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REINFORCED CONCRETE SLAB UNDER SOFT IMPACT AT MEDIUM SPEED : LESSONS LEARNED FROM VTT IMPACT PROJECT

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ABSTRACT

This paper presents some lessons learned from the impact tests performed by the Technical Research Centre of Finland (VTT) in the framework of the IMPACT Project, described in Lastunen et al., (2007), in which IRSN is involved. The typical experimental arrangement is a reinforced concrete (RC) square slab impacted by a deformable steel pipe, in its centre. The outputs of two series of tests are discussed: the ones in which the slab exhibits only flexural behaviour, called bending tests, and the ones in which some local punching is combined to a global bending of the slab, called combined tests. The paper focuses on the effect of liquid placed in some missiles, on the validity of simplified methods for the prediction of the target behaviour, and on practical assumptions that can be used.

EFFECT OF LIQUID CONTAINED BY THE MISSILE

The consequences of the impact of a missile or an airplane on a nuclear building are a safety technical issue as soon as the building plays a role for the safety of the facility. The importance of such an issue has been especially enhanced with the September 2001 event that showed that the crash of a commercial airplane had to be considered. From the beginning of IMPACT Project, tests were dedicated to that issue (see Tarallo et al., 2007 and Tarallo et al., 2009). In two recent series of tests of that project, the missile impacting the slab is a steel tube that can be partially or fully filled with water. The slabs dimensions are 2 m x 2 m x 150 mm, they are simply supported on four sides, and their longitudinal reinforcement is 5.65 cm^2/m each way each face. The whole mass of the missile is about 50 kg, the water content is either 0%, 50% or 75% of the missile mass. It has been observed that the performances of a missile containing water, in terms of maximal and permanent slab displacements, are significantly increased compared to those missiles of same total mass and of same hitting speed, but without water. That general finding is illustrated on Figure 1.

One reason comes from the impulse increase due to the splashing water rebound (see Tarallo et al., 2013). Another reason comes from the fact that the tube filled with water has a reduced length in order to accommodate a whole mass around 50 kg. Such length reduction has the effect to shorten the loading signal that raises the impact force and better excites the fundamental resonant frequency of the slab. Such qualitative conclusions are eased by the use of simplified models (see Rambach et al., 2008 for instance) that allow sensitivity studies. The series of L1 to L9 tests on RC slabs is completed by a series of “force plate” tests that measure the loading signal from the impacting missiles filled with different water amounts. The tests show explicitly that the vibration frequency of the slab decreases after the displacement peak, and even more sharply when the momentum increases. Conversely the damping increases when the momentum increases. Both terms are damaging markers.

