Numerical Studies on Impact Loaded Reinforced Concrete Walls

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ABSTRACT

Reinforced concrete structures are used for protecting vital parts and equipment of nuclear power plants against projectile impact. In areas with dense air traffic the external containment buildings have been traditionally designed for accidental impact loads, which could be due to both civil and military aircraft. Recent events have shown that also civil aircraft can be used as weapons for intentional sabotage, emphasizing the need to look more carefully at impact load determination when designing protective structures and containment buildings of modern nuclear power plants.

In order to get any confidence with the numerical results, experimental, recorded data is needed for verification. In the open literature there are some fairly well documented test results on the subject of deformable missiles to be used as references in developing and calibrating the finite element simulation models and assessing the obtained numerical results. However, test results for fluid filled soft projectiles are not available in the open literature. Experimental data are needed also for verification of numerical results on impact loaded reinforced concrete structures collapsing by bending mechanism.

An experimental set-up has been constructed at VTT for medium scale impact tests. The main objective of this effort is to provide data for the calibration and verification of numerical models of a loading scenario where an aircraft impacts against a nuclear power plant. The experimental set-up is described in [1]. Methods to evaluate the spreading (e.g. release, penetration and dispersion) of fuel are presented in [2].

Methods and models for predicting the response of reinforced concrete structures subjected to impacts of deformable projectiles that may contain combustible liquid ("fuel") are studied, developed, applied and taken in use. Loading, structural behaviour, like collapsing mechanism and the damage grade of the reinforced concrete wall are predicted by simplified methods and by using extensive non-linear finite element models. Sensitivity studies on the effect of material parameters are conducted. Numerical results are compared with the experimental findings.

NUMERICAL ANALYSES OF IMPACT EXPERIMENTS

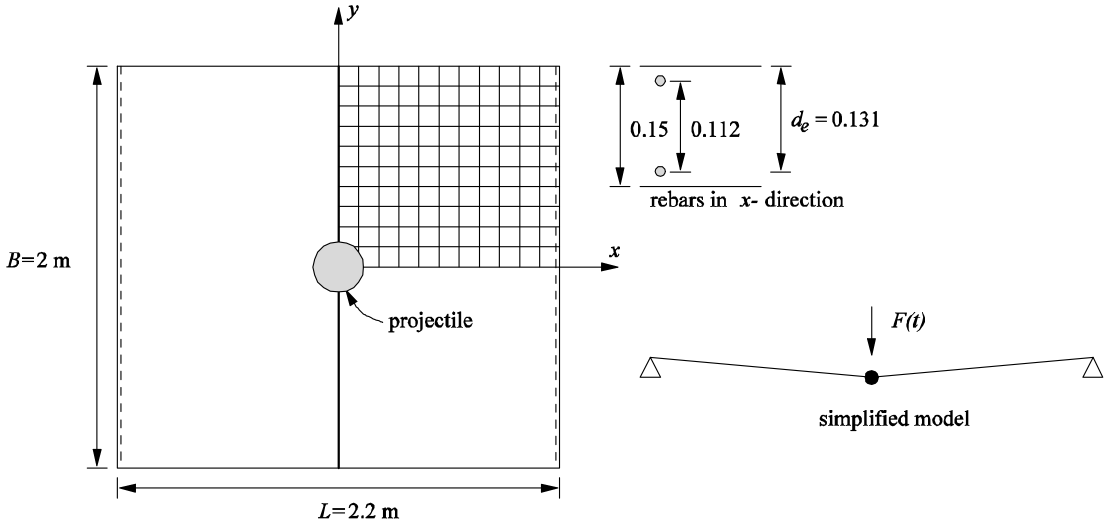

Fig. 1. Reinforced concrete one-way slab impacted by a missile.

In a test series wet and dry aluminum missiles were shot on reinforced concrete one-way target plates. The dimensions of the slabs were: width 2 m, length 2.3 m, support length 2.2 m and thickness 0.15 m. The slabs were simply supported on two opposite sides and free on the two other sides, depicted in Fig. 1 with a finite element mesh, a reinforced cross section and a simplified structural model for overall behavior. The reinforcement was made using bars with a diameter of 8 mm and a spacing of 50 mm, in each way and on each face.

