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PREDICTION OF COMBINED BENDING AND PUNCHING RESPONSE OF REINFORCED CONCRETE SLABS SUBJECTED TO IMPACT LOADING

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ABSTRACT

While considering the impact load carrying capacity of reinforced concrete slabs, two failure mechanisms are of importance, namely bending failure of the slabs and punching shear under impact. In many cases, however, the dynamic response of reinforced concrete slabs subjected to projectile impact is governed by a combination of both bending and punching failure mechanisms. Within the framework of the IMPACT III benchmark project, organized by VTT Technical Research Centre, Finland and funded by several institutions including Swiss Federal Nuclear Safety Inspectorate ENSI, several experiments were carried out focusing on a combined bending and shear response of slabs impacted by a projectile. To investigate the ultimate resistance of the slabs with different layouts of longitudinal and transverse shear reinforcements, square shaped reinforced concrete slabs with a lateral dimension of approximately 2.1 m and a thickness of 0.25 m were subjected to impact of missiles with a mass of 50 kg and an initial velocity of up to 168 m/s. Aim of this paper is to improve numerical predictions of a combined bending and punching response of shear reinforced slabs subjected to impact loading and to discuss the challenges involved. In order to evaluate the influence of shear reinforcement on the improvement of the impact load capacity of the concrete slabs, some of the experiments are simulated using three-dimensional nonlinear finite element analyses by explicitly modelling the transverse shear reinforcement. The results obtained from numerical analyses and their comparison to the experimental measurements can facilitate a better understanding of shear failure due to punching under impact.

INTRODUCTION

Benchmark project IMPACT III is an international project organized by VTT Technical Research Centre, Finland, and funded by several institutions including Swiss Federal Nuclear Safety Inspectorate ENSI. A series of combined bending and punching tests of reinforced concrete slabs subjected to missile impact were carried out as a part of this project.

This paper outlines the contribution of ENSI and their consultants Basler & Hofmann AG to IMPACT III by predicting the combined bending and punching tests X6 and X7. Blind numerical simulations of these tests and the comparison of the results with the experimental measurements are outlined here. The current work represents the capability of finite element models to predict the impact response of reinforced concrete slabs and discusses the improvement of numerical predictions by comparing the results to the experimental data.

EXPERIMENTAL TEST DESCRIPTION

Square shaped target reinforced concrete slabs with a lateral dimension of 2087 mm and a thickness of 250 mm were subjected to the impact of a projectile with an initial velocity of 166.7 and 166.5 m/s for tests X6 and X7, respectively.

The slabs contained longitudinal reinforcements of 8.7 cm2/m (∅10 mm, c/c 90 mm) in each direction and each face, and transverse shear reinforcement of 34.9 cm2/m2 (∅8 mm, c/c 90 mm / 160 mm). The slabs were reinforced in transverse direction using closed stirrups and T-headed bars for tests X6 and X7, respectively. The concrete compressive strength for tests X6 and X7 were 55, and 57 MPa, respectively. The missile was a steel tube with a total length of 1304 mm and a total mass of 50 kg.

The testing facilities, target slabs, as well as the supporting conditions are comparable to the experimental setup outlined for the test X3 in Zinn et.al (2014).

NUMERICAL ANALYSES

Method and Assumptions

Numerical evaluations are carried out using finite element analyses, which applies explicit solutions of LS-DYNA software (R 8.0) for three-dimensional modelling of the impact on a reinforced concrete slab.

The basic assumption for both models is that the target remains stationary. It is assumed that the steel support structure provides enough stiffness and large target deformations are not expected. A perfect bond is assumed between concrete and reinforcement. Numerical simulations are carried out by fully modelling the impacting projectile.

