Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division V

VERIFICATION OF PUNCHING DAMAGE OF REINFORCED CONCRETE SLABS UNDER SOFT IMPACT WITH RCC-CW PUNCHING RESISTANCE

Anthony Darraba[1], Bastien Lafon[2], Mathieu Galan[3], Christian Schneeberger[4]

[1] Expert engineer, EDF, Lyon, France (anthony.darraba@edf.fr)
[2] Structural engineer, EDF, Lyon, France
[3] Expert engineer, EDF, Lyon, France
[4] Deputy Section Head, Swiss Federal Nuclear Safety Inspectorate ENSI, Brugg, Switzerland

ABSTRACT

In the case of soft impact of a deformable missile on a reinforced concrete slab, as in the case of Airplane Crash loading on Nuclear Power Plants structures, one of the possible failure mode of the slab is punching cone failure. Punching resistance under soft impact, with known impact force, is already available in CEB (1988) and in the RCC-CW (2021) civil works code. Even though for the latter, the concrete and shear reinforcement contributions defined in Appendix DH are not initially dedicated to impact, their use in this frame is proposed in Appendix DC of the code, together with the lower bending reinforcement contribution as a net effect.

This punching resistance, described in RCC-CW, is assessed against many impact tests results at different scales, all involving punching damage under soft impact and low, moderate or advanced damage of concrete in the punching cone. The ratio between the punching resistance and the impact shear force is calculated. It provides a good estimate of the slab damage, either in a "Design" or in a "Verification" purpose. It is there assumed that respectively high or optimized margin to failure is expected.

INTRODUCTION

In reinforced concrete structures subjected to impact, different damage modes can be observed in tests, as already pointed out by many authors, see Fila et al. (2015) for instance. As mentioned by Fila, Finite Element (FE) calculations can be accurate when bending behavior is dominant, which can be the case of a slab under soft impact. Simplified methods like yield lines theory can also be useful, to get a rough estimate of the slab bending capacity. But supporting conditions or impact area, when differing too much from ideal cases, can make simplified methods not well suited. On the contrary, perforation failure mode of slabs subjected to hard impact mainly involves out-of-plane shear, after the concrete compression strength is exceeded in the loading area. Simplified methods based on perforation formula are mainly influenced by the concrete compression strength, see Li et al (2005). Small influence of shear reinforcement, for tests at reduced scale at least, was pointed out in Blahoianu, Orbovic, Sagals (2015) and Galan, Orbovic (2015). As a consequence of the major role of confined concrete, it is not easy to get accurate result of perforation under hard impacts with FE calculations. Perforation formula as CEA-EDF in RCC-CW are used at least to get first estimate or as a validation tool of FE calculations.

A third damage mode is punching under soft impact. It can be related to the size or crushing strength of the missile, that makes the shear resistance of the slab exceeded. Even though there is some bending deformation of the slab, punching damage is a more local and brittle one than in bending. But there is no excessive penetration of the missile in the concrete as it can be the case in hard impacts, with straight cracks in the thickness of the slab at least in the initial phase of penetration of the missile. Because of inclined cracks in punching under soft impacts, from the upper to the lower slab faces, both concrete and reinforcements, bending and shear ones, are contributing to the slab resistance, as observed in tests comparisons. Hard impact formula can be over conservative to estimate the slab resistance, without any shear reinforcement contribution, without any energy dissipated in the missile and the bending contribution may be low.

In the case of a soft impact, the impact force can be estimated by the so-called Riera method from Riera (1968). RCC-CW includes a punching resistance, that is not initially dedicated to impact loadings. However it was also validated for impact loadings, consequently added to Appendix DC together with a bending contribution to punching resistance under impact.

Resulting punching resistance is compared to the impact shear forces, through the calculation of a punching ratio. It is applied to impact tests from the X tests series of the international IMPACT project, carried out at the VTT Research Centre since 2005. In these tests, a less deformable missile than in bending tests is used, so that the punching capacity of the slab is exceeded. This kind of impact tests was studied for example in Saarenheimo et al. (2015). The main interest lies in the method consistency with various observed punching damage, given calculation material properties and contributions of concrete, shear reinforcement and bending reinforcement. A calculation of punching ratio is also performed on Meppen tests, which have the same damage mode at a higher scale.

PUNCHING RESISTANCE

The whole analysis is performed with analytical formula, both for the impact force on the basis of Riera method, and for the slab resistance to punching.

