BENDING AND SHEAR PUNCHING STUDIES ON IMPACT LOADED REINFORCED CONCRETE WALL, PART 2

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INTRODUCTION

At VTT an ongoing shear punching test series is carried out by using as a target a two way simply supported concrete plate with a span of 2 m and a thickness of 25 cm. The amount of the shear reinforcement is varied. The mass of the stainless steel missile in the test has been 50 kg and the impact velocity about 166 m/s. For this study the load intensity was increased.

So far, however, no clear shear punching failure of slab has occurred in the tests. Therefore further numerical studies are carried out with a modified more intensive loading function. This is achieved by increasing the wall thickness of the missile from 3 mm to 5 mm. At the same time the mass is increased from 50 kg to 58 kg. The capabilities of different types of calculation methods in assessing local shear deformation and possible shear punching cone formation are studied.

TEST SETUP

The impact test setup is described in Vepsä et al. (2011) and the test support frame behaviour is discussed in the joint paper ID 476.

Reinforced concrete slab

The dimensions of the simply supported slab used in the stainless steel missile impact tests are: the span l = 2 m, the thickness h = 0.25 m and the effective thickness h_e = 0.225 m (assuming concrete cover of 20 mm and rebar diameter of 10 mm). In both slabs the bending reinforcement consists of bars with a diameter of 10 mm and a spacing of 90 mm. The shear reinforcement is made with 6 mm closed stirrups. The amount of shear reinforcement is varied. In slab X1 the amount of shear reinforcement is 17.45 cm^2/m^2. In slab X2 the shear reinforcement is reduced to 11.66 cm^2/m^2. The properties of reinforcement are: the modulus of elasticity $E_s = 210\text{ GPa}$, the yield stress $\sigma_y = 500\text{ MPa}$, the ultimate stress $\sigma_u = 600\text{ MPa}$, reached at $\varepsilon_u = 0.1$.

In numerical analyses of the concrete slab X1 the modulus of elasticity of concrete is $E_c = 23.425\text{ GPa}$, the Poisson ratio is $\upsilon = 0.2$, the compressive cubic strength of concrete is $f_c = 40.6\text{ MPa}$ and the tensile strength of concrete is $f_t = 3.03\text{ MPa}$.

In analyses of the concrete test slab X2 the modulus of elasticity of concrete is $E_c = 26.341\text{ GPa}$, the Poisson ratio is $\upsilon = 0.2$, the compressive cubic strength of concrete is $f_c = 44.1\text{ MPa}$ and the tensile strength of concrete is $f_t = 2.98\text{ MPa}$.

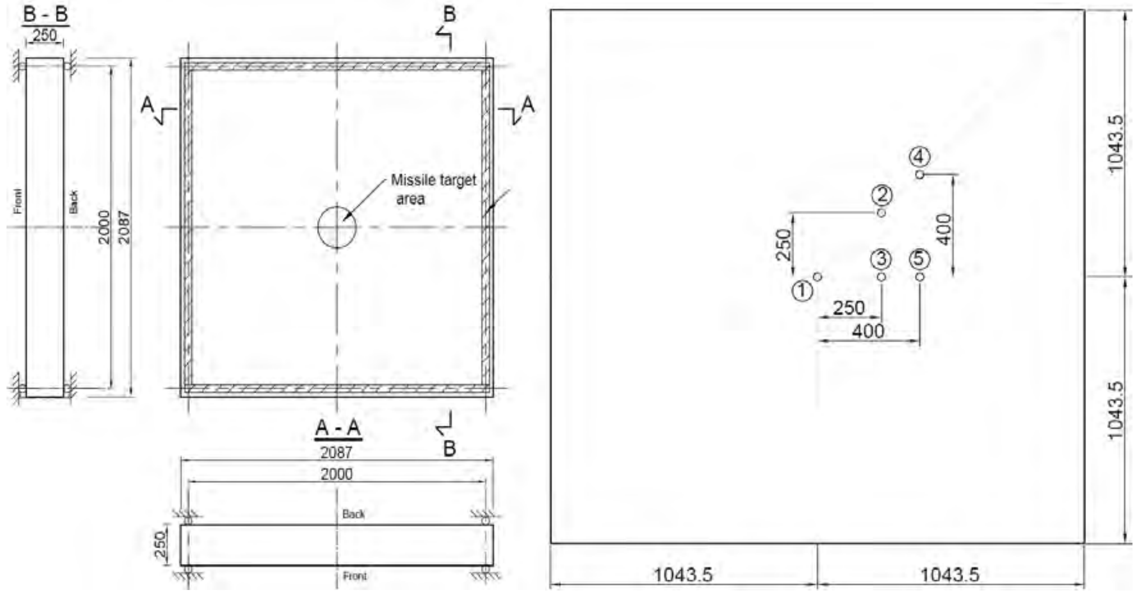


Figure 1. Test wall and locations of displacement sensors in Test X1.

