reinforcement ratio [%] (each face each way) (Barr, 1990) and h is the plate thickness. For equal amount of front and rear face reinforcement $\rho_p = 100\frac{a_r}{c_r h}$, where a_r is the rebar cross sectional area, c_r is the bar spacing and h is the plate thickness.

The perforation velocity formula (4) (named CEA-EDF(1) in (Buzaud, 2007)) is valid in the following range: $30 < m < 300$ kg, $0.1 < d < 0.3$ m, $20 < f_c < 50$ MPa, $150 < M_a < 250$ [kg/m^3], $0.5 < \rho_p < 0.8$ % ewef, $0.2 < h < 2$ m, $20 < v_p < 200$ m/s, $2 \times 103 < m/(dh^2) < 105$, $0.2 < d/h < 3$, $0.2 < c_r/h < 0.3$, c_r being the rebar spacing

From (4) is obtained a perforaton thickness equation

$$e = 0.82\rho_c^{-1/8} f_c^{-3/8} \left(\frac{m}{d}\right)^{1/2} v_0^{3/4} \left(\rho_p + 0.3\right)^{-\frac{3}{8}}. \quad (5)$$

Forrestal's penetration equations

In Reference (Li, 2003b) the dimensionless penetration depth of the model of (Forrestal, 1994) is written in the form

$$\frac{p}{d} = \sqrt{\frac{(1+k\pi/4\tilde{N})}{1+I/\tilde{N})}\frac{4k}{\pi}I}, \quad \frac{p}{d} \leq k \text{ or } \frac{p}{d} = \frac{2}{\pi}\tilde{N}\ln\left[\frac{1+I/\tilde{N}}{1+k\pi/4\tilde{N}}\right] + k, \quad \frac{p}{d} > k, \quad (6)$$

where I is an impact function $I = \frac{1}{S}\frac{mv_0^2}{d^3 f_c}$ and $\tilde{N} = \frac{m}{N\rho_c d^3}$.

For deep penetration $k = 2$ is proposed in (Forrestal, 1994). In (Li, 2003) the penetration theory of (Forrestal, 1994) was extended for small to medium penetration depths $p/d < 5$. Assuming on Prandtl's slip line field gives $k = \sqrt{2}/2d + h_{\text{nose}}$, where h_{nose} is the nose length of the projectile. In (Li, 2003) is proposed a modified formula for shallow penetration depths, p/d less than ~ 0.5, based on experiments and curve fitting.

In (Li, 2003b) are derived perforation thickness formulae for the model of (Forrestal, 1994). During perforation a conical shear plug with a height of h_p is assumed to form and detach from the plate. The resisting force F_s in the direction of missile trajectory of the shear plug due to concrete F_{sc} and the rear face bending reinforcement F_{sb} can be calculated as in (Dancygier, 1997) and (Chen, 2008). Also the contribution of shear reinforcement F_{ss} can be added to the equation of motion. The shear capacity due to concrete and reinforcement is then calculated by the equation $F_s = F_{sc} + F_{sb} + F_{ss}$. The perforation thickness normalized by the missile diameter is

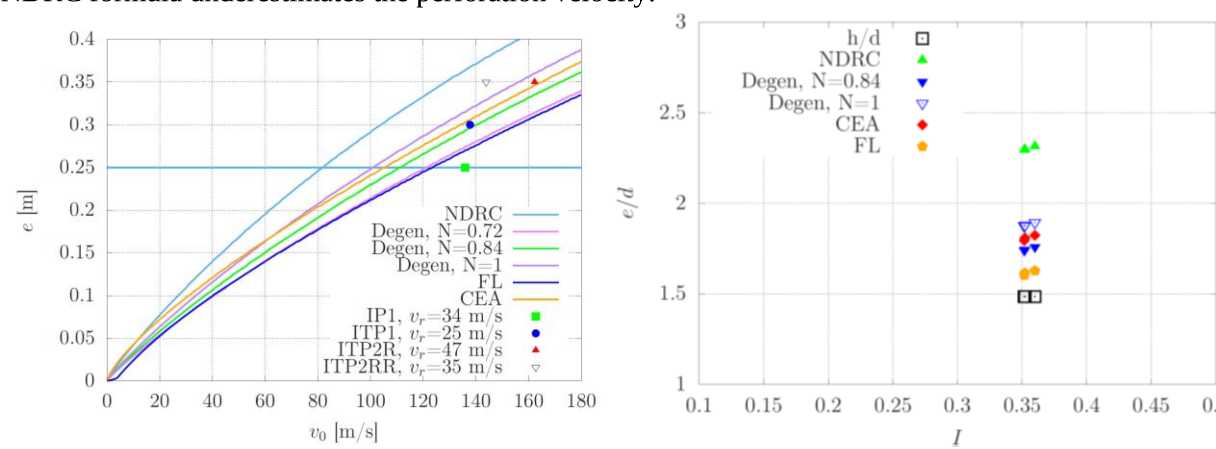
$$\frac{e}{d} = \frac{h_p}{d} + \frac{p}{d}. \quad (7)$$