As mentioned in Saarenheimo et al. (2015), an independent method for analysing the punching capacity of concrete slabs subjected to soft missile impact was developed in Jowett and Kinsella (1989). It was reported in the well-known CEB (1988) report for impact and impulsive loadings and afterwhile in IAEA (2018). The punching resistance F_p, to be compared with the average impact force, is as follows :

$$F_p = 8170\left(\rho_p . f_c\right)^{1/3} \pi . d_e (d_{load} + 2.5 d_e) \quad [\mathrm{MN}] \tag{1}$$

Where ρ_p is the bending reinforcement density on the rear side [m²/m], f_c is the concrete cubic compressive strength [Pa], d_e the lower bending rebar level arm [m] and d_{load} the effective loading diameter [m]. Concrete and bending reinforcement are considered in the punching capacity. The damage mechanism may be discussed in this formulae given the various contributions and parameters, and without any shear reinforcement contribution.

The average impact force is calculated from the impact impulse and duration. When the impact force is decreasing along the impact duration as in the VTT X tests series (see Figure 4), this average can be somehow different from the maximum impact force.

This method was applied recently in Tarallo et al. (2019). It was pointed out that the shear reinforcement shall be included in the punching resistance. ETC-C (former version of the RCC-CW code) shear reinforcement contribution was therefore added to F_p to estimate the punching damage in tests.

For the design of new civil structures, AFCEN codes are used by EDF as the reference documentation. RCC CW (2021) provides the following punching resistance in Appendix DH :

$$V_{rd} = V_{rd,s} + V_{fd} = a_{sw} . f_{yd,t} . \frac{z}{\tan(\theta)} + \frac{d}{\gamma_c}\left[\sigma_{cp}\left(\frac{k_2}{f_{cd}} + k_3\right) + k_4 . f_{cd} + k_5\right] \ [\mathrm{MN/m}] \tag{2}$$

Where the first series of parameters is associated to shear reinforcement : the density a_{sw} (area per unit surface [m²/m²]), the yield strength $f_{yd,t}$ [MPa], the effective depth of the cross section z [m] and the punching cone angle θ [deg]. The second series of parameters are related to the concrete contribution to shear resistance V_{fd} [N/m] : the effective depth of the cross section d [m], a partial factor γ_c [-] assumed equal to 1.0, k_2 equal to 0.736 MPa ($\sigma_{cp} \geq 0$), k_3 equal to 0.081 [-] ($\sigma_{cp} \geq 0$), k_4 equal to 0.03 [-], k_5 equal to 0.27 MPa, and f_{cd} the calculation compressive strength [MPa]. For strain rates under soft impact in the range of 0.01 s^{-1} to 1.0 s^{-1} approximately, concrete compressive strength is increased by 1.1 for Design and by 1.25 for Verification, according to Dynamic Increase Factor (DIF) documented in Bischoff and Perry (1991). A DIF coefficient of 1.1 is assumed for steel yield strength of the shear reinforcement, whatever the Design or Verification objective. The concrete confinement due to bending and shear reinforcement is also considered. According to CEB-FIP (1990), a parameter “CONF” of 1.2 is applied to the concrete compressive strength. Resulting values of f_{cd} and $f_{yd,t}$ are in Table 1.

In addition to the concrete and shear reinforcement contributions in V_{rd}, the effect of bending reinforcement at the rear side, as a net effect, may be considered. As the damage state associated to the net effect is an advanced damage state of the slab, this contribution may be used in a Verification purpose. It may not be used with the aim of reducing the shear reinforcement ratio in a Design purpose. In this paper, the objective is to assess the ultimate limit state of the slabs in punching shear and to quantify the margins when the resistance is calculated with a Design approach.

The bending reinforcement contribution to the punching resistance, denoted V_{bend}, is calculated as follows from RCC-CW (2021) Appendix DC :

$$R_{ctl} = 4\pi . A_l . f_{yd} . u_{ctl} \ [\mathrm{MN}] \quad (3)$$

$$\text{with } u_{ctl} = \left(\frac{3}{2} l^2 \varepsilon_{uk}\right)^{0.5} \quad (4)$$

$$\text{and } l = a + d . \mathrm{cotan}(\theta) \quad (5)$$

$$V_{bend} = \frac{R_{ctl}}{2\pi . l} = 2 . A_l . f_{yd} . \left(\frac{3}{2} \varepsilon_{uk}\right)^{0.5} \ [\mathrm{MN/m}] \quad (6)$$

Where, in the ultimate strength of bending reinforcement R_{ctl}, A_l is the bending reinforcement density [m²/m], f_{yd} is the calculation yield strength [MPa] and the ultimate displacement u_{ctl} [m] is evaluated from the strain at maximum load ε_{uk} [m/m], assumed equal to 5 %. l is the radius of the cone [m] at the depth of bending reinforcement, a is the missile radius [m]. f_{yd} is equal to the specified resistance f_{yk} for Design. For Verification, the measured yield stress is considered for the tests in this paper, the mean value f_{ym} is also used as a sensitivity analysis.