CALCULATION METHODS AND MODELS FOR REINFORCED CONCRETE PLATE

Preliminary studies

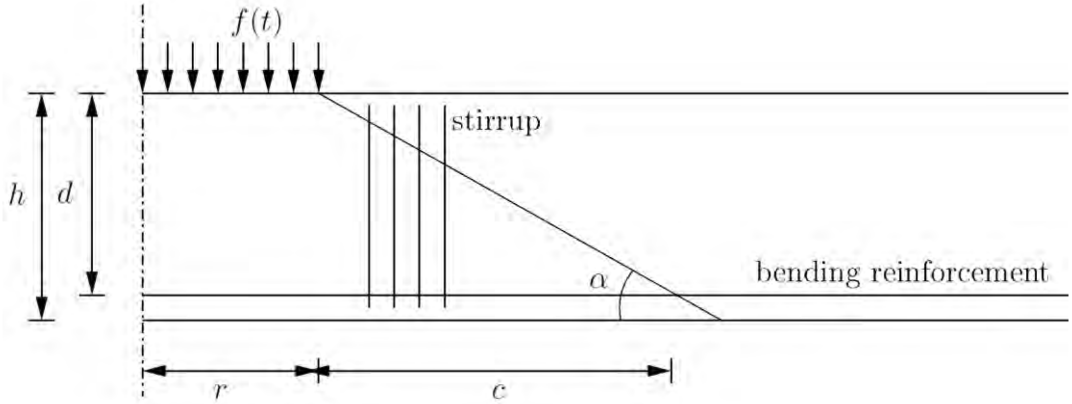


Figure 2. Determination of punching load.

Pre-calculations were carried out by applying a punching capacity formula for deformable missiles, Jowett (1989). The punching strength of a concrete slab, F_p, can be obtained from the formula

$$F_p = 8170(\rho_p f_c)^{\frac{1}{3}} \pi d(d_l + 2.5d), \tag{1}$$

where ρ_p is the average percentage of reinforcement on the tensioned face of slab, [%], f_c is the compression strength of concrete, [Pa], d is the distance between the front face and reinforcement, [m], $d_l = 2r$ is the diameter of loaded area, [m], r being the radius. Formula (1) holds best, when the load duration exceeds the time for reaching the maximum deflection of plate. Formula (1) is experimentally verified in the range:

$$\begin{aligned}
&0.07 < d < 0.9 \text{ m}, \\
&0.66 < d_l / d < 1.3, \\
&0.22 < \rho_p < 1.26\,\%, \\
&25 \text{ MPa} < f_c < 63 \text{ MPa}, \\
&0.05 < a_g / d < 0.07,
\end{aligned} \tag{2}$$

where a_g is the aggregate size of concrete.

According to Reference Jowett (1989) the punching shear resistance formula can be applied for dynamical soft impact cases by checking the condition

$$\bar{F} \le F_p, \tag{3}$$

where $\bar{F}$ is the average value of the time dependent force resultant of the missile, and it can be obtained from the total impulse I by the formula

$$\bar{F} = \frac{0.9I}{t_{0.9I}}, \tag{4}$$

in which $t_{0.9I}$ is the time, when $0.9I$ (90% of the total impulse) is reached in a dynamical loading process (a possible long tail of the loading function $F(t)$ is discarded).

The scabbing strength, F_s, is calculated by equation (1) by using a coefficient 7040 instead of 8170.

The shear capacity due to stirrups can be determined assuming a circular load area with a diameter of d_l and a shear cone angle of inclination of α measured from the horizontal plane. The required shear reinforcement area, A_{ss}, is obtained from

$$A_{ss} f_y = \frac{F_{sh}}{\pi((r+c)^2 - r^2)}, \tag{5}$$

in which $c = d / \tan\alpha$ and $r = d_l / 2$ and F_{sh} is the load in shear design.

