Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division III Applied Computation, Simulation and Animation

SPH MODEL FOR SIMULATION OF IRIS_2012 SLAB PUNCHING

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ABSTRACT

This paper deals with the modeling by SPH (Smooth Particles Hydrodynamics) method of a reinforced concrete (RC) slab when hit by a hard missile up to perforation. The experiment chosen for the simulation is the one used in the benchmarks IRIS_2010 (Vepsa et al., 2011) and IRIS_2012 (Orbovic et al., 2013 and Tarallo at al. 2013), the P1 test. Among the models developed by IRSN for this test simulation, the SPH method provides very promising way of modeling.

The model by particle topology named “Smooth Particle Hydrodynamics” (SPH) seems a promising way of simulating the punching of a slab up to perforation. Whatever the type of modeling involved, a comparison of simulation results with data from empirical formulae or from known similar experiments should be systematically done by fast dynamic analysts, in order they improve the reliability of their conclusions. The simulations of the triaxial and Brazilian concrete tests made by the code RADIOSS provide rather reliable and consistent results and constitute a useful validation of the concrete behavior law.

The simulation of the slab with perforation (P1) using SPH modeling correctly predicts the perforation and damaging of the slab and the residual velocity of the missile. The displacements and strains are however less accurate and differ from the experimental values. Simulated displacements are up to ten times higher than the measured ones whereas the simulated rebar strains are lower than their experimental values. There is no clear explanation of this observation.

IMPACT OF A RC SLAB BY A HARD PROJECTILE: TEST RESULTS OF P1 SLAB

The hard type (Ø168 mm, m = 47 kg) projectile is launched at the velocity V = 135 m/s against the 250 mm thick and 2 m x 2 m slab made of reinforced concrete and simply supported along its 4 edges. The slab is perforated by the projectile with a residual velocity of 35 m/s. Displacement gauges on front surface and strain gauges on rebars and on slab surface provide recordings of time histories of the motion and deformation during the impact. They are used to understand the behavior of the slab and to control the simulation results.

SPH MODELING: METHOD, NECESSARY DATA

The code used for the modeling is the fast dynamic solver RADIOSS® with the SPH module. SPH modeling principles are quite different from those ones of the Finite Element Method (FEM): the concrete parts of the slab are modeled by particles that are linked together by behavior laws. The steel rebars are modeled by FEM and both meshes are merged. The necessary data for behavior laws are identical whatever the type of model. The discretization (size of particle) shall be consistent with the expected motion and rupture modes. The typical size of concrete particles in central part of slab is about 15 mm. The projectile is modeled by using a FEM model.

A great care has been taken in order to validate the behavior law of the concrete by modeling the behavior of the specimens used in the determination of the mechanical characteristics of the concrete.

CONCRETE LAW VALIDATION BY SIMULATION OF TESTS ON CONCRETE SAMPLES

Model: Mesh, Limit Conditions and Material Law

The triaxial tests and Brazilian test performed on the concrete specimens are themselves simulated in order to validate the concrete material law (Material #24 of RADIOSS®). Only 5 parameters must be fixed by the analyst. In the present study the following values are chosen[1]:

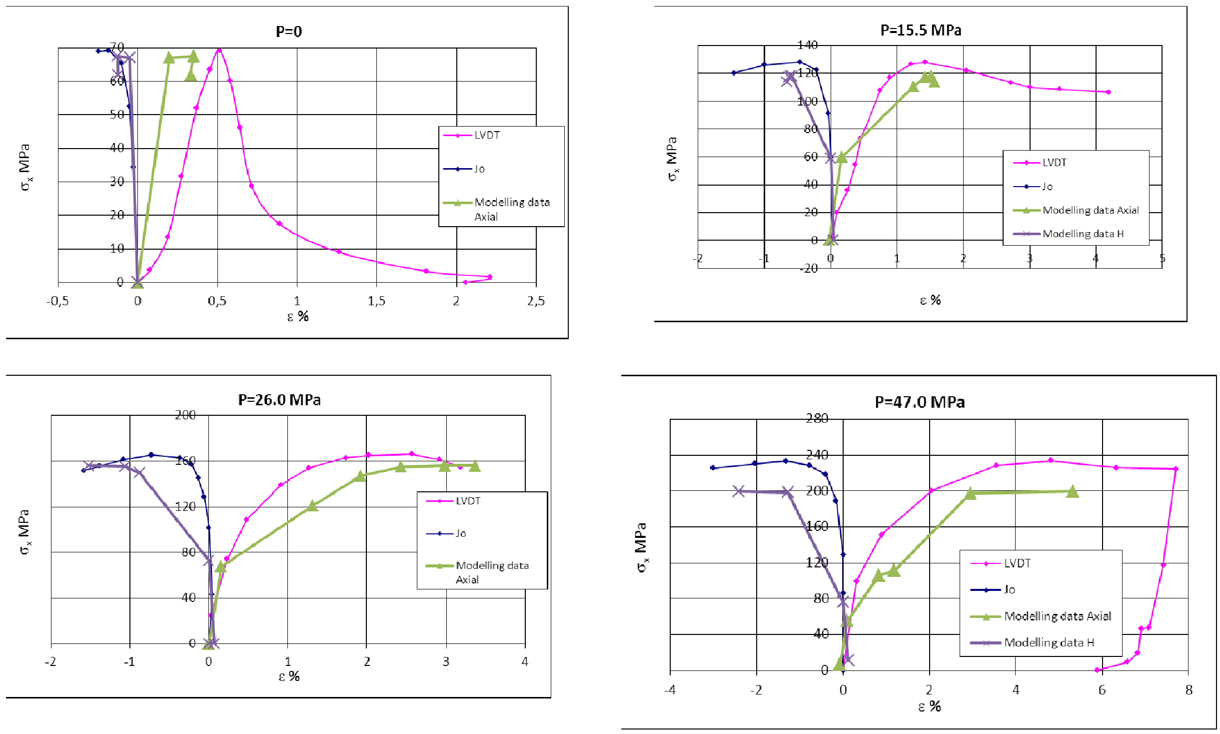
Density d = 2.4 Young's modulus E = 29,000 MPa Poisson's ratio ν = 0.2

Uniaxial concrete strength Rc = 60 MPa Uniaxial tensile strength Rt = 4 MPa

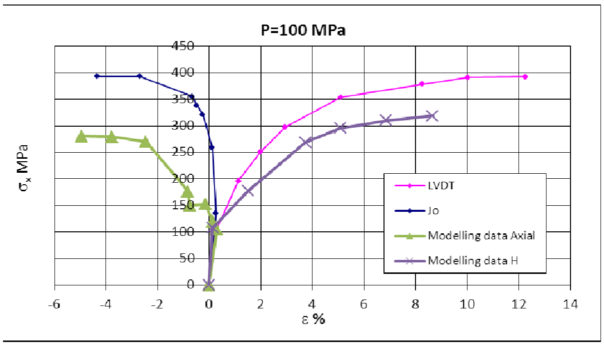
Triaxial Test

The triaxial tests are a set of 5 tests up to the rupture of cylindrical specimens of concrete, with confining pressure at 0 MPa (i.e. uniaxial compression), 15.5 MPa, 26 MPa, 47 MPa and 100 MPa.

For the triaxial tests simulations, the concrete samples are modeled by using FEM brick elements. On figure 1, for each confining pressure, the deformations (extension) along circumferential direction are presented on the left side (i.e. with negative values) and deformations (contraction) along axial direction are presented on the right side (i.e. with positive values). There was no attempt made to more accurately fit the experimental curves, the idea was to limit the input data to the 5 values here above indicated by keeping their standard values to the other parameters. The simulation curves fit rather fairly the experimental curves.



[1] The other parameters are set by default



LVDT stands for an longitudinal deformation by measuring the longitudinal shortening of the whole lengthh of the specimen;

J0 stands for a longitudinal or circumferential local deformation obtained by strain gauges

Fig 1. Triaxial tests: comparison of tests results with the numerical simulations

Brazilian Test

Simulations with FEM's brick elements and with SPH (Smoothed-Particle Hydrodynamics) are done: the value of the applied diametral force at splitting is consistent with the concrete limit in tension. Sensitivity to mesh refinement is also checked.

