

## NUMERICAL SIMULATION OF MISSILE IMPACT ON REINFORCED CONCRETE SLABS: EFFECT OF CONCRETE PRE-STRESSING

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### ABSTRACT

This paper describes the work conducted by the Canadian Nuclear Safety Commission (CNSC) related to the influence of concrete pre-stressing on perforation capacity of reinforced concrete (RC) slabs under “hard” missile impact (impact with negligible missile deformations). The paper presents the results of simulation of three tests on reinforced concrete slabs conducted at VTT Technical Research Centre (Finland), along with related sensitivity studies.

The baseline setup (the first test) was slab (2.1m\*2.1m\*0.25 m) with longitudinal reinforcement only. In the second and third tests the specimens have been cast with DYWIDAG bars placed in PVC sleeves in order to avoid the contact between the bars and the concrete. In the second test the Dywidag bars are without initial pre-tensioning and in the third test they were pre-tensioned in order to introduce 10 MPa pre-stressing in the concrete slab. The impact missile velocity was selected using empirical formulas for just perforation as presented in Orbovic et al. (2015).

Non-linear dynamic behavior of reinforced concrete slabs was analyzed using commercial Finite Element (FE) code LS-DYNA. Explicit version was selected for the entire modelling. FE predictions based on Winfrith MAT084 concrete material model without strain-rate were compared with tests results. Concrete erosion criteria as well as other “non-physical” parameters of FE model were selected identical to earlier authors work on modelling concrete slab without pre-stressing. The behaviour of Dywidag bars was also examined. FE predictions obtained are in good agreement with tests, showing similar trend for concrete damage patterns at both front and back sides of the slab. Subsequently, it was concluded that FE model developed earlier for slabs without pre-stressing could be successfully used for pre-stressed concrete structures as well.

### INTRODUCTION

Modern Canadian and International design codes and regulatory documents for Nuclear Power Plants require design against impact of externally or internally generated missiles on concrete safety related structures. This requirement stimulated a large amount of analytical and experimental work conducted in different countries. Previously, due to complexity of the problem, the analysis of a containment impact was limited to using simplified methods, such as Riera loading functions (Lee et al. (2014)). Excluding the full scale test at Sandia (a Phantom fighter, supported by a sledge and powered by rockets, was run onto a concrete block, with an impact velocity of 215 m/s, Sugano et al. (1993)), the experimental work and numerical simulations were conducted mostly for concrete slabs impacted by missiles. The most noticeable tests were conducted in Germany (so called Meppen Impact Tests, Nachtsheim and Stangenberg (1981)) and in Finland (Impact I-III tests conducted by VTT Technical Research Centre, Calonius et al. (2009) and Vepsä et al. (2011)). Based on publicly available data from these tests, two

simulation workshops IRIS\_2010 and IRIS\_2012 were conducted; see Berthaud et al. (2011), Vepsä et al. (2011) and Orbovic et al. (2011) for IRIS\_2010 and Orbovic et al. (2013) for IRIS\_2012. As a result of the last two workshops, numerous papers were produced for several SMIRT conferences and in relevant scientific journals. Orbovic et al. (2011), Berthaud et al. (2011) and Orbovic et al. (2013) provide a good overview of the work conducted by participants of these workshops and results obtained. The authors of the current paper also actively participated in both workshops and developed an adequate FE model (Sagals et al. (2011) and (2013)) that is capable of predicting the main characteristics of post-impact state of a concrete slab, such as perforation velocity, size and shape of damaged area, crack patterns, etc.

However, the work described above was limited to reinforced concrete slabs without pre-stressing. Despite the well-known advantages of concrete pre-stressing, the use of pre-stressed concrete for impactive and impulsive loading is not well studied and documented in the literature. . A few known tests conducted at VTT (Orbovic et al. (2009), (2011), Calonius et al. (2009) and Galan et al. (2015)) and numerical simulations (Calonius et al. (2009) and Tuomala et al. (2010)) bring new elements but further research is needed. Most semi-empirical formulas and simplified methods also do not include concrete pre-stressing or include it very approximately as in Barr (1990).