In the following calculation models it is assumed that the distance of the center of reinforcing bars from the plate face is 19 mm. The effective plate thickness d_e then becomes 0.15 - 0.019 = 0.131 m.

The reinforcement ratio, if defined as $\rho_s = A_s/d_e$, in which A_s is the cross sectional area of reinforcement per unit length and d_e is the effective slab thickness, becomes in this case 0.767 %.

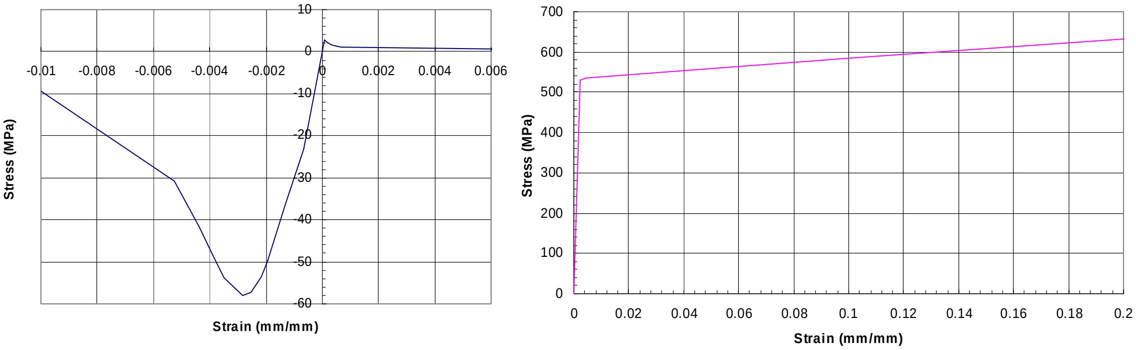

Fig. 2. Uniaxial stress-strain curves for concrete and for reinforcing steel.

The measured ultimate compression crushing strength of the concrete material is 58 MPa. The assumed compression stress as a function of strain is shown in Fig. 2.

If the concrete wall is rather weakly reinforced, then the assumed stress strain dependency after tensile cracking may affect the calculated result considerably. The tensile strength, 2.9 MPa, is predicted by the splitting tensile tests. In the following analyses the ascending stress-strain curve in tension is given in accordance with Ref. [3]

$$\sigma_t = E_0 \varepsilon_t, \quad \varepsilon_t \le \varepsilon_{cr},$$

$$\sigma_t = f_{t0} \left(\frac{\varepsilon_{cr}}{\varepsilon_t} \right)^{0.4}, \quad \varepsilon_t > \varepsilon_{cr},$$

where E_0 is the modulus of elasticity of concrete, f_{t0} is the cracking stress of concrete and ε_{cr} is the cracking strain of concrete. The uniaxial stress-strain curve is shown in Fig. 2. The ascending part of the tension curve models also the tension stiffening of reinforced concrete. Strain rate sensitivity of concrete strength values is not taken into account here.

The stress strain curve of the reinforcing steel, based on the test results and used further in the finite element analyses, is also shown in Fig. 2. Because the used reinforcing steel is known to be strain rate sensitive, the dynamic yield strength is taken into account by the Cowper-Symonds formula for uniaxial tension or compression:

$$\sigma_{y,dyn} = \sigma_y \left[1 + \left(\dot{\varepsilon} / D \right)^{1/q} \right] ,$$

where σ_y and $\sigma_{y,dyn}$ are the static yield stress and the dynamic flow stress, respectively, D and q are material parameters. For mild steel D = 40 1/s and q = 5 can be used [4].

