MODELLING OF REINFORCED CONCRETE SLABS UNDER IMPACT LOADING

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ABSTRACT
This paper describes work conducted by the Canadian Nuclear Safety Commission (CNSC). Non-linear dynamic behavior of reinforced concrete slabs under impact loading by “hard” and “soft” missiles was analyzed using commercial Finite Element code LS-DYNA. FE predictions based on Winfrith concrete material model were compared with tests conducted by VTT Technical Research Centre (Finland) together with CNSC.

Concrete reinforcement was modeled using beam FE coupled with 3-D concrete FE at coincident nodes. Two different test cases resulting in (a) flexural and (b) punching with perforation slab responses were simulated. The FE predictions were in good agreement with both test results.

This modelling was part of the large International benchmark of numerical simulations of projectile impacts on reinforced concrete (RC) slabs that has been launched by OECD/NEA (The Organization for Economic Co-operation and Development/Nuclear Energy Agency) research program under the acronym IRIS_2012. The brief description of IRIS_2012 objectives, results and the place of the CNSC team modelling efforts were also discussed.

KEY WORDS
Modelling, FEA, Tests, Reinforced Concrete, Missile Impact, Perforation.

1. Introduction

Modern Canadian and International regulatory documents require the assessment of the design of Nuclear Power Plant's structures against the impact of externally or internally generated missiles.

This requirement stimulated a large amount of analytical and experimental work conducted in different countries. Due to complexity of the problem, the research was conducted mostly for concrete slabs impacted by missiles. The most noticeable works were conducted in Germany (so called Meppen Impact Tests [1]) and in recently finished OECD/NEA project called IRIS_2012, see publications in the special section of SMiRT 22 devoted to this work, for example [2, 3].

The current paper describes the results of FE modelling of missile impact conducted by the Canadian Nuclear Safety Commission (CNSC). The main objective was to develop an adequate FE model capable of predicting the main characteristics of post-impact state of a concrete slab, such as slab and reinforcement deformations and stains, size and shape of damaged area, crack patterns, etc. For the punching case with slab perforation it is also very important to predict final (exit) missile velocity. It was decided to model two tests (one punching and one flexural) that were provided as part of IRIS_2012 Benchmark. Fig. 1 shows an experimental set-up that has been constructed at Technical Research Centre of Finland, VTT for the punching test [4]. Similar set-up with deformable missile was constructed for the flexural test to study slab bending during and after missile impact, see Fig. 2. Contrary to missile properties, parameters of the concrete constitutive model could be defined only with the significant inherent scatter. Therefore, a comprehensive sensitivity studies should be conducted to identify and rank the effect of variations of concrete and reinforcement parameters and their influence on FE predictions. However, in the current paper we focused our attention on the comparison of our FE predictions with two tests in the frame of IRIS_2012 benchmark as well as with results obtained by other participants.

2. FE Model

FE model was developed for the missile impact of the reinforced concrete slab with velocity range covering both flexural (bending) and punching (penetration up to perforation) behaviour. Missile impacts are usually classified as either “hard” or “soft” according to the missile's deformability. “Hard” missile typically produces localized target damage such as punching or perforation without significant global flexural response of the target. Permanent global post-impact deformations are usually negligible for “hard” missile. “Soft” missile impact typically produces significant global flexural response of the target with or without residual target displacements. Significant missile deformations also occur during this type of impact. However, in our FE modelling both missile and slab were always discretized using appropriate default 3-D and shell FE with linear shape functions.

The detail modelling of concrete reinforcement and its interaction with concrete and missile during impact is very complicated. Therefore, three different simplifying assumptions were examined in preliminary runs as follows:

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Reinforcement was “smeared” inside the appropriate concrete layer.

Reinforcement was explicitly modelled using 2-noded beam FE with full x-, y- and z- coupling between concrete & re-bars (spherical joint). Reinforcement was modelled using previous assumption without additional coupling between horizontal layers of re-bars in two orthogonal directions.

Surface-to-nodes contact was assumed between missile and reinforcement for all three cases above. The preliminary runs conducted show clearly that the second assumption yields the best FE predictions. Therefore, this assumption was used for all further FEA conducted.

The Missile:
- Hard missile (steel cylinder with light concrete infill) with the same characteristics used in all tests.
- The total mass of the missile is 47 kg.

Reinforced concrete slab:
- Supported length/slab thickness: 2.00/0.25 = 8
- 24x24 re-bars ø10@90 mm

Based on preliminary runs and results of our participation in previous IRIS_2010 benchmark, Winfrith material model without strain-rate (mat#85 in LS-DYNA) was selected for concrete. Bi-linear elastic-plastic material models with Cowper-Symonds strain-rate law and limiting fracture strain were selected for all metal parts (missile head and shell and concrete reinforcement and frame). Contact interaction during missile-target impact was modeled using surface-to-surface contact with possible erosion of concrete FE.

