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QUANTIFICATION OF PERFORATION RESISTANCE OF PRE-STRESSED WALLS WITH TRANSVERSE REINFORCEMENT AND LINER UNDER HARD MISSILE IMPACT BASED ON TEST RESULTS

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ABSTRACT

Based on impact of hard missiles on concrete targets test results, the increase of perforation resistance of various slabs configurations, in comparison with reinforced concrete walls is assessed. 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 5 considered impact tests on reinforced concrete slabs with a variation of +/- 5 % around the calculated "experimental just-perforation velocity" 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, prestressing, and combination of transverse reinforcement, prestressing and liner). Perforation capacity of the reinforced concrete slab is not increased due to the presence of transverse reinforcement. This observation is due to the much localized hard impact scenario, implying a particular rupture mode of the slab for which the role of transverse reinforcement is not significant. An increase of perforation capacity can be identified in this paper, due to a 10 MPa prestressing of the slab (+10 % to + 15%) and due to the combination of a 10 MPa prestressing in the concrete, the presence of transverse reinforcement and liner (+20 % to + 25 %). This paper completes the observations made in Orbovic et al. (2009), (2011), (2013) and (2015).

INTRODUCTION

The hard impact tests presented in this paper were carried out at VTT test facility in Espoo, Finland. The present analysis is a continuation of the work performed in previous SMIRT papers, providing detailed insight in the phenomena related to hard impact on civil structures and their consequences. In this paper, additional results and analyses are presented.

Based on impact of hard missiles on concrete targets test results, the purpose of this paper is to quantify the increase of perforation resistance of pre-stressed walls with transverse reinforcement and liner, in comparison with reinforced concrete walls. Five impact tests on reinforced concrete slabs with bending reinforcement only (A21, A12 and the three punching tests performed during 2010 OECD_IRIS campaign P1, P2 and P3) are used as a "baseline" result of perforation capacity of reinforced concrete slabs. A21 is not described in detail because it is already presented in Orbovic et al. (2015). A step-by-step demonstration is proposed in order to gradually assess the increase of resistance due to each experimental parameter. For this purpose, the following impact tests, having the same set-up and design of the slabs, are also exploited:

- specimen P6 for which transverse reinforcement (T-headed bars) is added;
- specimen C2 for which a 10 MPa pre-stressing (ungrouted tendons) is added;
- specimen CTL3 for which a combination of a 10 MPa pre-stressing (ungrouted tendons), transverse reinforcement (T-headed bars) and liner are added.

In all these impact tests, perforation of the slab was achieved, that is to say that the missile passes through the slab with a residual velocity superior to 0. This choice will allow:

- calculating an "experimental just-perforation velocity" based on the measured impact and residual velocities;
- assessing the perforation capacity of slabs, in various configurations.

TEST SPECIMENS

The specimens which are analyzed in this paper have the following common characteristics:

- the projectile is hard cylindrical missile, constituted of a full of concrete 12.5 mm thick steel pipe, welded to a 50 mm thick steel dome (see Figure 1). This projectile has a constant 0.168 m diameter. Its mass is 47.5 kg;
- 2.1m*2.1m square reinforced concrete walls having a 0.25m thickness are used. The slabs are 2-ways simply supported, the supporting span being around 2.0 m in each direction (see Figure 2);
- Bending reinforcement layers whose characteristics are Φ10mm@90mm each way each face (i.e. 8.7 cm²/ml ew/ef leading to a 0.35 % reinforcement ratio ew/ef) are put in place (see Figure 2). The yield strength of steel is 500 MPa.