Thus the shear capacity due to stirrups in the case X1 is 0.3 MN and in the case X2 0.2 MN when assuming a shear cone angle of $\alpha = 45^{\circ}$.

In the bending reinforcement case with reinforcement areas of $A_{sx} = A_{sy} = 0.000873 \text{ m}^2/\text{m}$ and $f_c = 41.6$ MPa, the punching and scabbing capacities by Equation (1) become $F_p = 1.144$ MN and $F_s = 0.986$ MN, respectively. Calculation results are summarized in Table 1.

Table 1. Capacities [MN].

Test	F_p	F_s	F_{sh}	$\overline{F}$	$F_{\max}$
X1	1.14	0.986	0.3	0.69	1.03
X2	1.17	1.001	0.2	0.69	1.03
X1B	1.14	0.986	0.3	1.41	2.10
X2B	1.17	1.001	0.2	1.41	2.10

NUMERICAL STUDIES WITH HIGHER IMPACT LOAD OF CASES X1B AND X2B

Further numerical studies on shear punching were carried out by increasing the impact load intensity in order to obtain clear shear punching. In the following the cases are referred to as case X1B and X2B. Some of the calculation methods and models were already described in the joint paper ID 476. The TDOF model and an inherent finite element code using a four noded plate element based on the Reissner–Mindlin plate theory is used. The Abaqus shell element model is not used in these studies since it is not capable of simulating nonlinear transverse shear behavior. The TDOF model and Abaqus 3D solid finite element model are described in the joint paper ID 476.

Reissner-Mindlin plate element model

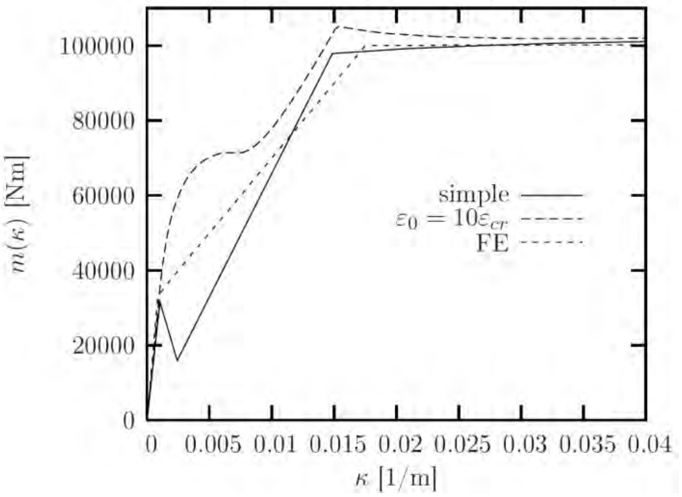


Figure 3. Moment curvature relationship.

In analysing possible shear punching of concrete slab subjected to deformable missile impact finite element model with plate element based on the theory by Reissner and Mindlin can be used. In the present study a four noded element with linear polynomial interpolations for the plate deflection and for cross section rotations is adopted. A special treatment is needed for transverse shear strain interpolation, so called covariant strain interpolation. For bending the constitutive model for reinforced concrete is similar to that used in the Kirchhoff plate theory element BFS. Possible yielding due to transverse shear is modeled in terms of transverse shear force resultants. In the principal bending moment transverse shear plane the yield surface or in this case curve is rectangular in shape. For simplicity the yielding in shear is assumed to be independent of bending. This should alleviate the development of strain localization in transverse shear in the missile impact area.

First a static analysis of test slab X1 was carried out. The plate is loaded with a central point load *P*. The load deflection curves obtained with different finite element mesh densities (for one quarter plate) are depicted in Figure 4. In Figure 4 *t* is load factor. For simply supported square plate load factor value *t*=1 corresponds to point load plastic limit value $P_p = 8m_p$, where m_p is the plastic moment of cross section. Some strain hardening of reinforcing steel is assumed in the limit load calculation. In Figure 4 label l16 refers to Kirchhoff plate theory BFS element, label lm to Reissner-Mindlin theory element. One quarter of plate is divided into 10 by 10 or 20 by 20 element meshes. The used mesh is denoted by label 10 or 20. The used load step is 0.001.

