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TESTS TO DETERMINE THE INFLUENCE OF TRANSVERSE REINFORCMENT ON PERFORATION RESISTANCE OF RC SLABS UNDER HARD MISSILE IMPACT

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ABSTRACT

This paper presents the results of three tests on reinforced concrete slabs under hard missile impact with the goal to assess the influence of transverse reinforcement on their perforation capacity. Based on tests with missile velocity below perforation velocity performed by the authors, it was expected that transverse reinforcement improve the perforation resistance. Three slabs are tested under almost identical conditions with the only variable in transverse reinforcement. One slab was designed without transverse reinforcement, the second one with the transverse reinforcement in form of conventional stirrups with 180 degree and 135 degree hooks on two ends respectively and the third with the transverse reinforcement in form of T-headed bars. Although the transverse reinforcement reduces the overall damage of the slabs (the rear face scabbing), the conclusion of the tests is that the transverse reinforcement does not have important influence on perforation capacity of concrete slabs under hard missile impact. However, the slab with T-headed bars presented slight improvement comparing to the baseline specimen without transverse reinforcement. The slab with conventional stirrups presented slightly lower perforation capacity (higher residual missile velocity) than the slab without transverse reinforcement. Therefore, performed test show better performances of transverse reinforcement in form of T-headed bars than conventional stirrups with 180 degree and 135 degree hooks regarding perforation capacity under hard missile impact.

INTRODUCTION

This paper presents three tests performed by the Finnish company VTT as a part of IMPACT program. The paper is a follow-up of the papers presented by the same authors in Orbovic et al. (2009) and Orbovic and Blahoianu (2011) with the goal to determine the influence of transverse reinforcement on perforation resistance of RC slabs under hard missile impact. The empirical formulae for perforation of reinforced concrete elements (slabs) are established for the elements with longitudinal reinforcement only; transverse reinforcement is not taken into account. The tests with missile velocity below the perforation velocity in Orbovic and Blahoianu (2011) clearly show an improvement in overall behavior RC slabs behavior with transverse reinforcement under hard missile impact. Therefore, it is expected to have the same improved behavior for just perforation velocity and to increase perforation capacity of concrete elements.

TEST SETUP AND INPUT PARAMETERS

The VTT facility and the test setup were described in Lastunen et al. (2007). The tests are preformed using the same Ø 169 mm diameter, 47.4 kg hard missile, against the same simply supported 2-way RC slab (2.1 m x 2.1 m x 0.25 m, with 2.0 m span in both directions) as in Orbovic et al. (2009) and Orbovic and Blahoianu (2011) Figure 1. The concrete with very similar unconfined compressive strength was used in all cases three cases: 39.0 MPa, 39.0 MPa, and 40.6 MPa, respectively. The only variable was transverse reinforcement.

