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A SYNTHESIS OF THE VTT IMPACT PROJECT PHASES II AND III

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ABSTRACT

This paper presents an EDF summary of lessons learnt through impact tests carried out in the frame of phases II and III of the international IMPACT project, carried out at the VTT Research Centre between 2009 and 2020. The objective of the tests was to evaluate the mechanical behavior of reinforced and/or pre-stressed concrete slabs subjected to the impact of deformable or rigid missiles. This IMPACT project greatly contributes to the improvement of knowledge over several years in the area of impact loadings on civil engineering structures, as well as the continuous improvement of industrial tools, in the context of increasing needs of studies for fast dynamics loadings.

Three tests series are mainly analysed, each tests matrix is associated to a different failure mode. Two test series are focused on bending dominated tests and on combined bending and punching failure mode with punching cone, both series under soft impact with different stiffnesses of the missile. The third test series is focused on perforation damage mode under hard impact, with almost perfectly rigid missiles. For each of the test matrix, main parameters of interest are looked for and observations in tests are reported when modifying the test conditions.

INTRODUCTION

The test system is detailed in Calonius et al (2007). Tests are described for example in Vepsä et al. (2011) and Saarenheimo et al. (2015). on existing structures and for new projects. This summary is based on the analysis of approximately 50 impact tests. Phases I and II of the project were conducted from 2004 to 2008 and then from 2009 to 2011 respectively. In phase I, the tests were divided into two categories :

- impacts of rigid projectiles on reinforced or pre-stressed concrete slabs to study the punching behaviour of structures up to perforation – “Punching” matrix
- impacts of deformable projectiles on reinforced concrete slabs, with damage dominated by the bending mode of the slab – “Bending” matrix

The third phase of the project took place between 2012 and 2018. There is a wide range of test matrices in this phase :

- the behavior of reinforced concrete slabs for which the shear reinforcement vary from one test to another. The deformability of missile is also a main parameter in this matrix in which the objective is to analyse the non-linear behavior of slabs in bending and punching - “Combined bending and punching” matrix.
- the vibrations induced by the impact of deformable missiles on more complex structures than a single slab, to study the impact induced vibrations in structures – “Vibration” matrix. Tests are performed on mock-ups with different slabs connected to each other, in a similar way as ofr the OECD IRS3 benchmark mock-up described in Le Gratiet et al. (2022). Tests were performed in IMPACT phase III on this mock-up for instance, after OECD tests.
- the effect of fluid partially or totally filling the missile – “Liquid” matrix (in the continuity of the first tests already carried out in phase II)

LESSONS LEARNT FROM THE BENDING TEST MATRIX

The series of tests TF was intending to study the slab damage with dominant bending mode, for increasing impact velocity from 110 m/s to 170 m/s. The tests TF11, TF12, TF15, TF17 and TF19 were dealing with the impact of a hollow steel missile, weighing 50 kg, with 2 mm thick pipe, on slabs with the same design. The slab span width is 2.0 m and the thickness is 15 cm. Slabs are two-way supported. Figure 1 shows the rear face of the slab after each test. On the front face of each slab, there is no particular damage observed, except the missile footprint at the centre.

TF11	TF12	TF15	TF17	TF19

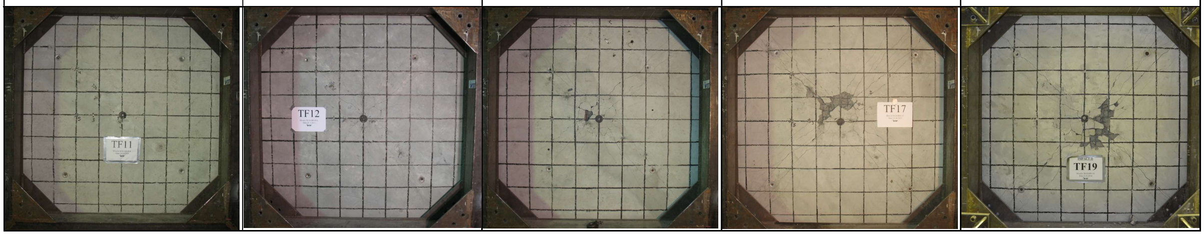

Figure 1. Rear face of the slab after tests TF11, TF12, TF15, TF17 and TF19

In the tests TF13, TF14, TF16 and TF18, the missile were filled in with water. Consequently, the impact force is increased when compared to dry tests at the same impact velocity. These tests are not analysed in this paper, see for instance Heckötter et al. (2015).