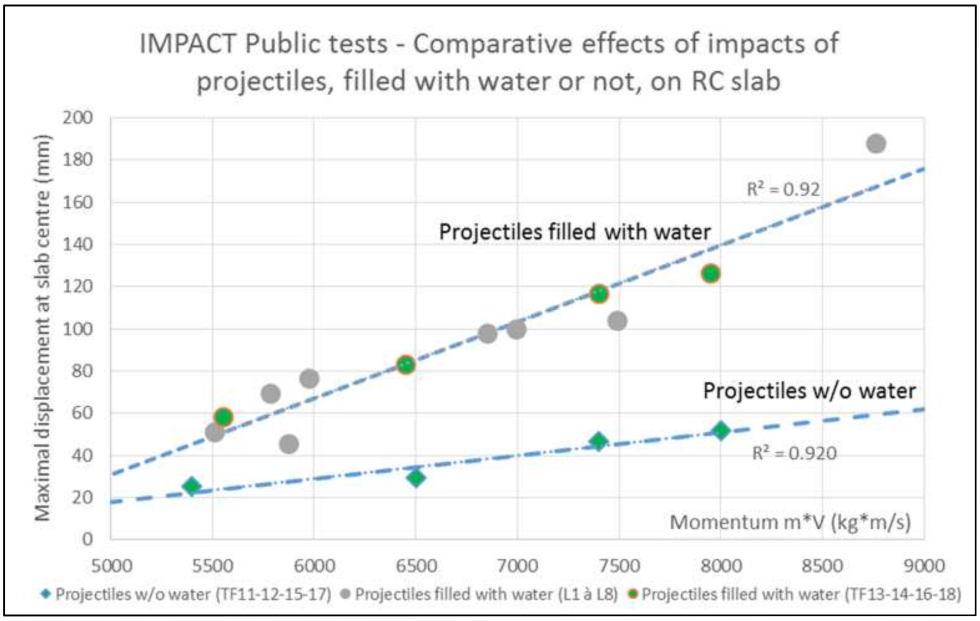

Figure 1. Comparative effects of impacts of projectiles, filled with water or not, on RC slab

PREDICTION OF BENDING BEHAVIOUR BY SIMPLIFIED MODELS

The prediction of bending behaviour is conducted with the help of a simplified model (see Rambach et al., 2008) build upon the following factors which are, by decreasing order of importance:

- the impact force time history: the better efficiency of the water filled projectiles can be taken into account by increasing the momentum transmitted to the slab,
- the limit bending moment at longitudinal rebars yielding,
- the rigidity, i.e. the vibration frequency, after the 1st displacement peak,
- the damping after the 1st displacement peak.

The simulation, by a SDOF (single degree of freedom) response model, of the slab behaviour during the different tests consolidates the following assumptions:

- the increase of the momentum due to the presence of water is about 12%,
- the value of the limit bending moment is consistent with the Ultimate Limit State computation of the RC section multiplied by a global DIF (Dynamic Increase Factor) of about 20%,
- the rigidity of the slab after the shock is roughly divided by a factor ranging from 3 to 6, depending of the damaging, i.e. the momentum,
- the after peak damping is comprised between 10% and 15%, depending of the damaging, i.e. the momentum.

Those practical lessons learned are not linked to a particular mechanical model, but they should be valid for any analysis, whatever the nature and the complexity of the numerical tools involved in the analysis.

COMBINED TESTS: A FEW LESSONS LEARNED

Thirteen tests of the IMPACT Project were designed so as the concrete slab impacted by a deformable missile shows both global bending and local punching failure modes. Those tests are called combined tests.

Typically, the slabs dimensions are 2 m x 2 m x 250 mm, reinforced by longitudinal and shear rebars, and the cubic resistance of concrete is in the order of 50 MPa. Missiles are stainless steel pipes, with a diameter between 200 to 300 mm, a length between 1.5 to 2 m, and their mass is generally equal to 50 kg. The impact velocity of the missiles range from 132 to 167 m/s.

In the framework of a sensitivity study, parameters of interest may differ from a test to another: for instance stiffness or velocity of the missile, amount or type of reinforcement. A few lessons learned from the combined tests are presented here below.

Effect of shear reinforcement. Scattering of the tests

In the combined tests set, three tests are designed for a study of the effect of shear reinforcement on the behaviour of the slab: tests X1, X2 and X5 are identical, except for the amount of shear reinforcement that is respectively equal to 17.1 cm²/m², 11.7 cm²/m² and zero. In the slabs of tests X1 and X2, only a moderate cone cracking is observed, with closed cracks, while the X5 slab exhibits cracks widths roughly equal to 30 mm. Those results confirm that shear reinforcement is needed to avoid a brittle failure of the slab, characterized by an important displacement of the punching cone.

Three other tests (X6, X7 and X8) are designed for a study of the effect of the shape of the shear reinforcement on the behaviour of the slab. Those tests are identical, including a shear reinforcement amount equal to 34 cm²/m², except for the shape of that reinforcement: closed stirrups for X6, double headed bars for X7 and c-shaped stirrups for X8. Those variations do not significantly affect the punching capacity and the bending behaviour of the slab, but a more important scabbing is observed on X7, equipped with double headed bars.

