FINITE ELEMENT SIMULATION OF SOFT MISSILE IMPACTS ON REINFORCED CONCRETE SLABS

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ABSTRACT

The Technical Research Center of Finland (VTT) conducted a series of soft missile impact tests on reinforced concrete slabs. These tests are part of an international research program called IMPACT that investigates the response of structural concrete components to missile impacts. The United States Nuclear Regulatory Commission (USNRC) is one of the organizations that participate in the project IMPACT. An objective of this research program is to experimentally benchmark numerical modeling codes used to simulate the response of concrete slabs to impact loads. This paper compares results obtained with a commercial finite element code, specifically the dynamic, nonlinear explicit finite element code LSDYNA, to the observed responses of reinforced concrete (RC) slabs subjected to soft missile impacts. The missiles consist of hollow cylindrical aluminum or steel pipes either empty or partially filled with water. The paper presents the results of medium scale tests and, for the modeling assumptions used, assesses the ability of the finite element code to capture the response and behavior of the slabs for varying support conditions, impact speeds and missile characteristics such as empty and water-filled missiles.

The test specimens consisted of 150-mm thick RC slabs. The slabs are either 2082mm×2082mm square slabs simply-supported on all sides or 2300mm×2000mm rectangular slabs simply-supported on opposing sides. The baseline reinforcement for the tests consists of two layers of orthogonal flexural reinforcement near each face of the slab. Reinforcement variants in addition to the baseline reinforcement consisted of the addition of transverse steel reinforcement in the form of closed loop stirrups. The tests impacted the vertical slabs with either empty or partially water-filled missiles of varying shapes and strength at varying speeds.

The baseline finite element model of the slabs used the Winfrith constitutive model with strain rate effects for the concrete (LSDYNA material No. 84), eight-node solid elements with one point numerical integration for the concrete and bar elements with elastoplastic steel isotropic hardening for all steel reinforcement. The missiles were modeled using shell elements for the missile hollow cylinder and missile cap. Various modeling techniques were used for partially water filled missiles namely consideration of an increased mass per unit length and the use a smooth particle hydrodynamics (SPH) technique. The paper also identifies limitations of the models which, for the Winfrith model, primarily relate to the slab response following the first response cycle, which is the cycle in which the significant slab damage occurs. Although the simulations did not predict all aspects of the response with the same degree of accuracy they captured the primary characteristics of the slab response and damage.

INTRODUCTION

This paper compares results obtained with a commercial finite element code, specifically the dynamic, nonlinear explicit finite element code LSDYNA [1], to the response observed in three medium scale tests of RC slabs subjected to soft missile impacts. The missiles consisted of hollow cylindrical aluminum or steel pipes either empty or partially filled with water, which hit the center of the slab, approximately, in a direction perpendicular to the plane of the slab. All test specimens analyzed consisted of 150-mm thick concrete slabs with two layers of orthogonal flexural reinforcement near each face as well as transverse reinforcement in the form of closed loop stirrups. The modeling and analysis used default modeling parameters for the LSDYNA code, to the extent possible, as well as material models already available in LSDYNA. Impact loads were modeled by explicitly modeling the impact of the missile on the plate at the specified test speed.

The following section identifies and provides a brief description of each of the three tests analyzed. This section is followed by a section with a description of the finite element models and a summary of the material properties used in the analyses. The subsequent section provides a comparison of calculated results and predicted damage to observed results and damage. The paper concludes with a summary, conclusions and a brief description of ongoing related studies.

TESTS DESCRITPION

All test specimens consisted of 150-mm thick RC with two layers of orthogonal flexural reinforcement near each face as well as transverse reinforcement in the form of closed loop stirrups. Each testing specimen was mounted vertically on a testing frame which clamped the supported edges of the slabs with rollers. An additional horizontal roller at the bottom of the frame provided the vertical support for the slabs. The edges of the front face (impact face) and back face of the slabs were covered with the steel plates anchored to the concrete where the slabs were clamped to the frame through the rollers [2, 3].