The maximum displacement of the slab rear face is given in Table 1. In some of the tests, sensor at the slab centre was destroyed, the value is therefore measured at some distance from the center. Rotation at supports θ is calculated from the maximum displacement, $\theta = \tan^{-1}(u_{max}/(L))$, where L is the distance between the displacement sensor to the closest support. In each of these five tests, there were 4 or 5 reliable measurements of displacements. The mean rotation, calculated from the support rotation for each sensor, is close to the value reported in Table 1.

Compression strains of concrete were measured along the yield lines formed on the bi-supported slab. Strain gauges are positioned outside the loading area, that is to say, outside the area where the strains are minimal, to get reliable measurements. The distance of the gauge in relation to the centre, where the minimum value is measured, corresponds to about 2 to 3 times the radius of the projectile (200 mm to 350 mm from the centre).

The drawback of the strain gauges, glued on bending reinforcement, is that they can reflect a local deformation of the steel, particularly if the gauge is positioned close to a crack, and hence not necessarily reflect any overall deformation of the slab. Besides, questions about the strain gauges reliability have often been raised during the project. They should be considered for the strains order of magntiudes, with an analysis of the measurements scattering, in order to confirm that the passive reinforcement actually reached values significantly beyond plastic limits.

The scattering of measurements related to maximum slab displacements and minimum concrete strains is relatively low, in the order of 20%, from the results of the tests carried out by the VTT laboratory as part of the OECD IRIS phases 1 (2010) and 2 (2012) program.

In the five TF tests, plasticity and non-linearities are clearly visible, concrete cover is sometimes removed. But the slab keeps a significant residual capacity even in the case of the highest loading. This is also verified on the basis of the measured residual displacements. They show an elastic return although a certain level of plasticity reached.

Table 1. Minimum concrete compressive strains, maximum rebar tensile strains and rotations at the supports – "Bending" tests TF11, TF12, TF15, TF17 and TF19

Test number	**TF11**	**TF12**	**TF15**	**TF17**	**TF19**
Impact velocity of the missile [m/s]	108.3	130.1	148.3	159.6	167.9
Concrete compressive strength on cylinder [MPa]	56.0	60.7	55.9	48.5	53.9
Concrete tensile strength [Mpa]	3.5	4.5	4.2	3.2	3.5
Maximum displacement measured on gauge, rear face (distance from slab center)	26 mm	24 mm	42 mm	53 mm (250 mm)	77 mm (0)
Rotation at supports θ, from the measured maximum displacement	**1.5 deg**	**1.8 deg**	**3.2 deg**	**4.0 deg**	**4.4 deg**
Maximum permanent displacement measured afterwards, by auscultation of the slab (rear face)	7.8 mm	8.4 mm	23 mm	31 mm	35 mm
Minimum strain in compression measured on gauge	**- 2 ‰**	**- 4.5 ‰**	**- 6 ‰**	**- 6 ‰**	**- 5.3 ‰**
Maximum tensile strains in lower reinforcement layer	6.8 %	5.1 %	5.1 %	9.2 %	3.5 %

From all of the TF tests, it appears that scabbing on the rear face of the slab is linked to the combination of bending and punching phenomena, when the slab is in an advanced damaged condition for one of these two failure modes :

- Bending deformation with a maximum rotation at supports higher than approximately 3 to 4 degrees;
- Or punching capacity of the slab exceeded by the shear force of the impact loading, when the punching capacity is calculated according to the RCC-CW (2021) civil works code. It is deduced from water filled missile TF tests and also from combined X tests, which are introduced in the next section.