Load function

Two types of missiles used in the impact tests [1] are considered. The first one is an empty aluminium missile (dry) and the second one is filled with water (wet). The mass of both missiles is about 50 kg. The length of the empty missile is 1.5 m whereas the length of the water filled missile is only 0.6 m. The impact velocities of the dry missile and the wet missile were 109 m/s and 105 m/s, respectively. The impact loads due to the dry and the wet aluminium missiles are calculated with the Riera method [5] assuming a folding visco-plastic mechanism in calculating the crushing force, P_c. The Cowper-Symonds visco-plastic power law type strain rate dependency is assumed for aluminium with parameter values D = 6500 1/s and q = 4, Fig. 3. The impulse of the load function of the dry missile is I = 5414 Ns and the corresponding value for the wet missile is I = 5376 Ns. The effect of water is taken into account in calculating the mass flow term in Riera's method.

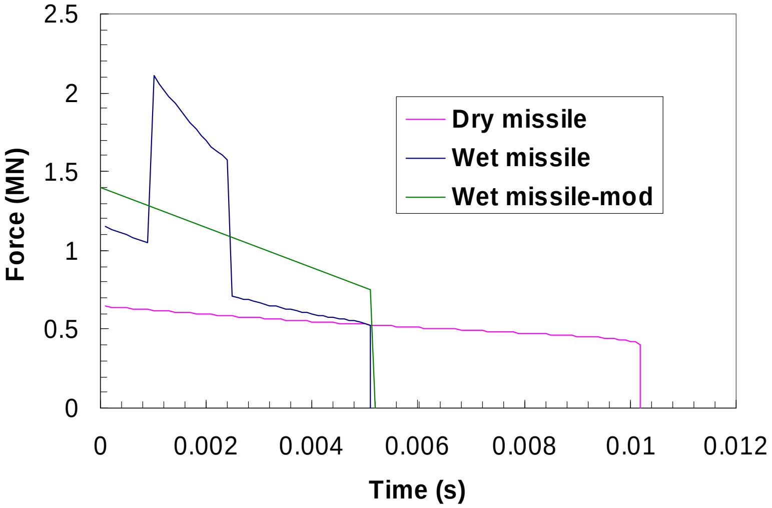

Fig. 3. Load functions due to dry and wet aluminium missiles.

Simplified methods

Simplified models with only few degrees of freedom can be constructed for assessing the global behaviour of impact loaded structures. These models are useful for preliminary design of impact experiments as well as for real structures and for checking the results of more refined and extensive numerical models. With a single degree of freedom model, [7], the midpoint deflection time history of an impact loaded slab can be calculated. With a two degree of freedom model besides bending mode behaviour also possible shear cone formation and displacement at the impacted site can be modeled, [8]. In the present examples bending behaviour dominates the plate response and cracking connected with an emerging shear cone is analyzed by a three dimensional solid element model.

Assuming f_c = 58 MPa for concrete and σ_y = 560 MPa for steel (a stress value obtained at 5 % strain value in the stress strain curve used in finite element calculations) the plastic moment capacity becomes $m_p = \rho_s d_e^2 \sigma_y [1-\rho_s \sigma_y / (2 f_c)]$ = 0.0698 MNm/m.

An equivalent yield stress of a homogeneous plastic plate, $4m_p / h^2$ = 12.42 MPa, can be defined so that the plastic moment capacity is the same as for the reinforced slab.

Assuming E_c = 35000 MPa and ν_c = 0.2 the bending rigidity of the concrete slab section becomes D_c = 10.254 MNm. The reinforcement gives its share of D_s = 1.81 MNm to the bending rigidity. For cracked cross sections according to [9] the bending rigidity can be obtained from $D = 0.5\, d_e^3 (5.5\rho_s + 1/12)\, E_c$ = 4.93 MNm.

The stiffness of a single degree of freedom elasto-plastic oscillator (SDOF oscillator) is for the one-way slab $k = 48DB/L^3$ = 51.2 MN/m.

The plastic limit load calculated by the mechanism with one yield line crossing the plate, in Fig. 1, is $F_p = 4m_pB/L$ = $3.636m_p$ = 0.254 MN. The internal plastic force of the SDOF oscillator is thus also R_p = 0.254 MN.