EVALUATION OF THE RCC-CW PUNCHING RESISTANCE ON IMPACT TESTS

Tests overview, punching cone damage

The evaluation is performed on the IMPACT project Combined tests X1 to X10. Extensive test data are available : specimen compression and tensile tests for concrete at the time of impact tests and tensile tests for steel, measurements on bending and shear reinforcement inside and outside the punching cone, cross sections of slab after tests and assessment of concrete cracks.

The slabs dimensions are 2 m x 2 m x 250 mm with a C40/K50 concrete class and 500 MPa specified yield stress for rebars. The real concrete resistance at the day of the impact test may vary significantly from the specified resistance, and from one test to another (see Table 1). Missiles are hollow pipes made of stainless steel, with a mass of 50 kg. Missile diameter is 256 mm or 219 mm, the thickness of the missile pipe is 3.0 mm or 6.4 mm. Missile velocity is also reported for each test.

Next figure shows slab damage after tests. X1 and X2 tests are associated to a moderate damage, even if these tests were designed so that the impact shear force is close to the punching shear resistance calculated with the civil works code RCC-CW. Thin cracks are observed, no plastic strain in shear reinforcement, local and moderate plastic strains in bending reinforcement which result in low displacements when compared to impact tests where bending damage is dominant. The next tests X3 to X10 were designed to reach significantly higher damage, again thanks to a calculation with the RCC-CW code. The punching cone damage is more developed, with plastic strains in shear reinforcement. X4 test was designed to reach perforation, based on the feedback on X1 to X3 and given the conservatism of the civil code formulae, evidenced in the first three tests. Failure is actually reached in X4 with 25 m/s residual velocity of the missile. Apart from X4, the X5 test has the most advanced damage state with clear cone detachment. It is the only test without any shear reinforcement. It was designed to observe the effect of shear reinforcement on the punching shear damage mode, targeting "just perforation" state of the slab.

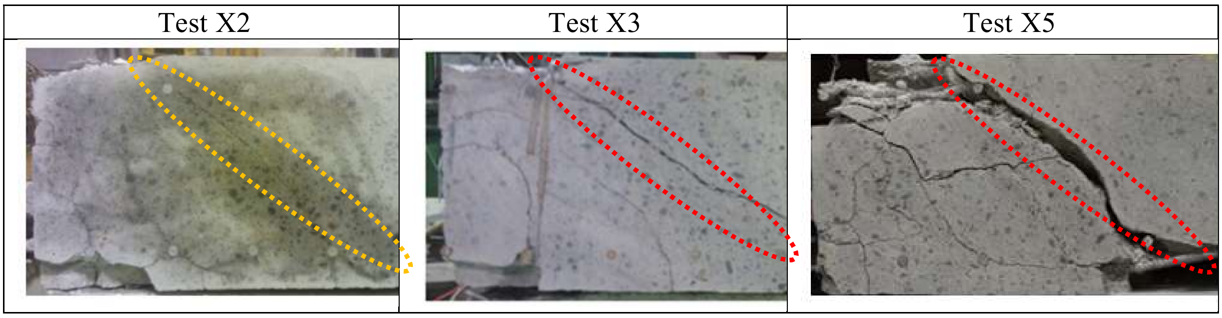

Test X2
Test X3
Test X5

Figure 1. Cross sections of slabs after impact, wider crack observed. The dotted shape that highlights the wider crack is inclined at 37° from the slab plane

From the slab cross sections after each test, in both directions, angle θ with respect to the slab plane can be estimated based on the wider crack in the thickness. Obviously there are many cracks, in the cone area. For shear reinforcement contribution in particular, the wider crack is supposed to be related to the punching cone separation from the slab. It can be observed that whatever the damage level is, in all of the 10 tests including X4 with perforation, θ is the range of 30 to 50 degrees and often close to 40 degrees. Therefore the 40 degrees value proposed in RCC-CW, for slabs without any prestressing or tension stress, is considered as well suited (see Figure 1) and is chosen for punching ratio calculations.

The next table summarizes main impact parameters and calculation material properties considered for punching resistance in X tests, for Design or Verification purpose. Note that for the particular case of test X5 without any shear reinforcement in the slab, the confinement parameter CONF is assumed equal to 1.0 instead of 1.2.