Explicit simulation using LS-DYNA (version ls971d, 64-bit version on Windows XP) with default value of time step was used for all analyses. Properties of the selected baseline model are provided below:

- Steel Reinforcement for concrete:
  - E=200 GPa, v=0.3, ρ=7800 kg/m³,
  - UCS=UTS=550 MPa, failure strain 17.9%
- Missile Head and Shell (steel):
  - E=200 GPa, v=0.3, ρ=7800 kg/m³,
  - UCS=UTS=758 MPa
- Concrete Slab (Winfrith Model):
  - E=26.5 GPa, v=0.17, ρ=2246 kg/m³,
  - UCS=58 MPa, UTS=4 MPa, erosion for max. principal strain εₘₐₓ>70% & min. principal strain εₘᵞₙ<70%
  - average aggregate size (radius) a=4 mm, fracture energy Gₙ=85.5 N/m
  - crack width at which crack-normal tensile stress=0 w = 2*Gₙ/UTS=42.3E-6 m
  - default pressure-volumetric strain relationship was selected since test data were not available
- Lightweight Concrete Filling for “hard” Missile (Winfrith model):
  - E=10.6 GPa, v=0.17, ρ=1090 kg/m³,
  - UCS=3 MPa, UTS=1 MPa,
- Initial Missile Velocity: v₀=135.85 m/s and 110.15 m/s for punching and for flexural tests respectively
- Total Missile Mass: M=47.4 kg and 50.5 kg for punching and for flexural tests respectively
- FE Mesh:
  - Punching test: 4 layers of FE through concrete cover thickness. 22 layers of FE between front and rear
reinforcements. Total for slab: 417K nodes, 397K FE. Total for missile: 2K nodes, 1.8K FE. Flexural test: 3 layers of FE through concrete cover thickness. 18 layers of FE between front and rear reinforcements Total for slab: 567K nodes, 526K FE. Total for missile: 6.8K nodes, 6.6K FE.

Figs. 3 - 5 show the details of FE model for the punching test together with boundary conditions (BC). Due to symmetry, only one-quarter of the entire system was modelled with symmetry BC. However, the comparison between the two models conducted for two typical cases (target perforation and missile rebound) shows adequacy of one-quarter model. The adequacy of the selected mesh density was also validated by comparison with coarse and refined meshes ((14 and 58 solid FE through slab thickness respectively).

Numerous runs conducted show that for Winfrith material model FE erosion is needed for adequate modelling in cases involving target penetration and/or perforation for the following reasons:

- To prevent excessive FE deformation in the impact zone leading to non-convergence
- To allow missile movement through the target for Lagrange FE formulation
- To model material damage and failure

Winfrith concrete model used in current paper does not have erosion inside the material constitutive law. Moreover, as pointed by L. Schwer (Schwer Engineering & Consulting Services, Windsor CA USA, http://www.schwer.net/SECS/), this model also does not have material softening after concrete strength in uni-axial compression is exceeded. Therefore, some kind of erosion is needed to model concrete compression more realistically. LS-DYNA option for including erosion (*MAT_ADD_EROSION) has in total 14 different erosion criteria. Unfortunately, none of them has the direct physical correlation with the concrete damage during impact. Based on numerous test runs, authors selected the following two criteria:

- Maximum principal stress at failure $\varepsilon_1 > \varepsilon_{\text{max}}$ (positive value) that governs erosion in tension, and
- Minimum principal stress at failure $\varepsilon_3 < \varepsilon_{\text{min}}$ (negative value) that governs erosion in compression

In case with equivalent absolute values of $\varepsilon_{\text{max}}$ and $\varepsilon_{\text{min}}$, the selected criteria could be reduced to only one: maximum shear stress at failure $\gamma_{\text{max}} = \varepsilon_{\text{max}} = \varepsilon_{\text{min}}$ since $\gamma = (\varepsilon_1 - \varepsilon_3)/2$. However, the authors found that for some benchmark cases different values of $\varepsilon_{\text{max}}$ and $\varepsilon_{\text{min}}$ produced better results.

Failure for reinforcement FE and missile head and shell was incorporated in the correspondent material models using maximum fracture strain value.

3. Modelling Results

As was mentioned earlier, all simulations were conducted using LS-DYNA with default value of time step. The different simulation time (50 ms and 200 ms) was selected for punching and flexural cases to adequately capture complete missile reflection or perforation. To stabilize the solution, viscous contact damping of 10% was selected as recommended in LS-DYNA manual. No additional material or stiffness damping was introduced since all simulation results show reasonably low residual oscillations for all output variables examined.
3.1 Comparison between FE predictions and tests

FE model developed was verified using number of tests conducted at Technical Research Centre of Finland, VTT. However, the current paper presents only the comparison between FE predictions and two test results (one punching test P1 and one flexural test B1)) obtained in framework of IRIS_2012 Benchmark [2, 3]. The FE predictions obtained earlier (2011) during previous IRIS_2010 Benchmark are also provided for comparison on some graphs. These earlier predictions were based on Winfrith concrete model with strain-rate and slightly different material properties.