Summary

The slab withstand mechanically, with margins, the impact load under the following observations :

- Plastic strains of rear side bending reinforcement are locally higher than the standard value of 5% for ultimate limit state, defined in the international standard APC methodology, see ERIN (2011) and IAEA (2018). Up to 10% strain is measured locally on the reinforcement layers, without bending failure of the slab ;
- Rotation of the supported slab which reached a value slightly greater than 4 degrees, value consistent with the criteria defined by the American code ACI 349 for slabs with shear reinforcement. These values are reported in IAEA (2018). For water filled missile TF tests, higher rotation values than 4 degrees are reached without failure of the slab ;
- Concrete compression strains reach values between -5 ‰ to -10 ‰ in the front face plastic hinges areas, while the slab is keeping a significant residual mechanical resistance.

As a consequence, the admissible strain criteria for concrete and steel materials, for non-linear bending analyses, defined in the international standard APC methodology are consolidated by the analysis of bending tests from the IMPACT project.

LESSONS LEART FROM THE COMBINED BENDING AND PUNCHING TEST MATRIX

In the combined X tests series, missiles have a pipe thickness that is increased when compared to bending tests such as TF tests. Consequently, the impact force is increased and the impact duration is decreased. Missiles are weighing 50 kg, as in TF tests. The missile diameter is similar to the one in TF tests. Information on X tests can be found for example in Saarenheimo et al (2015) or Tarallo et al (2019).

The effect of shear reinforcement density is studied between tests X1, X2 and X5. The lower density in X2 than in X1 does not lead to a significant difference in the punching damage, which is moderate in these two tests, cracks wide is in the order of 0.1 mm. The X5 test is conducted under the same conditions of impact as the X1 and X2 tests, but without shear reinforcement. This test highlights the contribution of the concrete in the punching resistance. The damage of the slab is close to the ultimate state. The lower bending reinforcement actually acts as a net effect, retaining the punching cone.

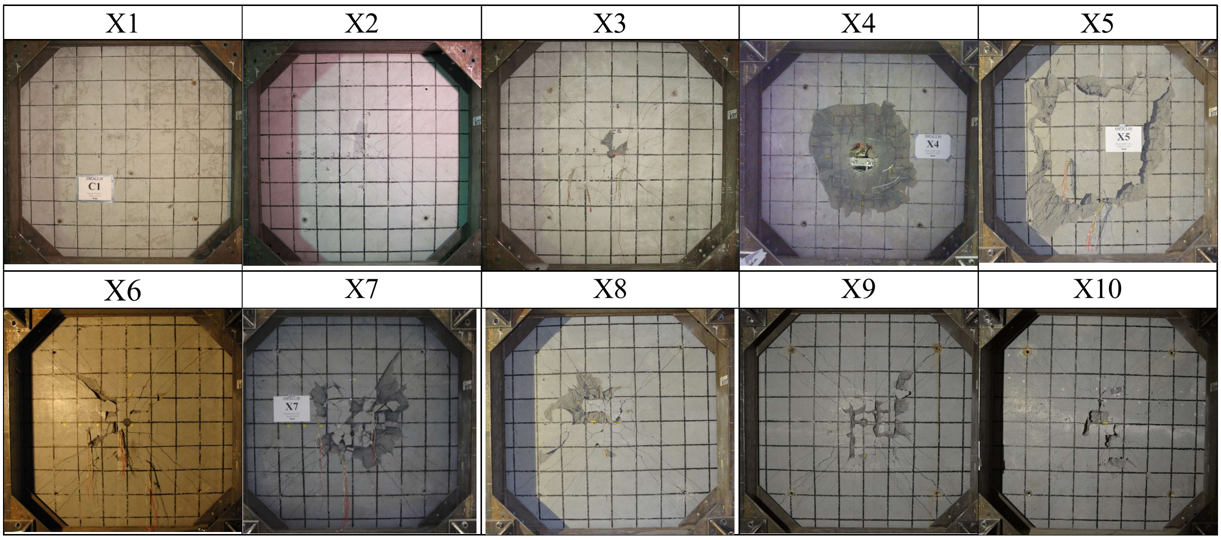

Figure 2. Rear face of the slab after tests X1 to X10

In the test X3, the objective was to ensure that the maximum impact force is well beyond the punching capacity of the slab, by a factor of approximately 2 with the RCC-CW design punching capacity. If the punching damage process is significantly more advanced than in the X1 and X2 tests, the slab after the test is not representative of an "ultimate" state close to just-perforation.