Table 1. X tests - Main parameters and calculation material properties

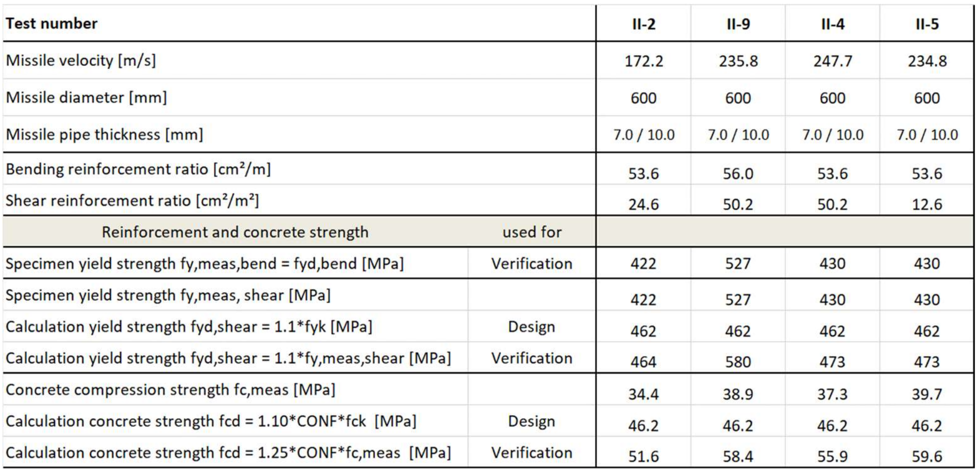
Test number		**X1**	**X2**	**X3**	**X4**	**X5**	**X6**	**X7**	**X8**	**X9**	**X10**
Missile velocity [m/s]		165.9	164.5	142.7	168.5	162.5	166.7	166.5	166.7	165.1	165.7
Missile diameter [mm]		256	256	219	219	256	219	219	219	219	219
Missile pipe thickness [mm]		3.0	3.0	6.4	6.4	3.0	6.4	6.4	6.4	6.4	6.4
Bending reinforcement ratio [cm²/m]		8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	5.6	12.6
Shear reinforcement ratio [cm²/m²]		17.5	11.7	17.5	17.5	0.0	31.0	31.0	31.0	31.0	31.0
Reinforcement and concrete strength	used for										
Specimen yield strength fy,meas,bend = fyd,bend [MPa]	Verification	540	537	559	537	541	541	541	541	567	565
Specimen yield strength fy,meas, shear [MPa]		630	630	630	630		590	560	590	567	567
Calculation yield strength fyd,shear = 1.1*fyk [MPa]	Design	550	550	550	550		550	550	550	550	550
Calculation yield strength fyd,shear = 1.1*fy,meas,shear [MPa]	Verification	693	693	693	693		649	616	649	624	624
Concrete compression strength on cylinder fc,meas [MPa]		40.6	44.1	46.6	41.7	59.2	57.8	57.8	57.7	61.6	61.1
Calculation concrete strength fcd = 1.10*CONF*fck [MPa]	Design	52.8	52.8	52.8	52.8	44.0	52.8	52.8	52.8	52.8	52.8
Calculation concrete strength fcd = 1.25*CONF*fc,meas [MPa]	Verification	60.9	66.2	69.9	62.6	74.0	86.7	86.7	86.6	92.4	91.7

The punching evaluation is also performed on a few Meppen tests, so that the method is verified at a higher scale. Meppen tests are described in GRS (2010). They were previously analysed for instance in Koechlin (2007). As for IMPACT X tests, Meppen are soft impacts with punching capacity exceeded, resulting in a punching cone at various damage levels. Slab dimensions are 6.0 m x 6.5 m with a thickness from 50 cm to 90 cm. Missile velocity or reinforcement density can also be modified from one test to another.

Four tests are chosen with various damage state after impact, all the slabs being 70 cm thick. In tests II-2, II-9 and II-4 a moderate damage is observed as in X1 and X2 tests. Damage increases in these three tests, from minor inclined cracks in II-2 to wider cracks and a damage state almost reaching scabbing initiation in II-4, though no piece of concrete is detached from the slab. The damage is far more advanced in test II-5 : concrete inside the punching cone is destroyed, significant pieces of concrete are ejected from the lower face and the first bending rebars are broken. Therefore the slab is close to failure. Based on the wider cracks through the slab thickness depicted in tests reports, to estimate punching cone failure, the angle of 40 degrees from X tests is still considered a good order of magnitude for the four tests.

With the same assumptions as for X tests, calculation properties are summarized for Meppen tests in Table 2, on the basis of materiel strengths mentioned in Jonas et al (1982), Riech et al (1983) and GRS (2010). The tensile strength of shear reinforcement was assumed equal to the bending reinforcement one.

Table 2. Meppen tests - Main parameters and calculation material properties



Test number		II-2	II-9	II-4	II-5
Missile velocity [m/s]		172.2	235.8	247.7	234.8
Missile diameter [mm]		600	600	600	600
Missile pipe thickness [mm]		7.0 / 10.0	7.0 / 10.0	7.0 / 10.0	7.0 / 10.0
Bending reinforcement ratio [cm²/m]		53.6	56.0	53.6	53.6
Shear reinforcement ratio [cm²/m²]		24.6	50.2	50.2	12.6
Reinforcement and concrete strength	used for				
Specimen yield strength fy,meas,bend = fyd,bend [MPa]	Verification	422	527	430	430
Specimen yield strength fy,meas, shear [MPa]		422	527	430	430
Calculation yield strength fyd,shear = 1.1*fyk [MPa]	Design	462	462	462	462
Calculation yield strength fyd,shear = 1.1*fy,meas,shear [MPa]	Verification	464	580	473	473
Concrete compression strength fc,meas [MPa]		34.4	38.9	37.3	39.7
Calculation concrete strength fcd = 1.10*CONF*fck [MPa]	Design	46.2	46.2	46.2	46.2
Calculation concrete strength fcd = 1.25*CONF*fc,meas [MPa]	Verification	51.6	58.4	55.9	59.6