In calculating the effective mass of the SDOF model an equivalent density of the slab, 2546 kg/m^3, taking the reinforcement into account, is used. The mass of the SDOF model is $m = M/3 = (0.15 \cdot 2.2 \cdot 2.0 \cdot 2546)/3$ = 560 kg, where M is the mass of the slab. This effective mass is obtained by assuming a piecewise linear deflection mode for the slab, as depicted in Fig. 1. Another possibility would be using the first vibration mode. The damping coefficient c of the SDOF model can be calculated by the formula $c = 2\xi\sqrt{mk}$, where ξ is the damping ratio, m and k are the mass and the stiffness coefficient of the SDOF model, respectively.

The equation of motion of the elastic-plastic SDOF model can be integrated conveniently numerically e.g. by the central difference method (CD). By discarding the elastic part of deformation even a simpler model, a rigid plastic SDOF model, is obtained.

The impact load due to a dry aluminium pipe missile is shown in Fig. 3. The impact force is diminishing from 0.653 MN to 0.4086 MN during a time interval of 0.0102 s.

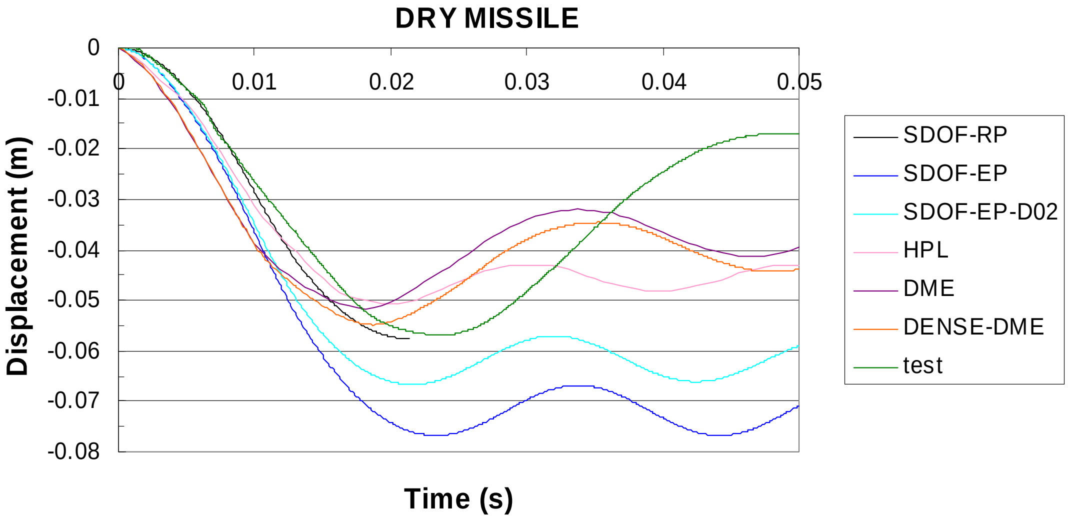

Fig. 4. Central deflection of one-way slab subjected to impact of dry aluminium missile with impact velocity 109 m/s.

The central point displacement time histories of the test slab impacted by a dry aluminium missile, obtained by various models, are depicted in Fig. 4. Curves labeled SDOF-RP and SDOF-EP are obtained with SDOF models. RP refers to a rigid plastic solution and EP to an elastic plastic solution. For the sake of comparison preliminary solutions with a computer program ABAQUS/Explicit [6] are calculated using the shell element mesh and the loading area depicted in Fig 1. DME refers to a damaged plasticity solution and HPL to a homogeneous plastic solution in which the yield stress is defined so that the plastic moment is the same as in other solutions.

In the homogeneous plastic solution model (HPL) and in the damaged plasticity solution (DME) 11 integration points are used in the plate thickness direction. Curve DME in Fig. 4 is calculated by assuming visco-plastic behaviour of the reinforcing steel using the Cowper-Symonds uniaxial formula with parameter values D = 40 1/s and q = 5.