Therefore, the main objectives of this paper were as follows:

- (i) include concrete pre-stressing in already developed FE model (Sagals et al. (2011) and (2013))
- (ii) compare FE predictions with existing test results, perform sensitivity studies and
- (iii) based on results obtained discuss the effect of concrete pre-stressing upon perforation strength and damage resistance under missile impact

## FE MODEL

FE model developed earlier for the missile impact of the reinforced concrete slab (Sagals et al. (2011), (2013)) was modified to include concrete pre-stressing. The reference geometry and material models were also taken from Sagals et al. (2013). In order to compare with publicly available test results, missile, concrete, reinforcement and pre-stress properties were selected identical to test data presented by Orbovic et al. (20015) and provided in Table 1. The pre-stressing in tests was introduced using post-tensioning DYWIDAG Bar System. The bars were placed to introduce compression and minimizing the moment due to their eccentricity. No transverse reinforcement was introduced in these tests. Pre-stressing bars were put in PVC sleeves to avoid bond between them and concrete to simulate greased tendons. Full description of these tests was provided in (Orbovic et al. (2009) and (2015)).

The selected tests are as follows:

1. Test A1 (K): no DYWIDAGs , no pre-stressing
2. Test P5 (L): DYWIDAGs without pre-stressing
3. Test C21 (M): DYWIDAGs with pre-stressing 10 MPa

Test identification was selected identical to Orbovic et al. (2015).

Table 1: Test Data (Orbovic et al. (2015))

Property	Test A21	Test P5	Test C21
	‘hard’ steel missile with concrete infill		
Mass, kg	47.2	47.4	47.4
Impact velocity, m/s	120.2	120.4	117.9
	Concrete Slab		
Compr. Strength <sup>1</sup> , MPa	66.3	58.1	61.7
Tensile strength <sup>2</sup> , MPa	3.17	3.17	3.17

<sup>1</sup>cube (as used in FE model)      <sup>2</sup>cube after 34 days for test C21

The longitudinal reinforcement ratio was kept constant in all three specimens: Ø10 mm deformed bars A500HW with yield strength of 500 MPa were spaced at 90 mm at each face and in each direction. The longitudinal reinforcement ratio was 0.35% per face and per direction.

The pre-stressing was introduced using Ø26.5 mm DYWIDAG bars spaced at 180 mm in horizontal and 82 mm in vertical direction. The ultimate stress of the bars was  $f_{pu} = 1030$  MPa. The bars were anchored with external anchors. The detailed bar properties could be found on the manufacturer's website [www.dywidag-systems.com](http://www.dywidag-systems.com).

Similar to earlier paper (Sagals et al. (2013)) commercial Finite Element (FE) code LS-DYNA was selected for the entire modeling. Winfrith MAT084 material model without strain-rate was selected for concrete and elastic-plastic material model with limiting fracture strain was selected for reinforcement. Since the exact strain-rate properties of the reinforcement during missile impact are unknown, two bounding cases were considered as follows:

- without strain-rate hardening, and
- with the commonly used Cowper-Symonds strain-rate law and typical parameters for mild steel ( $C=40 \text{ sec}^{-1}$  and  $p=5$ )

Reinforcement was modelled using 2-noded beam FE with coupling between concrete & re-bars nodes for all translational degrees of freedom (spherical joint). Further details of FE model were provided in Sagals et al. (2013).

The accurate modeling of pre-stressing is very difficult. Fig. 1 shows the sketch of the initial position of the missile, adjacent DYWIDAG bars and PVC sleeves. Despite the distance between DYWIDAG centres (90 cm) been greater than outer missile diameter (168 cm) the missile will shift DYWIDAG outwards by  $\delta=7.25$  mm. The presence of an initial gap between the PVC sleeve and DYWIDAG bar makes the modeling even more complicate. Therefore, the accurate modeling requires full surface-to-surface contact interfaces between missile, pre-stressed DYWIDAG bars and PVC sleeves (surrounded by concrete). However, the main objective of the current work is to assess the effect of pre-stressing on concrete slab.

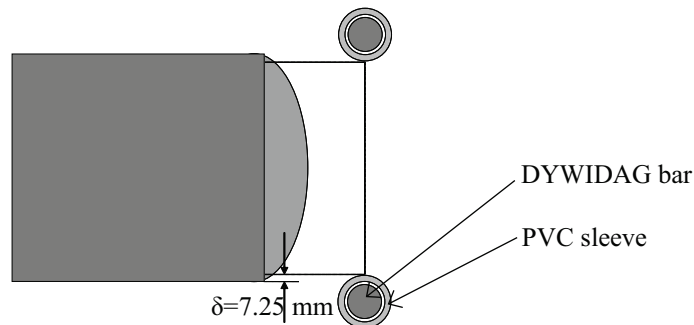


Figure 1 Missile – DYWIDAR bars layout

Therefore, DYWIDAG bars were modeled using beam FE with initial tensile axial stress. It was also assumed that DYWIDAG bars were not bounded to concrete.