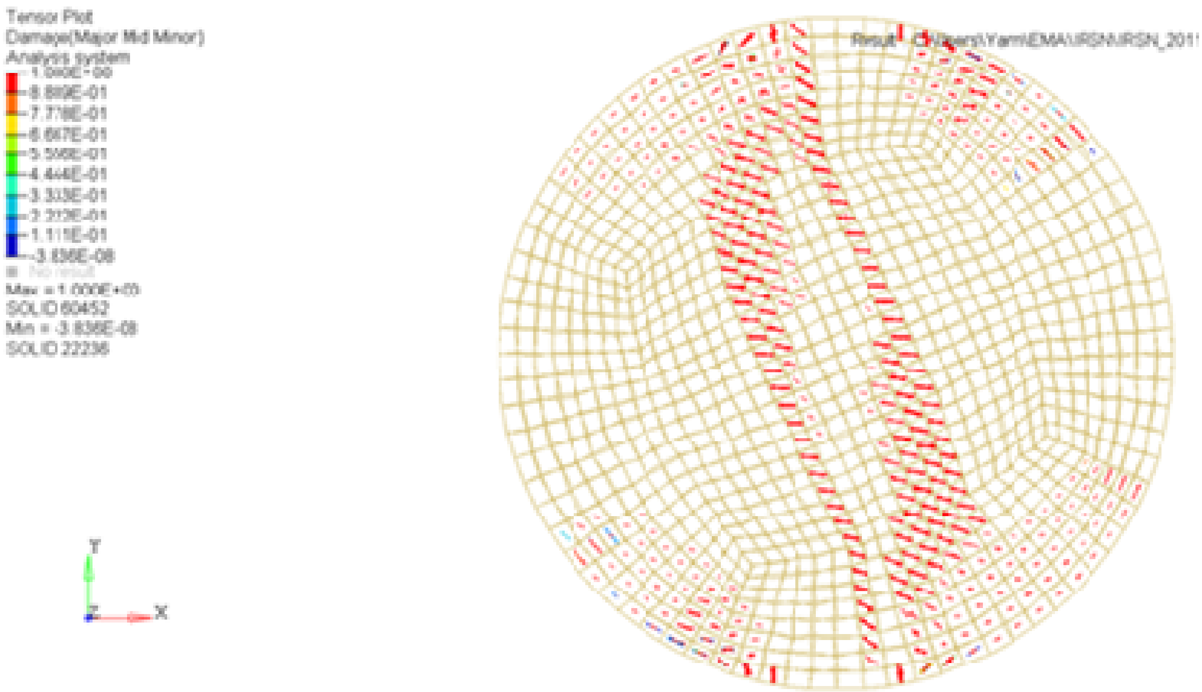


Fig 2. Brazilian test simulation with the brick model. View of the concrete damaging across a transverse section: the diametral splitting is correctly reached.

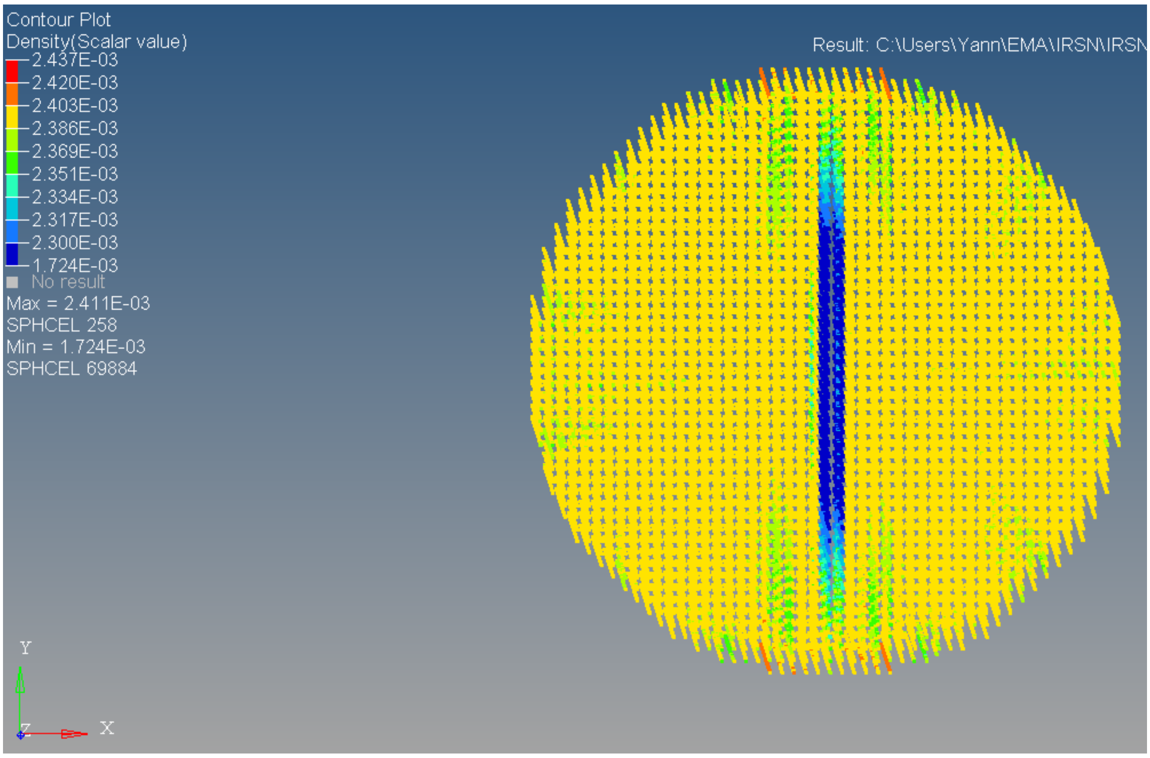
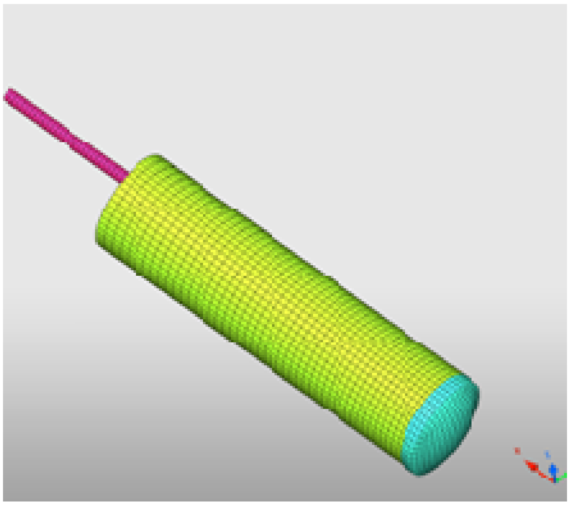