This observation can also be made for the tests X6, X7 and X8, designed with the same parameters in the three tests except for the type of shear reinforcement and with an objective of damage comparable to X3. The damage in these four tests can be considered as similar, with a clear cone crack open, and many smaller cracks inside the cone, see Figure 3. As already pointed out in Tarallo et al (2019), the shear reinforcement type, closed stirrups for X6, double headed bars for X7 and C-shaped stirrups for X8, does not significantly affect the punching capacity and the bending behaviour of the slab. Scabbing is observed on a wider area on the rear face in X7. It can be noticed that in X7, the concrete tensile strength is 10 % to 20 % lower than in X6 and X8. The damage in this latter test looks slightly lower and closer to the damage in X3.

The permanent displacements, which are an indicator of the plasticity damage state, are also compared between X6, X7 and X8 on Figure 4. There is no significant difference on the residual displacements and consequently on the plasticity damage state, whatever the shear reinforcement type.

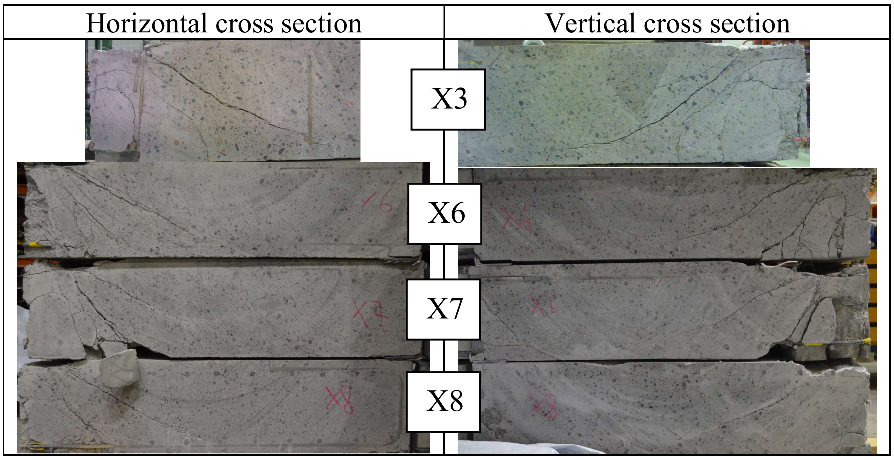

Figure 3. Cross sections of slabs after tests X3, X6, X7 and X8, in the two directions of the slabs

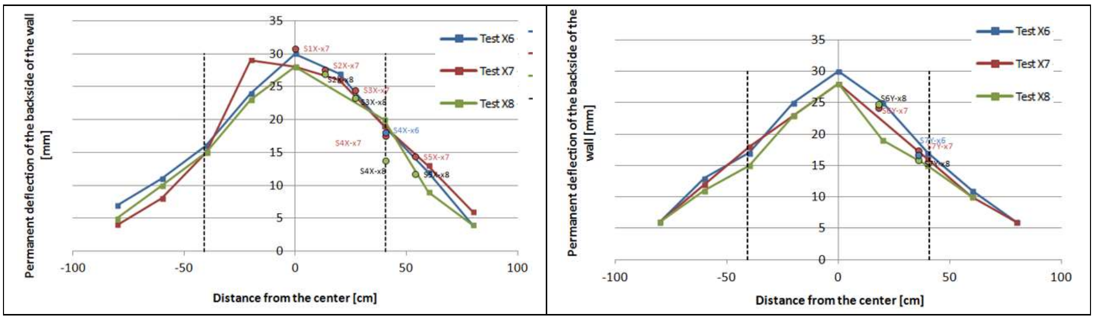

Figure 4. Permanent displacements at the rear face of the slab in tests X6, X7 and X8, in the two directions of the slabs (horizontal direction on the left, vertical direction on the right). Punching cone area is highlighted with the vertical dotted lines

One parameter of interest for the punching resistance assessment is the punching cone angle θ. Based on this angle, analytical calculation can be performed, and a punching ratio can be estimated between the punching capacity of the slab and the shear force associated to the impact loading. It can be observed that whatever the damage level, in all of the tests X1 to X10, including X4 with perforation, θ is the range of 30 to 50 degrees, and often close to 40 degrees as can be seen on Figure 5. Therefore the 40 degrees value proposed in RCC-CW (2021), for slabs without any prestressing or tension stress, is considered as well suited and is chosen for punching ratio calculations.