While impact could be modelled adequately using only explicit version of LS-DYNA, the pre-stress state could be modelled using both explicit and implicit versions. However, for the sake of consistency, the explicit version of LS-DYNA was used for the entire modelling. To minimize the unwanted residual oscillations the following sequence of events was applied:

1. First an initial tension stress was applied to all pre-stress bars to provide the required amount of average compressive stress in concrete slab. Dynamic relaxation and global mass-proportional damping decreasing with time were applied at this stage to ensure the suppression of the unwanted residual oscillations before missile impact was initiated. Optimum relaxation and damping parameters for this stage were selected based on numerous trial runs.
2. Missile impact was modelled at the second stage similar to Sagals et al. (2013). The contact interaction between different parts was modeled as follows:
  - contact with possible FE erosion between missile and concrete slab
  - automatic beam to surface contact for missile - reinforcement and missile - DYWIDAG bars to account for beam diameters
  - beam to beam contact for DYWIDAG bars

Fig. 2 shows the details of FE model together with boundary conditions (BC). Due to symmetry, only one-quarter of the entire system was modelled with symmetry BC. The comparison between the two models conducted earlier for two typical cases (rebound and perforation) shows adequacy of one-quarter model. The adequacy of the selected mesh density was also validated by comparison between coarse and refined meshes ((14 and 58 solid FE through slab thickness respectively), see Sagals et al. (2011)). Fig. 3 shows the details of FE modelling of slab pre-stressing using DYWIDAG bars.

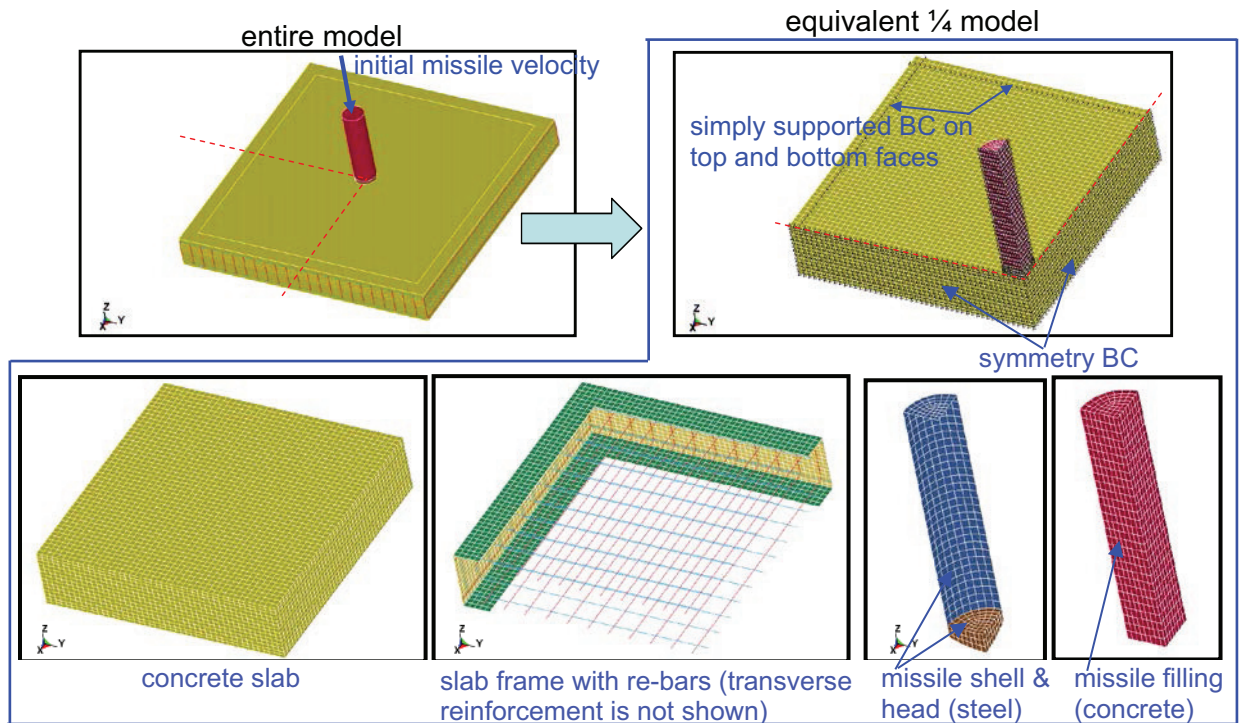


Figure 2 FE model of slab impact (from Sagals et al. (2013))