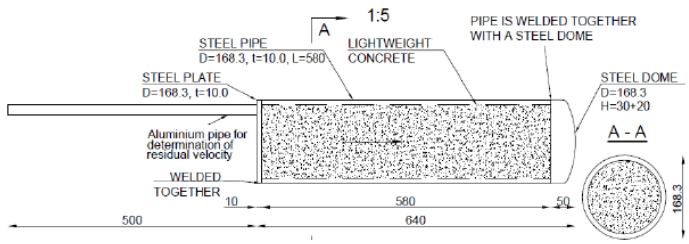


Figure 1. Hard missile used in the tests

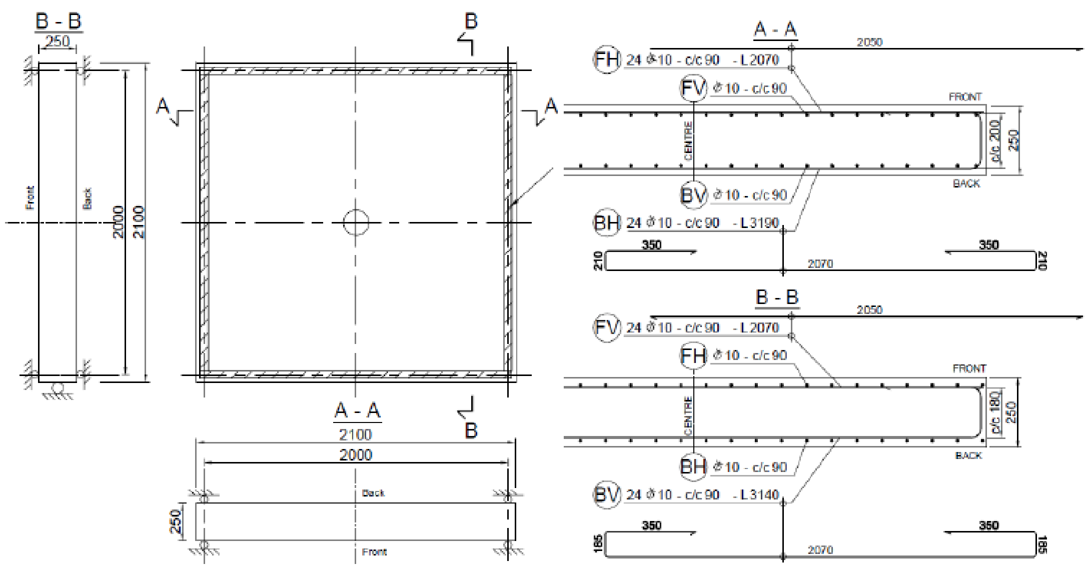


Figure 2. Baseline reinforced concrete specimen and reinforcement details

The slabs described in Figure 2 correspond to the ones of “baseline” specimen A21, A12, OECD IRIS P1, P2 and P3) with bending reinforcement only.

Three other specimens are analyzed. In specimens where transverse reinforcement is introduced (P6 and CTL3), one T-headed bar is placed at each intersection of longitudinal reinforcement (see Figure 3). The corresponding yield strength is 500 MPa.

In specimens where a 10 MPa pre-stressing in both directions is introduced (C2, CTL3), dywidag bars are put in PVC sleeves in order to avoid bond between the concrete and the pre-stressing bars (see Figure 3). The ultimate stress of the bars is f_{pu} = 1030 MPa. The bars are anchored with external anchors.

The liner used in test CTL3 is composed of three 1.5 mm thick welded steel plates, anchored at the edges of the concrete slab (see Figure 4).

The concrete compressive strength of specimens, casted at different times from different batches can vary (see **Table 1**).

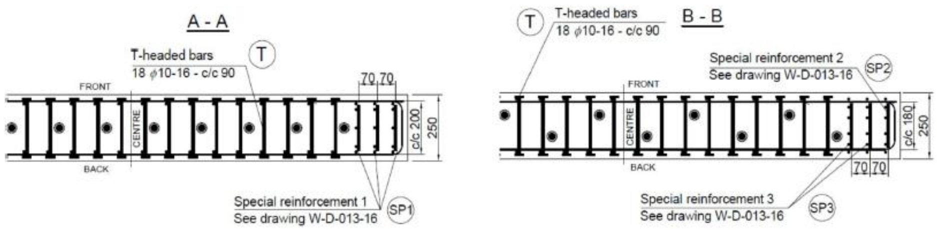


Figure 3. Description of pre-stressing rebars used in tests C2 and CTL3 and transverse reinforcement used in tests P6 and CTL3