Many other generally used penetration depth and perforation thickness formulae can found in Reference (Li, 2005).

Perforation thickness for tests IP1, ITP1, ITP2 and ITP4

The amount of bending reinforcement for plates with thicknesses of 0.25 m (IP1), 0.3 m (ITP1) and 0.35 m (ITP2 and ITP4) are 110, 91 and 78 kg/m^3 i.e. less than the limit 160 kg/m^3 stated in (Degen, 1980) for the perforation formula (1). According to (Degen, 1980) the nose factor N should be continuously augmented from 0.72 to 1.14 even for flat nose if d < 0.15 m. Now the missile diameter is about 0.17 m. In order to improve predictions with this method, the nose factor was chosen as a tuning parameter. Values 0.72, 0.84 and 1 were chosen to be used in comparison calculations. For NDRC formula N=0.72. In Figure 6, 7, 8 and 9 curves labelled Degen, show the effect of increasing the nose factor from 0.72 to 1. Bending reinforcement is taken explicitly into consideration only in CEA and FL (Forrestal and Li) formulae.

In Figure 6a are depicted the perforation thicknesses as a function of impact velocity v_0 calculated with NDRC, Degen, CEA and FL formulae compared with the slab thicknesses in test series IP1. The plates were reinforced with 10 mm bars using 90 mm spacing without shear reinforcement. For comparative reasons also impact velocities and slab thicknesses of tests ITP1, ITP2R and ITP2RR are shown. ITP1 and ITP2 plates were reinforced also with 10 mm bars using 90 mm spacing without shear reinforcement. During the test campaign the missile was developed in order to minimize its deformations. Hardness of the missile seems to effect the results. Different missile types are presented in the parallel paper by (Vepsä, 2022). Figure 6b shows the normalized perforation thickness as a function of impact function I in the IRIS 2010 test series. Degen with N=1 and CEA formulae probably predict the correct perforation velocity. NDRC formula underestimates the perforation velocity.



(a) (b)

Figure 6. a) Perforation thicknesses as a function of impact velocity v_0 calculated with NDRC, Degen, CEA and FL formulae for test IP1. b) Normalized perforation thicknesses as a function of impact function I compared with the normalized slab thicknesses in IRIS 2010 tests IP1, IP2 and IP3.

In Figure 7 are depicted the perforation thicknesses as a function of impact velocity v_0 calculated with NDRC, Degen, CEA and FL formulae compared with the slab thicknesses in test ITP1. Degen with N=0.84 and FL (even with an assumed cone angle of 50^o) formulae give non-conservative results. Degen with N=1 and CEA formulae probably predict again the correct perforation velocity.

In Figure 8a are depicted the perforation thicknesses as a function of impact velocity v_0 calculated with NDRC, Degen, CEA and FL formulae compared with the slab thickness in test series ITP2. The assumed shear cone angle is 50^o. Figure 8b shows the normalized perforation thicknesses as a function of impact function I in test series ITP1 and ITP2. Surprisingly only NDRC formula seems to give conservative perforation velocity in this case.