Based on the comparison (see Figure 2) of the results of tests X6, X7 and X8, the experimental scattering appears as low.

Effect of longitudinal reinforcement

Tests X9, X8 and X10 are designed for a study of the effect of the amount of longitudinal reinforcement on the behaviour of the slab, which is respectively equal to 5.6 cm²/m, 8.7 cm²/m and 12.6 cm²/m for those three tests. Tests X6 and X7, similar to X8, are added to the analysis. From the comparison of tests results, the longitudinal reinforcement controls linearly the displacement associated to the bending behaviour of the slab, as showed on Figure 2.

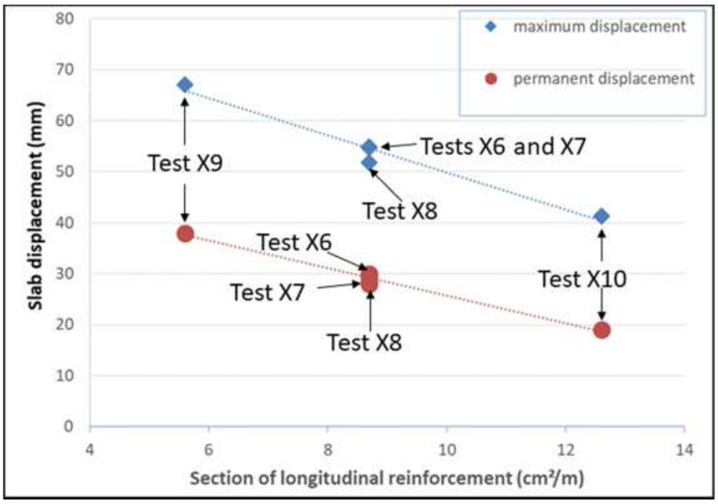

Figure 2. Combined tests sensitivity study. Effect of longitudinal reinforcement on the slab displacement

COMBINED TESTS: PREDICTION OF CONCRETE PUNCHING BY A DEFORMABLE MISSILE

Method for a punching failure prediction

A prediction of the failure of the slab, which can be successively cone cracking and perforation, is made using the method proposed in Barr (1990), along which the perforation should occur when the average dynamic load applied by the missile, noted F_{av}, reaches F_p, the dynamic punching capacity of the slab.

F_p is defined as follows: $F_p=8170(Rfcu)^{1/3}\pi T(D+2.5T)$, where R is the longitudinal reinforcement ratio, fcu the compressive strength of the concrete on cube, T the thickness of the slab and D the diameter of the missile, as shown on Figure 3.

A first application to the combined tests shows a non-conservative prediction for the slab X5 without shear reinforcement, and, more generally, the need of explicitly taking into account the shear reinforcement. As a consequence, the test X5, considered as not representative of usual civil structural elements, is excluded from the following analyses.

Then, the punching capacity due to the shear reinforcement is computed as proposed in the Appendix 1-C of ETC-C (2006): $F_{shear}=\pi T/\tan\alpha(D+T/\tan\alpha)A_{sw}f_{yk}$, where D is the diameter of the missile, A_{sw} the section of the shear rebars, F_{yk} the cylindrical compressive strength of the concrete, and α the angle of the punching cone.

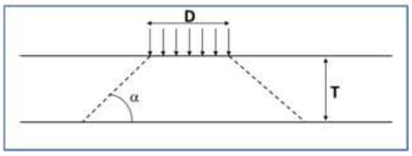

Figure 3. Notations for the punching analysis of a concrete slab

Finally, the total dynamic punching capacity of the slab is estimated as $F_{capac} = F_p + F_{shear}$, and the failure prediction is based on the ratio F_{capac}/F_{av}, called “margin factor” in the present paper.