Test results are in terms of maximum measured deflections at gages in the back or front face of the slab at a specified distance from the center of the slab, residual displacements of the slab, back face scabbing and front face spall if they occurred, and formation of punching shear cone if it were to form. Additional testing observations include cracking formation, including that observed in high speed videos and at the end of the tests.

Impact of Soft Missile on One-Way Slab (Test 673)

This was a 2300mm×2000mm rectangular slab simply-supported on opposing sides with a clear span of 2200 mm. The flexural reinforcement consisted of two orthogonal layers of 8-mm diameter bars at 50-mm spacing. The transverse reinforcement consisted of 6-mm bars at 50-mm spacing in each direction. Additional transverse reinforcement was placed near the edges of the slab. The soft missile consisted of a hollow aluminum pipe, with 5-mm thick walls, with a nose aluminum plate and a steel cap at the back. The missile had an approximate total mass of 51.3 kg, a length of 1800 mm and a diameter of about 250 mm. The missile hit near the center of the slab with a speed of about 127 m/s.

Impact of Soft Missile on Two-Way Slab (Test TF11)

This was a 2082mm×2082mm square slab simply-supported on all four sides opposing sides with a clear span of 2000 mm. The flexural reinforcement consisted of two orthogonal layers of 6-mm diameter bars at 50-mm spacing. The transverse reinforcement consisted of 6-mm bars at 50-mm spacing in staggered pattern in each direction. Additional transverse reinforcement was placed near the edges of the slab. The soft missile consisted of a hollow stainless steel pipe, with 2-mm thick walls, with a nose stainless steel plate and a steel pipe cap with a stiffener at the back. The missile had an approximate total mass of 50.0 kg, a length of 2161 mm and a diameter of about 254 mm. The missile hit near the center of the slab at a speed of about 108 m/s.

Impact of Soft Missile Partially Filled with Water on Two-Way Slab (Test TF13)

This was a 2082mm×2082mm square slab simply-supported on all four sides opposing sides with a clear span of 2000 mm. The flexural reinforcement consisted of two orthogonal layers of 6-mm diameter bars at 50-mm spacing. The transverse reinforcement consisted of 6-mm bars at 50-mm spacing in a staggered pattern in each direction. Additional transverse reinforcement was placed near the edges of the slab. The soft missile consisted of a hollow stainless steel pipe with 2-mm thick walls. The missile was 1387 mm long and filled with water at the front for a length of approximately 470 mm. A 3-mm thick stainless steel dome separated the chamber filled with water from the empty back part of the missile. The missile had a stainless steel cap with a stiffener. The total mass of the missile including the mass of water was 50.0 kg, the mass of the water was 26.4-kg, and the missile diameter was about 252 mm. The missile hit near the center of the slab at and offset of 18 mm and a speed of about 111 m/s.

FINITE ELEMENT MODELING

Common Modeling Approach

The finite element models for each test consisted of the model of the reinforced concrete (RC) slab, including the steel plates covering the edges of the slab, back and front faces, where the slab was clamped by rollers to the supporting test frame, as well as the model of the soft missile. The test frame was not modeled. Instead, the slab was restrained by restraining the displacement of selected nodes on each face of the slab in the direction normal to the plane of the slab. The location of the restrained nodes coincides with the location of the rollers that clamped the slab to the test frame. These nodes were allowed to displace in a plane parallel to the plane of the slab.

Solid, hexahedral (8-noded) elements (LSDYNA element 64) were used to model the concrete while truss elements (LSDYNA element 60) were used to model the reinforcing bars. Each model included all reinforcing bars, namely: two orthogonal layers of flexural reinforcement near each face of the slab, and transverse reinforcement in the form of closed loop stirrups. Shell elements (LSDYNA element 63) were used to model the missile and the steel plates at the edges of the slab. These elements shared nodes with the adjacent concrete elements.