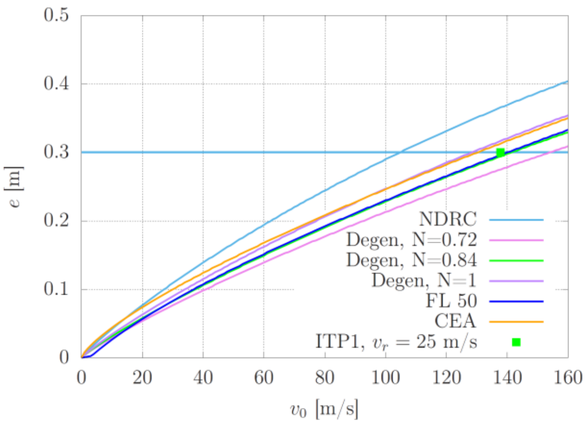
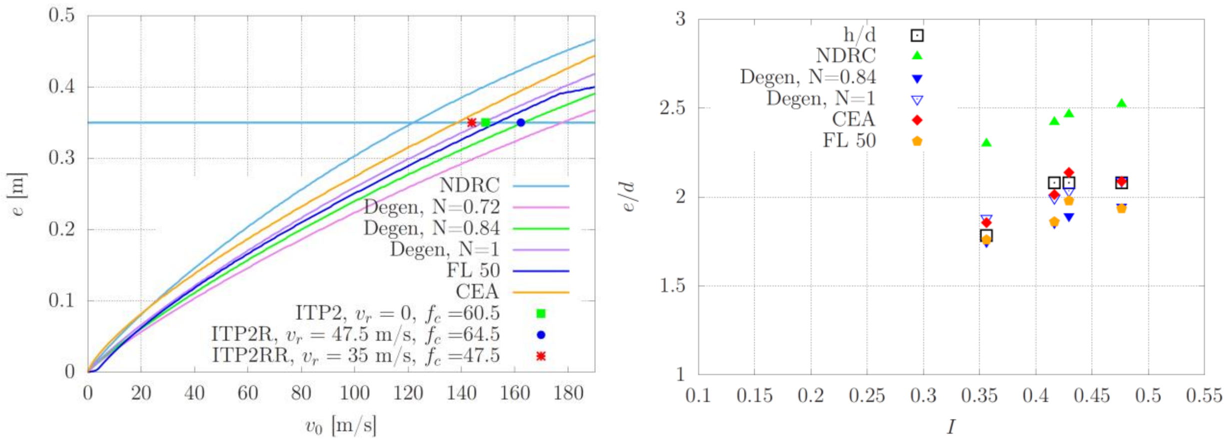
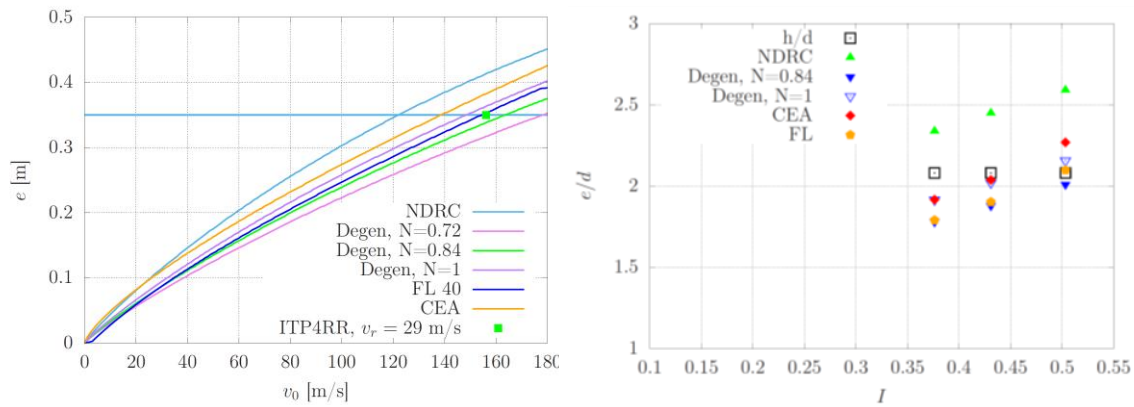


Figure 7. Perforation thicknesses as a function of impact velocity v_0 calculated with NDRC, Degen, CEA and FL formulae for test ITP1.



(a) (b)

Figure 8a. Perforation thicknesses as a function of impact velocity v_0 calculated with NDRC, Degen, CEA and FL formulae for tests ITP2*. b) Normalized perforation thicknesses as a function of impact function *I* compared with the normalized slab thicknesses in test series ITP1 and ITP2*.