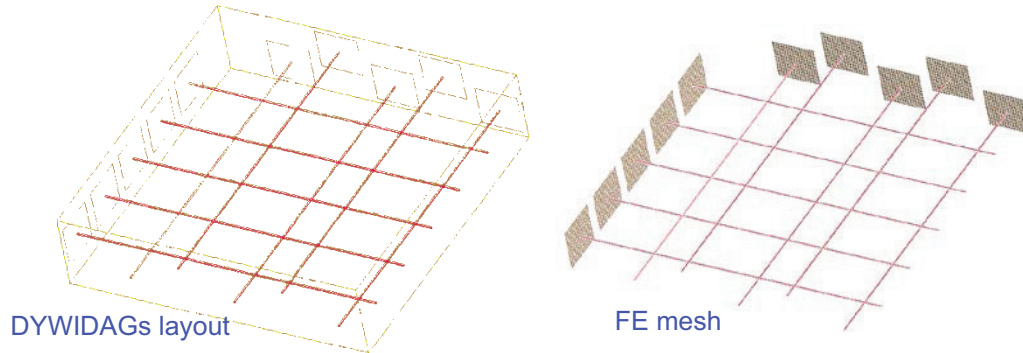


Figure 3 FE model of slab pre-stressing using DYWIDAG bars

## MODELING RESULTS

Modeling results were arranged into three groups as follows: (i) analysis of the final state of the target with and without pre-stressing, (ii) comparison between FE predictions and test results, and (ii) sensitivity analysis for DYWIDAG bar location relatively to the missile impact line.

Figure 4 shows 3-D view of final state of the slab for the test cases examined. The results do not show any significant difference in the size of perforation hole between these cases. However, the damage patterns through slab cross-section and on the back side of the slab are different. Next Figure 5 shows time history for average values of axial forces acting in DYWIDAG bars (away from the impact zone). As expected, the axial forces in DYWIDAG bars without initial pre-stressing are significantly higher for the bars closest to the slab center where missile impact occurs. These forces reach their maximum values at the time of contact interaction with missile. For the case with initial pre-stressing, DYWIDAG bars closest to slab center have lower axial forces due to significant slab softening as a result of concrete damage in impact zone. The slab stiffness away from the impact zone remains practically unchanged leading to almost constant axial forces in adjacent DYWIDAG bars.