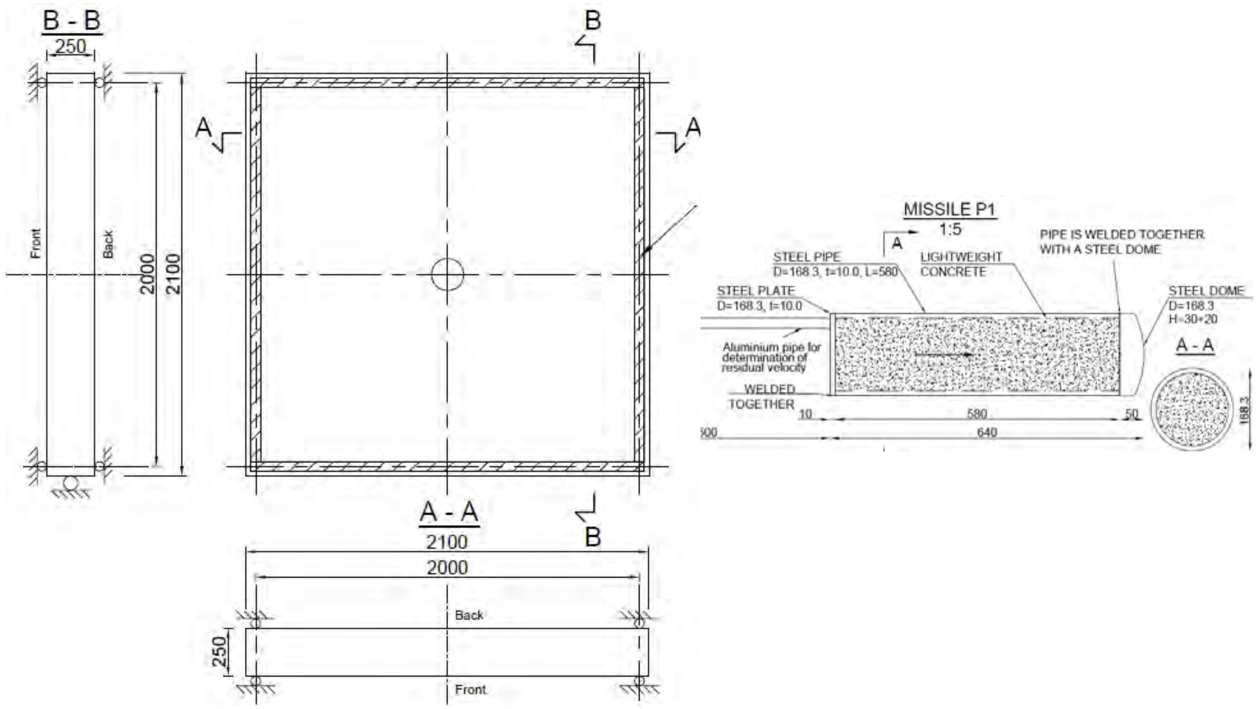


Figure 1 Concrete slab and the missile used in the tests

The longitudinal reinforcement is identical in all three slabs. The transverse reinforcement of the second and the third slab is identical in terms of re-bar diameter, spacing and material properties. The first slab is with longitudinal reinforcement only (Ø10 mm @ 100 mm EF/EW). The total reinforcement ratio is 1.4%, without counting lap splices. The second one is with T-headed bars at each intersection of longitudinal reinforcement (Ø12 mm). The third slab is with stirrups (Ø12 mm) with 180° hook at one end (rear) and 135° hook, at the other end (front). The transverse reinforcement is placed at each intersection of longitudinal reinforcement, as presented at Figure 2. In both cases the transverse reinforcement ratio is 1.4%, without taking into account the hooks and the bar heads. Therefore, the second and the third slab are heavily reinforced in transverse direction in order to achieve a distinct difference in the behavior comparing to the slab without transverse reinforcement.

The target velocity was established using Chang's formula for just-perforation (1) and for given parameters of the first two tests this velocity is 104 m/s (missile goes through the slab and stops with residual velocity equal to 0).

$$V_{Chang} = \left(\frac{h * f_c'^{0.5} * D^{0.5}}{0.0009 * W^{0.5}} \right)^{1/0.75} \quad \text{[m/s]} \qquad (1)$$

The domain of applicability of Chang's formula for perforation is as follows:

$$\begin{gathered}16\ \text{m/s} \leq v \leq 312\ \text{m/s} \\ 22.8\ \text{MPa} \leq f_c' \leq 45.5\ \text{MPa} \\ 0.11\ kg \leq \text{W} \leq 343\ kg \\ 51\ \text{mm} \leq \text{D} \leq 305\ \text{mm}\end{gathered} \tag{2}$$

Where v is missile velocity, f_c' is unconfined concrete compressive strength, W is missile mass and D missile diameter. The present test is within defined limits for Chang's perforation formula. However, the limits don't mention the longitudinal or transverse reinforcement ratio. It is supposed to be applicable to any longitudinal or transverse reinforcement ratio.

Figure 2 Transverse reinforcement in form of T-headed bars (above)
and conventional stirrups with 180 degree hooks (on the right)

TEST RESULTS

The results of the tests are presented in terms of residual missile velocity and overall damage in terms of spalled, scabbed and cracked (front and face). Just perforation velocity was targeted and achieved velocities were very similar in all three tests and close to target velocity: 102.2 m/s, 102.2 m/s, and 101.4 m/s, respectively.

The third slab with conventional stirrups has slightly higher unconfined concrete compressive strength and slightly lower missile impact velocity. If all other parameters were kept the same, its performance in terms of perforation resistance should be roughly 5% better than the first two slabs, which is not significant.

First Test – Slab with Longitudinal Reinforcement Only

In the case of the first slab (longitudinal reinforcement only) the residual velocity was 12 m/s (11.7 % of initial velocity). It should be noticed that the missile test velocity was below just-perforation velocity according the Chang's formula. However, the residual velocity was 12 m/s. There is an inherent uncertainty in application of empirical formulas and codes and standards recommend a coefficient 1.2 to cover this uncertainty.