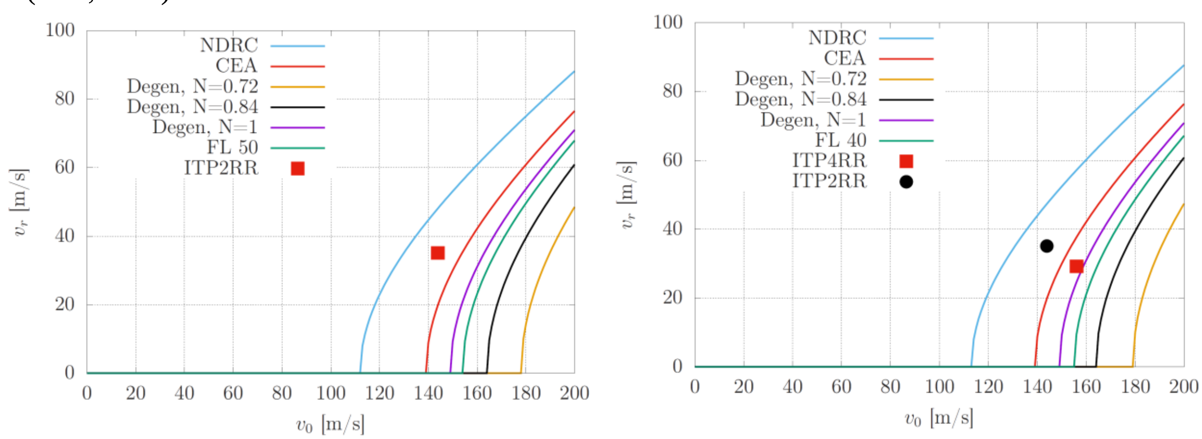
(a) (b)

Figure 9.a) Perforation thicknesses as a function of impact velocity v_0 calculated with NDRC, Degen, CEA and FL for test ITP4RR. (b) Normalized perforation thicknesses as a function of impact function *I* compared with the normalized slab thickness in test series ITP4* with shear reinforcement in the form of T-headed bars considered (only in FL formula).

In Figure 9a are shown the perforation thicknesses as a function of impact velocity v_0 calculated with NDRC, Degen, CEA and FL formulae compared with the slab thickness in test ITP4RR. The plates were reinforced with 10 mm bars using 90 mm spacing taking into account shear reinforcement in the form of T-headed 12 mm bars with a spacing of 90 mm. Figure 9b shows the normalized perforation thicknesses as a function of impact function *I* compared with the normalized slab thickness in test series ITP4. The assumed shear cone angle was 40°. Even with this angle results with FL formula seem borderline non-conservative. With larger cone angles the predicted perforation velocities tend to be way too large. NDRC result seems conservative. In (Orbovic, 2013) it was noted that in the presence of shear reinforcement the angle of possible shear cone tends to get smaller than in plates with bending reinforcement only. It may be concluded from their findings that the perforation capacity did not improve significantly with transverse reinforcement in the form of T-headed bars.

Residual velocity

The residual velocity can then be calculated e.g. with the method in (Kar, 1979). The conservation of kinetic energy gives for residual velocity $v_r = \sqrt{\frac{v_0^2 - v_p^2}{1+M_k/m}}$, where M_k is the shear cone mass, and the cone angle is calculated from $\theta = \frac{\pi/4}{(h/d)^{1/3}} \leq 3$, where h is the plate thickness and d is the missile diameter. The maximum cone angle is $\pi/3$. In the present cases the ratio h/d is in the range from 1.5 to 2.1 and the cone angle varies from 39.4° to 35.3°. It should be noted that in Kar's method the cone height is equal to the plate thickness. Putting $M_k = 0$ gives a residual velocity equation $v_r = \sqrt{v_0^2 - v_p^2}$, which is the same as Eqn. (3.4) in (Barr, 1990).



(a) (b)

Figure 10. Residual velocity in tests a) ITP2RR and b) ITP4RR.

Residual velocities as a function of impact velocity calculated with NDRC, Degen, CEA and FL formulae are presented in Figure 10 together with the residual velocity recorded from tests ITP2RR and ITP4RR. Also from these figures it can be concluded that NDRC formula combined with Kar's residual velocity formula predicts unquestionably conservative residual velocity values. CEA formula gives borderline conservative values. The FL formula is the only one taking the shear reinforcement into account, but on the other hand according to (Orbovic, 2013), shear reinforcement does not significantly improve the slab perforation capacity. Based on the experimental findings, the inclination angle of the rear face crater in perforated plates is steeper than that in plates without shear reinforcement. In this case shear reinforcement with T-bars appears advantageous. Larger impact velocity in test ITP4RR results in smaller residual velocity than in test ITP2RR. Test plates are identical except for shear reinforcement.