Fig 3. Brazilian test simulation with the SPH model. View of the density of the concrete sample across a transverse section: blue color for lower density, the diametral splitting is correctly reached.

SIMULATION OF THE PROJECTILE

Model: Mesh, Limit Conditions and Material Law



The light concrete is modeled by 11760 bricks, the steel envelope by 2796 shells (typical size 11 mm x 11 mm). The material law is of brittle plastic type (Johnson & Cook). Total number of nodes: 16252.

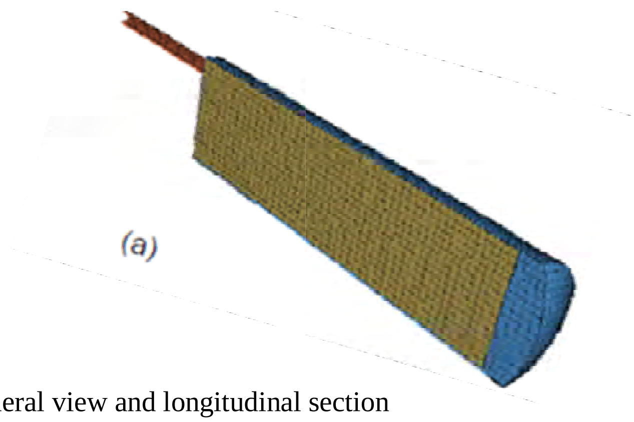


Fig 4. Projectile model by FEM. General view and longitudinal section

Motion

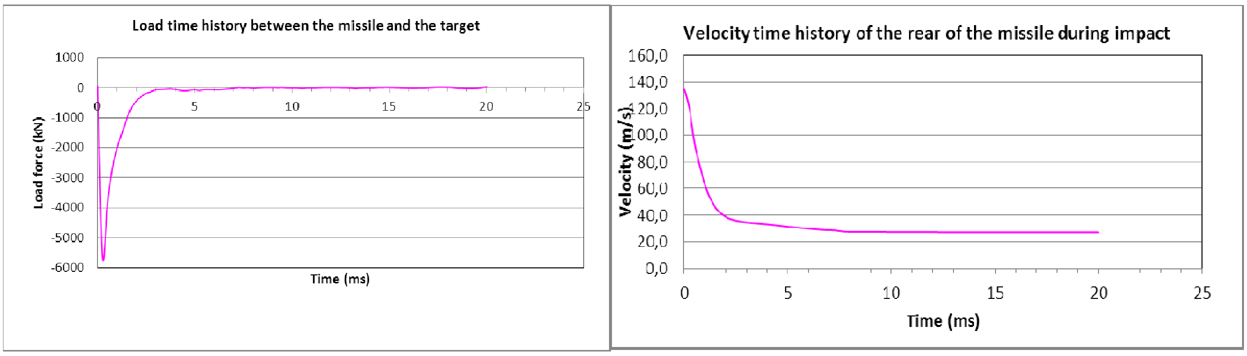


Fig 5. Results on the projectile: time history of the impact force and the velocity of the rear part