The front and rear face after the test are presented on Figure 3. Scabbed area on the rear face is 1.027 m^2 and additional cracked area is 0.33 m^2 which makes total damaged area on the rear side of 1.357 m^2.

A half of the horizontal cut in the middle of the slab is presented in Figure 4 with highlighted the "tunnel" created by the missile entering the slab at the front face (with the depth going beyond the layers of longitudinal reinforcement) and the punching cone defined with the angle $\theta = 34^o$ to the horizontal axes. The horizontal reinforcement was pulled out by the perforating missile creating scabbing of the concrete through entire width of the slab. There is no visible crack in the remaining concrete in the vicinity of the damaged area.

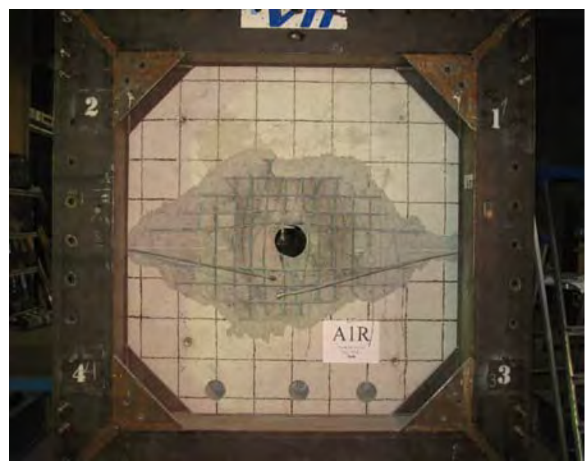


Figure 3 Front and rear side of the slab with longitudinal reinforcement only, after the test

Second test – slab with longitudinal and transverse (T-headed bars) reinforcement

In the case of second slab (transverse reinforcement in form of T-headed bars) the missile made a through-wall-hole and was eventually stuck in the wall without passing through. Therefore the residual velocity is equal to 0 and the missile did not go through the wall. The front and the rear side of the specimen after the test are presented on Figure 5.

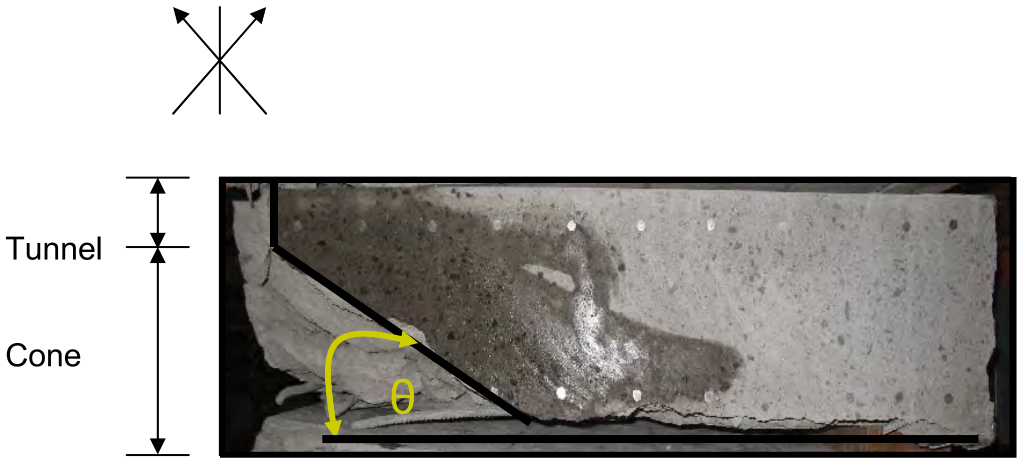


Figure 4 Horizontal cut in the middle of the slab without transverse reinforcement

The diameter of the hole in the slab is 17 cm (missile diameter 16.8 cm). A superficial spalling on the front face represents concrete cover. Scabbed area is 0.258 m^2 with additional cracked area of 0.090 m^2 making total damaged area on the rear face of 0.348 m^2. Four T-headed bars are ejected from the slab. Two horizontal and one vertical re-bars are broken. Two re-bars from the first layer horizontal reinforcement were retained by the second raw of T-headed bars. The second layer of the vertical reinforcement was retained by the first row of T-headed bars which reduced significantly the width and the depth of the scabbed area.