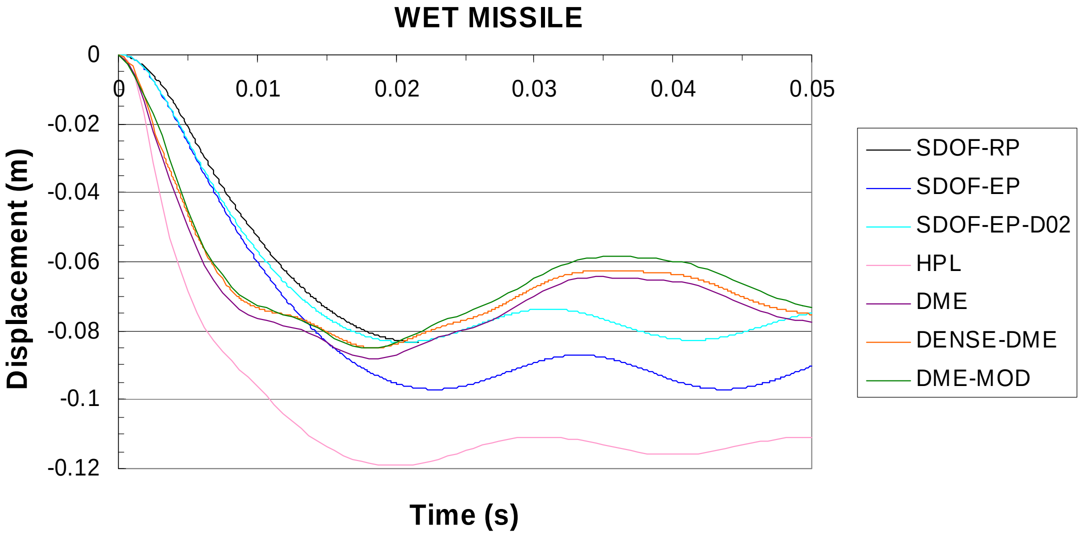

Fig. 5. Central deflection of one-way slab subjected to water missile impact with velocity 105 m/s.

In Fig. 3 the loading function of a wet aluminium missile with an impact velocity of 105 m/s is depicted. In the rigid plastic solution an equivalent load function, Wet missile-mod, having the same impulse as the original load, is used. Solutions for the central deflection obtained by various models are collected in Fig. 5. Curves SDOF-RP and SDOF-EP are again obtained by SDOF rigid plastic and elasto-plastic models, respectively. Curves DME and HPL are calculated with ABAQUS/Explicit using damaged plasticity and homogeneous plasticity material models, respectively. Label D02 refers to solution including Rayleigh type damping of 2 %. A damaged plasticity solution by ABAQUS using the same load function as in SDOF-RP solution is also shown. This solution, DME-MOD, demonstrates the effect of load history details. The simplified trapezoidal load history was used in SDOF-RP solution to enable easy exact integration of the equation of motion.

Finite element analyses

The actual finite element analyses of impact tests were carried out by a computer code ABAQUS/Explicit [6] using shell element and 3D solid element models. In shell models four-noded shell elements with reduced integration in reference surface direction and 11 point Simpson integration in thickness direction were used. In three dimensional (3D) models eight-noded solid elements were adopted. One quarter of the wall modeled with shell elements is presented on the left hand side in Fig. 6. The loading area on shell mid surface, based on an assumed spreading angle of 45° (in the shell thickness direction) at the intersection of the symmetry lines is shown in red color. A detail of the solid element model for one half of the wall with reinforcing bars is shown on the right hand side in Fig. 6. The solid element model contains over 100 000 8-noded solid elements modeling the concrete and over 12 000 truss elements modeling the rebars. The applied load functions are presented in Fig. 3 and the uniaxial material curves are shown in Fig. 2. No damping was applied in these analyses.