In terms of nuclear safety, the absence of cone cracking and the absence of perforation are linked respectively to the requirements of confinement, support of equipment fixed to the wall, and protection of the components and structures placed behind the wall.

Failure prediction with observed values of parameters

In a first step, the margin factor is calculated with the observed values of the parameters presented on Table 1: duration of the impact, strength of concrete, yield strength of the rebars, and angle of the punching cone.

Table 1. Combined tests. Parameters for punching analysis: observed and theoretical values

Test number	Duration of the impact (ms)		Cubic compressive strength of concrete fcu [MPa]		Yield strength of shear reinforcement fyk [MPa]		angle of the punching cone (°)	
	observed	calculated	observed	theoretical	observed	theoretical	observed	theoretical
X1	13	12	41.6	50	550	500	32	40
X2	13	12	46.0	50	550	500	40	40
X3	5	6.5	52.8	50	550	500	33	40
X4	5	7	44.0	50	550	500	35	40
X6	5	7	60.1	50	550	500	28	40
X7	5	7	62.4	50	550	500	50	40
X8	5	7	63.9	50	550	500	29	40
X9	5	7	68.9	50	550	500	36	40
X10	5	7	67.7	50	550	500	37	40
X11	10.5	10	62.6	50	550	500	45	40
X12	5	7	69.5	50	550	500	36	40
X13	7.5	6.5	56.3	50	550	500	43	40

The margin factor, and the punching damage observed during the test are represented for each test on Figure 4. It can be noticed that:

- when the margin factor is roughly equal to or smaller than one, a perforation may occur (test X4) or a punching cone is fully developed with cracks significantly opened, potentially leading to perforation (test X7),
- when the margin factor is superior to two, a punching cone might appear, which cracks are not opened,
- if the margin factor is between one and two, the result seems more uncertain, the cracks may significantly open.

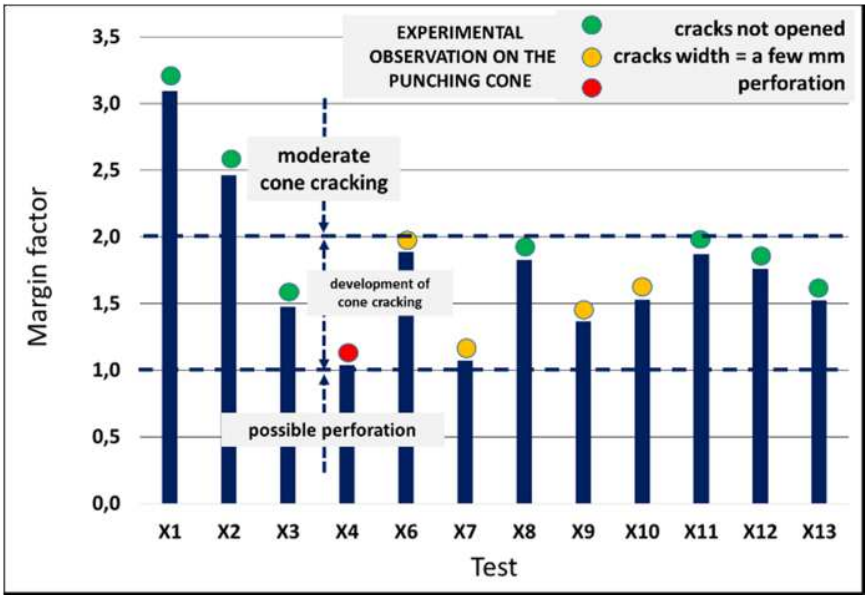

Figure 4. Punching failure on combined tests. Predictions with observed values of the parameters, and experimental observations

Failure prediction with theoretical values of parameters

In a second step, the same approach as above is followed, but with assumptions corresponding to the usual practice in civil engineering projects, when the as-built characteristics of the materials are not known. Then, theoretical values of the main parameters are chosen: duration of the impact derived from the Riera method, and theoretical values of the parameters presented on Table 1.
Based on the results presented on Figure 5, the method is not very discriminating: a margin factor smaller than 1.5 is found both for the test X4 with perforation and for the tests with moderate punching damage (X3 and X13). However, it can be observed that a perforation is avoided when the margin factor is higher than 1.5, and the cone cracking remains moderate (cracks not opened) when the margin factor is higher than two.