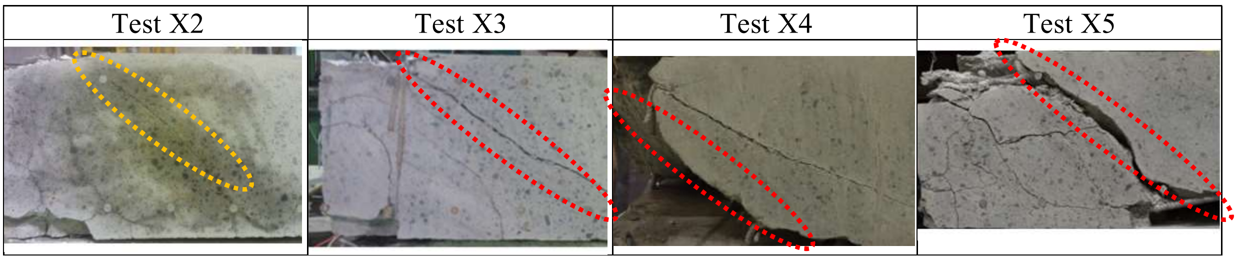

Figure 5. Cross sections of slabs after impact, wider crack observed. The dotted shape that highlights the wider crack is inclined at 37° from the slab plane

More details are given for punching resistance assessment with the RCC-CW code on X tests in Darraba et al.(2022). The main conclusion is that in a design purpose, without any contribution of the bending reinforcement as a net effect, a punching ratio equal to 1.0 results in a moderate damage of the slab, see Figure 6. Cracks are very small, the punching cone is not clearly visible, there are no or almost no plastic strain in shear reinforcement. For tests with advanced damage in the punching cone area, the punching ratio is close to 0.5.

If the objective is to estimate this kind of advanced punching damage state, a contribution of lower bending reinforcement can be added to the punching resistance. The punching failure of the slab is then fairly well predicted with the verification ratio.

In the tests X9 and X10, the bending reinforcement density is decreased and increased, respectively, with respect to the density in the reference test X8. This is affecting the displacements that are measured on the slab. However, the punching damage is not significantly modified.

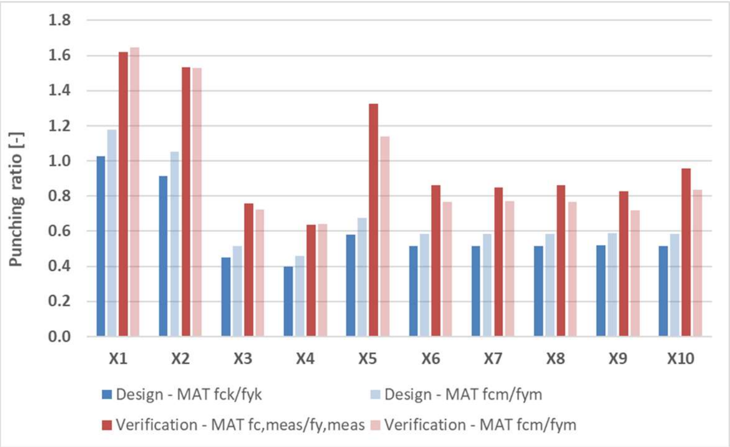

Figure 6. Punching ratio for combined X tests, in a design or a verification purpose

Summary

For the impact of a soft missile on a reinforced concrete slab, the punching resistance in RCC-CW (2021):

- Enables to make a relevant assessment, with quantified conservatisms, of the behavior of a reinforced concrete slab with respect to the punching damage ;
- Enables to quantify the ultimate damage state under punching, consistent with the experimental observations. This analysis deals with the contribution of concrete, the role of reinforcement, the geometry of the cone formed under the load (approximately 40° cracking angle).