3.2 Punching test

The first Fig. 6 shows comparison for the final inflicted damage in the punching test. It is worth to mention that predicted crack patterns displayed in Fig. 6 should be treated with certain caution. LD-DYNA post-processor results show all cracked FE including very small micro-cracks that are practically invisible. These cracked FE could be filtered by selecting the relative crack width limit for display. Unfortunately, this limit does not have direct correlation with the real crack size. Therefore, we decided to display all cracks in our Figures. The results Table in Fig. 6 also shows very good agreement between predicted and measured exit missile velocity. The next Figs. 7 and 8 show comparison between FE predictions and test results for two output variables recorded: displacement at the slab front and reinforcement axial strain. Taking into account the complexity of the process modeled, the agreement could be considered as reasonably good.

Figure 5. FE model of “hard” missile components

Figure 6. Comparison with test results (punching test): crack patterns and residual (exit) missile velocity

<table>
<thead>
<tr>
<th>Case</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>FEA 2010</th>
<th>FEA 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact velocity m/s</td>
<td>135.85</td>
<td>134.86</td>
<td>136.46</td>
<td>135.85</td>
<td>135.85</td>
</tr>
<tr>
<td>Residual velocity m/s</td>
<td>33.8 ± 1.4</td>
<td>43.5 ± 1.8</td>
<td>35.8 ± 1.6</td>
<td>51.9</td>
<td>38.3</td>
</tr>
</tbody>
</table>

Figure 7. Comparison with test results (punching test): slab displacement
3.2 Flexural test

Figs. 9 - 12 show comparison between FE predictions and flexural test for the deformed missile shape, slab crack patterns and selected output variables. Similar to previous test, the agreement between FE predictions and test results is reasonably good.
4. FE Predictions in the Context of IRIS_2012 Benchmark

IRIS_2012 Benchmark was a large International project with 25 participating teams from 14 countries. The main objective of this project was to create numerical models capable of adequately simulate punching and bending tests described earlier. Full sets of two test data were provided to all participants well in advance. Additional sets of concrete material tests (one Brasilian tensile test and five tri-axial compression tests with different confining pressures from 0 to 100 MPa) were also provided. The participants were encouraged to create both full and simplified models. Simplified models should be used to capture the most significant features of the tests as well as for verification of more complicated models. An extensive synthesis of modelling results obtained by all participants was done by authors of this paper. However, we will discuss further only some aspects of this synthesis related to the place of our modelling among all participants.

Fig. 13 shows histogram of relative errors for both maximum displacement W1 and reinforcement strain D3 for flexural test. Each participated team was assigned a unique team number shown on the x-axis. Not all teams simulated both tests. The gaps in team numbers reflect this fact. Some teams provided more than one simulation for each test. This is represented by an additional letter after the team number, see for example #28 and #28a on Fig. 13. Similarly, Fig. 14 shows histogram of relative errors for residual (exit) missile velocity in punching test which is the single most important output parameter. The authors of this paper are team #8 on Figs. 13 and 14. It is clear, that we have got one of the best overall results for both tests. Finalizing, the authors of the models described in this paper were among only 8 teams (out of 25) that were within 40% error for both punching and flexural tests.

Figure 13. Synthesis of IRIS_2012 relative errors: maximum displacement W1 and reinforcement strain D3 for the flexural test. Team #8 (green circle) consists of authors of the models presented in this paper

Figure 14. Synthesis of IRIS_2012 relative errors: residual missile velocity for punching test. Team #8 (green circle) consists of authors of the models presented in this paper

5. Conclusion

FE model capable of modelling of missile impact involving deep penetration and perforation of concrete slab was developed based on commercial code LSDYNA. Comparison with both flexural and punching tests conducted at Technical Research Centre of Finland (VTT) for initial missile velocities 110 and 136 m/s shows a reasonable agreement for both tests. FE analysis conducted show the following:

• ¼ of the entire model with fine mesh produces adequate results in reasonable time
• Double precision version of LSDYNA is recommended
• FE erosion should be introduced for concrete slab to get realistic modelling. The type and values of erosion criteria have very significant effect on both post-impact state and missile exit velocity. Based on trial runs, the best erosion criteria are maximum/minimum principal strains +/- 70%
• Out of 8 concrete models available in LS-DYNA, Winfrith model without strain-rate shows the best performance for both tests
• The authors of the FE model presented in this paper are among only 8 teams (out of 25 total) that have predicted the most essential output parameters within 40% error for both tests

References

the Results, *Transactions of the 22nd SMiRT*, San Francisco, USA, 2013.