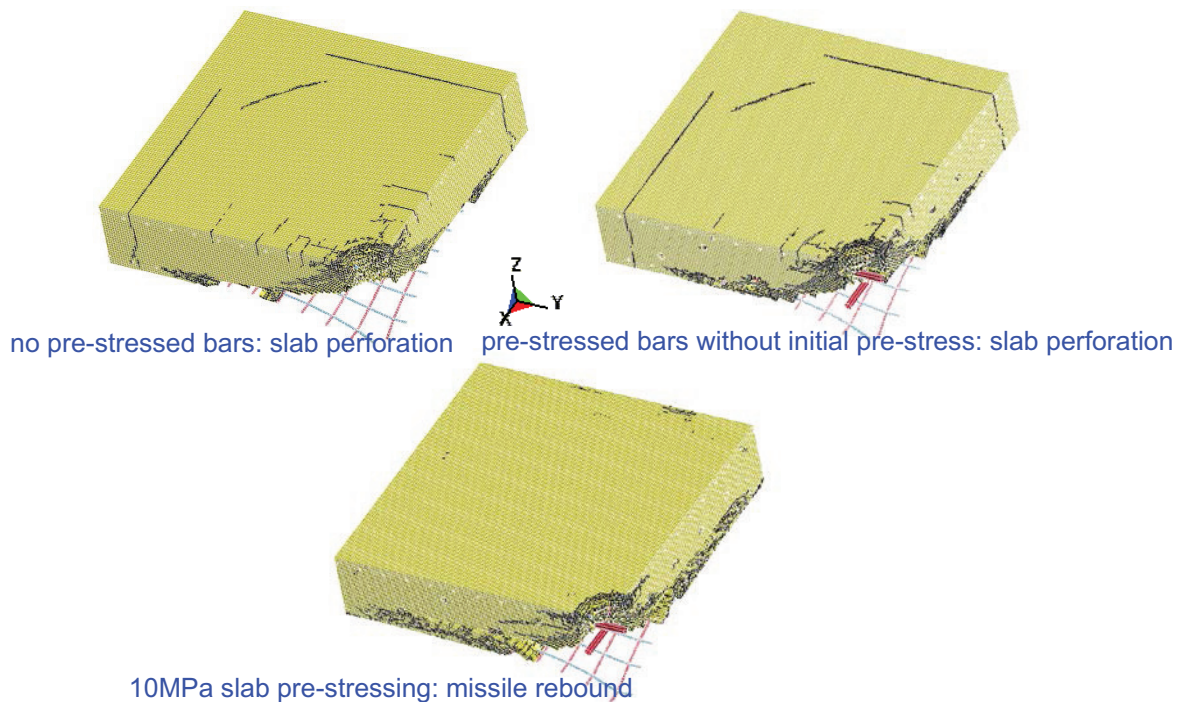


Figure 4 3-D view of final state of the target with and without pre-stressing

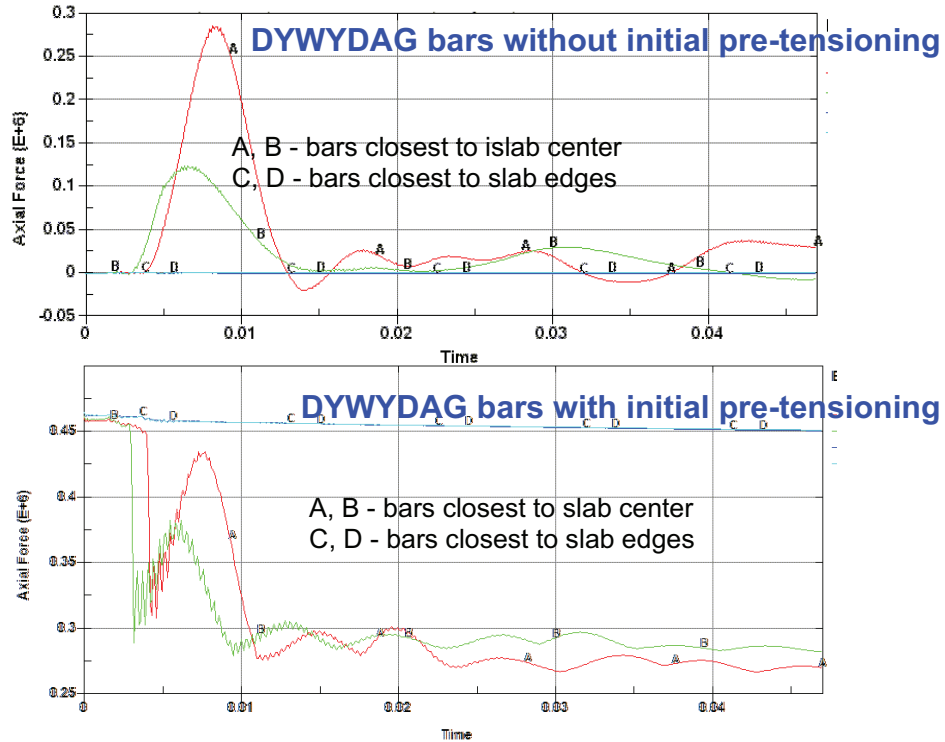


Figure 5 DYWIDAGs axial forces (average values) before, during and after impact

Next Figures 6 and 7 show comparison between FE predictions and test results. Figure 6 shows tabulated results characterising the residual (exit) missile velocity for both FE predictions and tests. The results on this Figure show clearly that:

- ignoring strain-rate hardening of reinforcement results in significantly “softer” slab, and
- current modeling with selected strain-rate hardening of reinforcement better represents residual (exit) missile velocity.

FE predictions follow the increase/decrease trends in test results. The results on Figure 6 also show that the introduction of pre-stressed bars, even without initial pre-stressing leads to a decrease of residual missile velocity. The introduction of 10 MPa pre-stressing changed the final state from perforation to rebound leading to the conclusion that slab pre-stressing increases perforation resistance.