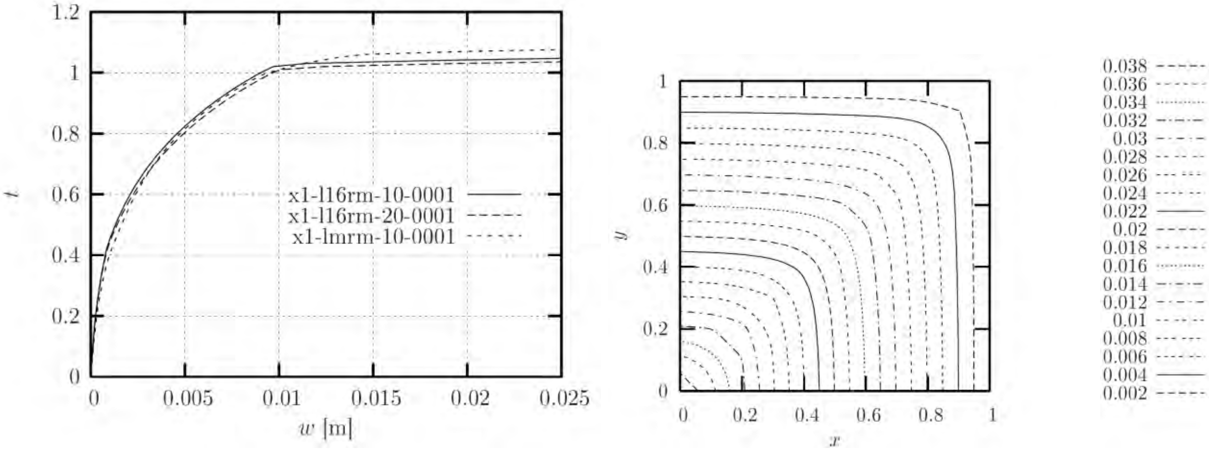


Figure 4. Load deflection curves in static analyses of plate X1 and static deflection surface after reaching the limit load.

In the impact studies with heavy missiles possible transverse shear deformation must be taken into account. The transverse shear capacity of plate can be calculated from

$$\tau_p = f_t + A_{ss} f_y, \tag{6}$$

where f_t is the tensile strength of concrete A_{ss} is the area of shear reinforcement and f_y is the yield stress of reinforcement.

The shear capacity of plate section is obtained from

$$q_p = \tau_p d \tag{7}$$

where *d* is the effective thickness, 0.225 m, in the present case.

For slab X1 one obtains

$$q_p = (3.03 + 0.001745 \bullet 500)0.225 = 0.88 \text{ MN/m}$$

and similarly for plate X2

$$q_p = (2.98 + 0.001167 \bullet 500)0.225 = 0.80 \text{ MN/m}$$

Loading function

The wall thickness of the missile is assumed to be 5 mm while in the joint paper ID476 it was 3 mm. Also the total mass of this new missile is somewhat higher, 58 kg. Loading function of the heavier missile due to an impact velocity of 166 m/s calculated with the Riera method, denoted by B, is shown in Figure 5. In the same figure is shown also the original load function with dashed line.

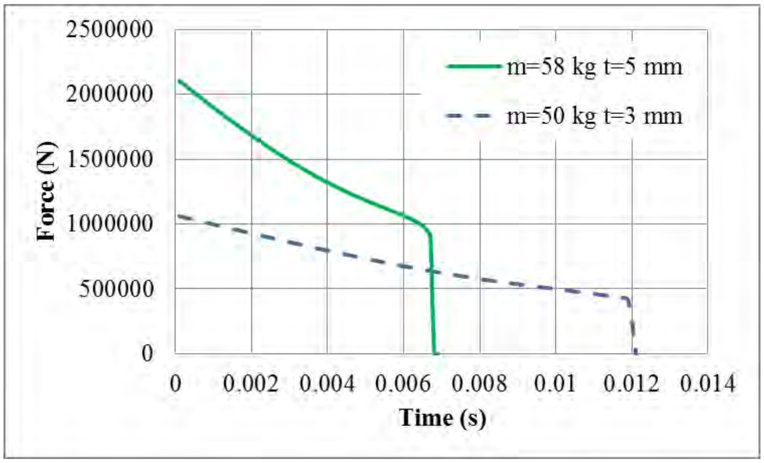


Figure 5. Loading function B obtained with missile with wall thickness of 5 mm and mass of 58 kg.