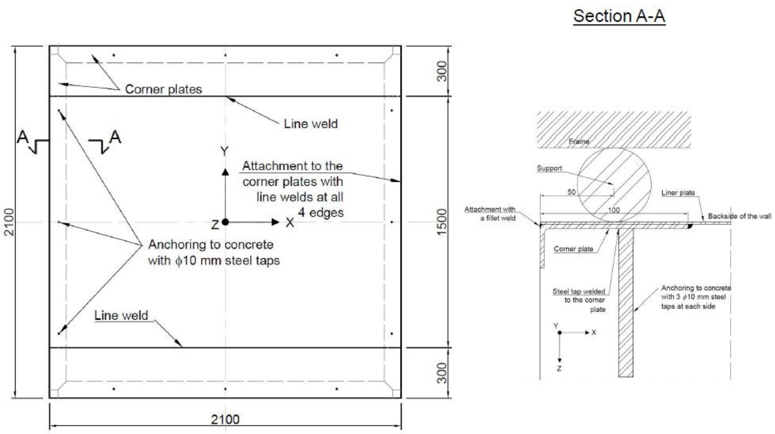


Figure 4. Description of the liner used in test CTL3

A synthesis table of the analyzed impact tests is given below:

Table 1 : description of the impact tests

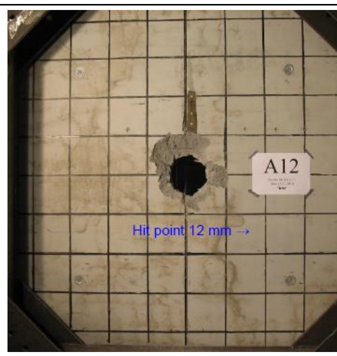
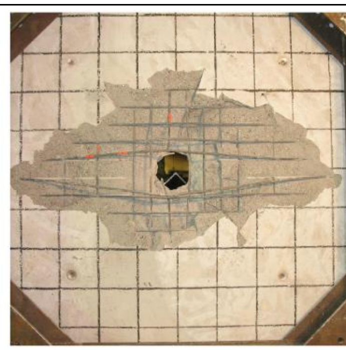
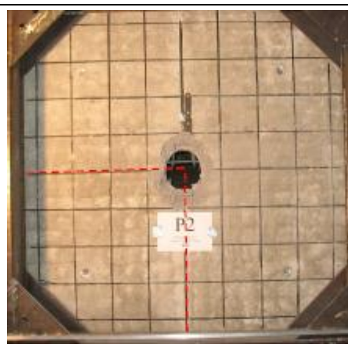
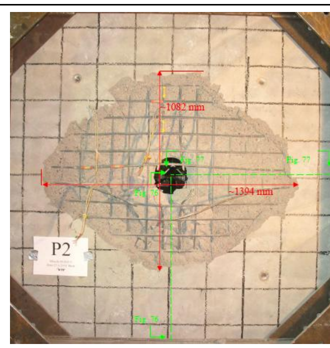
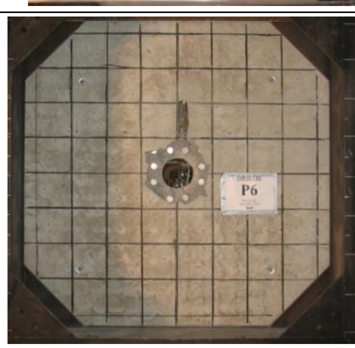
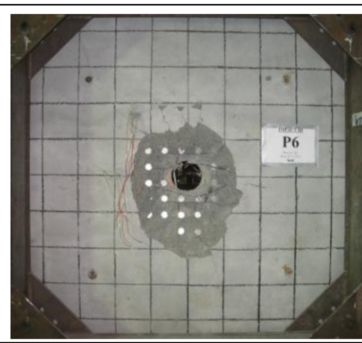
Test n°	**Transverse reinforcement**	**10 MPa Prestressing in the concrete**	**Liner**	**Concrete compression strength on cylinder f_{ck} [MPa]**	**Impact velocity Vo [m/s]**
A12	Bending reinforcement only			50.3	110,2
A21				55.3	120,2
IRIS P1				60,5	135,9
IRIS P2				58,3	134,9
IRIS P3				60,5	136,5
P6	T-headed bars Φ10mm@90mm = 96.9 cm²/m²	No	No	49.7	123,4
C2	No	10 dywidag bars Φ26.5mm@180mm = 31.8 cm²/ml ED (non grouted tendons)	No	54,2	141,6
CTL3	T-headed bars Φ12mm@90mm = 140 cm²/m²	Same as C2	1.5 mm thick liner	58.7	148,8