LESSONS LEARNT FROM THE PUNCHING MATRIX (HARD IMPACTS)

In this test series, many parameters were studied, so that to better understand the resistance of a reinforced concrete slab to the hard impact of a rigid missile. Many formulas, analytical or semi-empirical ones, are available to estimate slab resistance to this kind of impact, see Li et al (2005) for instance. These formulas highlight the main part of the concrete strength in the slab resistance. The parameters of interest in the IMPACT “punching” test series are the shear reinforcement, the slab pre-stressing, the contribution of a steel liner anchored to the slab rear face, and others. Missile is a 168 mm diameter rigid missile, weighing approximately 47.5 kg and made of steel nose and pipe with light concrete filling. Impact velocities are in the approximate range of 100 m/s to 160 m/s.

Based on test results of a hard missile impact on a reinforced concrete slab, the increase of resistance to perforation of various slabs configurations is assessed in Galan and Orbovic (2015). Five impact tests on reinforced concrete slabs with bending reinforcement only are used as a “baseline” result of perforation capacity of reinforced concrete slabs.

The paper shows that experimental scattering is not significant for the five considered impact tests on reinforced concrete slabs with a variation of +/- 5 % around the calculated “experimental just-perforation velocity” (or ballistic limit) mean value. A step-by-step demonstration is then proposed in order to gradually assess the increase of resistance due to each experimental parameter (transverse reinforcement, pre-stressing, and combination of transverse reinforcement, pre-stressing and presence of a liner).

Perforation capacity of the reinforced concrete slab is not increased due to the presence of transverse reinforcement. This observation is due to the very localized hard impact damage mode, for the particular scale of the tests, slab and missile. This scale implies a particular failure mode of the slab for which the role of transverse reinforcement is not significant. This effect would not be applicable for larger scale structures, for which the transverse reinforcement is beneficial to the punching capacity of the slab. An increase of the perforation capacity can be identified, see the aforementioned paper, due to a 10 MPa pre-stressing of the slab (+10 % to +15%) and due to the combination of a 10 MPa pre-stressing in the concrete, the presence of transverse reinforcement and a liner (+20 % to +25 %).

Kar formula

The ballistic limit of the slab, or “just-perforation” velocity $\mathrm{V_{jp}}$, is estimated on the basis of the impact velocity, denoted $\mathrm{V_o}$, and of the residual velocity of the missile, denoted $\mathrm{V_R}$, both measured during the test. On the basis of the energy balance of the impact :

$$\mathrm{V_{jp}}(\theta) = \sqrt{\mathrm{V_o}^2 - \left(1 + \frac{\mathrm{M_c}(\theta)}{\mathrm{M}}\right)\mathrm{V_R}^2} \quad (1)$$

Where M is the mass of the missile and M_c is the mass of the concrete cone.

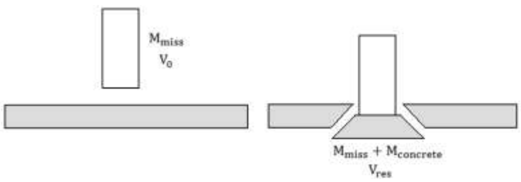

Figure 7. Schematic description of the energy balance of a test that reaches perforation

The concrete cone is actually destroyed during the missile penetration, and lots of small concrete pieces are ejected from the slab. The total mass lost can still be approximately measured after the test. It can also be predicted considering a cracking angle of 40°, which is consistent with the angle in appendix DC of the RCC-CW. In the IMPACT tests conditions, the 25 cm thick slabs, M_c is then estimated to 80 kg, assuming that concrete density is 2500 kg/m^3.

Figure 8 shows that the Kar formula, combined with the CEA-EDF perforation formula, can be used to estimate the residual velocity of the projectile after perforation. Tests P1, P2 and P3 are outside the IMPACT project and were performed in the frame of the OECD IRIS 2010 benchmark. The impact velocity of 135 m/s is nearly the same in all of the three tests. Missile mass and dimensions, as well as slabs dimensions and bending reinforcement, are the same as in punching tests of the IMPACT project. The concrete compressive strength was approximately the same in the three tests: 60.0 MPa for P1 measured on cylinder in test hall conditions, and 57.4 MPa for P2 and P3. It is considered that there is a low scattering in the measured residual velocities, as well as in the scabbed area of slabs. In all of the three tests, the cracking angle is high in a first step of the missile penetration, with almost straight failure of the slab, the angle could be estimated to 70° with respect to the slab plane, up to roughly one half of the slab thickness. In a second step of the missile penetration, the cracks angle decreases significantly to roughly 20°. This angle could have been higher with shear reinforcement in the slab. It results in the wide spread scabbing area observed. Consequently, the angle of 40° can be considered as a mean value of the cone angle through the slab thickness, from the observations of cracks angle through the slab thickness. The angle of 40° is also consistent with the angle proposed for the Kar formula in ERIN (2011) of 39°, once applied to the missile diameter and the slab thickness of the tests.