Figure 5 Front and rear side of the slab with longitudinal reinforcement and transverse reinforcement in form of T-headed bars after the test

On the rear face, beyond the longitudinal reinforcement, the concrete cover is pulled out up to the third longitudinal bar in vertical direction. Through the thickness of the slab, in the vicinity of the tunnel created by the missile, a series of four inclined cracks can be noticed (dashed bright lines). Without transverse reinforcement this part of the slab would be pulled out creating a punching cone. The strains of the transverse reinforcement were not measured. The width of the cracks during the impact is unknown.

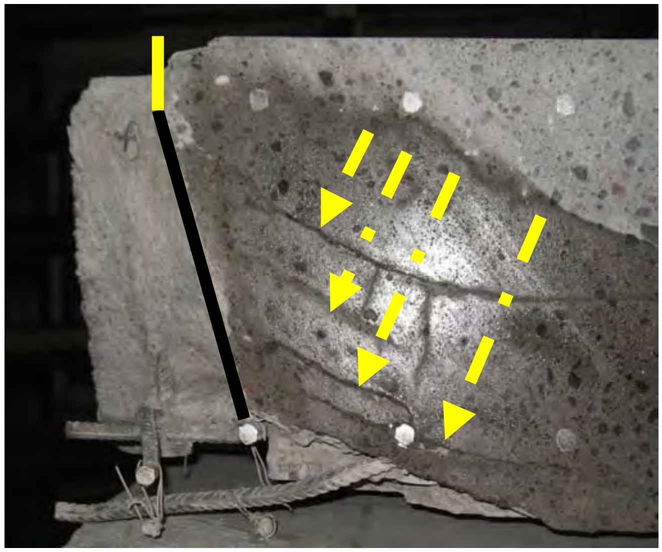


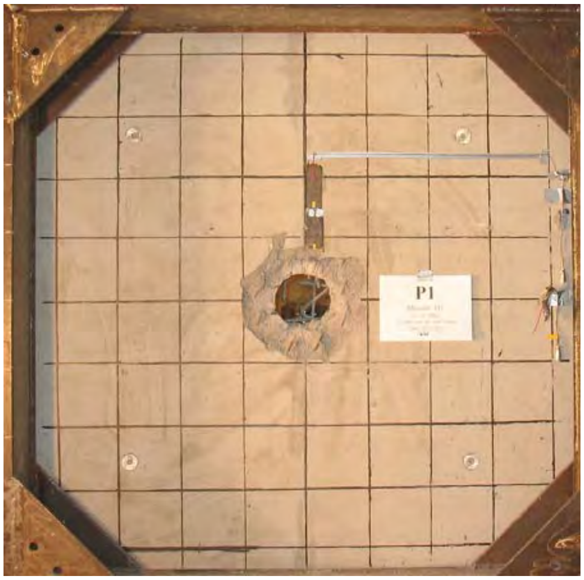
Figure 6 Detail of the horizontal cut in the middle of the slab with transverse reinforcement

Figure 6 shows that the presence of transverse reinforcement modified significantly the perforation mechanism comparing to the slab with longitudinal reinforcement only. The punching cone can not be clearly defined as in the previous case. A tunnel with the diameter of the missile can be noticed up to the first layer of the front face reinforcement (bright line). Through the thickness of the slab the tunnel

becomes larger but only up to the next transverse reinforcement in place at the intersection of rear longitudinal reinforcement (black line).

Third test – slab with longitudinal and transverse (conventional stirrups) reinforcement

In the case of the third slab (transverse reinforcement in form of stirrups with hooks at both ends) the residual velocity was 17 m/s (16.8% of initial velocity). The front and the rear side of the specimen after the test are presented on Figure 7. The diameter of the hole in the slab is 17 cm (missile diameter 16.8 cm). A superficial spalling on the front face represents concrete cover. Scabbed area is 0.250 m^2 with additional cracked area of 0.193 m^2 making total damaged area on the rear face of 0.443 m^2. Four stirrups are ejected from the slab and four longitudinal re-bars broken (two in each direction). On the rear face, beyond the longitudinal reinforcement, the concrete cover is pulled out up to the third longitudinal re-bar in vertical direction. Through the thickness of the slab, Figure 8, in the vicinity of the tunnel created by the missile, a series of two inclined cracks can be noticed (dashed bright lines). Without transverse reinforcement this part of the slab would be pulled out creating a punching cone. The strains of the transverse reinforcement were not measured. The width of the cracks during the impact is unknown.



