IRIS_2010 - PART III: NUMERICAL SIMULATIONS OF MEPPEN II-4 TEST AND VTT-IRSN-CNSC PUNCHING TESTS

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ABSTRACT

The benchmark IRIS_2010 is an activity in the OECD/NEA/CSNI framework. IRIS is the acronym for the title of an activity initiated inside CSNI/IAGE working groups: "**I**mproving the **R**obustness assessments, methodologies for structures **I**mpacted by missile**S**". This paper is the 3rd of a series of 5 companion papers Reference [1] to Reference [4] that present the objectives, the experiments to be simulated, the simulations of tests with punching failure, the simulation of tests with bending failure and the lessons and recommendations.

The goal of this paper is to present two sets of numerical simulations: one set related to the tests on reinforced concrete slabs: a Meppen test and the other to three repeated VTT punching tests. The Meppen test is one of the tests carried out in the Meppen test campaign in Germany during 80's. The Meppen test results were available to the participants in advance with the goal to calibrate the numerical models. The results of three repeated VTT punching test were not available to the participants in advance. It was a blind prediction. Both tests were with dominant punching behavior. The Meppen test was punching combined with flexural behavior of the slab, without perforation. In the VTT tests the slab was perforated. Three repeated tests were performed to assess the repeatability of the tests.

26 teams simulated Meppen test and 24 teams VTT punching test. This paper provides a summary of the results with a discussion regarding the main issues faced in these simulations. A comparison of the simulations of two tests will be carried out, taking into account that both tests show dominant punching behavior. Recommendations are provided for the follow-up of this benchmark.

INTRODUCTION

The general presentation of the OECD/NEA/CSNI benchmark IRIS_2010 is in Reference [1]. The IRIS_2010 exercise was organized with two goals: to assess the repeatability and scatter of hard and soft missile impact tests on reinforced concrete slabs and to evaluate current capabilities to simulate this kind of tests and scatter of numerical results. Three different types of tests were chosen: 1) soft (highly deformable) missile impact test with a velocity below perforation velocity with combined punching and bending behavior or Meppen II-4 test 2) hard missile (undeformable or with very limited deformation) impact test with a velocity beyond perforation velocity or in this series of papers called VTT-IRSN-CNSC punching test and 3) soft missile impact with flexural behavior of the concrete slab or VTT-IRSN flexural test. The tests were designed to achieve three different structural behaviors typical under impact loading. Three repeated tests of the first type (P1 to P3 in this paper) and two repeated tests of the third type were carried out to assess the scatter and repeatability of tests results. The concrete slabs utilized in all three types of tests are with longitudinal reinforcement only. The intention was to model the cases as simple as possible to facilitate the analysis, and to make conclusions and recommendations on samples with limited number of parameters, taking into account the complexity of the problem. The first type of test was a single test (Meppen II-4) and the results were provided to the participants in order to calibrate numerical models for blind predictions of the tests 2) and 3). The test set-ups and test results are presented in Reference [2]. The simulations results of the tests 1) and 2) with dominant punching behavior are presented in this paper. The simulation results of the test 3) with dominant flexural behavior are presented in Reference [3]. The overall conclusions of IRIS_2010 and recommendations for future activities are presented in Reference [4].

NUMERICAL SIMULATIONS

The simulation by 26 teams was carried out using different computer codes. The most common were explicit versions of Ls-Dyne and Abaqus. Other computer codes were: Autodyne, Europlexus, Radioss, EMU, ULCA-D1 and SAP2000.

Slab Modeling

Most of the computations (more than 4/5 of teams) have been made using 3D finite elements for concrete and only a quarter of the model for symmetry reasons. Three teams have used shell elements and one team Reissner Mindlin shell elements. Most of time, the frame is not modelled (five teams have modelled the support mainly by metallic beams).

Concerning the concrete and rebars, the FE for concrete are mainly 3D elements; six teams used shell elements The rebars are mostly modelled using beam elements or truss (only two teams used layers or homogenized material).