Shear punching behavior by TDOF model and by Reissner-Mindlin plate element model

In Figure 6 are shown the force histories calculated by the TDOF model. r1 and r2 are force histories of springs 1 and 2. X1B and X2B refer to plates X1 and X2. In Figure 7 are shown the strains in bending reinforcement.

Figure 8 shows the strain in stirrups in the punching cone. The strain in stirrups is calculated initially from

$$\varepsilon_s = (u_2 - u_1)/(h/3) \quad (8)$$

where h is the plate thickness.

Later in the cracked state the stirrup strain is evaluated from

$$\varepsilon_s = (u_2 - u_1)/(0.9h) \quad (9)$$

as in CEB model, CEB (1988).

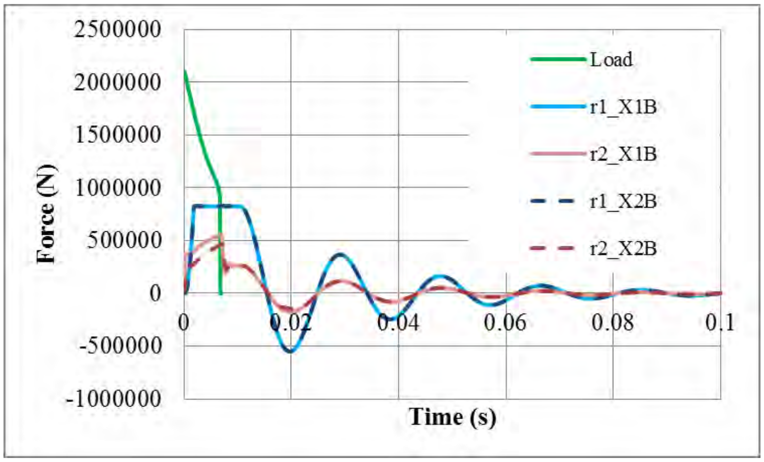


Figure 6. Force histories for cases X1B and X2B.

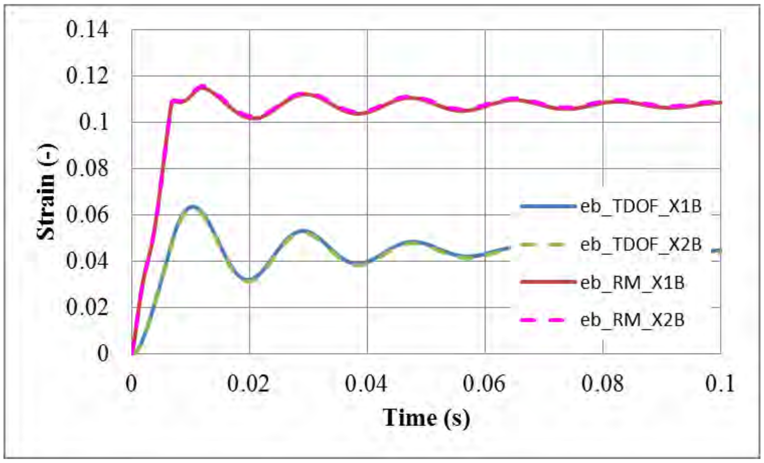


Figure 7. Strains in bending reinforcement.

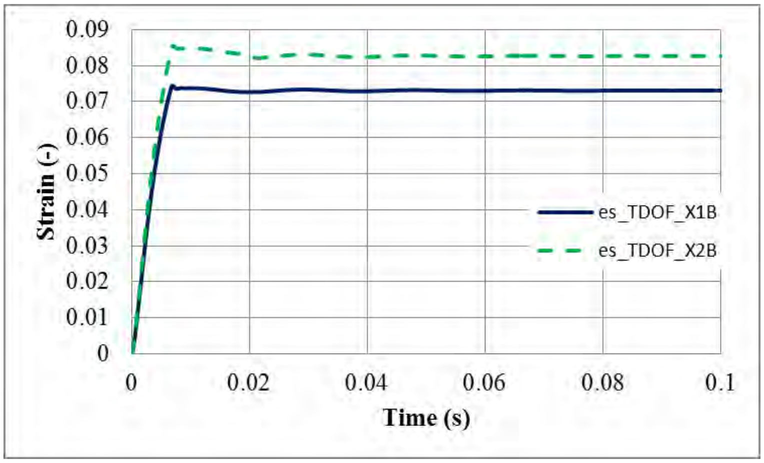


Figure 8. Strains in shear reinforcement.