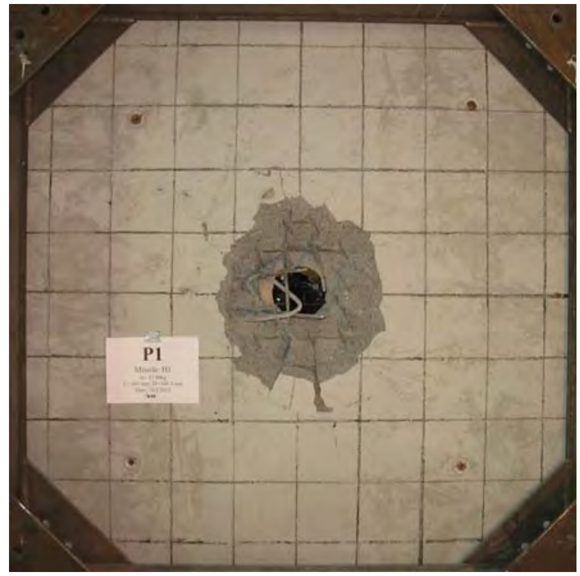


Figure 7 Front and rear side of the slab with longitudinal reinforcement and transverse reinforcement in form of conventional stirrups, after the test

Figure 8 shows that presence of transverse reinforcement modified significantly the perforation mechanism comparing to the slab with longitudinal reinforcement only. The result is very similar to the previous test with T-headed bars.

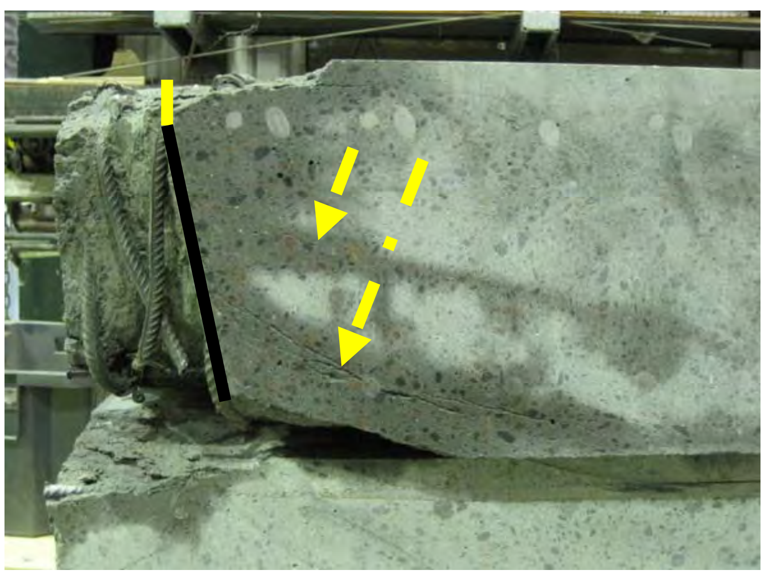


Figure 8 Detail of the horizontal cut in the middle of the slab with transverse reinforcement

A tunnel with the diameter of the missile can be noticed up to the first layer of the front face reinforcement (bright line). Through the thickness of the slab the tunnel becomes larger but only up to the next transverse reinforcement in place at the intersection of rear longitudinal reinforcement (black line).

DISCUSSION

Three tests are performed in order to assess the influence of transverse reinforcement on perforation velocity under hard missile impact. High reinforcement ratio of transverse reinforcement (1.4%, equal to the total reinforcement ratio in longitudinal direction) was chosen with the goal to achieve distinct difference in behavior of slabs with and without transverse reinforcement. These tests are a follow up of the tests presented in Orbovic et al. (2009) which were performed with the missile velocity under perforation velocity. The test campaign showed significant improvement of the behavior of concrete slabs with shear reinforcement comparing to the slabs without transverse reinforcement under impactive loading. It was expected to get similar results for missile velocities equal or higher than just perforation velocity. Moreover, the goal was to assess the difference between T-headed bars and conventional stirrups with 180 and 135 degrees hooks. The summary of the results is presented in Table 1. Regarding the residual velocity, the specimen with stirrups presented the weakest performance in term of perforation resistance.