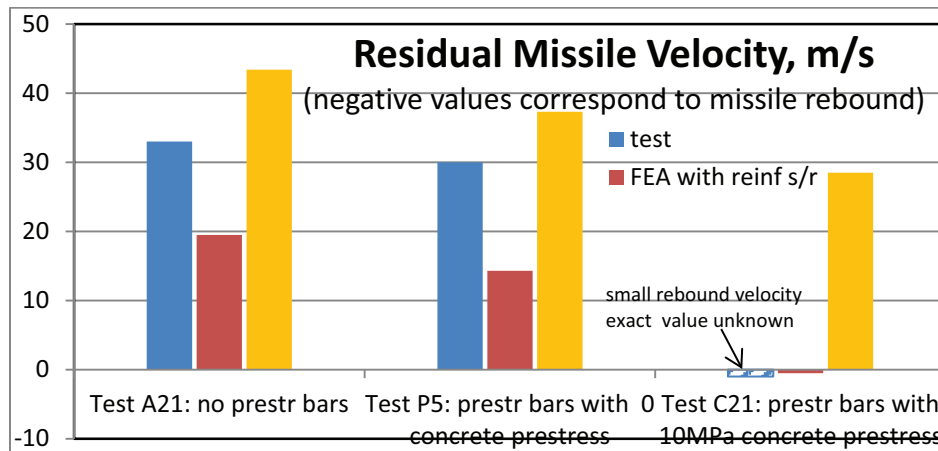


Figure 6 Residual missile velocities for both FE predictions and tests

Figure 7 shows FE predictions for the final state of damaged slab. Both back side of the slab and 3-D view showing slab cross-section are presented on this Figure. Since FE modelling was conducted for the one-quarter of the entire system, the modeling results showing back side of the slab were symmetrically reflected along symmetry planes. Only the exposed slab back surface bounded by slab frame is displayed.

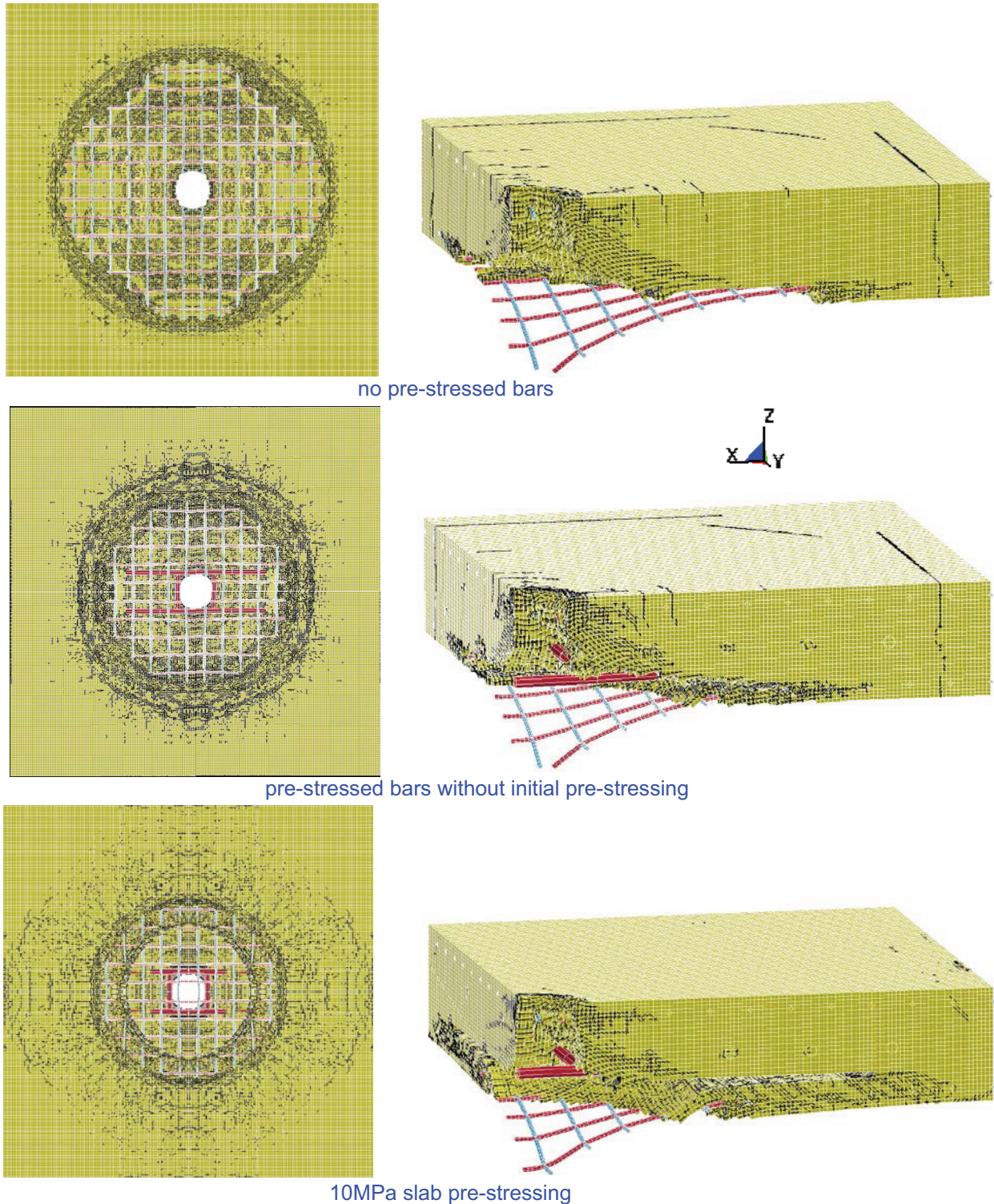


Figure 7 FE predictions and test results (Orbovic et al. (2015)) for the post-impact state of the slab