Dimensions of the concrete elements were chosen so that all reinforcing bars shared nodes with concrete elements thus assuming perfect bond between the bars and the concrete. The dimensions for the concrete elements were chosen so that the locations for the flexural and transverse reinforcement would be the same for the test model and the analysis model. Those parts of the reinforcing bars corresponding to the anchoring (development length) of reinforcing bars were not included in the model. The ends of the vertical legs of the stirrups shared the same nodes with the concrete and the reinforcing bars in the flexural reinforcement layers. However, the model did not include that part of the stirrups that looped over the flexural reinforcement.

Because the test slabs were positioned vertically gravity forces induced small axial stresses in the slab but did not induce out of plane deflections and stresses. For this reason, it was assumed that gravity forces would not have a significant effect on the response of the slab, which is mostly an out of plane response. This is expected to be a good assumption especially for the first cycle of the slab response following the missile impact which, as expected, was the response cycle during which all significant damage was inflicted to the test slab.

Figure 1 is an example of the finite element model for the test slab, namely that for Test TF13, which shows one-half of the full slab model used for this test. Figure 1 only shows the modeling of the reinforcement and of the steel cover plates and does not show the solid elements for the concrete. Figure 2 is an example of a missile model, namely that for Test TF 13, which shows half of the model used in the analysis of Test TF13.

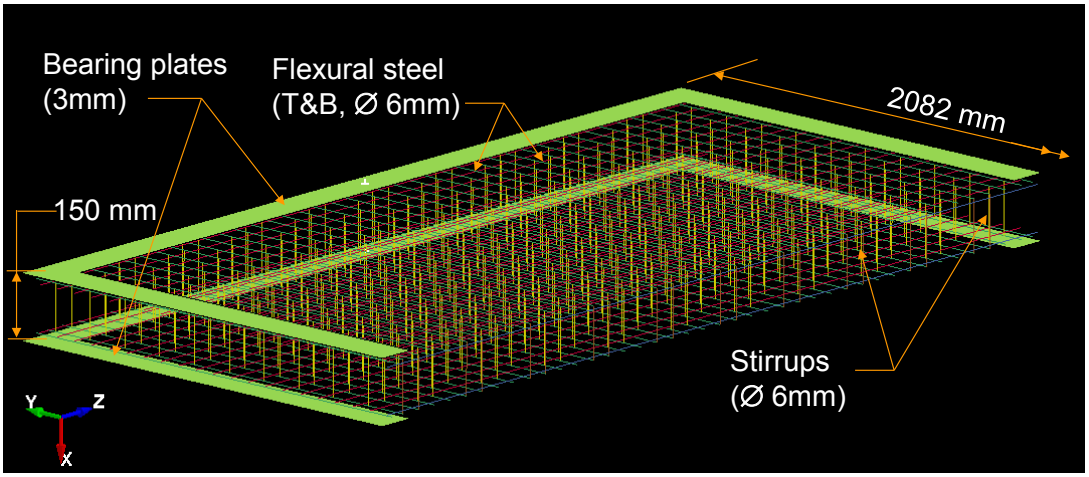

Fig. 1: RC panel model for Test TF13 (not showing the solid elements)

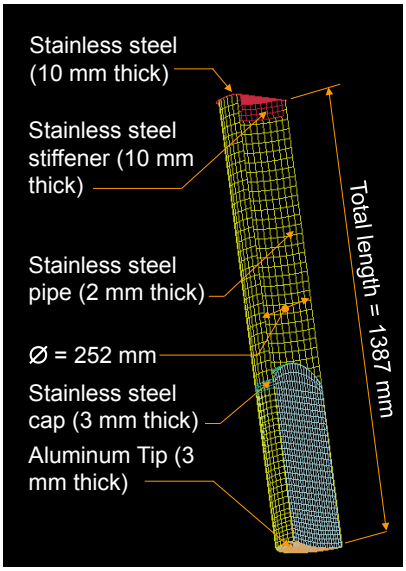

Fig. 2: Missile model for Test TF13

Material models

Concrete – All analyses used the LSDYNA Winfrith concrete model with strain rate effects (LSDYNA material model 84). For this concrete model, LSDYNA uses a single integration point for each solid element. This dramatically reduces the execution speed but requires the use of numerical techniques to control hourglass response modes. The analysis used the standard LSDYNA viscous form for hourglass control with an hourglass coefficient of 0.10.