Most of the time perfect bounding is supposed for the computation between rebars and concrete. The constitutive law of rebars elements is based most of the time on rate independent plasticity, perfect or with hardening. A strain rate effect is sometimes included in the models (for rebars) but it seems that it has not an important effect in the modelling results. The Johnson and Cook or Cowper-Symonds are used as well.

Several different concrete constitutive equations were used taking into account concrete plasticity and concrete damage. Some participants have used FE deletion (erosion) as a numerical method to simulate concrete damage. Most of the teams used the same concrete constitutive model to simulate three types of tests.

Missile Modeling

The missile is modelled by shell elements most of the time, using the same constitutive equations as for rebars. The behaviour is supposed to be plastic (perfect or with hardening). The strain rate effect has been taken into account for soft (deformable) missile modelling. Instead of missile modelling, some teams introduced loading using Riera function.

MEPPEN II-4 TEST SIMULATIONS

Test Data

The complete test data is presented in Reference [2]. Necessary data are presented here to facilitate the reading of the paper.

In the Meppen test, a 700 mm thick reinforced concrete wall was impacted with a deformable missile with mass of 1016 kg and with the impact velocity of 247.7 m/s. Span width of the wall was 5.4 meters and it was both simply supported at each side and additionally tied to the supporting system with tie-rods. Support forces generated during the impact were measured with multiple load cells and strain gauges on the tie-rods. Displacements and accelerations were measured at the back surface of the wall and strains were measured from the reinforcement at multiple locations as presented on Figure 1. The displacements are measured in the points B1 to B8 close to the points with accelerometers W1 to W7. In the following test W1 to W7 are used for displacements.

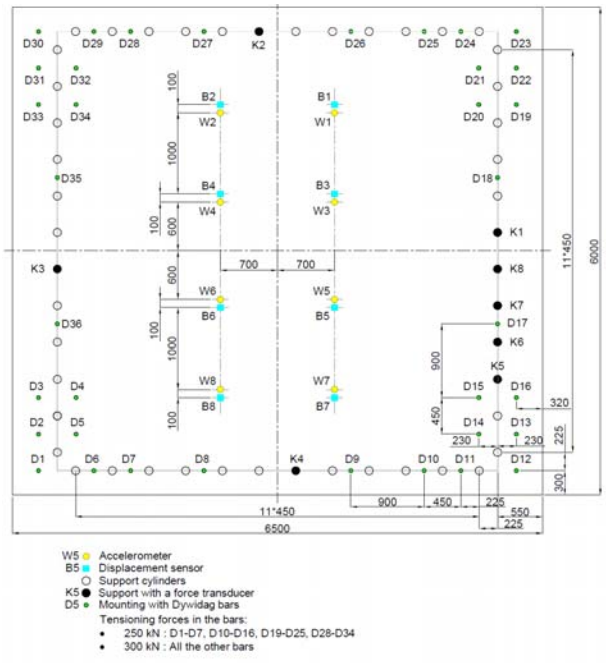

Figure 1. Supports and measurement sensors in Meppen II-4 test

Loading

In this test, the highly deformable missile rebounded form the slab, Reference [2]. There is a noticeable discrepancy in the numerical results for prediction of the loading (between the soft missile and the target, see Figure 2 and Figure 3. It is surprising that some teams did not find a momentum equal (at least approximately) to the momentum obtained via time integration of the average force). Moreover, one team found some negative values for the impulse momentum.

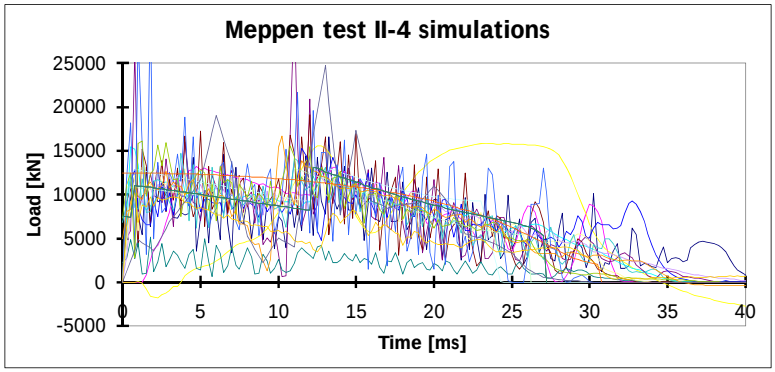

Figure 2. Meppen II-4: evolution of the loading history between the missile and the target.