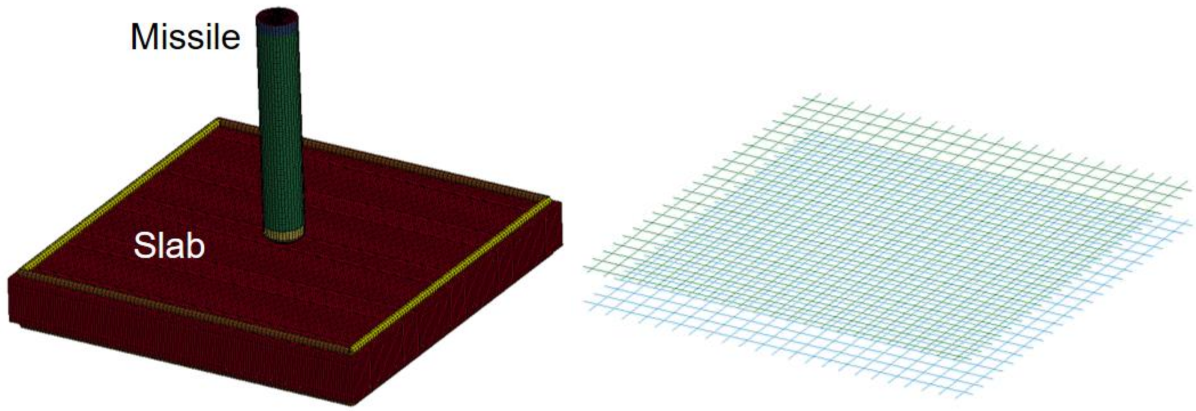
Element Types and Material Models

Full three-dimensional models including the impacting projectile are developed here. The reinforced concrete slabs are represented by solid elements for concrete, beam elements for bending and stirrup reinforcement (Figure 1). The impacting projectile is modelled by shell elements and the supporting bars between the slab and the supporting frame are modelled using solid elements. Eight-node hexahedron constant stress solid elements and two-node beam elements are used for the modelling. Slabs are represented by a mesh size of 15mm×15mm, where 20 elements are defined through the wall thickness (12.5mm thick).

The continuous surface cap model (material model 159) of LS-DYNA is used for the concrete. This material model allows definition of an erosion criterion for the concrete. An eroding constant of ERODE=1.2 is used in this case. This allows erosion of the concrete elements when the damage exceeds 99% and the maximum principle strain exceeds 20%. An additional eroding parameter is introduced here for concrete, limiting the shear strain at failure to 60%. The values for the compressive strengths, as well as the elastic modulus of concrete are taken from experiments on concrete cylinders. The details of the material model can be found in the LSDYNA keyword and theory manuals (LS-DYNA 2014).

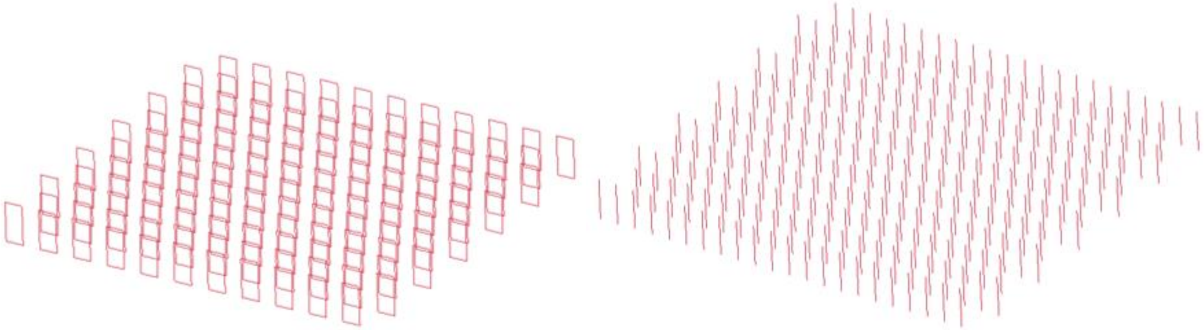
The constitutive model for the longitudinal bars and stirrups is bilinear, with strain hardening. The reinforcements erode when the strain in the beam elements exceeds 12%. The concrete and reinforcement elements are assumed to have a perfect bond, where the concrete solid elements are connected to the reinforcement beam elements at nodal points. The same nodes are defined for the reinforcement and the concrete where they are in contact with each other.

The impacting missile and the supporting system are modelled using bilinear models with strain hardening.



Reinforced concrete Slab

Bending reinforcement



Shear reinforcement: Test X6

Shear reinforcement: Test X7

Figure 1. LS DYNA solid model including missile: model geometry and reinforcement layout

Loading and Support Conditions

The initial position of the impacting missile is defined at the surface of the slab to save computation time. The missile is then subjected to a predefined initial velocity.

Contact surfaces are defined between the missile and the concrete slab, as well as between the concrete slab and the supporting bars. The contact forces between relevant members are calculated by applying the penalty method. Eroding contact options are employed here, which allow deletion of the eroded elements. The outer nodal points of the supporting bar elements are defined by fixed boundary conditions.