Reinforcing steel – All analyses used the LSDYNA material model 3 and the Cowper-Symonds model to account for strain rate effects. A failure criterion was used for all reinforcing bars with a rupture tensile failure strain of 0.20.

Steel Plates – All analyses used the LSDYNA material model 3 and the Cowper-Symonds model to account for strain rate effects. Accurate material properties for this steel were not deemed relevant as the function of these plates in the analysis was only to prevent local crushing of the concrete from the bearing of the rollers.

Aluminum – The analysis used LSDYNA material model 3. Strain rate effects were not considered because accurate modeling of the behavior of this material was not deemed necessary to get an adequate representation of the loads imparted to the slab.

Stainless Steel – The analysis used the standard LSDYNA bilinear plasticity model (LSDYNA material model 3) with kinematic hardening. Strain rate effects were not considered because accurate behavior of this material was not deemed necessary to get an adequate representation of the loads imparted to the slab.

Table 1 shows the material properties for the concrete and reinforcing steel used for the analysis which are those reported for the tests. In particular, the concrete strength is the strength at the time of testing and it refers to the cube strength which is the one used with the Winfrith model. The density for the concrete was 2300 kg/m^3 while the fracture energy for the Winfrith model (strain softening) was 150 J/m^2. The parameters for the Cowper-Symonds model for steel, $F_{yd} = F_{ys}(1+\varepsilon_R/C)^{1/q}$, where C = 50 and q = 5.

Table 1: Material properties for concrete and reinforcement

	Concrete			Reinforcement		
Test	Compressive Cube Strength (MPa)	Tensile Strength (MPa)	Tangent Modulus (MPa)	Yield Strength (MPa)	Failure Strain	Post-Yield Modulus (MPa)
673	59	3.6	27000	535	0.20	550
TF11	67.7	3.5	28200	623	0.20	694
TF13	62.8	3.5	27220	623	0.20	1627

Modeling of Impact of Soft Missile on One-Way Slab (Test 673)

Only one-quarter of the test slab and missile were modeled for this analysis. The model used 18 solid elements through the slab thickness for a total of 132480 solid elements. It used 10448 beam (truss) elements for the reinforcement and 2560 shell elements for the plates at the supports. The missile model used 1488 shell elements.

Modeling of Impact of Soft Missile on Two-Way Slab (Test TF11)

Half of the test slab and missile were modeled for this analysis. Missile offset was not included because this was a pre-test analysis. The model used 37840 solid elements with 10 elements through the slab thickness. It used 11892 truss elements for the reinforcement and 1792 shell elements for the plates at the supports. The missile model used 3168 shell elements.

Modeling of Impact of Soft Missile Partially Filled with Water on Two-Way Slab (Test TF13)

The analysis did not take advantage of symmetry to represent the 18-mm missile offset. The model used 75680 solid elements for the slab with 10 elements through the slab thickness. It used 23894 truss elements and 3584 plate elements. Two approaches were used for the modeling of the missile. One approach, herein called Model 1, used 3940 shell elements and 37632 SPH elements to model the water. The other approach, herein called Model 2, does not explicitly model the water and adjusts the density of the steel at the front of the missile to represent the total mass per unit length of the steel pipe and water infill. Analysis for Test TF13 also explicitly modeled the rollers clamping the edge of the slabs to the test frame. This was done by modeling half cylinders with solid steel elements and the contact between these cylinders and the steel plates at the edges of the slabs using a dynamic coefficient of friction of 0.3.

COMPARISON TO TEST DATA

For each test, comparison of the analysis to the test data is provided here, primarily, in terms of calculated and measured gage displacements. The paper also provides a few additional comparisons of reinforcement strains and overall damage descriptions, slab deformations and cracking.