Check with the impulse

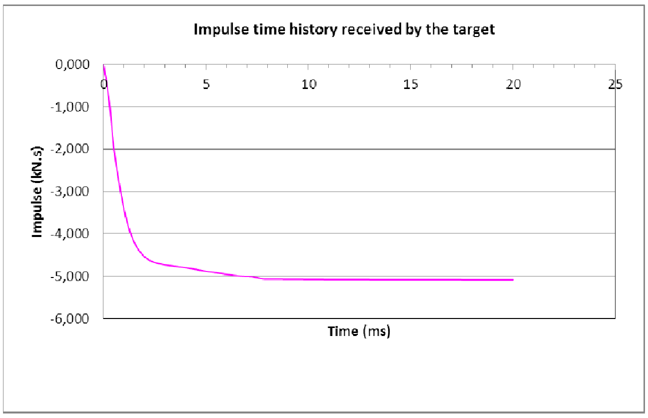


Fig 6. Impulse time history

The impulse plateau, which absolute value is 5.07 kN/s, is consistent with a 47 kg projectile hitting the target at 135 m/s with a residual velocity about 27 m/s:
$5.07 \approx 47.(135 - 27)$.

SIMULATION OF THE TARGET: THE SLAB P1

Model: Mesh, Limit Conditions and Material Law

The meshing of the slab is of “meshless” type, based on the particle topology named “Smooth Particle Hydrodynamics” (SPH). The typical size of the particles is 15x15x15 mm^3. The behavior law of the concrete is the one used for the simulation of the concrete specimen tests, with the same values of parameters. The slab model is fixed along 4 lines of nodes parallel to the edges of the slab. The rebars are modeled by 6600 15 mm long truss elements. The rebar/concrete interaction is obtained by a “merging” procedure that enables a common deformation. The rebar steel behavior law follows the Johnson & Cook law:

$$\sigma = \left(a + b\varepsilon_p^n\right)\left(1 + c\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)$$

with a=650 MPa, b=1,667 MPa, c=0 and n=1 (ε_P: plastic deformation)
Elastic characteristics: Young’s modulus E=200,000 MPa and Poisson’s ratio ν=0.3
Yield limit f_{su}=700 MPa and rupture deformation ε_{su}=10 %

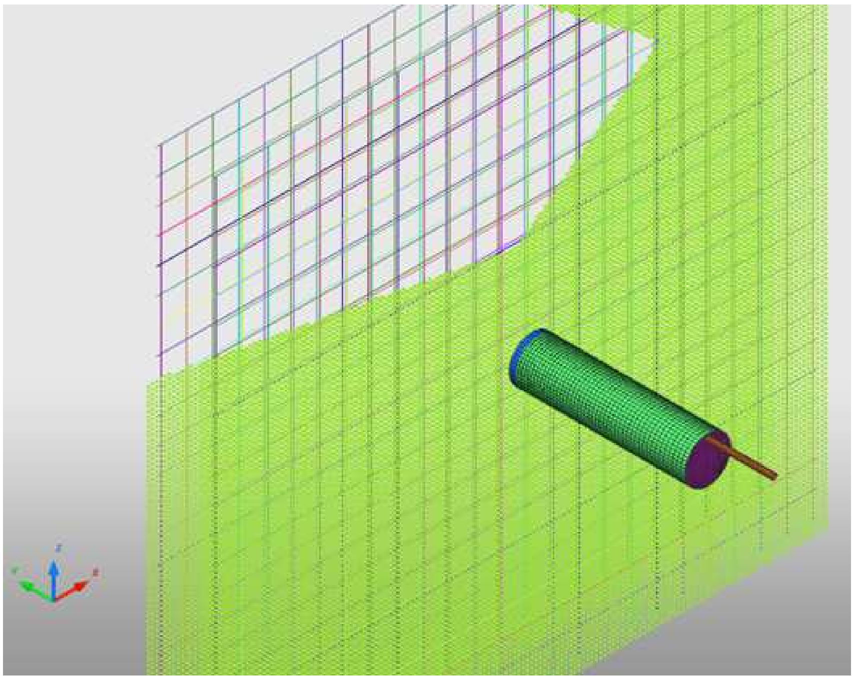


Fig 7. View of the projectile model and of P1slab model showing the rebars

Slab Motion

The computed displacements of the slab are far above tests results (see Fig 8. hereafter). There is no clear explanation of that result.