Loading : maximum impact force

As the maximum impact force is involved in the punching assessment, the impact force over time should be estimated carefully. In the frame of IMPACT project, so-called force plate tests (FP) aimed at measurement of the impact force of deformable missiles on a rigid plate. The result for FP8 test, at 102.2 m/s, is presented hereafter. The missile is similar to the missiles used in X tests, it is made of stainless steel, except that the pipe thickness is 2 mm. The missile diameter is 256 mm, as in X1, X2 and X5 tests and somehow larger than the 219 mm of the other X tests.

The impact force is computed with the Riera formulae. Missile crushing strength is calculated from Jones (2012). In this strength, Cowper-Symonds parameters are assumed to the usual values for steel, D=40 s^{-1} and q=5. As pointed out by Jones, there is some uncertainty on these parameters at impact strain rates. For D=100 s^{-1} and q=10, that can be considered for stainless steel, the maximum impact force is decreased by 10 % in FP8 test. Other uncertainty is on the steel yield stress. From specimen tensile tests and resulting engineering stress-strain curves presented on Figure 2, a value of 375 MPa is considered for the calculation of the crushing strength.

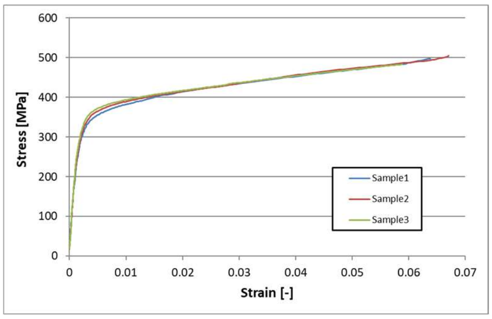


Figure 2. Specimen tensile test on a sample sawn out of a missile pipe in IMPACT project

Missile shortening in the Riera calculation is 862 mm, in good agreement with the 871 mm measured after the test. Maximum force is 0.42 MN, putting aside the short duration peak (roughly 0.15 ms duration). It is caused by the thicker area at the connexion between missile head and pipe. The impact force, measured with force transducers, is compared to the force estimated with Riera calculation. Both test and calculated impulses are matching the initial missile momentum of 5110 N.s. Test and Riera impulses are in good agreement along the impact duration.

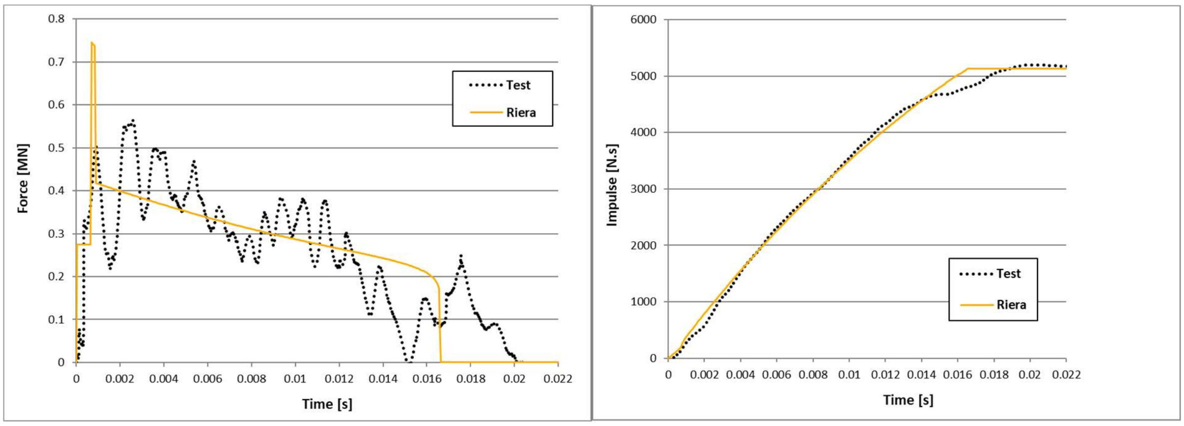


Figure 3. Loading force and impulse, FP8 test of a 2 mm thick missile on a rigid plate

The impact forces for X tests are presented in Figure 4. The maximum impact force is estimated at 1.1 MN (the associated maximum shear force, denoted V_{max}, is 0.6 MN/m) in X1, X2 and X5 tests, sharing the same kind of missile and approximately the same impact velocity. It is estimated at 2.3 MN (V_{max} = 1.4 MN/m) in X3 and 2.6 MN (V_{max} = 1.6 MN/m) in the remaining tests. Shortening in Riera calculation is also provided, against missile shortening measured after each test. There is not much difference except for X4 that reached failure. Even though some part of the initial energy is transferred to the slab. That can be explained by the low displacements and the brittle damage mode in the slab, the plastic strains in bending reinforcement being limited in space.