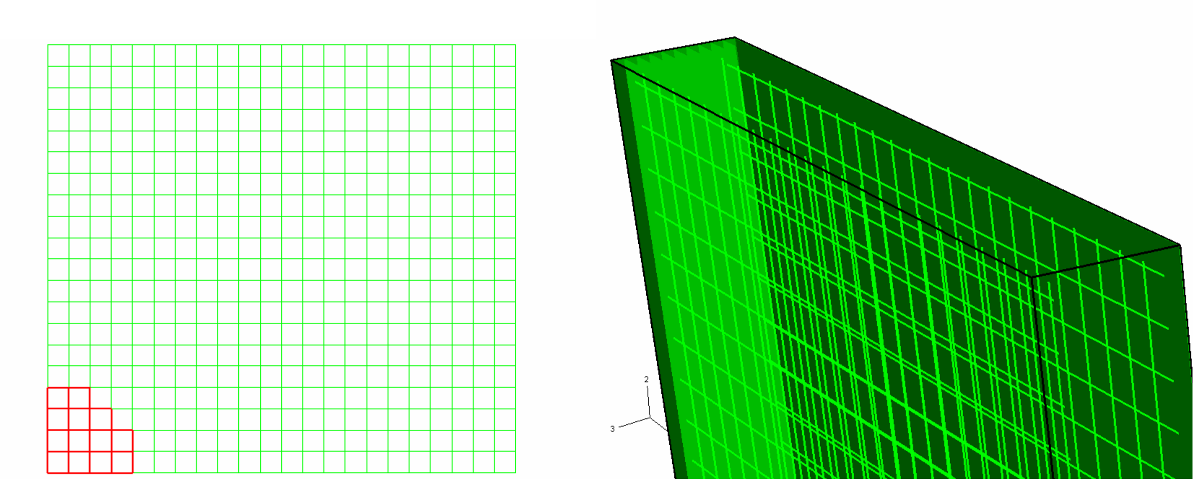

Fig. 6. One quarter shell element model and a detail of one half 3D solid element model.

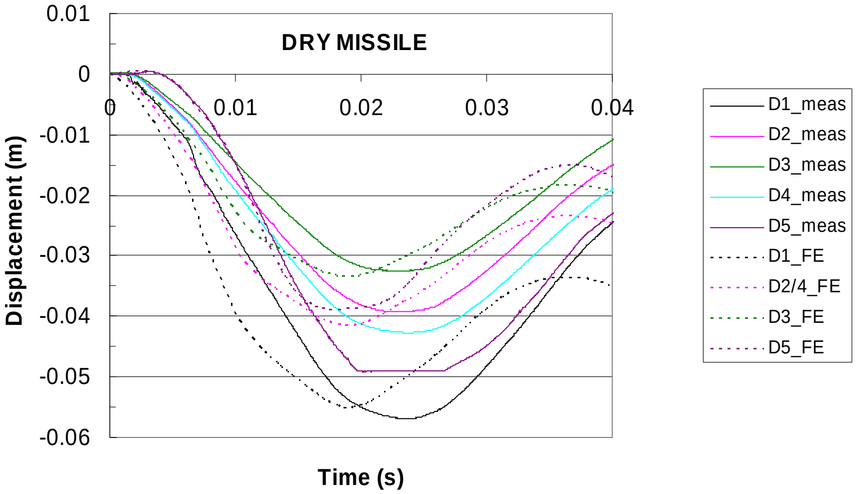

Fig. 7. Measured and calculated displacements as functions of time in dry missile test.

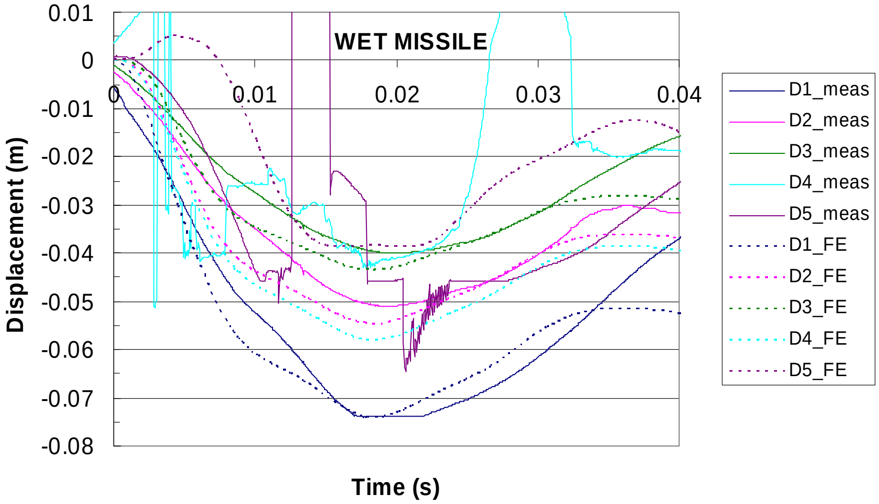

Fig. 8. Measured and calculated displacements as functions of time in wet missile test.