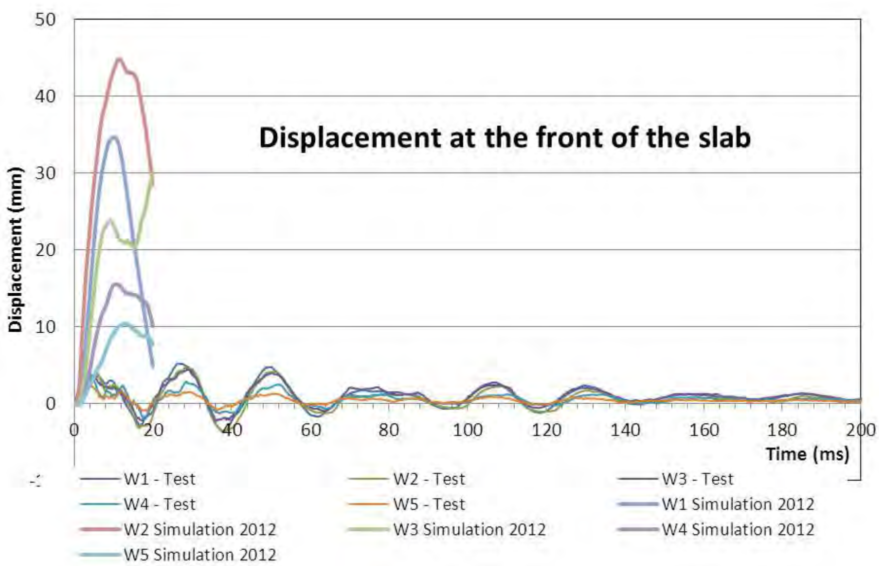


Fig 8. Simulated versus experimental displacements of the slab P1: simulated displacements are greater than the experimental ones.

Slab Damaging during the perforation

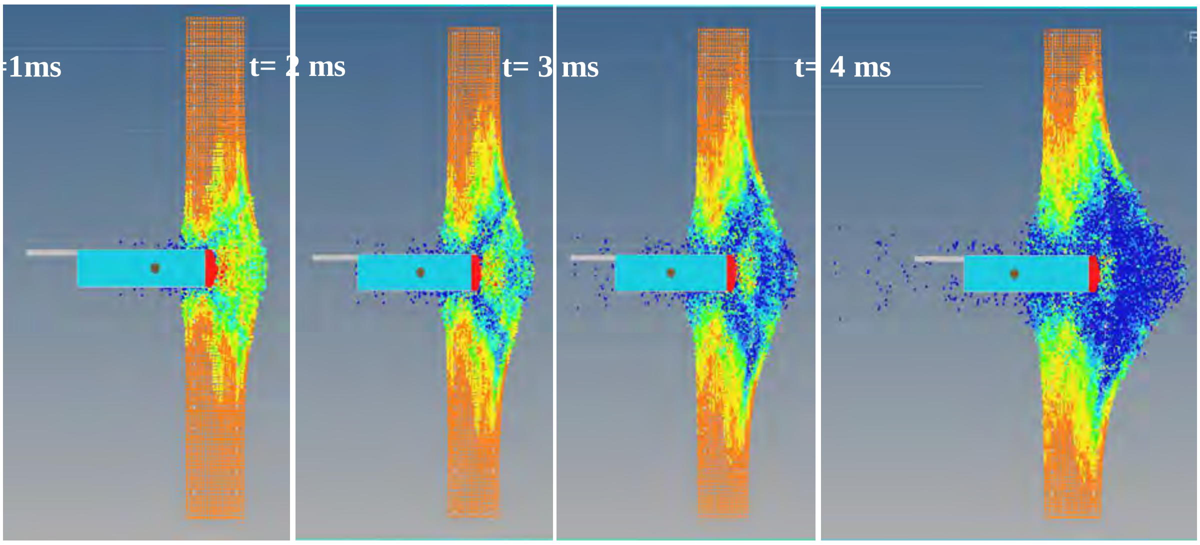


Fig 9. Slab P1. Successive deformation states computed with SPH method. The color variation corresponds to the material density: blue color = very low concrete density = crack or concrete expulsion

Concrete and Rebars Strains

The comparison of the computed plastic strains in the rebars is represented on the figures here below (in red color, given by computation and in blue color measured by gauge) at 2 locations. The simulation is not so bad.