PREDICTED RESULTS AND COMPARISON

Impact Load Time Histories

The impact load time histories defined as contact forces between missile and target slab for both analyses (tests X6 and X7) is plotted against the loading function derived by simplified method proposed by Riera (1968) for soft missile impact in Figure 2. The duration of impact and the average load values obtained from finite element and simplified methods correlate reasonably as it can be seen from this comparison. The numerical analyses predicted no perforation of the missile through the slab, which matches the experimental outcome for both tests.

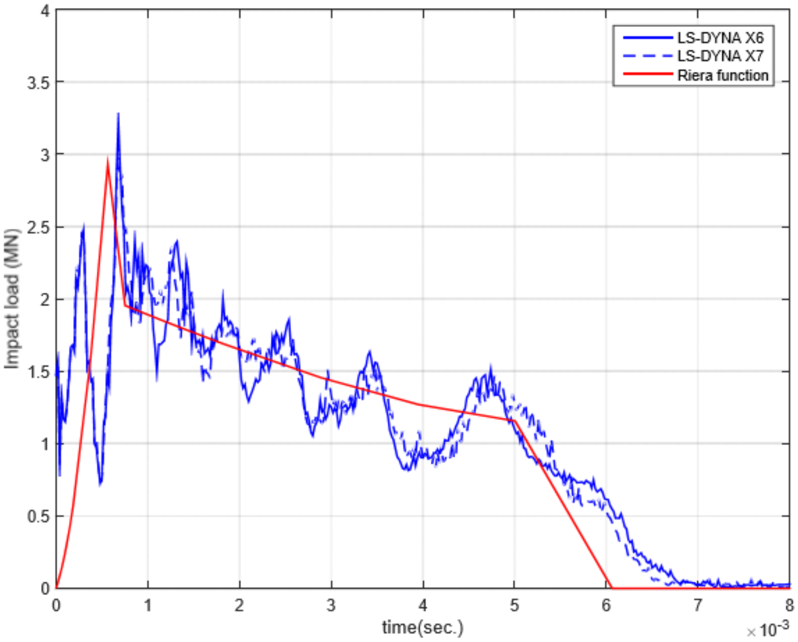


Figure 2. Comparison of impact load time histories

Deflection Time Histories

Figure 3 demonstrates the maximum slab deflections at the slab centre behind the loading area (sensor 1). Deflections obtained from finite elements models are smaller compared to the deflections from experimental measurements for X6 but have a good agreement with the measured data in test X7.

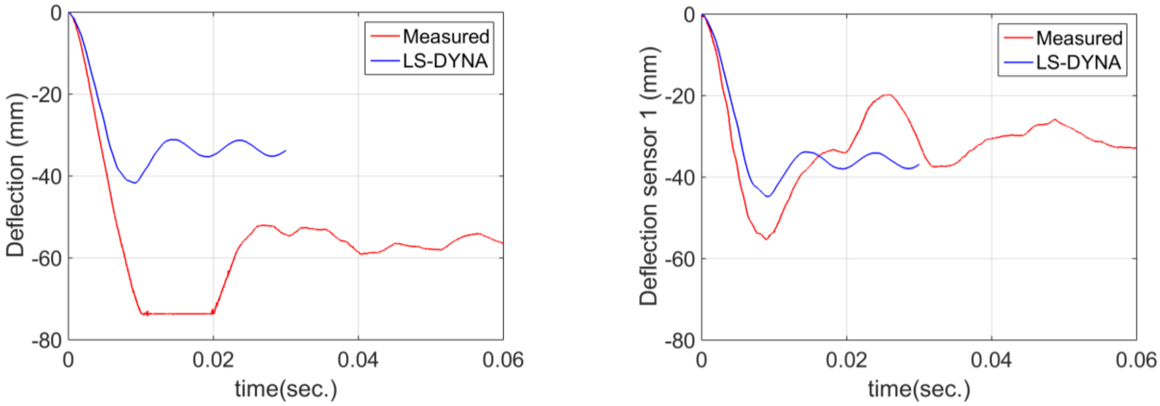


Figure 3. Deflection time histories at the slab centre for: Test X6 (left) and Test X7 (right)

Additionally, the displacement time histories at the locations of sensors 2 and 5, which were placed, respectively, at 135 mm, and 540 mm from the slab centre (see Figure 4, bottom), are plotted against the experimental data in Figure 4, where the deflections are underestimated by the numerical analysis for sensor 2 in Test X6.