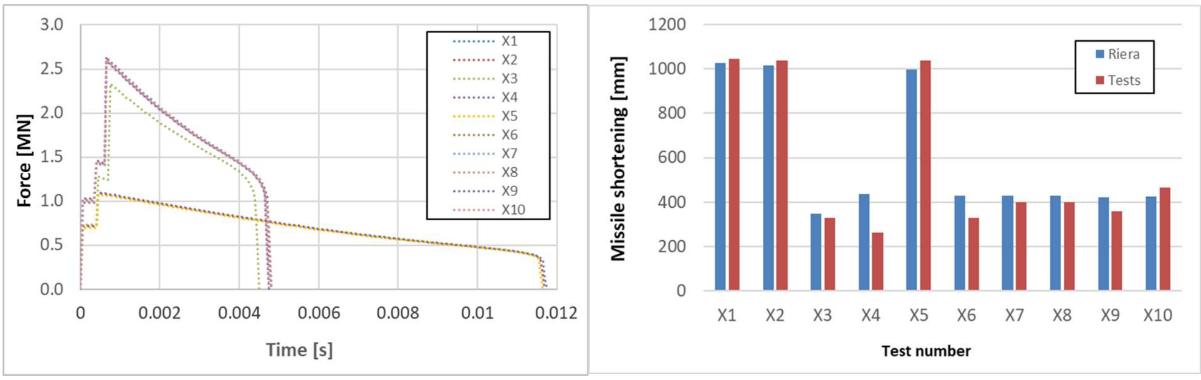


Figure 4. Impact force calculation for X tests (on the left), missile shortening in calculations and tests (on the right)

For Meppen tests, impact force is taken from Jonas et al (1982). Maximum impact force in tests II-2, II-9, II-4 and II-5 are respectively 7.0 MN (V_{max} = 1.6 MN/m), 11.7 MN (V_{max} = 2.6 MN/m), 13.1 MN (V_{max} = 2.9 MN/m) and 11.9 MN (V_{max} = 2.6 MN/m).

Results : punching ratios

The ratio of the slab punching resistance to the maximum shear force is calculated with two sets of assumptions : Design and Verification configurations. The Design ratio is calculated with the resistance V_{rd}, Eq. 2. The verification ratio is calculated with a punching resistance, that is straightforwardly assumed to be the sum of V_{rd} and V_{bend}, Eq. 2 and 6. This ratio would be used for example for the verification of buildings without any safety requirement. The maximum shear force V_{max} is given in the previous section for each test.

Two additional punching ratios are calculated, so that sensitivity on material properties can be estimated. In the Design punching resistance, specified material properties are replaced by mean properties f_{cm} and f_{ym}, with $f_{cm} = 1.2\ f_{ck}$ and $f_{ym} = 1.1\ f_{yk}$ as proposed by RCC-CW (2021), see results in clear blue on Figure *5*. In the Verification punching resistance, measured properties are also replaced by mean properties, see results in clear red. The new Verification ratio estimates how different would be the ratio without any test data, in a Verification approach.