Impact of Soft Missile on One-Way Slab (Test 673)

Figure 3 is a comparison of measured displacements of the back face of the slab with analysis results. The results indicate that the first cycle displacements are consistent with the measured displacements. The test results indicate a few free-vibration cycles after the first response cycle that are not captured by the analysis. In addition, the analysis underestimates the permanent displacements. It is noted that essentially all slab damage occurred during the first response cycle, which is to be expected for impulsive loads.

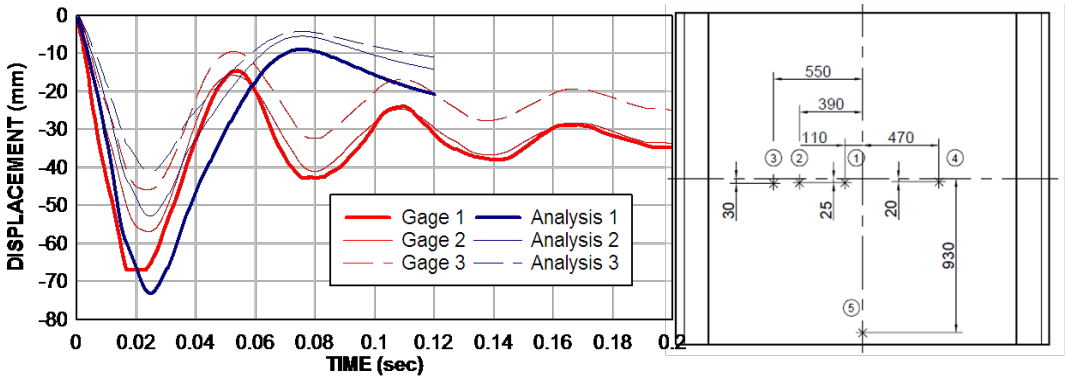

Fig. 3: Measured and calculated displacements for Test 673

Figure 4 shows strains in the horizontal bars near the back face of the slab measured at a few selected locations (also shown in that figure) together with the calculated strains. Strains from the analysis depend on the gage length (if they are calculated for a single element or averaged over a few elements) and vary rapidly with the location in the slab. In general, for the gages shown, the calculated strains are reasonably consistent with the measured strains. For gage 5, the calculated residual strains are significantly less than the measured strains. Measured strains for gage 2 would be expected to be similar to those measured for gage 5. However, measured strains for gage 5 and gage 2 are significantly different. Examination of the records indicates that gage 2 might have malfunctioned. For this reason only the strains measured for gage 5 are compared to the calculated strains.

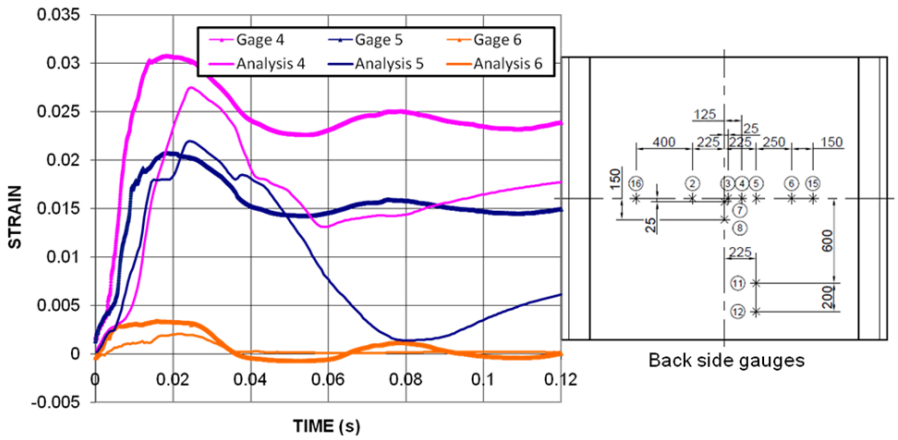

Fig. 4: Measured and calculated strains for Test 673

Impact of Soft Missile on Two-Way Slab (Test TF11)

Displacements for this test were relatively small and the observed damage was light to moderate. Test TF11 also is useful to compare the slab response when impacted by an empty missile and a missile with the same

total mass and similar speed but partially filled with water at the front of the missile (Test TF 13). Figure 5 is a comparison of measured and calculated displacements of the back face of the slab with analysis results. The results indicate that the first cycle displacements are consistent with the measured displacements although the predicted response is somewhat softer. Test results indicate a few free-vibration cycles after the first response cycle that are not captured by the analysis. The analysis also underestimates somewhat the permanent displacements. Note that all slab damage essentially occurs during the first response cycle, which is to be expected for impulsive loads. Test measurements indicate that the free-vibration of the slab continues for several cycles.