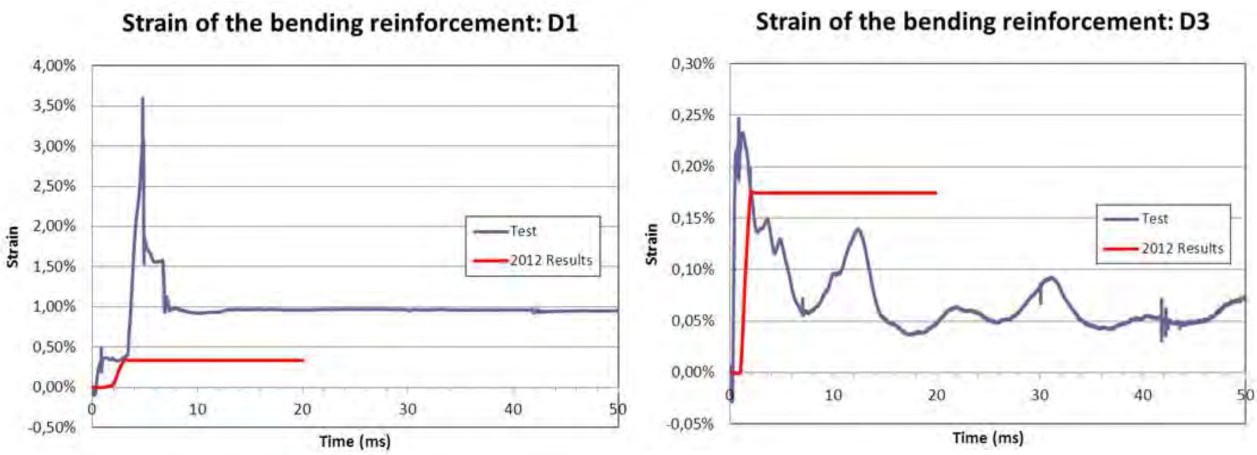


Fig. 10. Slab P1. Strains in the rebars. Comparison test-simulation

Final Slab Damaging

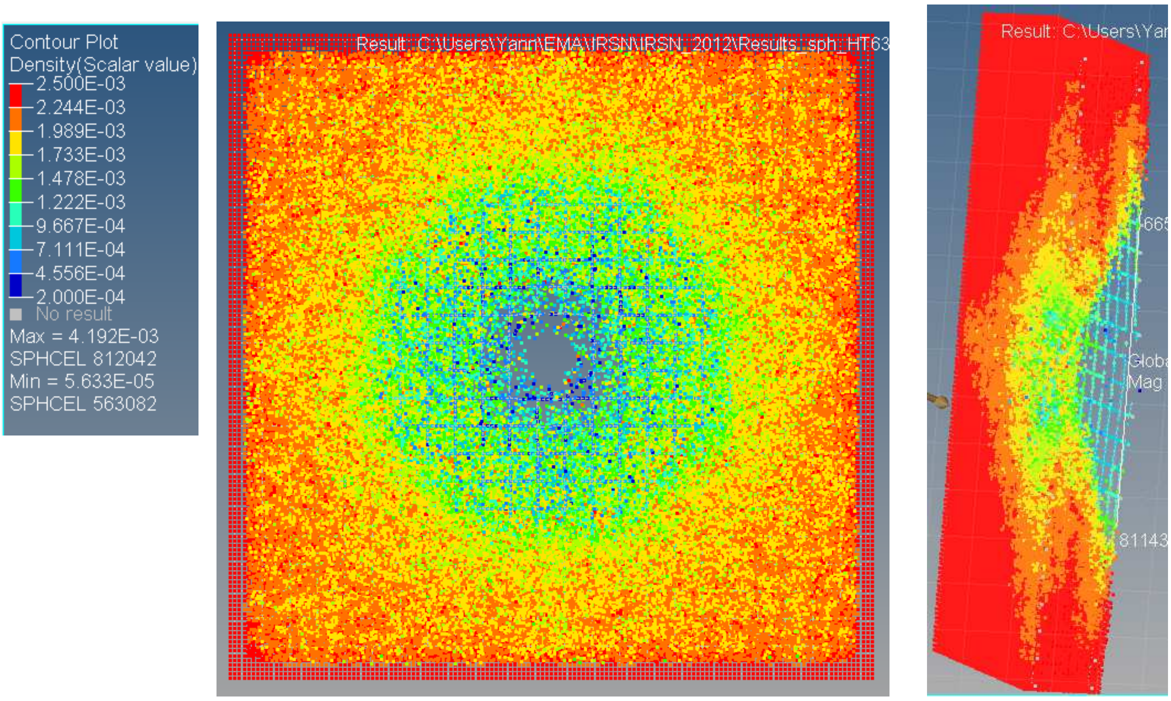


Fig 11. Slab P1. Map of concrete density variations in the slab, showing the target final damage

Checks and Sensitivity Studies

Kinetic energy (dashed red line on Fig 12 hereafter) is progressively transformed into internal energy (plain blue line). The total energy curve (dotted magenta line) is almost constant all along the motion. Slab modeling with FE brick element gives residual velocity of about 11 m/s (without erosion) while SPH modeling gives 27 m/s. The loss of energy by computation is about 7 %, which is acceptable. The ratio of final kinetic energy on the initial kinetic energy is about 0.9/4.26 ≈ 0.21: this ratio leads to a concrete mass of about 202 kg ejected with the velocity of the projectile residual velocity (27 m/s). The conservation of the momentum leads to a mass of ejected concrete particles of about 188 kg. These computational results are consistent with the measured residual velocity (35 m/s) and the mass of ejected concrete particles of about 134 kg projected with projectile residual velocity (as per momentum conservation).