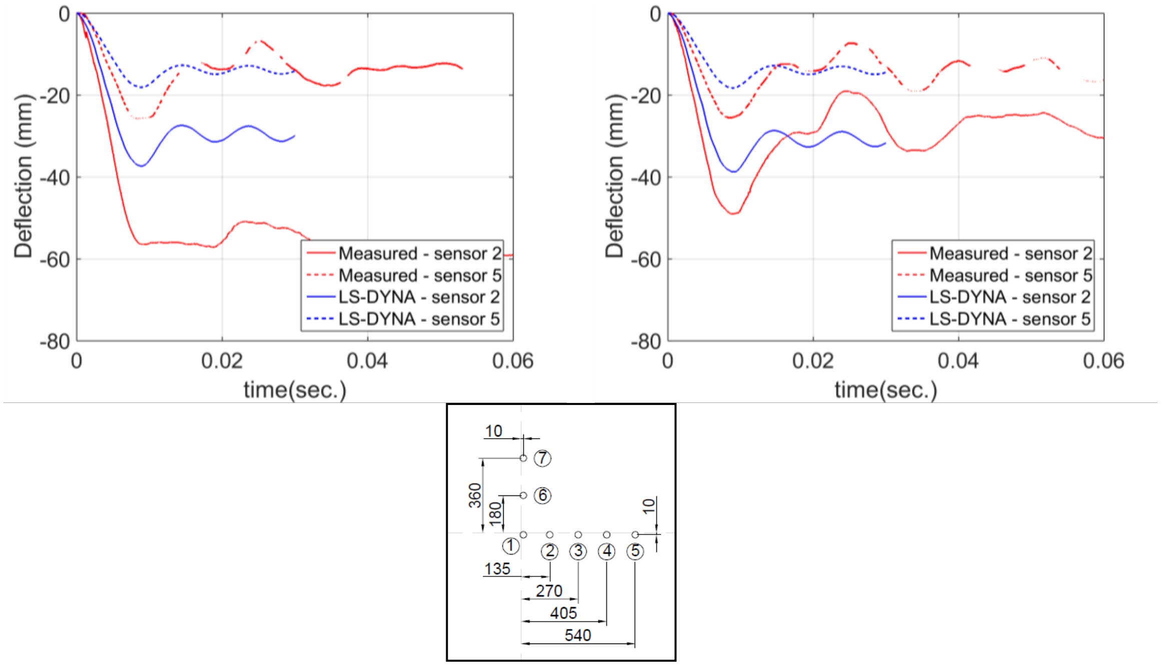


Figure 4. Deflection time histories of sensors 2 and 5 for Test X6 (left) and Test X7 (right), position of the sensors (bottom)

Support Reaction Forces

The total support reaction force time histories during impact for both models are compared with the test data in Figure 5. The support forces obtained from finite element analyses are the contact forces between the slab and the supporting bars in the loading direction.

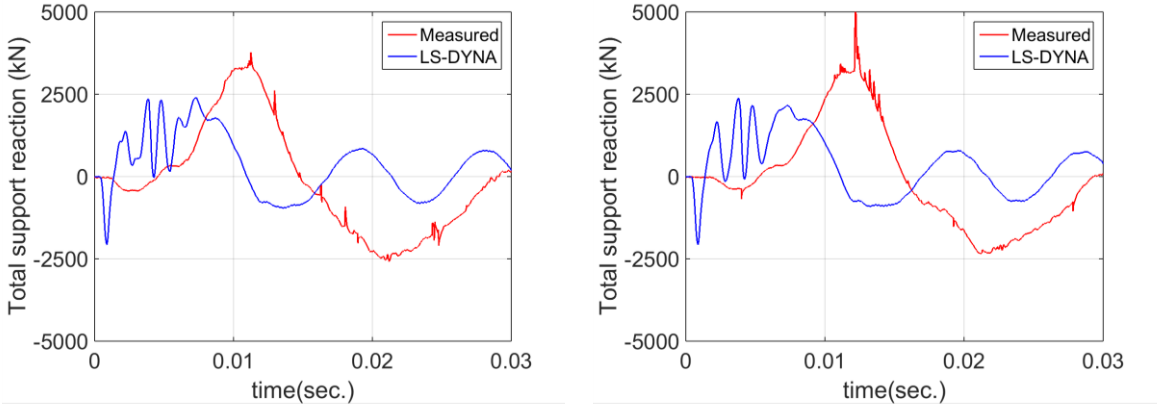


Figure 5. Support reaction force time histories for Test X6 (left) and Test X7 (right)

The comparison shows that the peak values from the numerical models are lower than those measured during the experiments. The numerical vibration frequency does not match the experimental data. This may be due to the simplifications in defining the support boundary conditions in the numerical models.