Table 1: Test results in terms of residual missile velocity and damaged area at the rear side of the slab

Test	Longitudinal reinforcement only	Longitudinal and transverse reinforcement in form of T-headed bars	Longitudinal and transverse reinforcement in form of conventional stirrups
Residual velocity	12 m/s	0 m/s, the missile made a through hole but did not pass through	17 m/s
Damaged area on the rear side of the specimen (scabbed + cracked area)	1.357 m^2	0.348 m^2	0.443m^2

The specimen with T-headed bars presented the best performance and the specimen without transverse reinforcement is in between. Residual velocities were, respectively, 17 m/s (11.7% of initial velocity), 0 m/s, and 12 m/s. Despite significant amount of transverse reinforcement, the difference in residual velocity is not significant between the slabs with only longitudinal reinforcement and the transverse reinforcement in form of stirrups. Based on these test results it can be argued that transverse reinforcement do not have any role in "tunneling" portion of missile perforation (right in front of the missile nose through whole thickness of the wall). Moreover, it can play a role of a hard perforator with a "chisel effect". Hooks can even make the destruction of the concrete and perforation of the missile easier. In the case of T-headed bars, the heads contribute to the concrete confinement. They also distribute the forces and deformations to the concrete in more uniform way and that can explain that the obtain results were better with T-headed bars. It can be argued as well that the key parameter of the concrete resistance in this "tunneling" portion is its confined compressive strength. Regarding the overall damage, transverse reinforcement plays an important role in "punching cone" portion of missile perforation. Once again T-headed bars perform better that stirrups but the difference is less pronounced than in the case of perforation capacity and residual missile velocity. In IMPACT program, another series of three tests was performed using the same missile but with different, higher, velocity and the same geometry and reinforcement of the slabs but with higher concrete compressive strength. The results are the same and confirm the observations presented here. The next step would be to perform tests with different slab-thickness-to-missile-diameter ratio and to verify whether here presented observations can be generalized to any concrete slab impacted by any hard missile.

Blind numerical simulations of the tests are performed and presented in Sagals and al. (2013) using Ls-Dyne software. With some simplifications regarding the anchorage of stirrups, the simulations end up with the same conclusion as the conclusion presented in this paper, regarding the influence of transverse reinforcement on perforation capacity and the overall damage of concrete slabs.

CONCLUSIONS

Three slabs were tested in almost identical conditions. All slabs have the same longitudinal reinforcement. The only variable was presence of heavy transverse reinforcement in form of T-headed bars in the second slab and classical stirrups with hooks, in the third slab. Taking into account the presence of significant amount of transverse reinforcement, it was expected that perforation capacity of slabs would be considerably improved (considerably lower residual missile velocity). The results showed improved performance in terms of perforation capacity of the slab with transverse reinforcement in form of T-headed bars comparing to the slab without transverse reinforcement but not significantly. The performance of the slab with conventional stirrups, with 180 and 135 degree hooks, showed lower perforation capacity (higher residual missile velocity) than the slab without transverse reinforcement. The results of numerical simulations presented in Sagals and al. (2013) performed prior to the tests independently are consistent with test results. Regarding the overall damage, transverse reinforcement play an important role in reducing scabbing of the concrete and localizing the damage to the hole with missile diameter. Additional test with different slab-thickness-to-missile-diameter ratio and to verify whether here presented observations can be generalized to any concrete slab impacted by any hard missile.

REFERENCES

Lastunen A., Hakola I., Järvinene E., Hyvärinene J. and Calonius K., (2007). Impact Test Facility, Paper # J08/2-1, SMiRT_19 Proceedings, Toronto, Canada SMiRT-19, August 2007,

Orbovic, N. and Blahoianu, A. (2011). "Tests on concrete slabs under hard missile impact to evaluate the influence of transverse reinforcement and pre-stressing on perforation velocity", SMiRT_21 Proceedings, New Delhi, India, SMiRT-21, November, 2011,

Orbovic, N., Elgohary, M., Lee, N.H., and Blahoianu, A. (2009). "Tests on Reinforced Concrete Slabs with Pre-stressing and with Transverse Reinforcement under Impact Loading" SMiRT_20 Proceedings, Espoo, Finland, SMiRT-20, August 2009,

Sagals, G., Orbovic, N. and Blahoianu, A. (2013). "Missile impact on reinforced concrete slabs: Effect of transverse reinforcement" SMiRT_22 Proceedings, San Francisco, USA, SMiRT-22, August 2013.