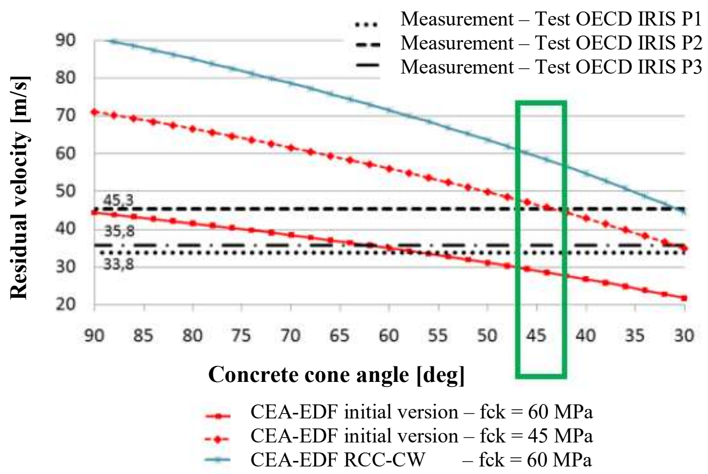

Figure 8. Residual velocity estimate with Kar and CEA-EDF formulas on OECD IRIS P1, P2 and P3 tests

CEA-EDF, modified version in RCC-CW (2021)

According to CEA-EDF formula from RCC-CW (2021), the just-perforation velocity is as follows :

$$V_p = 0.88 * \left[1.3784 * {\rho_C}^{1/6} * {f_{ck}}^{0.5} * \left(\frac{D*h^2}{M}\right)^{2/3} * N * \left(\frac{f_{ck}}{f_{co}}\right)^{-1/4} * \left\{0.35 * \left(\frac{m_a}{m_{ao}}\right)^{\gamma} + 0.65\right\}\right] \quad (2)$$

The just-perforation velocity is computed for various hard impact tests of the IMPACT project. It is given as a function of the concrete compressive strength, measured at the time of each test, in Figure 9. The initial and modified RCC-CW versions of CEA-EDF formula are used. As the latter depends on the bending reinforcement density, it is plotted for the following densities : 0.34 %, 0.69 % and 0.89 % each way each face. The following colors are used :

- blue corresponds to impacts on reinforced concrete slabs (0.34 %),
- violet corresponds to impacts on reinforced concrete slabs (0.69 %),
- green corresponds to impacts on reinforced concrete slabs (0.89 %),
- orange corresponds to impacts on pre-stressed concrete slabs (0.34 %).

For tests that did not reach perforation (“no perforation” is mentioned in the legend of the figure), the missile impact velocity V_0 is used in the figure, in a conservative way for the just-perforation velocity.

For tests that reached perforation (i.e. when nothing is mentioned in the legend of the figure), the figure shows the estimated just-perforation velocity with the Kar formula, on the basis of the measured residual velocity.