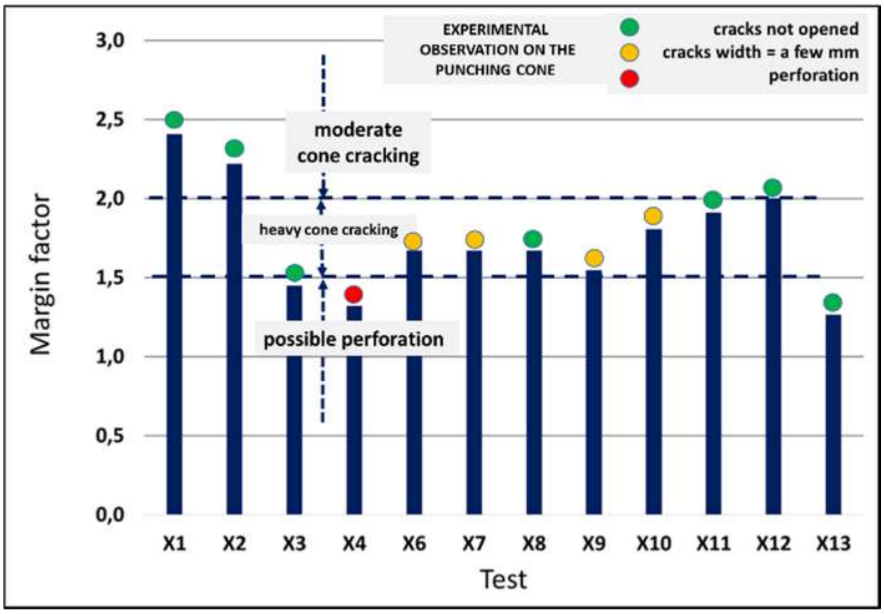

Figure 5. Punching failure on combined tests. Predictions with theoretical values of the parameters, and experimental observations

Synthesis: Prediction of the punching failure of a reinforced concrete slab impacted by a deformable missile

The analysis of the combined tests of IMPACT Project leads to the following recommendation concerning the margin factor method proposed above, for the prediction of the punching failure of a reinforced concrete slab impacted by a deformable missile:

- to limit the damage of the slab to a moderate cone cracking, the margin factor should be higher than two,
- to prevent perforation, the margin factor should be higher than 1.5.

However, those values still need to be confirmed with other experimental data, obtained either in the framework of the IMPACT Project, or in the scientific literature.

Scabbing prediction

A prediction of the scabbing of the slabs of combined tests is made hereinafter using the method proposed in Barr (1990). In this approach, the average dynamic load F_{av} applied by the missile is similar to the one used in the punching failure prediction presented above, but the capacity of the slab is defined as follows: $F_p=7040(Rfcu)^{1/3}\pi T(D+2.5T)$, with the same notations as above.

In the scabbing prediction, the shear reinforcement is not taken into account, and the margin factor is equal to F_p / F_{av}.

Taking into account the theoretical values of parameters (duration of the impact and strength of concrete), the theoretical margin factor associated to scabbing prediction is compared to the experimental observations, as presented on Figure 6. That comparison confirms the validity of the method, with a value of the margin factor equal to one: when the value of the margin factor is higher than one, no scabbing or only light scabbing is expected.