CONCLUSION

In both FE simulations, structural behaviour of the target wall was simulated quite accurately. The material properties corresponding to the real measured ones could be modelled. There are still some model parameters that could be calibrated, but the current parameter set gives generally the most realistic behaviour. The predicted residual velocity in Test ITP2RR is in a good agreement with the measured value. ITP4RR results were difficult to reproduce, mostly due to the modelling of T-headed bars. No perforation occurred in the numerical simulation but reaching close to ballistic limit was indicated. Since this type of FE analyses are time consuming with respect for both computer and real time, simultaneous simplified methods are useful for sensitivity studies and preliminary assessments, especially when considering structures of real size. In the course of the test campaign the non-deformability of the original missile type was compromised and thus the missile was redesigned (Vepsä, 2022).

In the studies with simplified methods, for 0.25 m thick plates, Degen's formula with nose factor *N*=1 (i.e. assuming non-flat nose) and CEA formula probably predicted well perforation velocity. NDRC formula underestimates the perforation velocity, the very reason why Degen developed new perforation thickness formulae to be used for the kind of cases studied here. In analyzing 0.3 m and 0.35 m thick plates without shear reinforcement, Degen's formula with a nose factor *N*=0.84 and FL method, even with an assumed cone angle of 50^o, gave borderline non-conservative results. Larger *h/d* ratios seem to require smaller assumed shear cone angles. Degen's formula with a nose factor *N*=1 and CEA formula probably predicted again well the perforation velocity. In the case of shear reinforced 0.35 m thick plate, surprisingly only the NDRC formula seems to give conservative perforation velocity. Even with the assumed shear cone angle of 40^o results with FL formula seem borderline non-conservative. With larger cone angles the predicted perforation thickness values tend to be way too small. It can be concluded that NDRC formula combined with Kar's residual velocity formula predicts conservative residual velocity values. CEA formula gives borderline conservative values. Based on the experimental findings, the inclination angle of the rear face crater in perforated plates with shear reinforcement is steeper than that in plates with bending reinforcement only.

REFERENCES

Abaqus Manual. (2019). Simulia. Dassault Systèmes.

Barr P. (1990). "Guidelines for the design and assessment of concrete structures subjected to impact." AEA, 1990.

Buzaud E., Cazaubon C., Chauvel D. (2007). "Assessment of empirical formulae for local response of concrete structures to hard projectile impact," CONSEC'07 Tours, France, 2007, 1365-1372.

Chen X. W., Li X. L., Huang F. L. Wu, H. J. and Chen Y. Z. (2008). "Normal perforation of reinforced concrete target by rigid projectile," *International journal of impact engineering*, 35, 1119-1129.

Dancygier, 1997 Dancygier A. N. (1997). "Effect of reinforcement ratio on the resistance of reinforced concrete to hard projectile impact," *Nuclear engineering and design*, 172, 233-245.

Degen P.P. (1980). "Perforation of reinforced concrete slabs by rigid missiles," *Journal of the Structural Division*, ASCE, 106, 1623-1642.

Fedoroff, A. and Calonius, K. (2020). "Using the Abaqus CDP model in impact simulations," *Rakenteiden Mekaniikka* (Journal of Structural Mechanics), Vol. 53, No. 3. pp.180-207.

Forrestal M.J., Altman B.S., Cargile J.D. and Hanchak S.J.(1994). "An empirical equation for penetration depth of ogive-nose projectiles into concrete targets," *International Journal of Impact Engineering*, 15, 395-405.

Fullard K., Baum M.R. and Barr P. (1991). "The assessment of impact on nuclear power plant structures in the United Kingdom," *Nuclear Engineering and Design*, 130, 113-120.

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

Li Q.M., Reid S.R., Wen H.M. and Telford A.R. (2005). "Local impact effects of hard missiles on concrete targets," *International Journal of Impact Engineering*, 32, 224-284.

Li Q.M. and Chen X.W. (2003). "Dimensionless formulae for penetration depth of concrete target impacted by a non-deformable projectile," *International Journal of Impact Engineering*, 28, 93-116.

Li Q.M. and Tong D.J. (2003b). "Perforation thickness and ballistic limit of concrete target subjected to rigid projectile impact," *Journal of Engineering Mechanics*, ASCE, 129, 1083-1091.

Orbovic N. and Blahoianu A. (2013). "Tests to determine the influence of transverse reinforcement on perforation resistance of rc slabs under hard missile impact," *Transactions, SMiRT-22,* San Francisco, California, USA.

Vepsä A., Christian Heckötter Ch., Darraba A., Fedoroff A., Sawada S., Schneeberger Ch., and Tarallo F. (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, SMiRT-26* Berlin/Potsdam, Germany.