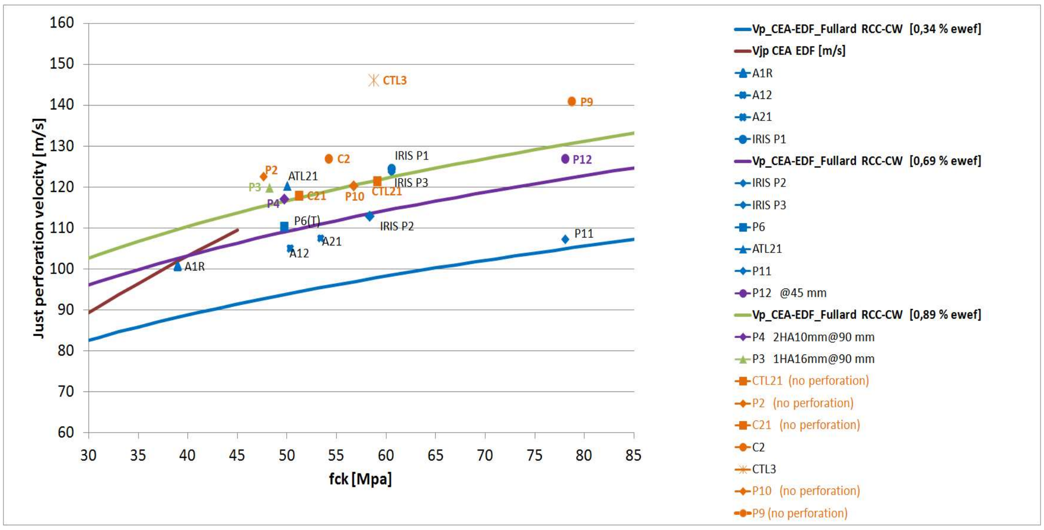

Figure 9. Just-perforation velocity, initial and modified RCC-CW versions of CEA-EDF formula, as a function of concrete compressive strength. Comparison with punching tests with three reinforcement densities, some of them with pre-stressing

The modified CEA-EDF formula from RCC-CW (2021) enables to assess the perforation resistance capacity of a slab with different bending reinforcement ratio, for a wide range of concrete classes.

The estimate of just-perforation velocity is relevant for all the impact tests with rigid projectiles carried out in the VTT IMPACT program. The margin depends on the concrete class, conservatism is noticeable up to fck = 60 MPa and slightly lower beyond this compressive strength.

It should be noticed that all of the analysed impact tests with rigid missiles are those for which the missile fulfilled its role, being almost not deformable missile. The tests for which the missile was deformed significantly (significant plastic strains, loss of material, welding defect, etc.), as in CT3R test, are not used in order to avoid skewing the analysis.

Summary

The effect of bending and shear reinforcement, pre-stressing or a liner anchored to the slab rear face are analysed in Galan and Orbovic (2015). Shear reinforcement does not significantly increase the resistance of the slab to perforation, at the scale of the slabs and missile in the tests. This is verified for the different types of shear reinforcement tested. This observation is consistent with the empirical perforation formulas. Shear reinforcement still reduces the volume of scabbed concrete on the rear face, as well as the surface of the scabbed concrete area, due to concrete confinement. At higher scales, it can be expected higher effect of shear reinforcement. Pre-stressing slightly increases the slab resistance, the more so as pre-stressing is combined to shear reinforcement and a liner.

The Kar formula, quoted in ERIN (2011), provides a relevant estimate of the residual velocity of a missile after perforation of the slab.

The CEA-EDF perforation formula in RCC-CW (2021) enables to assess the perforation capacity of a slab. It extends the validity domain of the original CEA EDF formula (f_{ck} from 30 MPa to 45 MPa, reinforcement density from 100 $kg.m^{-3}$ to 250 $kg.m^{-3}$). This is verified in particular for characteristic compressive strength of concrete up to 80 MPa and a wide range of bending rebar densities up to 0.9 % each way each face.

The estimated increasing perforation resistance with increasing concrete compressive strength is consistent with the experimental observations for high-performance concrete between 45 MPa and 80 MPa.

CONCLUSION

In IMPACT project phases II and III, three test series are summarized. In the "bending" tests series, many tests with the same very deformable missile and increasing impact velocity lead to conclusions about reinforced concrete slabs with dominating bending damage. The slab capacity, in terms of concrete strains, lower reinforcement strains and support rotations, is assessed.

In the second test series, a less deformable missile is used to better understand the punching resistance under soft impact. The main interest lies on the effect of shear reinforcement density, of shear reinforcement type and of bending reinforcement density. Punching resistance in the civil works code RCC-CW is evaluated so that the damage level in a design purpose can be assessed, based on analytical design method. The capacity to predict failure is also addressed.

In the third test series, punching damage under the impact of rigid missile is analysed. CEA-EDF formula from RCC-CW (2021) is well suited to predict the ballistic limit of slabs, including for high-strength concrete.

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