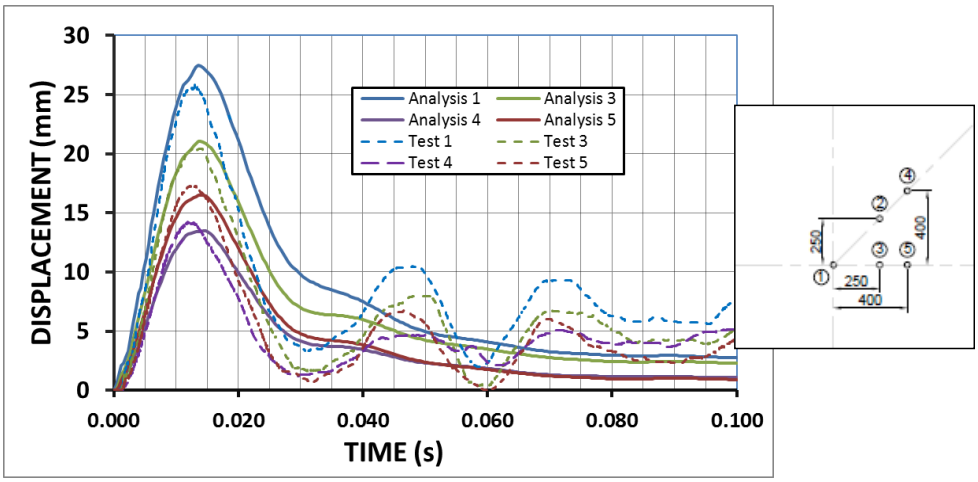

Fig. 5: Measured and calculated displacement for Test TF11

Impact of Soft Missile Partially Filled with Water on Two-Way Slab (Test TF13)

Displacements for this test were moderately large and the observed damage was moderate. Of interest, as noted in the previous subsection, is the comparison of the results for this test with those from Test TF11. In Test TF11 an identical slab was impacted by an empty missile with the same total mass and impact speed, that is, a missile with the same overall momentum.

Figure 6 is a comparison of measured (Figure 6a) and calculated displacements of the back face of the slab with results from two analysis models: Figure 6b for results calculated by explicitly modeling the water using SPH (Model 1) and Figure 6c for results calculated without explicitly modeling the water but using a modified steel density at the front of the missile to simulate the total missile mass per unit length in this region (Model 2). The comparisons indicate that the first cycle displacements are consistent with the measured displacements for both models although the calculated responses are somewhat higher. Test results indicate a few free-vibration cycles after the first response cycle that are not captured by the analysis. Note that all slab damage essentially occurs during the first response cycle, which is to be expected for impulsive loads. Test measurements indicate that the free-vibration of the slab continues for several cycles.

Results from Model 1 (SPH) and Model 2 indicate that the simpler analysis model can capture the effect of filling the front of the missile with water on the observed slab damage. Both models captured reasonably well the greater damaging effect of filling the front of the missile with water (Test TF13) as compared to the lesser damaging effect of an empty missile (Test TF11) for missiles with the same momentum and diameter.

Figure 7 is a comparison of the observed and calculated damage (Model 1) to the back face of the slab. The analysis predicted well the cracking pattern at the back of the slab.