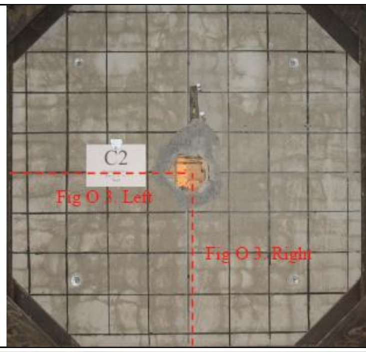
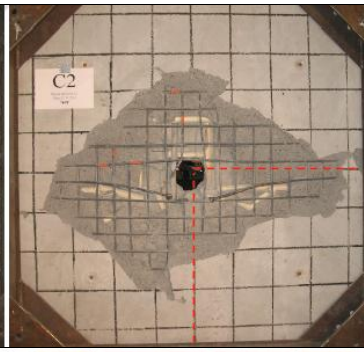
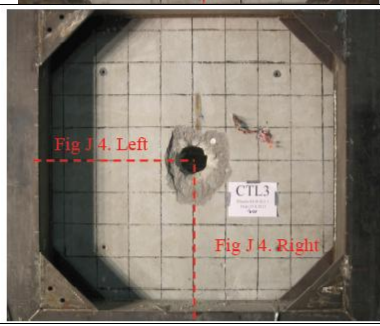
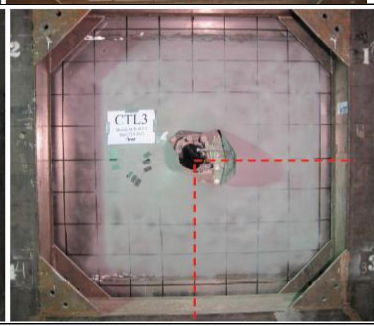
TEST RESULTS

Each specimen is perforated after the impact. The residual velocity of the missile after perforation is given in **Table 3**. A maximum of 2 horizontal and 2 vertical rebars (at front and rear faces of the slabs) were broken. In tests with pre-stressing, 1 or 2 dywidag bars are broken. The parameter playing a major role on the size of the scabbed area is transverse reinforcement ratio, as already mentioned in Orbovic et al. (2009). The scabbing area is approximately equal to 1 m² without T-headed bars and to 0.2 to 0.4 m² with T-headed bars.

An important point to have in mind is that in the tests chosen in this paper, the energy dissipated by deformation of the missile was not significant (see **Table 2**). These tests can be considered as "hard impact tests". As a consequence, the damage of concrete slabs can be compared from one test to another, and the influence of each parameter of the slab can be assessed.

Table 2 : Slabs and missiles after impact

Test n°	Front and rear faces of the slab after impact		Missile after impact
A12			
IRIS P2			
P6			

C2			
CTL3			

(*) *photos describing damage of A21 specimen are given in Orbovic et al. (2015)*

Numerical values describing main test results are given in **Table 3**:

Table 3 : Notable results of the considered impact tests

Test n°	**Residual velocity after peforation V_R [m/s]**	**Scabbing area Sc [m²]**	**Broken rebars in H and V directions**	**Mass of ejected concrete M_c [kg]**
A12	20,8	0.972	Front: 2H 1V Back : 1V	
A21	33,4	1.028	Front: 2H 2V Back : 1V	
IRIS P1	33,8	1.055	Front: 2H 2V Back : 1H 1V	30 – 60 kg
IRIS P2	45,8	1.0043	Front: 2H 2V Back : 1H 2V	116 kg
IRIS P3	35,8	1.123	Front: 2H 2V Back : 2H 1V	121 kg
P6	5,0	0.337	Front: 2H 2V Back : 2H 2V	
C2	39,0	0.999	Front: 2H 2V Back : 1H 1V Dywidag : 1H	
CTL3	17,5	0.205	Front: 2H 2V Back : 2H 2V Dywidag : 1H 1V	

PERFORATION CAPACITY OF SPECIMENS

The energy balance of hard impact can be written as follows:

$$E_0 = E_{jp} + E_m + E_R$$

Where:

- $E_0 = 0.5*M*V_0^2$ kinetic energy of the missile (with M and V_0 respectively the mass and impact velocity of the missile);
- $E_{jp} = 0.5*M*V_{jp}^2$ the energy necessary to just-perforate the wall with V_{jp} the just-perforation velocity of the structure;
- E_m the energy dissipated by deformation of the projectile. For hard missile impact, we consider that $E_m \sim 0$;
- $E_R = 0.5*(M+M_c)*V_R^2$ residual kinetic energy of the secondary projectile (including a concrete cone whose mass is equal to M_c) with V_R its residual velocity.