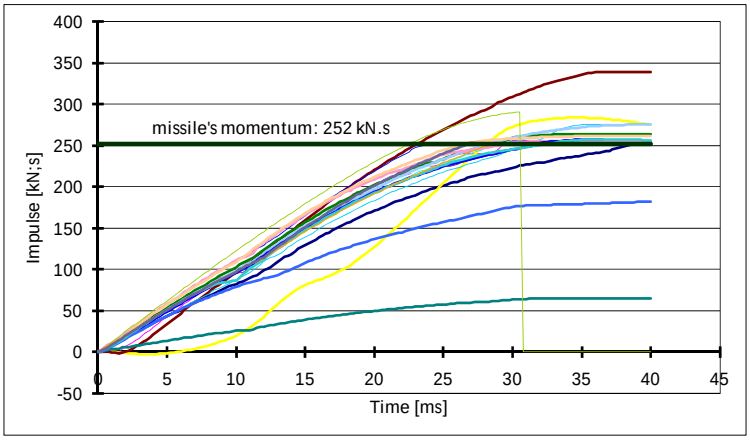

Figure3. Meppen II-4: evolution of the momentum received by the target

Deflections

The main damage indicators for combined punching and bending behaviour in MEPPEN II-4 test are deflections and concrete damage pattern. Regarding slab deflections there is a noticeable discrepancy in the numerical results concerning the deflection at the rear of the slab (the probe W3, W4, W5 and W6, which are symmetrical, have been considered, the COV is greater than 100 % for the maximal value). The result is displayed in Figure 4.

Concerning the residual deflection (this is useful information, since it informs of the damage state of the structure) about half of the team predict during the calculation time an irreversible deflection (some of them found oscillations of more or less amplitudes). Some teams found, after the impact, a deflection of opposite sign (which is not expected).

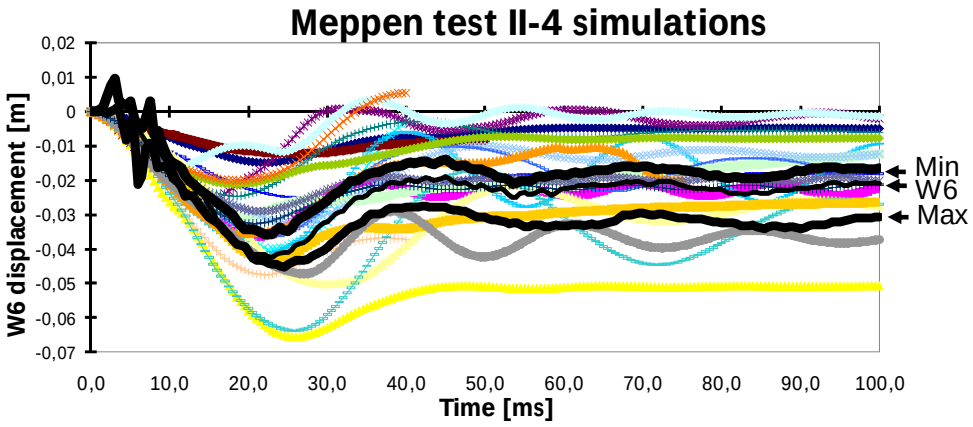

Figure 4. Meppen II-4 (W6, min & max of W3,W4,W5,W6, which are symmetrical): comparison between experimental and simulated evolution of displacement.

In order to synthesize the results, the residual deflection and the maximal deflection are plotted against the global error Δ , Figure 5:

$$\Delta = 100 \sum_{i=1}^{n_{\exp}} \left(u_{sim}(t_i) - u_{\exp}(t_i) \right)^2 ,$$

where n_{exp} is the number of values, u_{sim} and u_{exp} are the simulated and experimental deflections, respectively, at time t_i.

It shows that the residual value of displacement is a very good indicator of the global performance for the computations of the displacement (for the selected probe) i.e. the global error is smaller as the ratio simulated/experimental deflection reaches 1. This is not always the case for the maximal displacement, meaning that the prediction of the maximal displacement is more difficult to estimate.

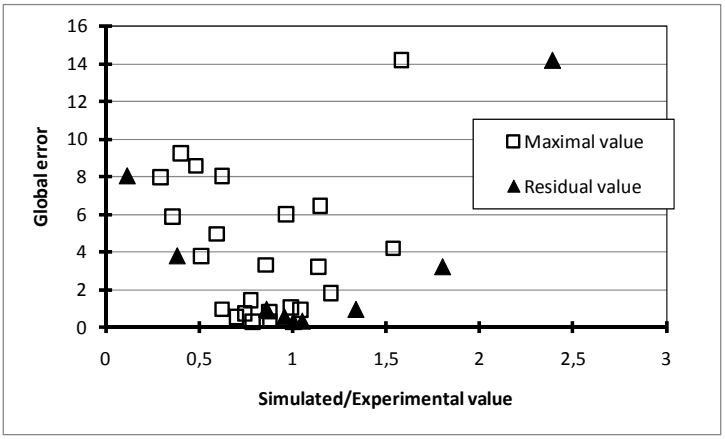

Figure 5. Meppen II-4 (W6): comparison between experimental and simulated evolution of displacement.

Damage Pattern

Concerning the damage pattern and the prediction of the size of the cracking zone, numerical results are very different from a team to another. However, the cracking pattern (provided by only less than half of the teams) is closed to the experimental one. It is worth to mention that crack patterns displayed in figures should be treated with certain caution. Ls-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. An example is given on Figure 6.

About half of the teams found a penetration of the missile. Few teams did not find any concrete damage of the slab.

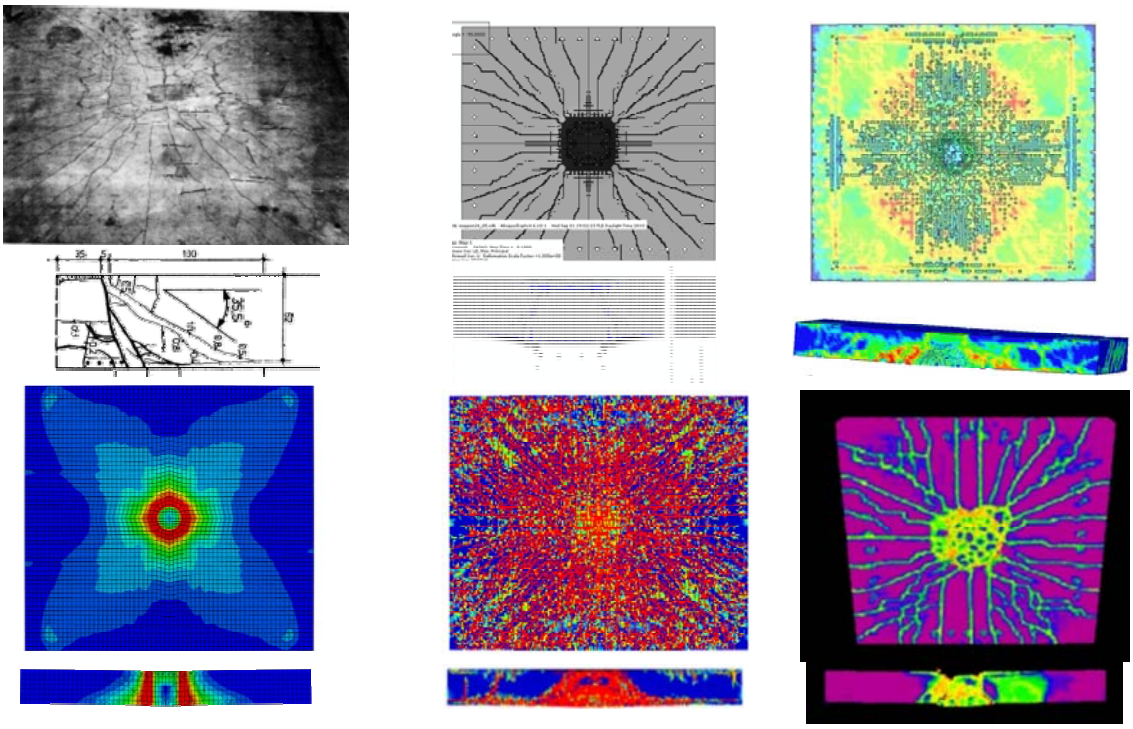

Figure 6. Meppen II-4: comparison between experimental and simulated cracking patterns.

VTT-IRSN-CNSC PUNCHING TESTS SIMULATIONS

Test Data

The complete test data is presented in Reference [2]. Necessary information is presented here to facilitate the understanding of the paper. The tests with the same concrete slab but with different missile velocities were presented in References [5] and [6]. The first goal in this type of test was to perforate the slab and to measure the residual velocity of the missile. This is the only type of test in IRIS_2010 exercise with this goal. Three tests were carried out using 250 mm thick simply supported two way reinforced concrete slabs with spans of 2.00 m in both ways with target missile velocity of 135 m/s. The second goal was to assess repeatability of tests and the test results.

a) Backside b) Front side

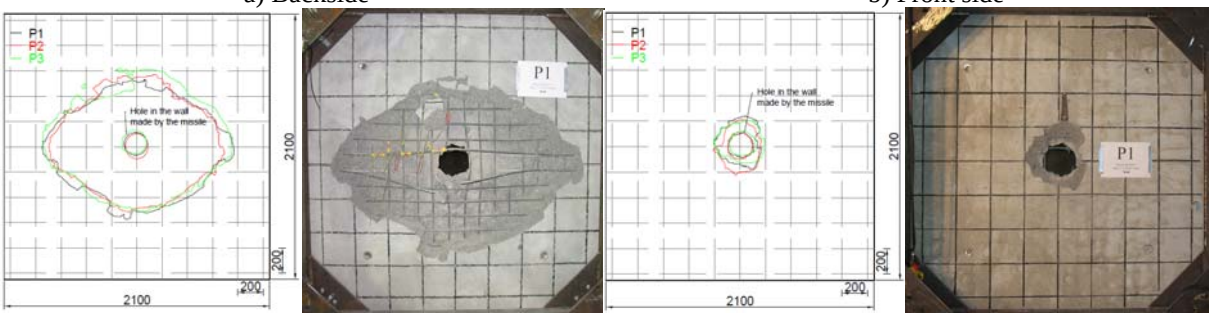

Figure 7. Drawings of the damage of walls P1 to P3 with scabbing and spalling areas and photographs showing the damage in the test P1.

As it can be seen on Figure 7, the damage pattern for the tests P1 to P3 as well as residual velocity are very similare.

	Impact velocity [m/s]	**Residual velocity [m/s]**	**Spalling area [m²]**	**Scabbing area [m²]**	**Concrete unconfined compressive strength [MPa]**
P1	**135.85**	**33.8**	**0.11**	**1.06**	**60.5**
P2	**134.86**	**45.8**	**0.11**	**1.00**	**56**
P3	**136.46**	**35.8**	**0.10**	**1.12**	**58.3**

Table 1. Repetability of tests and th test results

There is consistancy as well between the concrete compessive strength and residual missile velocity. It can be concluded that the the test repetebility is good.

Residual Velocities

Residual missile velocity is one of the main damage parameters in this type of tests.

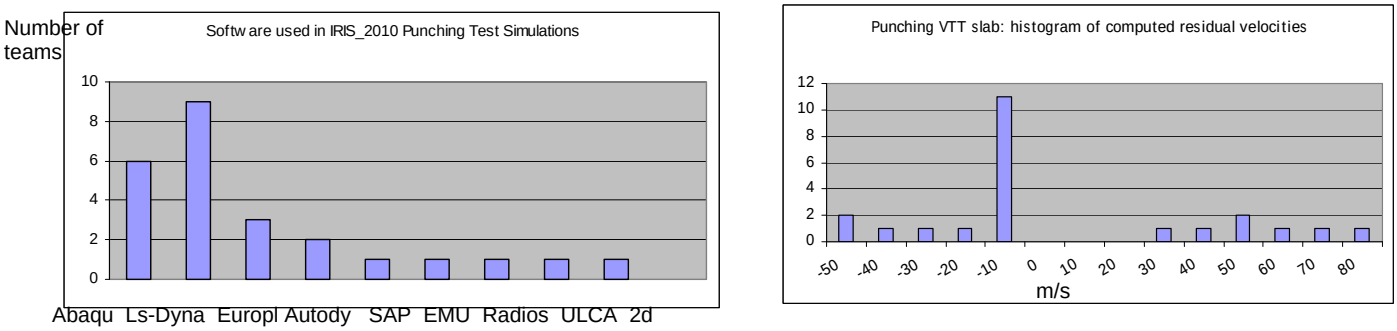

Figure 8. Histogram of software used in IRIS_2010 computed residual velocities

As it can be seen on Figure 8 only 7 teams out of 24 have predicted residual velocity greater than zero. Only 4 out of 24 teams are in the ±20 % range comparing to the test results.

The explanation of such result can be understood after the analysis of the selected results of damage patterns presented on Figure 9 a), b), c) and d).

Damage Patterns

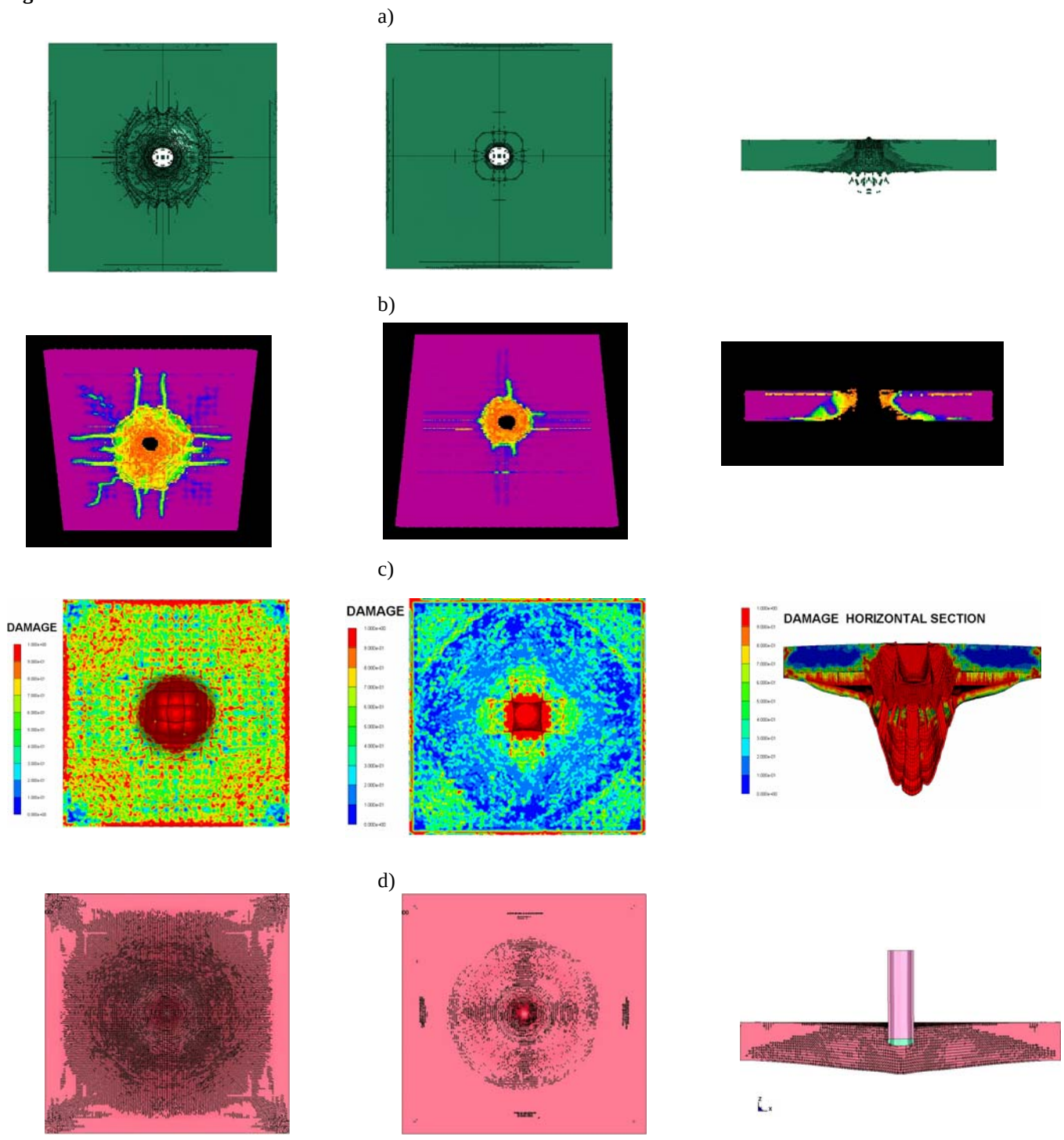

Figure 9 a, b) c) and d). Rear face, front face and cross section of the chosen slab models after the impact.

On Figures 9 a) and b) the missile perforated the target and its perforation velocity can be compared with measured perforation velocity. Scabbed (rear face) and spalled area (front face) can be compared with experimental results as well. On Figure 9 c) and d) the missile can rebound or be stopped by the slab. Engineering judgment is needed to asses whether it is caused by slab resistance or by the fact perforation is not numerically possible. It is very difficult to asses the concrete damage after the tests as well as residual missile velocity. Possibility of the software to eliminate the resistance of destroyed (eroded) concrete and steel elements from the analysis is the key element to simulate missile perforation. According to Reference [7], most of concrete models currently in use do not have erosion inside the material constitutive law. Moreover the models also do 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. For example, 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. If this problem is not solved it is very difficult to analyze any other parameter like slab deflection as well as strains in concrete or reinforcement.

CONCLUSIONS AND RECOMEDATIONS

The simulation results of two different types of tests: Meppen II-4 (combined punching and bending behavior) and VTT-IRSN-CNSC (punching behavior with perforation) were carried out within OECD/NEA/CSNI framework as a part of CSNI/IAGE benchmark IRIS_2010. The experimental results of Meppen II-4 test were provided to participants in advance to calibrate constitutive laws and numerical models for blind predictions of VTT-IRSN-CNSC test. Even for the test with known experimental results, the scatter of numerical results was important. General conclusions and recommendations of IRIS_2010 are presented in Reference [4], however based on the work presented in this paper it can be concluded that using the same constitutive model for the simulation of these two different types of test did not give satisfactory results mainly due to the fact that the tests deal with different physical phenomena. The rebound of a deformable missile in the first test and the perforation of the target by a hard missile in the second tests require different numerical approaches. Numerical simulation of perforation of a concrete slab by a missile (deformable or undeformable) is a challenge for engineering community. Based on experience form this benchmark and lessons learned, it is recommended that the same group of participants continue the exercise improving the existing models in the next phase of the CSNI/IAGE benchmark IRIS_2012.

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