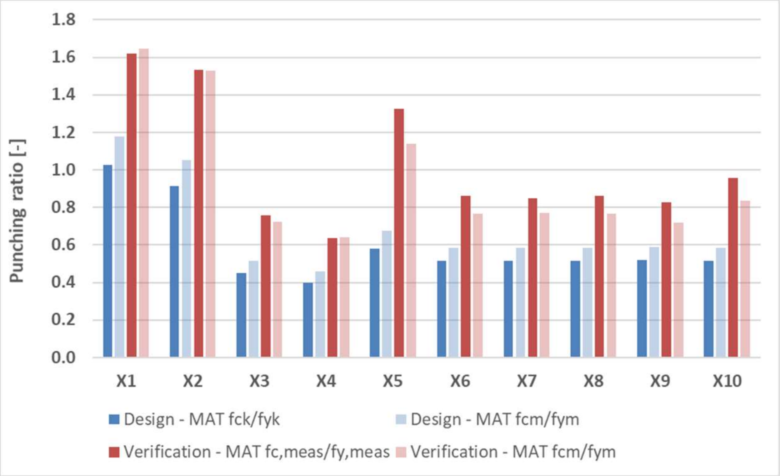


Figure 5. Punching ratio for IMPACT X tests, Design and Verification assumptions

One important verification is that punching ratios are consistent for tests with similar punching damage. X1 and X2, with moderate damage, small cracks and no plastic strain in shear reinforcement, have a Design ratio close to 1.0. Therefore this is the amount of damage that can be expected in a design purpose. The Verification ratio of these two tests is significantly higher than 1.0. On the contrary, tests with advanced punching damage, clear cracks, plastic strain in stirrups and partially destroyed concrete in the cone have a Design ratio close to 0.5. X4, which reached perforation, is slightly below 0.5. The Verification ratios of tests X3 to X10 with advanced damage, based on test material data, are in the approximate range of 0.8 to 1.0 (0.7 to 0.8 if mean properties are assumed), except for X5. X4 is not included as failure is reached, therefore damage state is not considered similar to other tests.

The comparison between X4 and X6 to X10, with similar loadings, shows that whatever the bending reinforcement, the punching damage is significantly influenced by the shear reinforcement density, which is almost twice in latter tests compared to X4. It's likely that the low shear reinforcement in X4 makes the resistance to punching more sensitive to the concrete shear resistance, and consequently to its tensile strength.

For X4 test, the punching ratio is not so much lower compared to other advanced damage tests, when failure is reached in X4. One possible reason is the punching brittle failure. However, it can also be noticed that for specified C40/K50 concrete, a mean concrete tensile strength f_{ctm} of 3.5 MPa can be expected from EN 1992-1-1 (2004). On X4 specimen, $f_{t,meas}$ turned out to be 2.3 MPa, when it ranges from 3.0 to 3.6 MPa in the other tests. The effect is estimated on the punching ratios, using EN 1992-1-1 (2004) formula (Eq. 7 for Verification, f_{ck} is also calculated for Design from $f_{t,meas}$ in the same way except that the 8 MPa is removed) :

$$f_{cm} = \left(\frac{f_{t,meas}}{0,3}\right)^{3/2} + 8 \quad \text{[MPa]} \tag{7}$$

The X4 ratio becomes somehow different from the other tests, once based on the measured tensile strength. The other ratios are less modified than the X4 ratio. One could also calculate the inverse of the punching ratio, to make a better distinction between all the ratios that are lower than 1.0 on Figure 6.

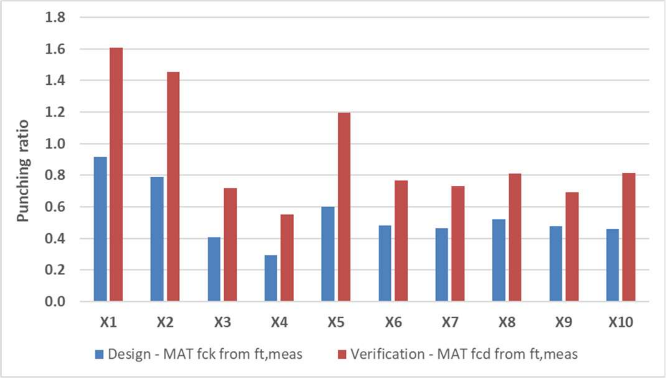


Figure 6. Punching ratio for X tests, from measured concrete tensile strength

The X5 test is specific as the slab has no shear reinforcement. It does not fulfill the usual design rules in nuclear civil works structures. The Verification ratio is higher than other tests with advanced damage, whereas damage in X5 is more pronounced than in other tests (obviously excluding X4). The only difference between X1, X2 and X5 is the shear reinforcement density, decreased from 18 cm²/m² in X1 to 12 cm²/m² in X2 and 0 in X5. There is no significant damage difference between X1 and X2. Consequently, a minimum density of shear reinforcement would be necessary so that concrete shear resistance is well estimated.

Besides, it was verified that without the bending contribution, Verification ratio for X5 including only concrete contribution is lower than 1.0. This is consistent with the punching cone detachment.

Punching ratio are now given for Meppen tests, as done for X tests on Figure 5. Conclusions drawn from X tests are confirmed at the higher scale. Tests with moderate damage have a Design punching ratio close to 1.0. The test with advanced damage (here close to failure) has a Design punching ratio of approximately 0.5. In the Verification approach, tests with moderate damage have ratio within 1.5 to 2.0 approximately. The test with pronounced punching cone damage is close to 1.0.

As in X tests, measurements properties or mean properties do not change that much the magnitudes of ratios. It remains true for Design calculations : specified or mean properties do not change the conclusions.

The particular case with no shear reinforcement is not included for Meppen tests. The big differences between shear reinforcement densities and associated damage of some tests, for example between II-9 and II-5, see Table 2, result again in significantly different ratios. When the shear reinforcement density is not far from the minimum density allowed, as in II-5, the punching resistance is probably more dependent on the concrete shear resistance and therefore its tensile strength, as mentioned for X tests. The concrete tensile strength was not found for Meppen tests.