The results on Figure 7 clearly show the reasonable adequacy of FE predictions for all test cases with and without pre-stressing, see paper by Orbovic et al. (2015)). Similar to test results, pre-stressing resulted in more cracking on the back side of the slab. Figure 7 also shows that similar to Orbovic et al. (2015)) punching cone angle is less in case with slab pre-stressing. However, it is difficult to extract the exact values of this angle from FE predictions.

Some discrepancy includes non-symmetrical damage patterns, smaller reinforcement deformations and smaller ratio of cracking/scabbing areas on the back side of the slab observed in tests. In authors opinion, the main reasons for this discrepancy are as follows:

- Lack of exact properties for some components, for example strain-rate hardening of reinforcement and DYWIDAG bars, pressure - volumetric strain relationship for concrete, etc.,
- Shortcomings in concrete material model and FE elimination criteria,
- Modeling of one-quarter of the entire system,
- Difficulties in distinguishing between partially cracked, fully cracked and crashed concrete FE in resulting plots.

Finally, Figures 8 and 9 show the results of sensitivity analysis conducted for DYWIDAG bars layout and the importance of the missile contact with the bars during the impact. The original layout shown in Figure 1 resulted in small 7.25 mm overlapping between missile trajectory and DYWIDAG bars cross-sections for two of them closest to impact line. Since the exact location of the missile impact cannot be predicted, two additional runs were conducted as follows:

- Two closest DYWIDAG bars were shifted 18 mm away from impact line to simulate the case with no direct contact with the missile
- Two closest DYWIDAG bars were shifted 18 mm toward impact line to simulate the case with direct contact with the missile
- All other DYWIDAGs were left in the original position to provide the required slab pre-stressing.

This analysis is necessary to assess the effect of DYWIDAG bar locations in the case of limited number of tests. Please, notice that due to symmetry moving of one bar, automatically moves the symmetric bar as well. The results in Figure 8 show clearly that DYWIDAG bar position has a significant effect upon missile exit velocity. Disallowing direct contact between DYWIDAG bars and missile leads to slab perforation regardless of pre-stressing level. From the other side, a direct hit of DYWIDAG bars by the missile resulted in missile rebound.

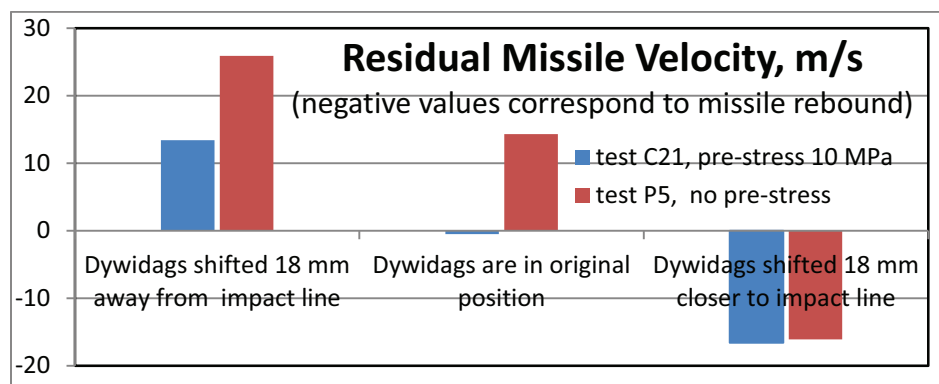


Figure 8 Effect of DYWIDAG bars shifting upon residual (exit) missile velocity

The final Figure 9 shows correspondent axial forces in DYWIDAG bars. The upper DYWIDAG bar closest to the missile and the output location near the bar centre were selected for these graphs to get the maximum values of axial forces. The results on Figure 9 show that for DYWIDAG bars layout resulting

in direct contact interaction with the missile the maximum axial force exceeds the plastic yield limit 523 kN. Consequently, plastic deformations were predicted in DYWIDAG bars in full accordance with test observations. The further increase in missile impact velocity will result in exceeding the ultimate limit of 579 kN and breaking of DYWIDAG bars as observed in Galan et al. (2015).