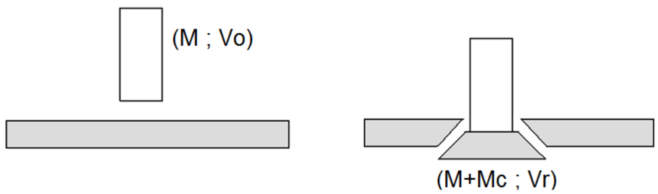


Figure 5. Definition of masses and velocities in the perforation process

Ejected concrete mass M_c is supposed to be a punching cone forming an angle $\alpha = \frac{\pi}{2} - \theta$ with the middle plane of the slab. Its characteristic radius are R (radius of the impacting projectile) and R_2=R+h*cotan(α). The ejected mass is calculated by:

$$M_c = \pi * \rho_C * \frac{h}{3} * (R^2 + R * R_2 + R_2^2)$$

With $\rho_c = 2500$ kg/m^3 concrete density and h the slab thickness.

Angle θ is calculated by Kar formula, as described in NEI 07-13 (2011): $\theta = \frac{45°}{\left(\frac{h}{2R}\right)^{1/3}} \leq 60°$

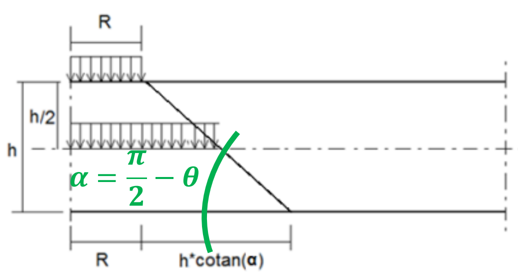


Figure 6. Definition of the punching cone angle

The numerical value of angle θ for all the considered impact tests is approximately equal to 40 degrees, using Kar formula. In some of the presented impact tests (in particular the ones with transverse reinforcement), the rupture mode of the slab is not clearly a punching cone with such an angle. In these cases, the rupture mode is close to a cylinder with a slight increase of the angle at the location of rear bending reinforcement (see Figure 7), with an angle of θ close to 0° (additional analysis on this topic is given in Orbovic et al. (2013)).

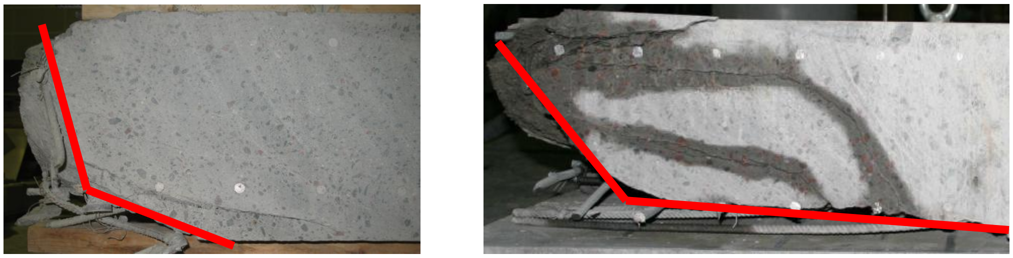


Figure 7. Horizontal cross sections of slabs P6 with transverse reinforcement (on the left) and IRIS P2 without transverse reinforcement (on the right)

A sensitivity analysis is carried out on this parameter because it influences the calculation of the ejected concrete plug mass. The ejected mass M_c is 75.6 kg for θ ~ 40° and 13.9 kg for θ = 0°.
In this paper, an "experimental just-perforation velocity V_{JP}" is estimated for a given slab configuration, knowing the measured residual velocity of the missile after perforation V_R, as:

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

The calculation is performed in the table below for θ = 40° and θ = 0°:

Table 4 : Calculation of "experimental just-perforation velocity" V_{jp}

	Test data		**Calculation for θ = 40°**	**Calculation for θ = 0°**
Test n°	Impact velocity **Vo [m/s]**	Residual velocity after perforation **V_R [m/s]**	"Experimental just-perforation velocity" **V_{jp} [m/s]**	
A12	110,2	20,8	105,0	107,6
A21	120,2	33,4	107,5	114,0
IRIS P1	135,9	33,8	124,5	130,4
IRIS P2	134,9	45,8	113,0	124,4
IRIS P3	136,5	35,8	123,7	130,3
P6	110,7	5,0	110,4	110,6
C2	141,6	39,0	126,9	134,5
CTL3	148,8	17,5	146,1	147,5

The "experimental V_{JP}" values given in **Table 4** cannot directly be compared between each test because the corresponding slabs do not necessarily have the same concrete compression strength (see **Table 1**).
As a consequence, the "experimental V_{JP}" values given in **Table 4** have to be corrected by a coefficient β_i taking into account this difference in the concrete compression strengths between each test.
Based on the CEA-EDF formula given in ETC-C (2012), it can be seen that the just-perforation velocity V_{JP} is proportional to the square root of concrete compression strength:

$$V_{jp} = \left[1.375 * {\rho_C}^{1/6} * {f_{ck}}^{0.5} * \left(\frac{D*h^2}{M}\right)^{2/3}\right] = \lambda * \sqrt{f_{ck}} \text{ with } \lambda \text{ a constant for these tests.}$$

The "experimental V_{JP}" values given in **Table 4** are consequently corrected by the following coefficient $\beta_i = \sqrt{\frac{f_{ck,base}}{f_{ck,i}}}$. Here, we take $f_{ck,base} = (f_{ck})_{A12}$ = 50.3 MPa.
In **Table 5**, the "corrected experimental just-perforation velocities" V_{JP}* are calculated by:

$$\boldsymbol{V_{jp}}^* = \sqrt{\frac{\boldsymbol{f_{ck,base}}}{\boldsymbol{f_{ck,i}}}} * \boldsymbol{V_{jp}}$$

The corrected V_{JP}* values can now be compared for each test because they correspond to the same concrete compression strength $f_{ck,base}$= 50.3 MPa.
Increase of perforation capacity for each slab configuration, in comparison with perforation capacity of reinforced concrete with bending reinforcement only, is then calculated by:

$\mu_i = \frac{(V_{jp}{}^*)_i}{(V_{jp}{}^*)_{rc}}$ with $(V_{jp}{}^*)_{rc} = mean\left((V_{jp}{}^*)_{A12}; (V_{jp}{}^*)_{A21}; (V_{jp}{}^*)_{IRIS-P1}; (V_{jp}{}^*)_{IRIS-P2}; (V_{jp}{}^*)_{IRIS-P3}\right)$.

The various coefficients μ_i are calculated in the following **Table 5**:

Table 5 : Corrected "experimental just-perforation velocity" V_{jp}*; increase of perforation capacity μ_i

	Test data	Calculation for θ = 40°		Calculation for θ = 0°	
Test n°	f_{ck} [MPa]	$V_{jp}{}^*$ [m/s]	**Ratio $\boldsymbol{\mu_i}$ [-]**	$V_{jp}{}^*$ [m/s]	**Ratio $\boldsymbol{\mu_i}$ [-]**
Baseline tests with reinforced concrete only **"RC"**					
A12	50,3	105,0	0,97	107,6	0,94
A21	53,4	104,3	0,96	110,7	0,97
IRIS P1	60,5	113,6	1,05	118,9	1,04
IRIS P2	58,3	104,9	0,97	115,6	1,01
IRIS P3	60,5	112,8	1,04	118,8	1,04
Effect of transverse shear reinforcement **"RCT"**					
P6	49,7	111,1	**1,03**	111,2	**0,97**
Effect of prestressing **"PC"**					
C2	54,2	122,3	**1,13**	129,5	**1,13**
Effect of prestressing combined with transverse reinforcement and liner **"PCTL"**					
CTL3	58,7	135,3	**1,25**	136,5	**1,19**

In **Table 5**, we can note that:
- Experimental scattering is not significant for the 5 considered impact tests on reinforced concrete slabs with a variation of +/- 5 % of the mean value $(V_{jp}{}^*)_{rc}$. This observation shows the good control of the performed impact tests and the high level of confidence of the corresponding results;
- 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 scenario, implying a particular rupture mode of the slab for which the role of transverse reinforcement is not significant (see Figure 7);

- A +10 % to +15% increase of perforation capacity can be identified in this paper, due to a 10 MPa prestressing of the slab;
- An increase of perforation capacity is observed, due to the combination of a 10 MPa prestressing in the concrete, the presence of transverse reinforcement and liner. This increase is estimated to be between +20 % to +25 %. This calculation allows quantifying the favourable effect of the combination of these parameters on perforation capacity against hard missile impact. It completes the qualitative observations made in Orbovic et al. (2011), on hard impact tests carried out at lower velocities (~100 m/s).