Measured and calculated displacements using the shell element model are presented in Fig. 7 for the dry missile impact and in Fig. 8 for the wet missile impact. The locations of displacement sensors and strain gauges are given in [1]. It should be noted that the locations of the displacement sensors, due to technical reasons, are not the same in all the tests. The calculated displacement values are in reasonable agreement with the measurements. Calculated central point displacement time histories for dry and wet missile impacts are presented in Figs 4 and 5, respectively. These curves calculated with the mesh shown in Fig. 6 are labeled DENSE-DME.

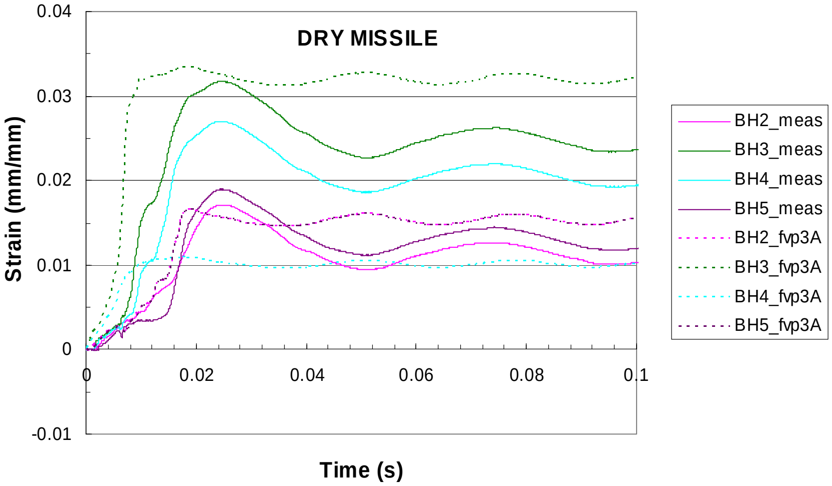

Fig. 9. Measured and calculated strains as functions of time in dry missile test.

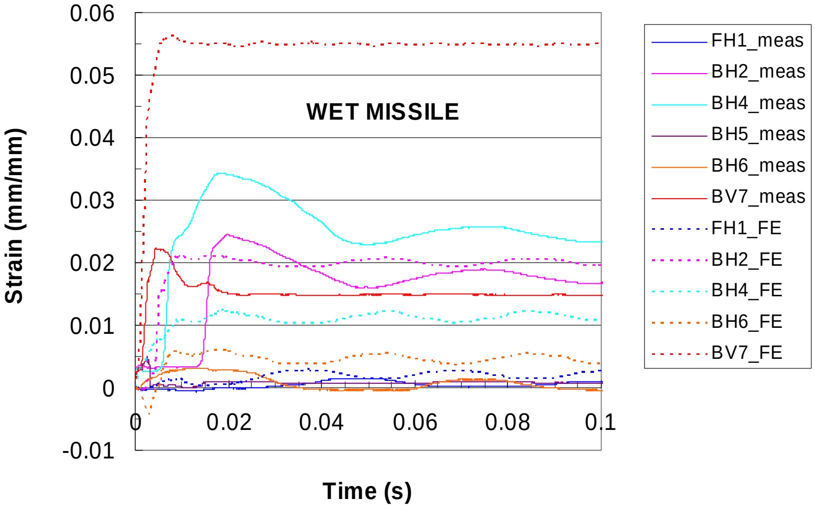

Fig. 10. Measured and calculated strains as functions of time in wet missile test.