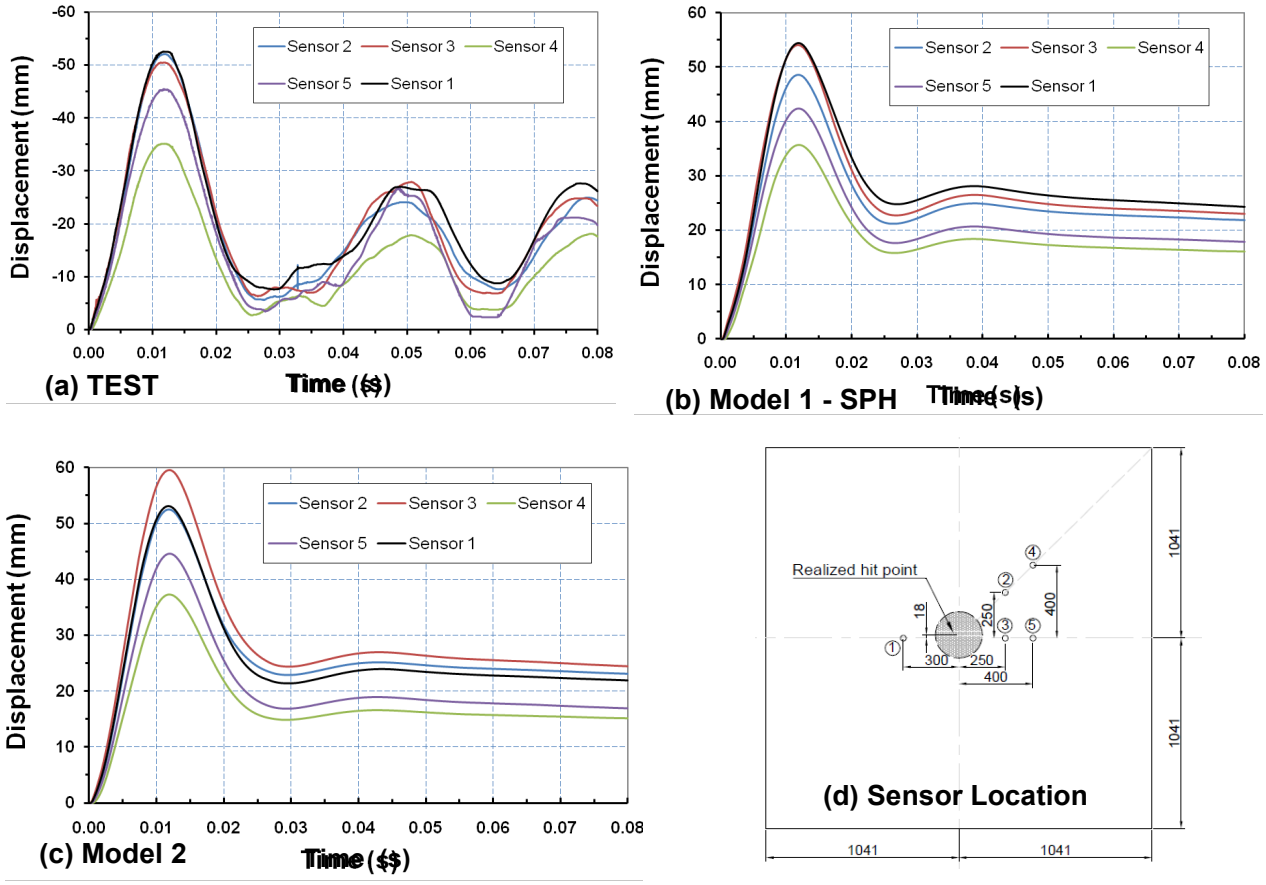

Fig. 6: Measured and calculated displacement for Test TF13

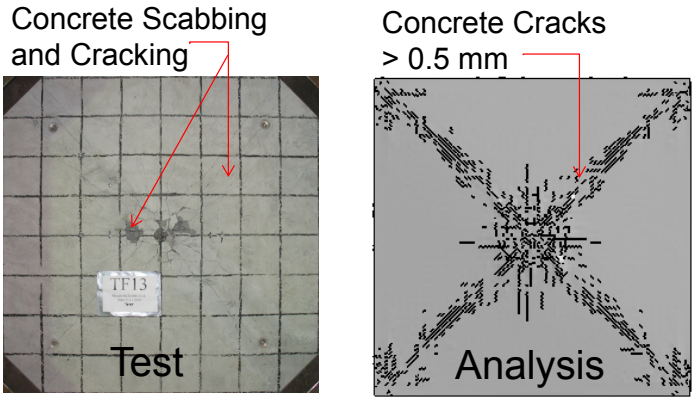

Fig. 7: Back face slab damage (Test TF13)