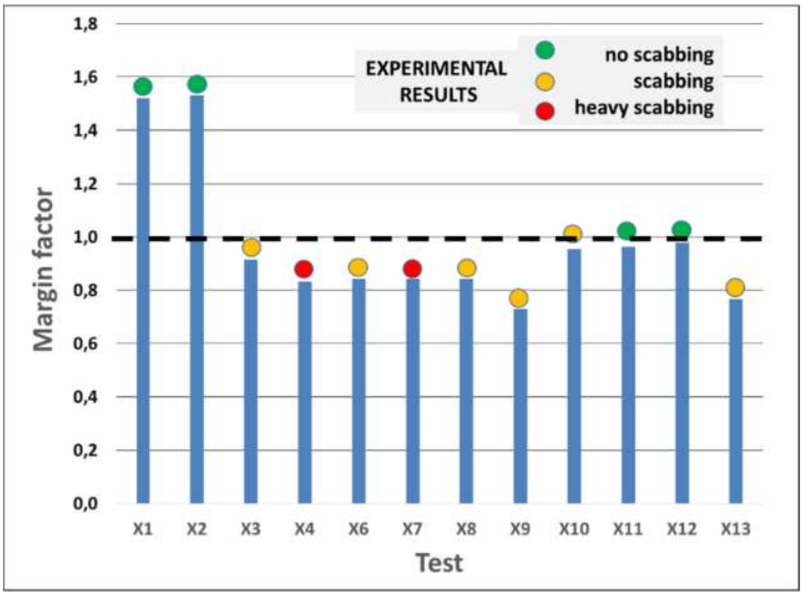

Figure 6. Scabbing in combined tests. Predictions with theoretical values of the parameters, and experimental observations

LOSS OF STEEL-CONCRETE BOND IN CASE OF CONCRETE CRACKING AND SCABBING

During the bending tests and the combined tests of the IMPACT Project, strain gauges fixed to the bars provide useful measurements. In the zones of the plastic hinges clearly visible on Figure 7, the strains recorded during the impact frequently reach 3 % or 5 %, while the permanent strains after the test frequently range between 2 % and 3 %. Those values are similar to the ones adopted as criteria in the nuclear safety cases.

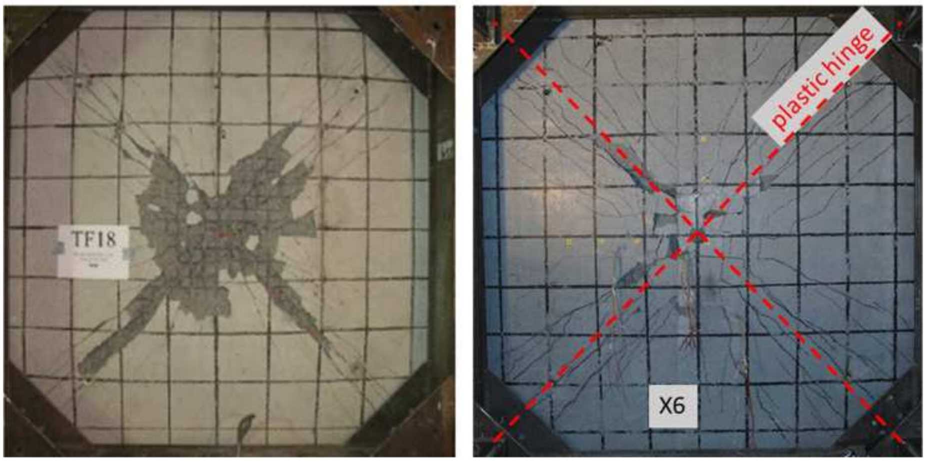

Figure 7. Back sides of the concrete slabs after the impact test: examples of bending test TF18 and combined test X6. Cracking associated to plastic hinges, and scabbing.

Two degradation phenomena, at work during the impact, may affect the steel-concrete bond within the reinforced concrete slab:

- concrete scabbing caused by the impact, locally removing the confinement of the rebars provided by the concrete cover, which is an adverse condition to the steel-concrete bond;
- flexure of the slab creating plastic hinges when the elastic resistance of the slab is exceeded, and concrete cracking detrimental to the steel-concrete bond.