Measured and calculated strain values in the reinforcement of the wall loaded by the dry missile are shown in Fig. 9 and the corresponding results for the wet missile impact are depicted in Fig. 10, respectively. The maximum strain value occurs in the back surface horizontal reinforcement at the mid span. The calculated values are reasonably close to the measured ones. It should be taken into account that the strain values are calculated in the centre of the element and this location is not necessarily exactly the same as the location of the corresponding strain gauge. On the other hand the measurement length of these strain gauges is 5 mm. The gradient in the strain distribution can be rather steep.

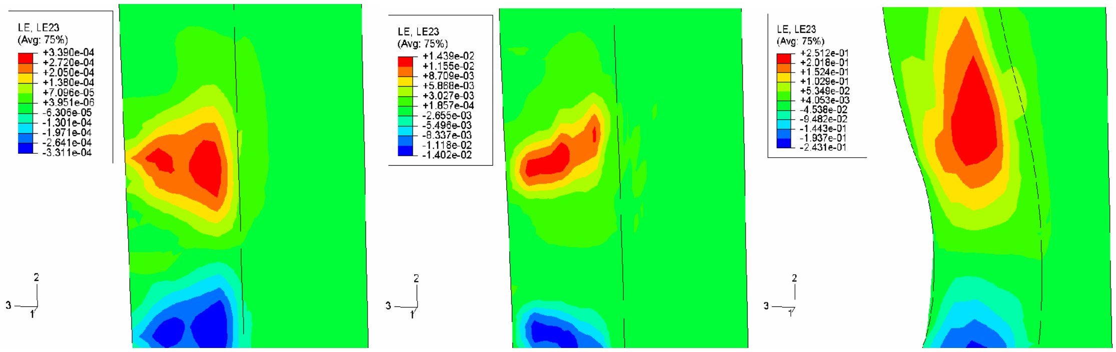

Fig. 11. Shear strain distributions at the impact site at *t* = 0.05 ms, 0.5 ms and 5 ms in dry missile test.

The development of the shear strain distribution through the wall thickness is calculated by the solid element model of Fig. 6 at different times and shown in Fig. 11 at different time steps. The shear deformations are connected with micro cracking of concrete beginning at the early stages of impact. However, from the macroscopic point of view no shear cone separation occurred in the considered tests.

SUMMARY AND CONCLUSION

An impact test set-up is constructed and taken in use for intermediate scale missiles. Reinforced concrete targets are tested for impact loads with empty and fluid filled deformable missiles.

The main aim was to predict the structural behaviour of the impact loaded wall collapsing by bending mode. No spalling or perforation occurred due to the impact load in the considered cases. Structural behavior of reinforced concrete walls loaded by deformable missiles is studied and simulated by using simplified analysis methods and with the finite element method.

A single degree of freedom (SDOF) oscillator is a useful tool in the preliminary design phase so long as mass, strength and stiffness properties for the oscillator can be assessed with a reasonable accuracy. The SDOF model is an effective tool also in verifying the analyses applied for more complicated constructions.

Nonlinear analysis of reinforced concrete structures is still a challenging task. In this study one aim was to assess the capability of shell elements in calculating the maximum displacement of walls under impact load when bending mode dominates the structural behaviour. Of course, when the failure mode is penetration, perforation or scabbing a more extensive solid element model is needed. This type of model was also applied in analysing the present tests. Shell elements capable for modeling inelastic transverse shear deformation could also be used in predicting the possible formation of shear cone due to projectile impact.

One main uncertainty in the real world is the applied loading transient. In this case one uncertainty is the load due to steel guiding rails, which support the missile during the acceleration. The rails fall away during the impact and it is difficult to define their contribution to the impact load exactly. In the dry long missile the length of the front rail was 15 cm and its mass was about 1.5 kg, so its effect is not too dominant. But the in the case of the short wet missile (length 600 mm) the total length of the rails was 400 mm.

Tensile strength of concrete is rather low when compared with its compressive strength, and it is sometimes even neglected. But when a plate with a rather weak reinforcement collapses in bending mode and when cracking occurs almost through the whole thickness the assumed tensile behavior of concrete may have a considerable effect on the results. Understandably the results are not so sensitive for the modeling of compressive behavior of concrete.

Numerical results were compared with experimental data. Deflections and strains in reinforcement were assessed rather well by shell element models.

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