In Figure 9 the deflection time histories of plate X1 at locations D1, D4 and D5 are shown. RM refers to Reissner-Mindlin theory finite element solution and label TDOF to 2-degree-of-freedom model. In the RM solution a damping ratio of 0.02 is assumed. In the TDOF model the deflection profile is assumed linear along the symmetry lines of the plate, and the values at points D4 and D5 are the same and they are calculated by interpolation.

Similarly, Figure 10 shows the deflection histories of plate X2 at the measurement points.

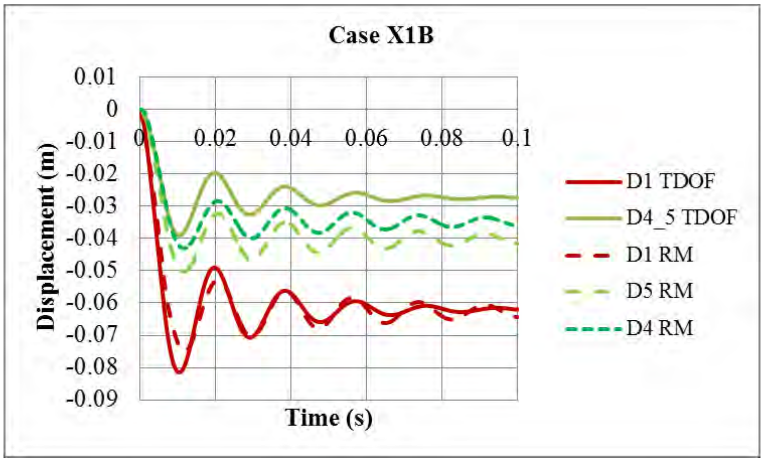


Figure 9. Deflections as function of time for case X1B.

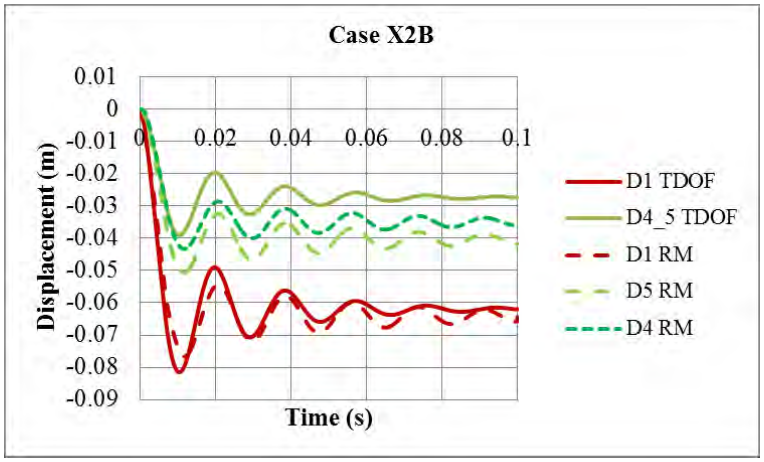


Figure 10. Deflections as function of time for case X2B.