This increase of perforation capacity observed in test CTL3 could partly be explained by the triaxial confinement state of concrete, in both horizontal directions with prestressing and in the transverse direction with T-headed bars, which can significantly increase the concrete compression strength (see Figure 8). Another effect, due to the presence of dywidag bars into the slab, is discussed in Orbovic et al (2015) and Sagals et al (2015).

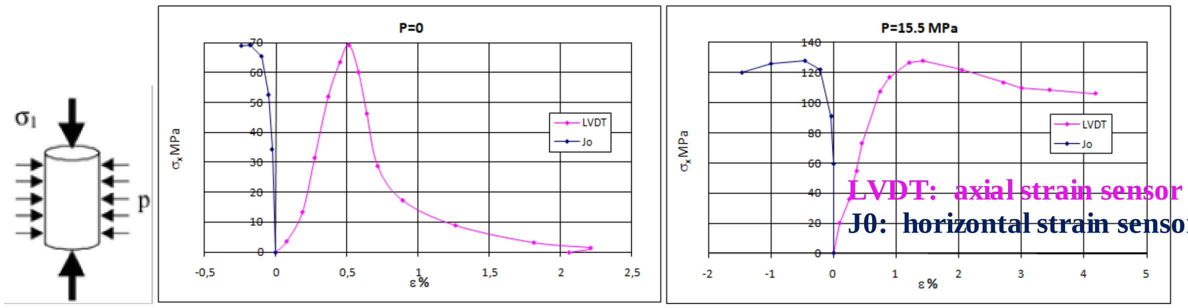


Figure 8. Triaxial tests on cylindrical concrete test pieces – input data from the OCDE_IRIS workshop 2012

Increase of concrete compression strength due to triaxial confinement can be calculated thanks to Eurocode 2 Part 1-1 (2005). By way of example, the lateral pressure σ_2 considered in the calculation is the 10 MPa due to prestressing.

$$\frac{\mathrm{f_{ck,c}}}{\mathrm{f_{ck}}} = 1.125 + 2.5 * \frac{\sigma_2}{\mathrm{f_{ck}}} \; for\ \sigma_2 > 0.05 * \mathrm{f_{ck}}$$

The increase of concrete strength $\frac{\mathrm{f_{ck,c}}}{\mathrm{f_{ck}}}$ is then assessed to be 1.55 in test CTL3 (with f_{ck} = 58.7 MPa).

As the just-perforation velocity V_{jp} is proportional to the square root of concrete compression strength, the increase of perforation capacity of the slab in a 10 MPa triaxial confinement state is estimated to be:

$$\frac{V_{jp,c}}{V_{jp}} = \sqrt{\frac{f_{ck,c}}{f_{ck}}} = \sqrt{1.55} \sim 1.25$$

This value can be considered as consistent with the calculated +20 % to +25 % increase of perforation capacity, based on CTL3 test result. On this topic, additional investigations should be carried out in order to more precisely assess the effect of confinement on perforation capacity.

CONCLUSION

Based on impact of hard missiles on concrete targets test results, the increase of perforation resistance of various slabs configurations, in comparison with reinforced concrete walls is assessed. The paper shows that experimental scattering is not significant for the 5 considered impact tests on reinforced concrete slabs with bending reinforcement, with a variation of +/- 5 % around the calculated “experimental just-perforation velocity” mean value, giving a high level of confidence in the results. An increase of perforation capacity is observed due to prestressing of the slab (+10 % to + 15%) and due to the combination of a prestressing in the concrete, the presence of transverse reinforcement and liner (+20 % to + 25 %). This increase could partly be explained by the favourable effect of concrete confinement in prestressed concrete slabs with transverse shear reinforcement.

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