



IRIS_2012 BENCHMARK – PART I: OVERVIEW AND SUMMARY OF THE RESULTS

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ABSTRACT

A benchmark of numerical simulations of projectile impacts on reinforced concrete (RC) slabs has been launched in the frame of OECD/NEA/CSNI research program under the acronym IRIS. The goal of the research program is to simulate RC structural, flexural and punching, behavior under soft and hard missile impact. The first phase the IRIS_2010 was a blind prediction of the tests performed at VTT facility in Espoo, Finland. The results showed significant scatter of the results for both flexural and punching simulation. The IRIS_2012 is the second, post-test, phase of the benchmark with the goal to improve simulations and reduce the scatter of the results. Based on the IRIS_2010 recommendations and to better calibrate concrete constitutive models, a series of tri-axial tests as well as Brazilian tests were performed as a part of the IRIS_2012 benchmark. 25 teams from 11 countries took part in this exercise. Majority of participants were part of the IRIS_2010 benchmark. Participants showed significant improvement in reducing epistemic uncertainties in impact simulations. Several teams presented both FE and simplified analysis as per recommendations of the IRIS_2010. The improvements were at the level of simulation results but also at the level of understanding of impact phenomena and its modeling. However, due to the complexity of the physical phenomena and its simulation (high geometric and material non-linear behavior) and inherent epistemic and aleatory uncertainties, the scatter remains important especially comparing to conventional, linear structural engineering analysis. The next goal is to further reduce the scatter and to concentrate on impact induced structural vibrations.

INTRODUCTION

Simulation of reinforced concrete structures under medium velocity hard and soft missile impact, including simulation of the perforation of the impacted structure, is a relatively new type of analysis. There is a need to present a current state-of-the-art on this topic and to provide some guidance for practitioners doing or reviewing this type of simulations. A benchmark of numerical simulations of projectiles impacts on reinforced concrete (RC) slabs has been launched in the frame of OECD/NEA/CSNI under the acronym IRIS. The IRIS_2012 is the second phase of the benchmark, organized as the first phase in collaboration of CNSC and IRSN with the workshop chaired and hosted by CNSC in Ottawa in October 2012. The first phase, IRIS_2010, deals with blind prediction of flexural and punching tests and is presented in a series of five papers: Rambach et al. (2011), Vepsa et al. (2011), Orbovic et al. (2011), Berthaud et al. and Tarallo et al. (2011). IRIS_2012 is a post-test simulation, a follow-up of IRIS_2010. This is the first in a series of two papers related to this new exercise. The second one, on lessons learned and recommendations, is presented in Tarallo et al. (2013).

25 teams from 11 countries and one international organization participated in this exercise (Table 1). Majority of teams participated in the IRIS_2010 benchmark. Three organizations were represented with more than one team: IRSN, France (4 teams), VTT, Finland (3 teams) and CNSC, Canada (2 teams).

Table 1: List of the IRIS_2012 participants

No.	TEAM NAME	ORGANIZATION	COUNTRY
1	AERB	Atomic Energy Regulatory Board	India
2	ANATECH	Anatech	USA
3	BARC	Bahba Atomic Research Centre	India
6	CANDU	CANDU Energy	Canada
7	CEA	Commissariat à l'énergie atomique et aux énergies alternatives	France
8	CNSC Team I	Canadian Nuclear Safety Commission	Canada
9	CNSC Team II	Vector Analyses Group - University of Toronto / Canadian Nuclear Safety Commission	Canada
10	EDF	Électricité de France	France
11	ENSI	Swiss Federal Nuclear Safety Inspectorate	Switzerland
12	F4E-IDOM	Fusion for Energy - IDOM	International
13	Fortum	Fortum	Finland
14	GRS	German Reactor Safety Authority	Germany
15	IRSN Team I	Institut de radioprotection et de sûreté nucléaire	France
16	IRSN Team II	Institut de radioprotection et de sûreté nucléaire	France
17	IRSN Team III	Institut de radioprotection et de sûreté nucléaire	France
18	IRSN Team IV	Institut de radioprotection et de sûreté nucléaire	France
19	JNES	Japan Nuclear Energy Safety Organization	Japan
20	KINS	Korean Institute of Nuclear Safety	South Korea
21	NRC-SNL	United States Nuclear Regulatory Commission / Sandia National Laboratories	USA
22	NRI	Nuclear Research Institute Res Energoprojekt Praha	Czech Republic
24	Swissnuclear	Swissnuclear	Switzerland
25	UJF	University Joseph Fourier - Grenoble	France
26	VTT Team I	VTT Technical Research Centre of Finland	Finland
27	VTT Team II	VTT Technical Research Centre of Finland	Finland
28	VTT Team III	VTT Technical Research Centre of Finland	Finland
29	Woelfel	Woelfel Group	Germany

RECALL OF IRIS_2010 RESULTS, LESSONS LEARNED AND RECOMMENDATIONS

The IRIS_2010 lessons learned highlighted: the scatter of blind simulation results, the effect of input data (in terms of lack of knowledge on concrete properties as well as a scatter in utilized input data), the modeling differences between flexural and punching behaviors, a need for simplified tools and, an approach that combines sophisticated and simplified models. To address the issues related to concrete material properties, a series of concrete tri-axial tests were performed to determine confined concrete compression strength as well as a Brazilian test, in order to determine concrete tensile strength. These tests as well as their results were provided for an additional series of simulations to calibrate concrete constitutive models. Several routines and parameters were discussed; especially the routines which model disintegrated concrete (concrete erosion). The goal of the IRIS_2012 is to improve the understanding of physical phenomena and to implement this understanding into the developed models (for IRIS_2010 participants), to carry out sensitivity studies and to recommend simulation approaches for complex models as well as to develop simplified tools. The software used in both the IRIS_2010 and IRIS_2012 are presented in Table 2.

Subsequently, the recommended input for the IRIS_2012 benchmark is:

- a single set of concrete material properties (unconfined concrete strength, tensile strength)
- tri-axial and Brazilian tests to calibrate concrete constitutive models

Moreover, it is recommended to perform:

- sensitivity studies to improve existing models for flexural and punching simulations
- analysis using simplified models along with complex FE simulations for sanity checks.

The type and complexity of simplified models were left to the choice of participants.

Table 2: Software (with the number of teams) used in the IRIS_2010 and 2012 benchmarks

IRIS_2010	IRIS_2012
6 ABAQUS	9 ABAQUS
9 Ls-Dyna	6 Ls-Dyna
2 Autodyn	2 Autodyne
2 Europlexus	2 Europlexus
Radioss	Radioss V11
SofiStik	SofiStik
SAP	VecTor2-VecTor3
EMU	BARC in-house
ULCA	Sierra/SM2012
2D Simplified	PENTABLOC Simplified
	Simplified VTT team II
	Simplified VTT Team III

IRIS_2012 TEST INPUT

Tri-axial and Brazilian tests



Figure 1: Specimens after tri-axial tests with confinement of 47 MPa and 100 MPa

Based on the conclusions of the IRIS_2010, the data of tri-axial tests were provided to the IRIS_2012 participants. The Tri-axial tests were performed at the University Josef Fourier in Grenoble, France and were provided courtesy of IRSN. The tri-axial tests were performed for confining pressure of 0 MPa, 12.5 MPa, 25 MPa 47 MPa and 100 MPa. The tests specimens after the tests and the tests results in terms of stress-strain curves for the confinement pressure of 47 MPa and 100 MPa are presented in Figures 1 and 2. The increase in concrete compressive strength and ultimate strains are significant comparing to unconfined conditions. Moreover, the rupture mechanism changes from vertical cracks (unconfined condition), inclined cracks (47 MPa confinement) to horizontal cracks (100 MPa confinement). A Brazilian test was performed by VTT giving concrete tensile strength of 4.04 MPa.

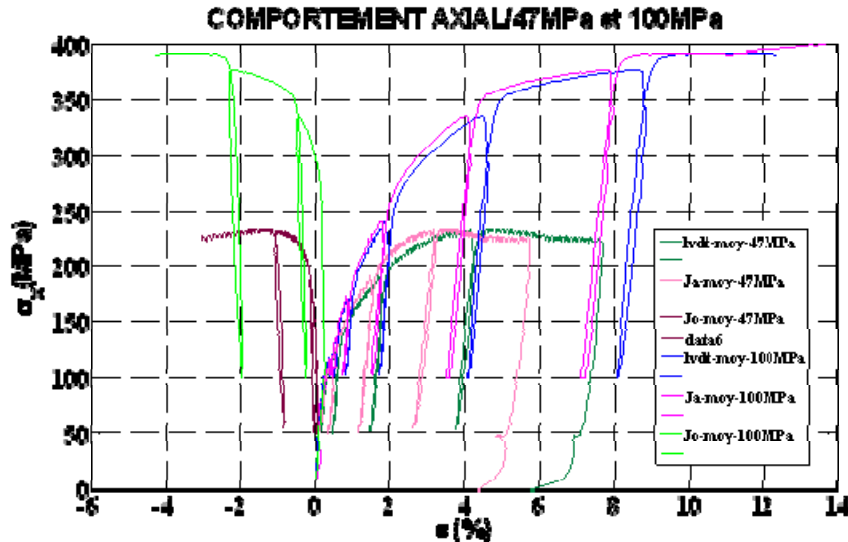


Figure 2: Stress-strain curves for tri-axial tests with confinement of 47 MPa and 100 MPa

Flexural and punching tests

The details regarding the flexural and the punching tests for the IRIS_2010 tests are presented in Vepsa et al. (2011). Flexural test was performed launching a 0.25 m diameter soft missile (mass 50 kg and $V=110$ m/s) against 2 m X 2 m X 0.15 m slab. Punching test was performed launching a 0.168 m diameter hard missile (mass 47 kg and $V=135$ m/s) against 2 m X 2 m X 0.15 m slab. A single set of input data for each test was provided to the participants: unconfined compressive strength of 55.2 MPa \pm 1.26 (cube 29 days 63.9 MPa) and tensile strength 3.71 MPa \pm 0.15, for flexural test and unconfined compressive strength 60.0 MPa \pm 1.16 (cube 29 days 67.6 MPa), tensile strength 4.04 MPa \pm 0.177 for punching test.

The results of the flexural tests in this paper are presented in terms of displacements. Displacements are the easiest and most reliable parameter to measure. It is much more difficult to get reliable information regarding reinforcement strains. The reinforcement strains are concentrated in the cracks and crack position is very difficult to predict beforehand and to place the gauge where needed. The scatter in measured strains is very important. The measured reinforcement strain can be very different from the maximum strain although the gauge is placed close to the location of the maximum strain. Therefore, the measured reinforcement strains can be easily misleading.

IRIS_2012 Results

Flexural test results

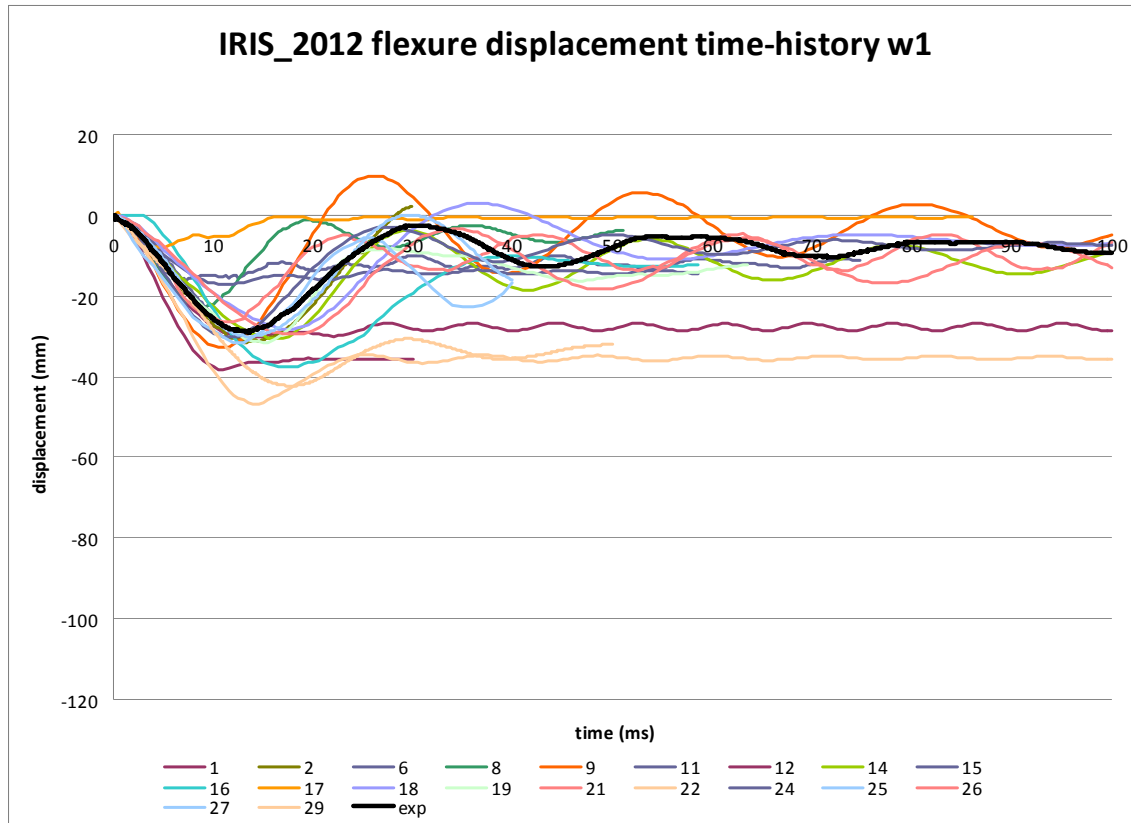


Figure 3: Maximum displacement time history: all simulations and the test results in black

The maximum displacement time history from all flexural simulations and the test measurements is presented in Figure 3. The plot clearly shows that, globally, simulations capture relatively well the maximum displacement. However, the induced vibrations, the damping and the residual displacement are more difficult to simulate. These three parameters represent induced damage due to the impact and this damage is difficult to simulate, especially if the model is calibrated to capture maximum displacement.

Figure 4 presents simulated maximum displacements in the IRIS_2010 blind prediction and in IRIS_2012 post-test simulations along with the measured test displacement (full black line). The Coefficient of Variation (COV) in the IRIS_2010 is 97% and in the IRIS_2012 the COV is 33%. Significant improvement was achieved between two exercises, especially if we look at the number of teams with the simulation results close to test results: in the IRIS_2010 two teams and in the IRIS_2012 twelve teams. However, the scatter is still high, especially compared to conventional linear structural analysis in civil engineering. It should be highlighted that due to the complexity of the problem and high non-linearity (geometric and material) there is an inherent uncertainties, epistemic and aleatory, which will remain and which have to be taken into account.

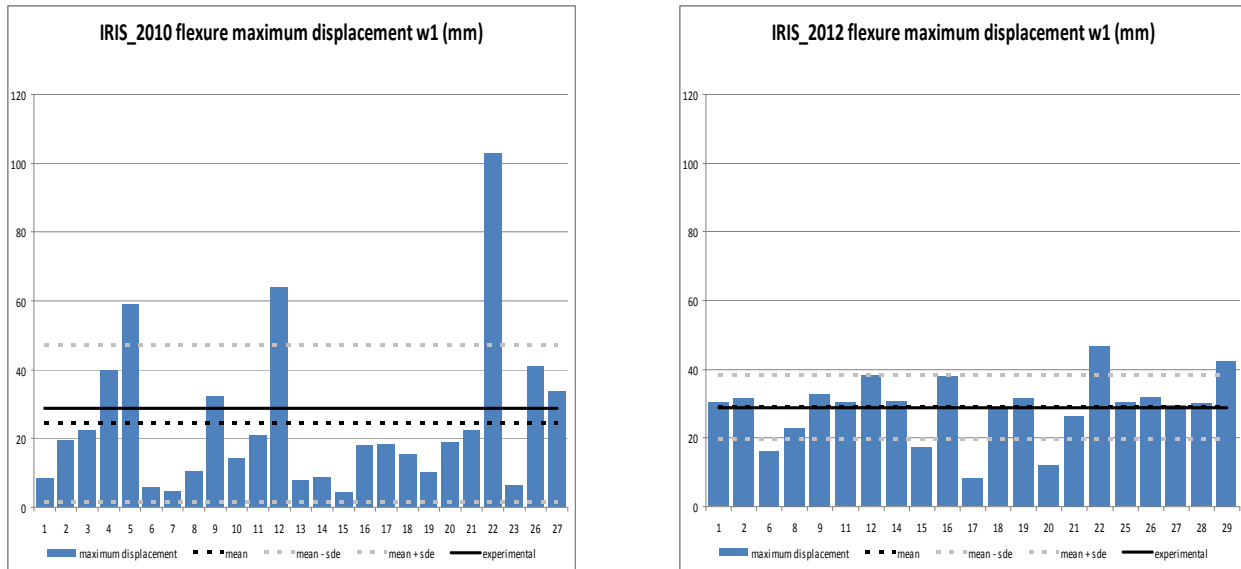


Figure 4: Maximum displacement simulation results in IRIS_2010 and IRIS_2012

Figure 5 present residual displacements and here we can quantify the observation from the Figure 3 regarding the difficulty to capture the damage of the reinforced concrete element under soft missile impact (impulsive type of loading). The COV in the IRIS_2010 was 132% and in the IRIS_2012 the COV was 75%. The improvement in the IRIS_2012 is significant but the COV of 75 % is very high. There is a need to improve concrete constitutive models to better capture the concrete damage.

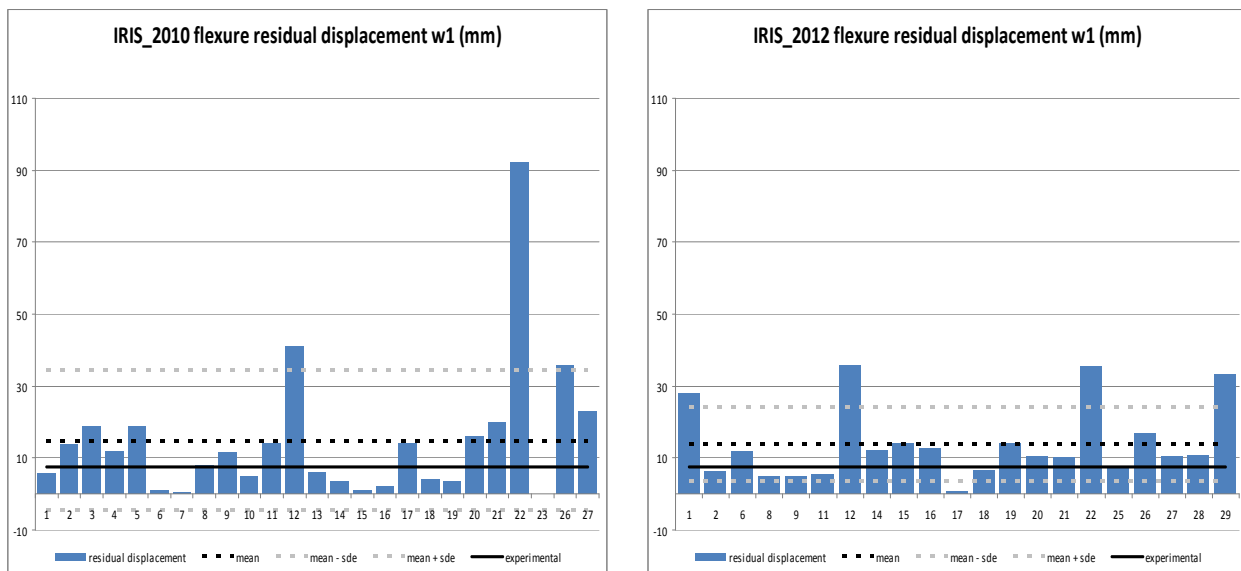


Figure 5: Residual displacement simulation results in IRIS_2010 and IRIS_2012

. Encouraging news is that several teams achieved good results in both maximum and residual displacements, especially teams 25 (University Josef Fourier), 27 and 28 (two VTT teams). Both teams participate in the IRIS_2010 and have certain experience in this kind of simulations.

Punching test simulation results

The most reliable information regarding the punching test, with slab perforation, similar to deflections in the flexural test, are: missile residual velocity, slab displacements and the concrete damage at the rear face of the specimen. In this paper the test results are presented in terms of missile residual velocities and slab displacements.

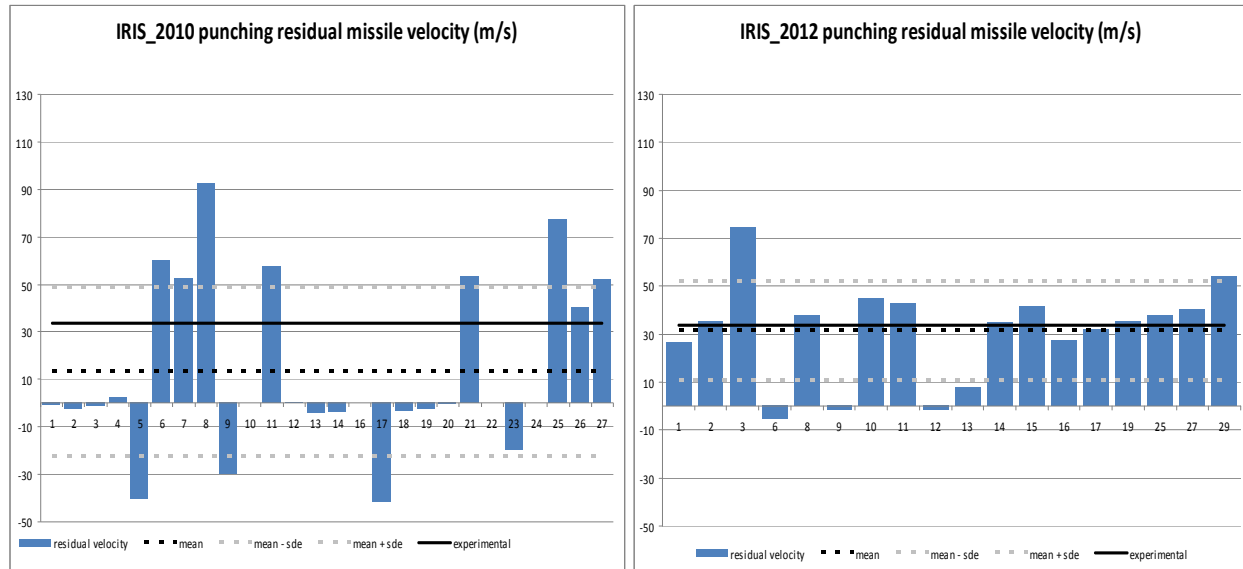


Figure 6: Residual velocities the IRIS_2010 and IRIS_2012

Regarding the missile residual velocities it is difficult to apply the same statistic as in the flexural case taking into account that some teams got negative residual velocity (rebound). However, based on the results shown in Figure 6, it can be easily noticed significant improvement comparing to the IRIS_2010 results. The main issue during the IRIS_2010 exercise related to punching behavior was the simulation of the missile perforation. To allow the missile to perforate the slab the disintegrated concrete should be removed from the model in terms of its stiffness but conserving its mass. The modeling and removing of the disintegrated concrete is done in most of the codes using ‘Erosion’ routine. The parameters used in this routine have no physical meaning. In some codes this routine is incorporated in the concrete constitutive model and sensitive to some physical input parameters like concrete tensile strength but without providing how this routine is implemented. In the IRIS_2010 only 8 out of 21 teams achieved the missile perforation. In the IRIS_2012 15 out of 18 teams simulated successfully missile perforation with the residual velocity close to the test residual velocity (continuous black line in Figure 6).

Regarding the slab displacement presented in Figure 7 comparison between the IRIS_2010 and IRIS_2012 results shows significant progress achieved by the participants since the first phase of the IRIS exercise. However, despite this significant improvement the IRIS_2012 displacement time histories, a similar statement can be made as in the flexural test simulations: induced vibrations with their frequency and damping are difficult to capture correctly. In the IRIS_2012 with globally significant improvement in simulations it can be clearly seen that due the complexity of the phenomena, it is difficult to simulate correctly several parameters. The constitutive models are calibrated to simulate correctly one result (such as maximum displacement and residual missile velocity) it is much more difficult to capture correctly several parameters simultaneously.

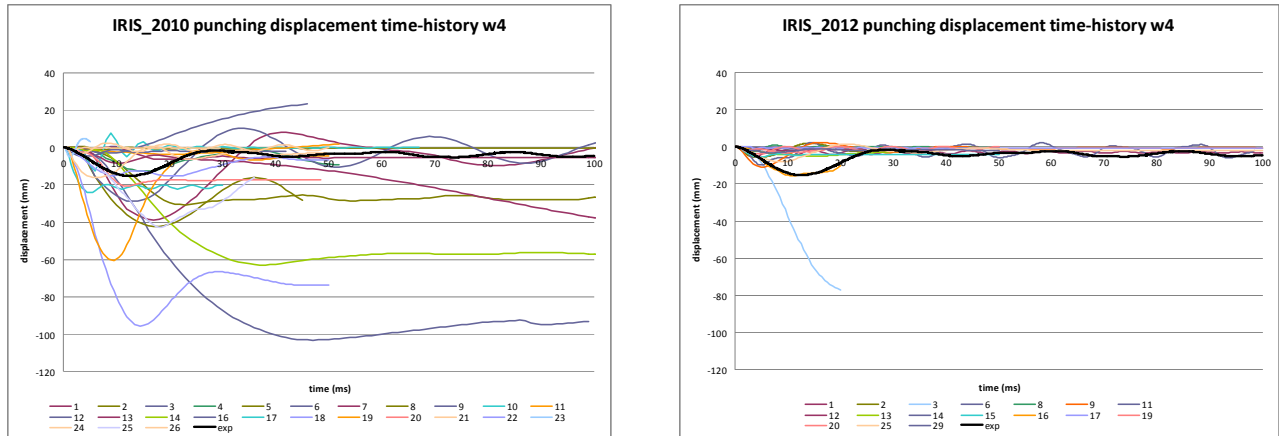


Figure 7: Time history of slab displacements in IRIS_2010 and IRIS_2012

Simplified models

Although the use of simplified models was strongly encouraged based on the first phase IRIS_2010, only five teams presented simplified approaches. The level of simplification was not specified by the IRIS Organizing Committee. Therefore the presented simplified approaches were very different, from analytical approaches presented in Excel sheet, to simplified FE models.

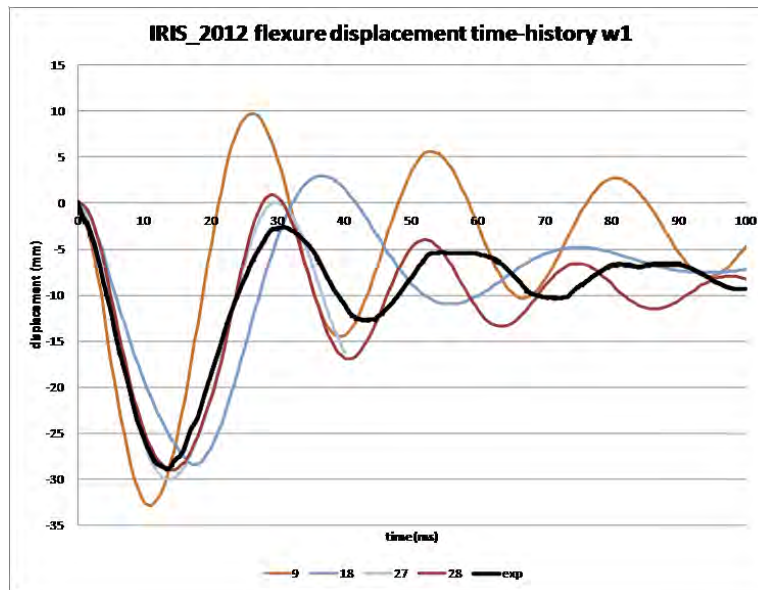


Figure 8: Time history of slab displacements in the IRIS_2012simplified flexural simulation

The goal of simplified models is to isolate and simulate one or few governing parameters, to easily perform sensitivity studies and to compare the results to the results obtained with complex FE models.

Due to the complexity of simulated phenomena, there is a need to have at least two different and independent approaches. The results of flexural test simulations presented in Figure 8 show that simplified models can capture well the chosen parameter (slab maximum displacement in this case).

CONCLUSIONS

The results of second phase of the OECD/NEA/CSNI research program IRIS_2012 presented in this paper show significant improvement in simulation capabilities compared to the previous IRIS_2010 phase. The improvement in understanding of impact phenomena can be seen at the level of the results but also at the level of technical discussions among participants during the workshop held in Ottawa in October 2012.

The first step in the IRIS_2012, based on recommendation of IRIS_2010, was the simulation of tri-axial and Brazilian tests. Most of the teams modeled these tests. However, it is not always stated whether or not the results of these simulations are used for calibration of constitutive models utilized for simulation of flexural and punching test. Some participants concluded inadequacy of static tri-axial tests for dynamic high strain-rate impactive loading performed in flexural and punching tests. Moreover, they concluded that it was not possible to calibrate constitutive models in commercially available software using these tests. The modeling of a Brazilian test ended up with similar conclusion as tri-axial tests.

The calibration of a constitutive model is strongly dependent of the type of loading case for which it is calibrated and it doesn't mean that it will give satisfactory results for another type of loading case (tri-axial, Brazilian, flexural and punching). However, the general finding is that different software, or/and different concrete models within the same software, can be calibrated to get similar results which are close to results for two different tests (flexural and punching). Knowing in advance the test results helped participants to tune existing models and for new participants to develop calibrated models. However, in most cases, the teams do not provide the main reason for the improvement. It looks like that the main model geometry and mesh refinement was not significantly modified. The main modifications are in concrete constitutive laws.

Simplified models, used mainly for simulation of flexural tests, are very useful tools for the analysis of one single parameter (such as maximum displacement and perforation velocity) and should be used in parallel with complex FE models that are able to model the whole structural impact phenomenon. The results obtained from simplified models in IRIS_2012 exercise are very similar to the results obtained from complex models for a given parameter.

The IRIS_2012 results show that the main simulation issues identified in the IRIS_2010 still remain because of the complexity of the problem. One example of these issues is the influence of physical parameters (e.g. concrete compressive and tensile strength) versus non-physical parameters (e.g. concrete erosion) in constitutive models on overall simulation results. Another example is the simulation of residual displacements. The simulation of residual displacements includes the simulation of structural damage (damping, frequency shift). Residual displacements and structural damage are much more difficult to capture than maximum displacements. Concrete constitutive models should be improved to better simulate concrete damage. Further conclusions and recommendations of the IRIS_2012 can be found in Tarallo et al. (2013).

The IRIS_2012 showed that along with residual displacements the modeling of structural vibrations due to an impact is another challenge. The next phase of the IRIS exercise will be the simulation of induced vibrations.

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