Strains of Bending Reinforcement

Strain time histories of bending reinforcements are compared to the measured values for eight strain gauges (four in each direction) in Figures 6 and 7. A good agreement is observed with the measured strains except for the sensor B6 in the horizontal direction and sensor B4 in the vertical direction. This may indicate a localized stress concentration at the location of the sensor during the experiment (e.g. due to specimen imperfection or cracking at this location), which is not predicted numerically.

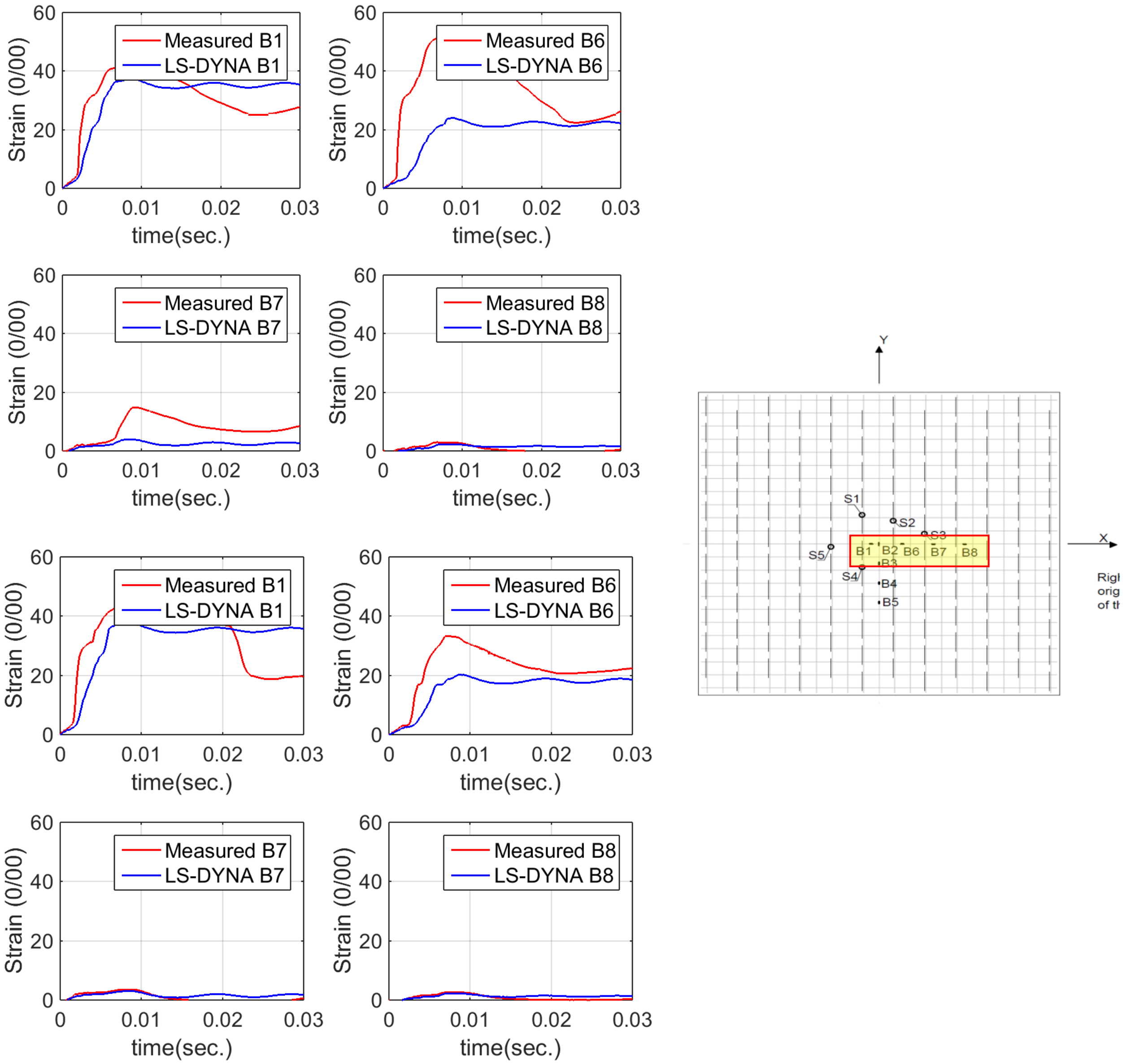


Figure 6. Strain time histories of bending reinforcements in X (horizontal) direction for Test X6 (top) and test X7 (bottom)

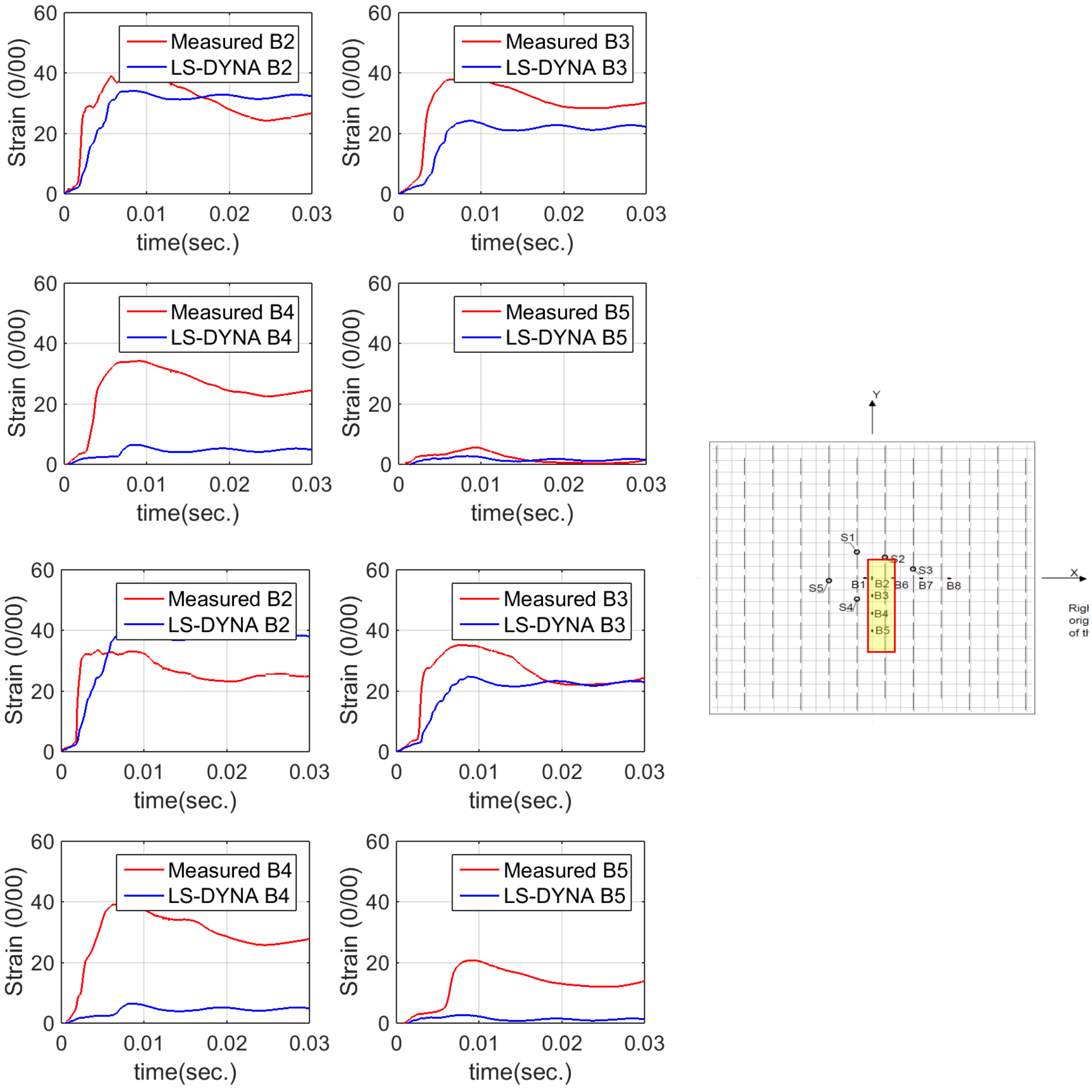


Figure 8. Strain time histories of bending reinforcements in Y (vertical) direction for Test X6 (top) and Test X7 (bottom)