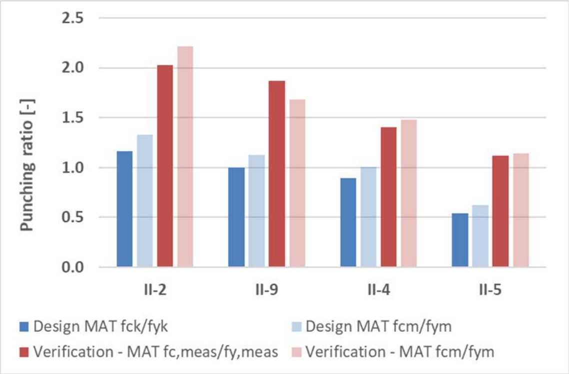


Figure 7. Punching ratio for Meppen tests, Design and Verification assumptions

CONCLUSION

The punching resistance given in RCC-CW is assessed with a series of impact tests from the IMPACT project. Modifications of bending and shear reinforcement densities, missile thickness or velocity are included in the X tests series. A verification at a higher scale is also performed on Meppen tests. All the tests involve punching damage under soft impact, from moderate to advanced (up to perforation).

The RCC-CW punching resistance, when compared to the maximum shear force, provides a good estimate of the slab damage. In a design purpose (Design ratio = 1), the slab damage is moderate, with limited cracks and plastic strain in reinforcement, far from the slab failure. Therefore RCC-CW formulae is clearly very conservative for the design of civil structures under aircraft crash. In the tests where the slab damage is advanced, or almost reached failure, the punching ratio is approximately 0.5. The effect of assumed material properties is quite low on this result.

In a Verification purpose, the punching ratio can also provide a good estimate of the slab punching failure.

The particular case where there is no shear reinforcement should be considered carefully in the Verification approach.

Both IMPACT X tests and Meppen tests show that the shear reinforcement plays a major role in the punching resistance under soft impact.

REFERENCES

CEB (1988) « Concrete structures under impact and impulsive loading », Comité Euro-international du Béton

RCC-CW (2021) « RCC-CW 2021 Edition – Rules for Design and Construction of PWR Nuclear Civil Works », AFCEN ed.

Fila A., Lehmann F., Tropp R. (2015). « Perforation resistance of reinforced concrete slabs affected by low velocity drop loads », *Proc., SMiRT-23*

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

Blahoianu A., Orbovic N., Sagals G. (2015). « Influence of transverse reinforcement on perforation resistance of reinforced concrete slabs under hard missile impact », *Nuclear Engineering and Design, 295, p716-729*

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 », *Proc., SMiRT-23*

Riera J.D. (1968). « On the stress analysis of structures subjected to aircraft impact forces », *Nuclear Engineering and Design, 8, 415-426*

Calonius K., Saarenheimo A., Tuomala M. (2015). « Shear punching studies on an impact loaded reinforced concrete slab », *Nuclear Engineering and Design, 295, 730-746*

Jowett, J., Kinsella, K., 1989. « Soft missile perforation analysis of small and large scale concrete slabs », *Bulson, P.S. (Ed.), Structures Under Shock and Impact. Elsevier, pp. 121–132*

IAEA (2018). « Safety Aspects of Nuclear Power Plants in Human Induced External Events : Assessment of Structures », Safety Report Series No. 87, International Atomic Energy Agency, Vienna, 2018

Koechlin P. (2007). « Modèle de comportement membrane-flexion et critère de perforation pour l'analyse de structures minces en béton armé sous choc mou », PhD report, Paris VI University

Bonhomme M.H., Chauveau Y., Rambach J.M., Tarallo F. (2019). « Reinforced concrete slabs under soft impact at medium speed : lessons learned from VTT IMPACT project », *Proc., SMiRT-25*

GRS (2010). « Impact Tests at the Test Facility in Meppen – Technical Report », GRS-V-RS1182-1/2010

Jonas W., Rüdiger E., Gries M., Riech H., Rützel H. (1982). « Kinetische Grenztragfähigkeit von Stahlbetonplatten », RS 165, Schlussbericht, IV. Technischer Bericht, Hochtief AG

Riech H., Rüdiger E. (1983). « Experimental and theoretical investigations on the impact of deformable missiles onto reinforced concrete slabs », SMiRT 1983 J8/3 pp 387-394

Bishoff P. H., Perry, S. H. (1991). « Compressive behaviour of concrete at high strain rates. », *Materials and Structures, 24, 1991, 425-450*

CEB-FIP (1990). « CEB-FIP Model Code 1990 – Design Code », *CEB Comité Euro-international du Béton*

Jones N. (2012). *Structural Impact, 2nd ed.* Cambridge University Press

EN 1992-1-1 (2004). « Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings »