ABSTRACT
A benchmark of numerical simulations of projectiles impacts on reinforced concrete slabs has been carried out in the frame of OECD/NEA under the acronym IRIS_2012. That exercise enlightened the conditions under which some 25 teams using various calculation codes could analyze the dynamic behavior of concrete slabs impacted by either deformable or rigid missiles.

Due to the fast dynamic nature of the solicitation and to the non-linear nature of the concrete, there is an inherent scatter of the results well beyond the scatter of an elastic analysis. Thus, for better understanding and modeling of the physical phenomena involved, a combination of testing and simulation is mandatory. The benchmark has also pointed out a number of sound methods and numerous skilled teams among the participants, leading to recommendations of good practice. Simplified analyses, with engineering attitude, have to be systematically adopted in parallel to the necessarily sophisticated simulations, because those analyses allow quick sensitivity studies and better learning of the basic phenomena by the engineers. The results of a numerical simulation should be accompanied by an appropriate margin, taking into account the accuracy range of the analysis. A future objective is to continue to enhance existing models, so that their coefficient of variation would be less than 20%.

The next phase of benchmarking will be focused on induced vibrations. The privileged way is the definition and performing of a “precision test” and its simulation through benchmarking that allows the multiplicity of models and the benefits of their inter-comparison.

INTRODUCTION
A benchmark of numerical simulations of projectiles impacts on reinforced concrete (RC) slabs has been launched in the frame of OECD/NEA under the acronym IRIS_2012.

This benchmark is the second, post-test, phase of the benchmark IRIS_2010 (see Rambach et al. (2011), Vepsä et al. (2011), Orbovic et al. (2011), Berthaud et al. (2011) and Tarallo et al. (2011)), with the goal to improve simulations and reduce the scatter of the results. The two simulations to be done in the frame of IRIS_2012 related to a series of two tests performed by the Finnish company VTT: the impact of a deformable Ø 254 mm projectile (mass 50 kg and V=110 m/s) on a 2-way reinforced concrete slab (2 m x 2 m x 0.15 m) exhibiting damaging mainly by flexural motion (so-called “flexural tests”) and the impact of a rigid Ø 168 mm projectile (mass 47 kg and V=135 m/s) on a 2-way RC slab (2 m x 2 m x 0.25 m) exhibiting damaging mainly by punching motion (so-called “punching tests”). A synthesis of the results of the IRIS_2012 benchmark is presented in Orbovic et al. (2013).

The aim of the present paper is to summarize the lessons that can be learned and the recommendations that can be proposed in terms of design, verification and assessment.
RECALL OF LESSONS LEARNED AND RECOMMENDATIONS OF THE BENCHMARK IRIS_2010

Main IRIS_2010 Lessons Learned

The main IRIS_2010 lessons were (see Tarallo (2011)):

- the scattering of the blind simulation results, with a coefficient of variation of about 100% for the flexural tests simulation (the good news was that the mean values of the displacement time history of the 25 simulations is not far from the recorded displacement time history); the simulations scattering of the punching tests was even greater (this is due in part to the binary aspect of the results, perforation or bouncing);
- the experimental scattering, evaluated by repeated tests, is limited, and is not the main source of scattering;
- the main origin of the scattering relies on the analyst’s choices among all possibilities offered by the computational codes and therefore on his experience in simulation and comparison with experimental results;
- the analysis, for such simulations, is highly non-linear and therefore highly sensitive to the input data; in particular the lack of knowledge on concrete properties has been identified as a probable source of simulations scattering;
- the modeling differences between flexural and punching behaviors have an influence on the modeling strategy: it is necessary to “feel” in advance the dominant rupture mode;
- the damaging of the slab, being difficult to be simulated, quantified and illustrated, is a key issue;
- there is strong interest of an approach that combines sophisticated and simplified models, in order to adapt the strategy and to control the results of the sophisticated models and in order to improve the accuracy of the simplified models.

As a general conclusion, the civil engineering community is still in a learning phase regarding the numerical analysis of concrete structures impacted by rigid or deformable missiles. This first exercise confirms the need to carry out research programs on this topic and to improve analysts’ skills as well as the tools for structural impact simulation.

Main IRIS_2010 Recommendations and Tracks for Future Works

- Provisions recommended when studying a problem (design verification or safety assessment):
  - strong background in calculation team is necessary,
  - several different numerical simulations shall be performed, with sensitivity studies,
  - results discrepancies between simulations shall be explained and understood, the dominant parameters shall be identified with their sensitivity range,
  - the uncertainties shall be assessed and quantified (as far as possible),
  - an appropriate margin shall be incorporated in order to take those uncertainties into account,
  - the codes and tools for calculation shall be used when the team is familiar with,
  - the codes and tools should include appropriate physics and calculation methods: as a first step, simplified hand calculations based on empirical formulae or/and energy and momentum balances shall be employed,
  - simplified calculations should always be done, both to obtain a first order of magnitude and for checking computer results and to improve the understanding of the critical parameters.

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1 By « sophisticated » model or code, it shall be understood model or code that encompass complex geometry and/or complex behavior law and that need significant computation means.
- **Provisions recommended when undertaking a numerical simulation:**
  - the models should be calibrated using representative test results, when available. However, due to all numerous numerical ways for matching the tests results, the selected one may cover either a computational “crime” or a physical law violation;
  - the case shall be presented as simply as possible;
  - concerning projectile modeling: when deformable (and target not perforated), it is advisable to apply to the target model a loading derived from an analytical approach, such as the Riera method. If the projectile is nevertheless modeled by FEM, the corresponding loadings should be assessed using the Riera approach; when less deformable compared to the target or if the target is perforated, the projectile should be modeled by FEM;
  - concerning target modeling (RC plates): in case of bending behavior of the plate, surface elements (such as shell element models) can be considered, though there are not the only valid choice; in case of punching behavior, volume elements appear as mandatory (at least in the area of the expected punching cone); the boundary conditions shall be carefully modeled (including the supporting frame if necessary); partial model of the civil structure, using the existing symmetry, may be done, with special attention to boundary conditions.

- **Provisions recommended when undertaking a FEM simulation:**
  In case of FEM analysis, it is recommended:
  - to carry out sensitivity studies to define adapted element size (check that the results do not change when the mesh is refined, or when the time step is reduced);
  - to carry out sensitivity studies for the selected concrete constitutive law: check by modeling the tested samples, by compression and splitting for example and compare with available test data.

- **Provisions recommended when analyzing the results of the simulation:**
  The analysis of the results needs a careful approach, comprising the minimum following provisions:
  - begin with a critical analysis, a “sanity check”, to confirm the consistency of the simulation: for example in a “soft” impact the projectile momentum should be more or less transmitted into impulse in the target,
  - present the results (post-processing) in a way that can be compared with usual structural engineering quantities.

- **Recommendations for simplified models:**
  Simplified models (based on analytical simulations and on experienced judgments) shall be used and developed in parallel with sophisticated models in order to allow and improve engineering judgment: more physical insights vs. more realistic simulation, calibration vs. checking of the order of magnitude.
  The empirical formulae regarding the response of RC plates impacted by a hard missile should be extended in order they encompass the nowadays concrete with higher strength and the present structures with larger thicknesses and heavier reinforcement ratios as well as the presence of transverse rebars.
  When using an empirical formula for hard impact analysis, the joint use of several formulae is advisable. Each formula should be used inside its validity range.

- **Recommendation for the development of more realistic models**
  Finite elements method is the most common way to simulate missile and target behavior, but other methods are well suited with concrete fragmentation (SPH, lattice discrete particle method, discrete element method, etc…). They should be developed and used more frequently, if appropriate.
IRIS_2012 RESULTS

The IRIS_2012 benchmark is one of the tracks for future works from the IRIS_2010 benchmark. Its organization and the synthesis of results are presented in Orbovic (2013).

The interest of the lessons and recommendations from IRIS_2012 are considered in the light of the results of the re-simulations by the participants, in terms of better knowledge of the input data (namely the concrete characteristics), the limitation (as far as reasonably achievable) of element erosion when FEM is used, the sensitivity of the governing hypotheses, the strategies used by the analysts, etc.

IRIS_2012 LESSONS LEARNED AND RECOMMENDATIONS

The lessons and recommendations from IRIS_2012 are considered in the light of the results of both IRIS_2010 and IRIS_2012 benchmarks, in terms of the role of the knowledge of the results in the strategy adopted by the analyst in his modeling, in terms of the governing hypotheses, in terms of the choice of type of element (Finite Element, SPH, other) and in terms of simplified accompanying models.

- The recommendations from IRIS_2010 are applicable, have passed the IRIS_2012 benchmark and are still valid.
- Impact engineering applied to concrete structures is a relatively new field of knowledge, which evolves and improves rapidly, granted to the effort of a large scientific community, backed by the quick progress of the computer means. Then, one must not be mislead by the results of the IRIS_2010 and IRIS_2012 benchmarks that exhibit significant scattering of the results obtained by the participating teams. Those benchmarks have also pointed out a number of sound methods and numerous skilled teams among the participants, leading to recommendations of good practice. Therefore, a design or an assessment currently based on a prudent approach conducted by experienced engineers should offer a reasonable protection of nuclear facilities against the risks induced by impacts.

- As a result of the discussions by the benchmark and workshop participants, following considerations may be added:
  - the most important is the understanding of physical phenomena;
  - the process of understanding, quantification and modeling of the governing phenomena requires an important effort, is time consuming and eye-burning and shall remain a continual process; to achieve this objective combination of testing and simulations is mandatory;
  - a simplified analysis, with engineering attitude, has to be systematically adopted in parallel to the necessarily sophisticated simulations. It was observed during the benchmark that the results of simplified analyses were globally as good as the FEM ones. Simplified analyses allow quick sensitivity studies and better learning of the basic phenomena by the engineers. Not one simplified model will be able to represent all the phenomena, for example flexural and punching behavior of targets;
  - for motion governed by flexion the limit conditions modeling is a key issue, they deeply influence the structural behavior, in particular the extreme and residual displacements and the free vibration modes;
  - energy consumption beyond elastic domain is rather of hysteretic nature than of damping nature;
  - the mechanical parameters to be introduced as input in the sophisticated codes are not fully independent, it is important to consider a set of consistent parameters, the consistency may be granted by a physical approach;
o the free vibration modes being correlated to the damaged state of the structure, it is important to compare these modes obtained by computation to the ones obtained by measures, if available;

o for problems governed by punching, and simulated with the help of FEM without erosion, a prediction of perforation can be tried on the basis on the velocity time history of the missile. If that velocity has not roughly stabilized to zero, the concrete plate will probably be perforated. That judgment should be backed with the help of empirical formulae.

For design purpose, the strains are very important, but it can be observed there are strain concentrations (the measured strains by gauges are often greater than the ones obtained by simulation): the design criteria shall incorporate this effect.

Due to the fast dynamic nature of the solicitation and to the highly non-linear nature of the concrete, there is an inherent scatter of the results well beyond the scatter in a conventional elastic analysis:

o the results of one numerical simulation should be accompanied by an appropriate margin, taking into account the precision range of the analysis; from IRIS benchmark experience, when a single simulation is provided, the order of magnitude of that margin could be some 30% on calculated deflections of structures behaving in flexion, and 50% on the residual velocity of a missile that perforates a concrete structure;

o the quantification of the uncertainties is not an easy task, however they can be evaluated considering several computations by different teams, different codes, by sensitivity studies focused on the dominant parameters;

o the simulation process shall include a justification of what is not simulated or how and why it has been simplified;

o when using test results on concrete specimen, as recommended, the analyst has to keep in mind that the confined tests depend on the stress path;

o before simulation, the analyst shall identify the issues to be focused on and then he shall apply a consistent set of hypotheses, namely concerning the limiting conditions and the concrete behavior law. The size of the mesh used in the model shall be consistent with the motion to be captured: when a general post elastic motion is of flexural type, a modal elastic analysis shall demonstrate that the 1st modes are consistent with the expected motion and when a local punching is awaited, the mesh shall be locally sufficiently dense to generate a punching cone;

o a kind of “push over” (i.e. without inertial forces), obtained by an increasing loading, either implicitly computed or explicitly according to a slow loading ramp, is a good practice, in order to check the aptitude of the model to react to a post elastic static loading.

Future objectives and tracks for future works:

o continue to improve the knowledge of physical phenomena and means for their simulation which should include an accurate prediction of induced vibrations; the privileged way is the definition and performing of a “precision test” and its simulation through benchmarking that allows the multiplicity of models and the benefits of their inter-comparison.

o continue to enhance existing FE models: the target criterion for scatter could be a coefficient of variation less than 20%;

o next phase of benchmarking will be focused on induced vibrations.

CONCLUSION

A benchmark of numerical simulations of projectiles impacts on reinforced concrete slabs has been carried out in the frame of OECD/NEA under the acronym IRIS_2012. That exercise enlightened the conditions under which some 25 teams using various calculation codes could analyze the dynamic behavior of concrete slabs impacted by either deformable or rigid missiles.
Due to the fast dynamic nature of the solicitation and to the non-linear nature of the concrete, there is an inherent scatter of the results well beyond the scatter of an elastic analysis. Impact engineering applied to concrete structures is a relatively new field of knowledge, which evolves and improves rapidly, granted to the effort of a large scientific community, backed by the quick progress of the computer means. Then, one must not be misled by the results of the IRIS_2010 and IRIS_2012 benchmarks that exhibit significant scattering of the results obtained by the participating teams. Those benchmarks have also pointed out a number of sound methods and numerous skilled teams among the participants, leading to recommendations of good practice. Therefore, a design or an assessment currently based on a prudent approach conducted by experienced engineers should offer a reasonable protection of nuclear facilities against the risks induced by impacts.

For better understanding and modeling of the physical phenomena involved, a combination of testing and simulation is mandatory. A simplified analysis, with engineering attitude, has to be systematically adopted in parallel to the necessarily sophisticated simulations, because that kind of analysis allow quick sensitivity studies and better learning of the basic phenomena by the engineers. The results of a numerical simulation should be accompanied by an appropriate margin, taking into account the accuracy range of the analysis. From IRIS benchmark experience, when a single simulation is provided, the order of magnitude of that margin could be some 30% on calculated deflections of structures behaving in flexion, and 50% on the residual velocity of a missile that perforates a concrete structure. A future objective is to continue to enhance existing models, so that their coefficient of variation would be less than 20%.

The next phase of benchmarking will be focused on induced vibrations. The privileged way is the definition and performing of a “precision test” and its simulation through benchmarking that allows the multiplicity of models and the benefits of their inter-comparison.

REFERENCES