Strains of Shear Reinforcement

In Figure 9, the recorded data is compared to the calculated stirrups strains at the corresponding measurement locations. In the case of slab with closed stirrups, the numerical simulations underestimate the experimental measurements considerably. This can imply that the confinement effect of the closed stirrups is not well represented with finite element analyses. The calculated stirrups strain in the numerical model for the slab with T-headed bar, which does not produce a confining effect in the slab, is, on the other hand, in a reasonable agreement with the experimental data.

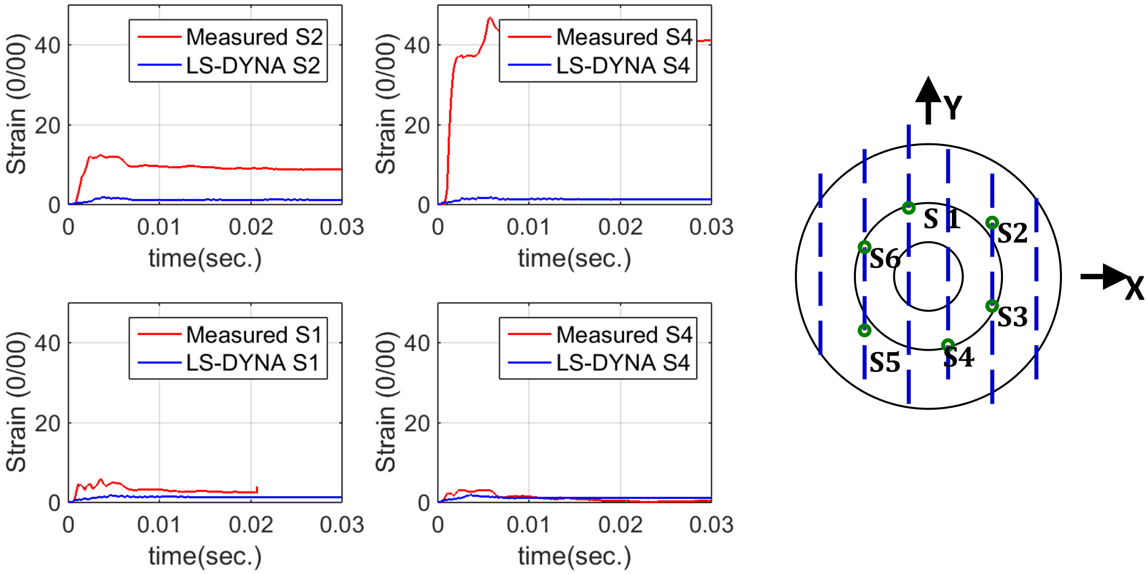


Figure 9. Strain time histories of shear stirrups S2 and S4 for Test X6
with closed stirrups (top) and S1 and S4 for Test X7 with T-headed bars (bottom)

CONCLUSION

Numerical analyses have been carried out here for the blind prediction of a combined bending and punching test X6 and X7. It aims at exploring the capability of finite element analyses to replicate the dynamic response of reinforced concrete slabs with different forms of transverse shear reinforcement. Finite elements models using explicit solutions with LS-DYNA software are used for the analyses.

Based on the comparison made with the experimental measurements, it could be concluded that finite element analyses performed reasonably well, predicting the overall response of the slabs. However, some of the results were not in a good agreement with the experimental measurements. Finite element analyses correctly predicted no perforation for both tests. The deflection and support reaction time histories were underestimated by the numerical analyses. The strains of the bending reinforcements were well predicted for both tests. The strains of the transverse shear reinforcements were predicted well for the test X7 with T-headed bars. However, the transverse shear reinforcement strains were highly underestimated for the test X6 with closed stirrups. This may be due to the modelling aspect that a full bond was assumed between concrete and stirrups, which may not properly represent the confining influence of the closed stirrups. It may be worthwhile to model the stirrups around the impact area by connecting stirrups and concrete nodes using bond link elements

The experimental data should be used to calibrate the finite element models and to improve the results predicted by the blind numerical simulations.

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