Figure 8 is a plot of the deformed shape of the slab for Model 1 showing contours of the maximum principal strain at the time of the maximum response. Figure 8 indicates that the analysis calculates large strains near the center of the slab, especially at the back face (bottom part in Figure 8), which indicates initiation of back face scabbing as shown in Figure 7.

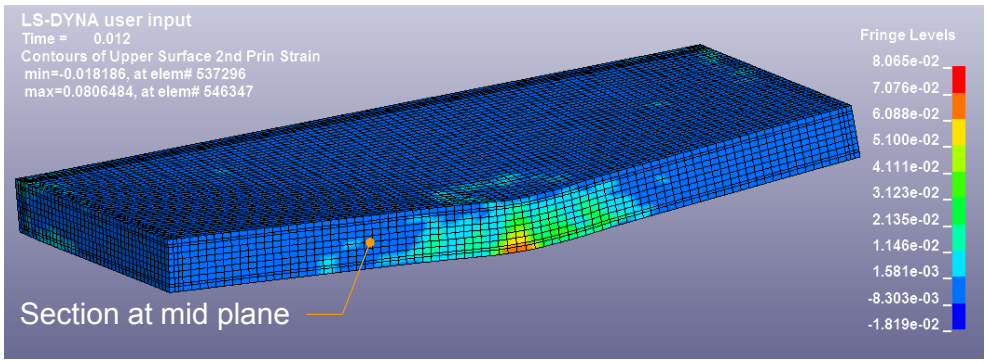

Fig. 8: Deformed shape and maximum principal strains at time of maximum displacement (Test TF13)

SUMMARY AND CONCLUSION

This paper compares results obtained with a commercial finite element code, specifically the dynamic, nonlinear explicit finite element code LSDYNA, to the observed responses of reinforced concrete (RC) slabs subjected to soft missile impacts. The missiles in the tests consisted of hollow aluminum or steel pipes either empty or partially filled with water. The paper presents results of medium scale tests and, for the modeling assumptions used, assesses the ability of the finite element code to capture the response and behavior of the slabs tested.

Modeling of the slabs used the Winfrith constitutive model with strain rate effects for the concrete (LSDYNA model 84), eight-node solid elements with one point numerical integration for the concrete and bar elements with elastoplastic steel isotropic hardening for all steel reinforcement. The missiles were modeled using shell elements for the missile hollow cylinders. Various modeling techniques were used for partially water filled missiles namely consideration of an increased mass per unit length and the use a smooth particle hydrodynamics (SPH) technique.

Although the simulations did not predict all aspects of the response with the same degree of accuracy they captured well the first cycle of response, in which the damage occurs for impulsive loads, as well as the primary characteristics of the slab response and damage. The results presented identified limitations of the models, namely that the Winfrith concrete model does not capture the free vibration of the slab if there is extensive concrete cracking and the slab suffers moderate or higher damage. An additional conclusion is that for missiles partially filled with liquids in the front of the missile, the use of adjusted materials densities to represent the total missile mass per unit length in the front of the missile predicted reasonably well test displacements and damage.

Ongoing work under this research activity includes the analysis of additional test data for soft missile impacts, consideration of different hourglass control methods, consideration of different concrete models, different modeling techniques for water-filled missiles and verification of methods to estimate soft missile loads.

DISCLAIMER

The findings and opinions expressed in this paper are those of the authors, and do not necessarily reflect the views of the US Nuclear Regulatory Commission. This work was performed under the auspices of the U.S. Nuclear Regulatory Commission (USNRC), Washington, D.C.

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