Those phenomena have only little consequences on the mechanical behaviour of the structural element as long as the rebars are continuous in the concerned area. But, if the bars are spliced by lapping, which is the usual case in existing civil structures, a local loss of steel-concrete bond may cause the failure of the structure, as shown on Figure *8*. That risk must be investigated, in order to precise which maximum rebar strain value can be accepted when an efficient steel-concrete bond is required. Hence, impact tests involving overlapping rebars shall be carried out in the next phase of the IMPACT Project.

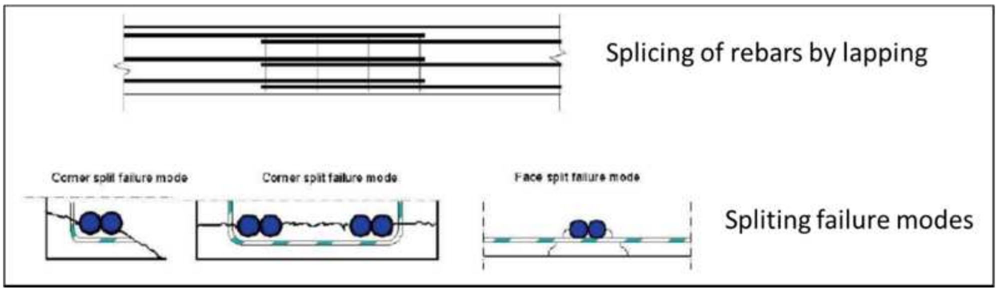

Figure 8. Splicing of rebars by lapping, and failure modes. From FIB (2014)

CONCLUSION

The phases 1, 2 and 3 of the experimental IMPACT Project have been conducted over more than ten years. They have provided valuable data concerning the behaviour of deformable missiles and reinforced concrete targets during medium velocity impacts, and they have pushed to the development of simplified methods of structural analysis, useful for engineering purposes.

Concerning impacts involving deformable missiles and a bending behaviour of the targets, the tests appear as consistent and repeatable. The tests show explicitly that the vibration frequency, i.e. the stiffness, of the slab decreases after the displacement peak, and even more sharply when the momentum increases. Conversely the damping increases when the momentum increases. Both parameters are damaging markers. For the prediction of the dynamic behaviour of the concrete target with the help of a simplified model, three main parameters must be estimated: the stiffness, the damping, and the limit bending moment of the slab. The authors propose typical values for those parameters.

Two series of tests were designed to study the effect of liquid contained by the missile. The greater severity of impact observed for tests in which missile is partially filled with water compared to the "dry" missile tests, is due to a greater impulse, corresponding to the splashing water rebound, but also to a shorter loading duration that raises the impact force and better excites the fundamental resonant frequency of the slab. In addition, due to the nonlinear behaviour of the slab in post elastic domain, the motion is sensitive to the shape of the loading signal.

Concerning impacts involving a severe local loading of the slab by a deformable missile, the risk of punching failure and the occurrence of scabbing can be assessed by a simplified classical method, with reasonable uncertainty.

Another issue is the effectiveness of the steel-concrete bond when the loading of the slab is important. In many of the impact tests, just like in "real world" projects and assessments, the dynamic response of reinforced concrete slabs involves significant strains in the rebars, while concrete scabbing is frequently observed. This situation obviously degrades the steel-concrete bond, and may cause the failure of the structural element, especially if the bars are spliced by lapping. That risk will be investigated, with the help of dedicated tests to be carried out in the framework of the next phase of the IMPACT Project.

The results and information gained through that project being abundant, more thinking and studies are needed to draw all the useful lessons. In particular, the simplified calculated methods presented in the present paper, and in previous ones, will be validated with other experimental data, obtained either in the framework of the IMPACT Project, or in the scientific literature.

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