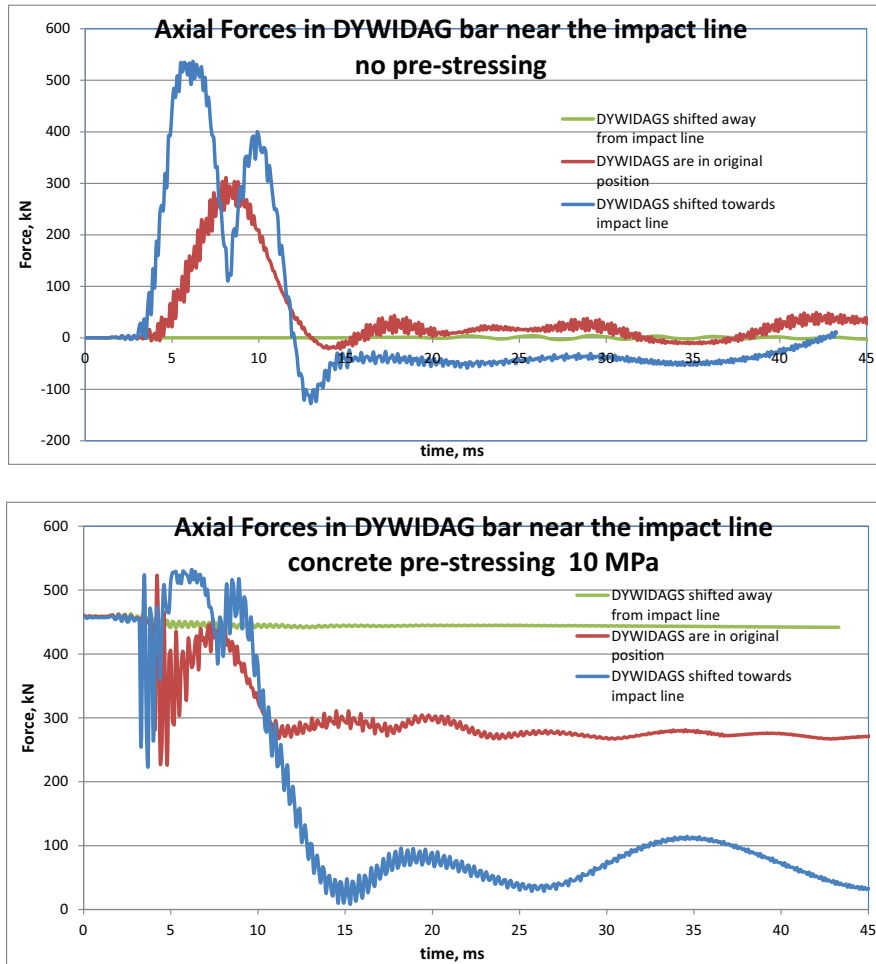


Figure 9 Effect of DYWIDAG bars shifting upon maximum axial forces

## CONCLUSIONS

FE model developed earlier and capable of modelling of missile impact involving deep penetration and perforation of concrete slab was modified to include pre-stressing using DYWIDAG bars. This model is based on commercial code LS-DYNA. Comparison between FE predictions and test results was conducted for 3 cases: without pre-stress bars and with unbounded DYWIDAG bars without initial pre-tensioning and to produce 10 MPa pre-stressing in the concrete slab respectively.

The results clearly confirm that LS-DYNA with appropriate material models could be successfully used for prediction of slab damage after impact with and without DYWIDAG bars. The results also show that the introduction of DYWIDAG bars, even without initial pre-stressing leads to a small decrease of residual missile velocity which can be considered as negligible. The introduction of 10 MPa pre-stress changed the final state from slab perforation to rebound. FE predictions were consistent with test results for all cases. Regarding slab damage, both FEA and test results show that the introduction of DYWIDAG

bars with or without initial pre-stressing does not reduce the overall damage of the slab. Moreover, the damaged area on the back side of the slab is larger for a 10 MPa slab pre-stressing.

The conclusion is that pre-stressing increases the slab perforation capacity. However, the position of the bars relative to the missile during the impact has an importance. Moreover, based on simulations and confirmed with the test results in Orbovic et al. (2009) and (2015) the pre-stressing increases the level of concrete damage. The performed tests and simulations clarify the effect of pre-stressing but more tests and simulations are needed to completely assess the effect of pre-stressing in the case of impactive and impulsive loadings.

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