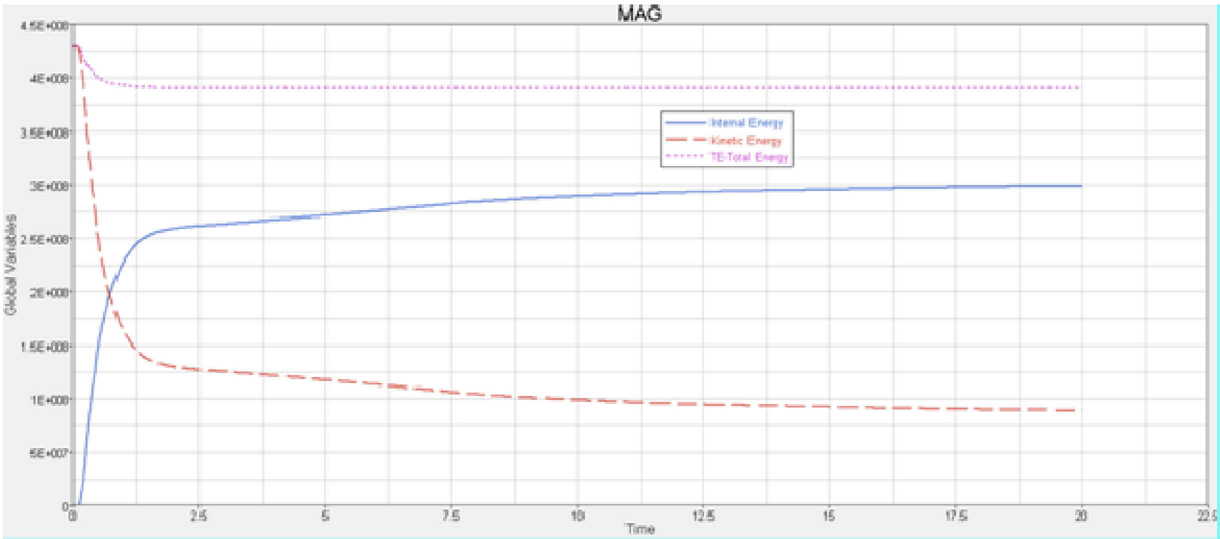


Fig 12. SPH simulation: time history of the kinetic energy (dashed red line), internal energy (plain blue line) and their sum (dotted magenta line).

RESULTS OF SPH METHOD VS FINITE ELEMENT METHOD

The results obtained, in terms of residual velocity of missile and of damages, are very satisfactory: the projectile residual velocity in SPH simulation is about 27 m/s. However slab displacements time histories and strain time histories in rebars and on concrete surface obtained in the simulation sensibly differ from the measured ones (such statement is observed for simulations by FEM, see Vepsa et al., (2011) and Orbovic et al., (2013).

Comparison of SPH modeling and FEM modeling lets appear that the residual velocity by FEM (11 m/s) is lower than the one given by SPH models. This is due to the fact that in this FEM simulation, no element erosion was supposed: the elements, even broken, continue to retain the projectile.

CONCLUSION

The model by particle topology named “Smooth Particle Hydrodynamics” (SPH) seems a promising way of simulating the punching of a slab up to perforation. Whatever the type of modeling involved, a comparison of simulation results with data from empirical formulae or from known similar experiments should be systematically done by fast dynamic analysts, in order they improve the reliability of their conclusions. The simulations of the triaxial and Brazilian concrete tests made by the code RADIOSS provide rather reliable and consistent results and constitute a useful validation of the concrete behavior law.

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REFERENCES

[1] Vepsä, A., Saarenheimo, A., Tarallo, F., Orbovic, N., and Rambach, J.-M., “IRIS_2010 – Part II: Experimental data”, *SMiRT_21 Proceedings*, New Dehli, India., SMiRT-21, November, 2011.

[2] Orbovic, N.,Tarallo, F., and Rambach, J.-M. “IRIS_2012 - Part I: Overview and synthesis of the numerical simulations”, *SMiRT_22 Proceedings*, San Francisco, California (USA), SMiRT-22, August, 2013.

[3] Tarallo, F., Orbovic, N., Rambach, J.-M. “IRIS_2012 - Part II: Lessons learned and recommendations”, *SMiRT_22 Proceedings*, San Francisco, California (USA), SMiRT-22, August, 2013.