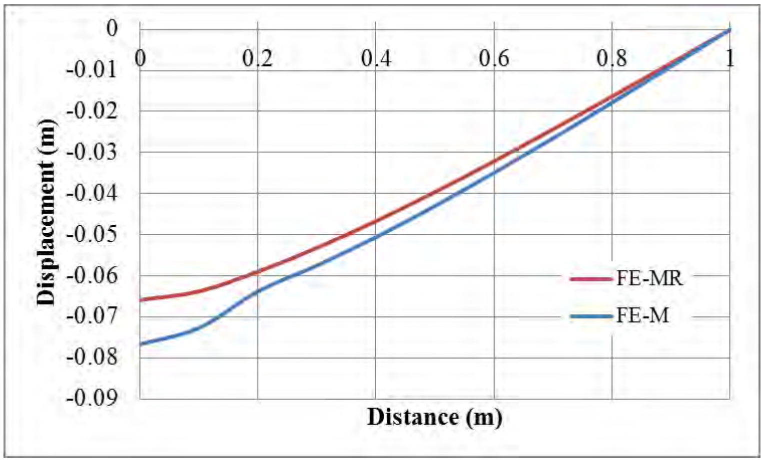
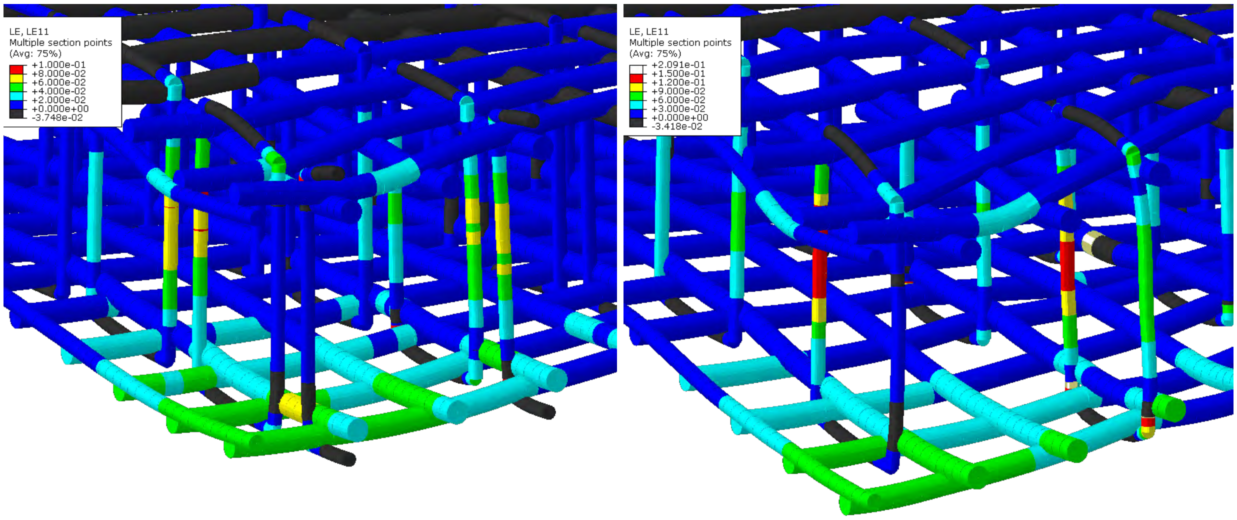


Figure 11. Displacement at the symmetry line at *t* = 11 ms.

The deflection profiles at the time of reaching the maximum central displacement are shown in Figure 11. Both solutions are computed by the Reissner-Mindlin theory FE method. In case labelled by FE-MR the transverse shear strength is infinitely large. In both cases elastic transverse shear deformations are taken into account. Figure 11 indicates the formation (at an early stage of loading) of punching cone. Similarly, the TDOF solutions predict shear punching under the adopted heavier impact load.

Shear punching behavior by 3D solid element model



a) b)

Figure 12. Results obtained by 3D solid element model. Strain distribution in reinforcement in case X1B (figure a) and in case X2B (figure b).

Strain distribution in reinforcement of plate X1 obtained by 3D solid element model with the modified missile B impacting the wall with a velocity of 166 m/s is shown in Figure 12a. The strains in shear reinforcement in the shear cone area are now exceeding 10% and clear shear cone formation can be predicted based on the results of this calculation. Corresponding results for the plate X2 are shown in Figure 12b. Now the strains in the shear reinforcement at the shear cone area are clearly over 10%. Due to the weaker shear reinforcement this could be expected.

CONCLUSION

In order to obtain more severe shear cone separation, further numerical studies were carried out using the same test walls as targets as in joint paper ID476 but increasing the load by modifying the missile.

The impact load due to a deformable missile impact is calculated with the Riera method and by using a 3D FE model in which both the missile and the impacted plate are discretized into finite elements and contact impact at the interface of missile and plate is solved.

Two finite element codes, Abaqus and a special purpose finite element program with a plate element capable of taking transverse shear into account, are used in calculating the responses of the test plates subjected to modified impact load. Additionally a simple TDOF model is also used for shear punching studies.

All used methods could predict the formation of shear cone. Bending vibration behavior of the slab could not be properly calculated with the solid model. But, of course, a 3D solid model is needed in studying local shear punching behavior of test plate in more detail.

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