Impact Simulations on Concrete Slabs : LS-OPT® Fitting Approach

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Abstract

This paper is based on a work realized for an international OECD benchmark initiated by IRSN and CNSC. The main goal of IRIS_2010 Benchmark was to evaluate the ability of simulation to reproduce experimental tests of impacts on concrete slabs for two different deformation modes: bending (flexural) and punching.

LS-DYNA® has been chosen by IRSN as their main explicit code for simulating such high speed impacts on concrete. Most LS-DYNA® concrete laws include two sets of physical parameters, a first one related to basic concrete parameters (Compressive strength, Poisson ratio), a second one related to each concrete model (Damage, strain rate effects). LS-DYNA® provides an automatic generation capability for the second set of parameters (based only on the Compressive strength) which leads to an acceptable level of accuracy for the majority of cases. However, this automatic set of parameters can usually be optimized to better fit experimental results.

For each benchmark case, we performed an advanced 3 steps fitting approach using LS-OPT®. A Monte Carlo analysis was done first on several model parameters to study sensitivities and correlations and identify which ones can affect the slab damage and may improve the results. Then, an Optimization of identified parameters was realized to fit the experimental results. Finally, a complementary Monte Carlo analysis on physical parameters (Concrete resistances, Poisson's ratio…) was used to evaluate the robustness of our optimal solution and to integrate in our calculation process uncertainty and variations of material data.

Introduction

IRIS_2010 Benchmark was based on three experimental tests of a medium velocity missile impact on concrete slabs: one test from the open literature with a few experimental results (Meppen) and two tests recently performed (VTT Flexural and Punching). The main goal of this project was to evaluate the ability of simulation to reproduce experimental tests of impacts on concrete slabs for two different deformation modes: bending and punching.

Like in most simulation problems, the biggest difficulty was a lack of experimental data provided for the study. Only basic input was given for concrete properties (unconfined compressive and tension strengths, tangent modulus) and stress-strain curves were given for steel without strain rate effects (except for Meppen test). As a consequence, a calibration of the constitutive law by basic sample tests before the real simulation was impossible.

In this Benchmark, we performed simulations using the automatic generation capability of concrete law parameters. Indeed, for most advanced concrete laws (*MAT_72R3 for example), LS-DYNA is able to provide, starting from a first set of physical parameters (unconfined compressive strength,…) a second set of parameters by internally fitting experimental results from CEB-FIP Model Code. This default set of parameters gives acceptable behavior for most of application with a standard concrete.

Due to the lack of experimental data on concrete, we could not calibrate the concrete law upstream. Therefore we were obliged to perform simulation with default parameters and modify these parameters in a second step in order to optimize our results. We used LS-OPT in order to realize a study in two steps:

- Sensibility analyses in order to find out of the large number of concrete parameters the ones that were affecting mainly the behavior.
- Optimization of these identified parameters to fit experimental results.

In addition, for every experimental data, and especially for concrete, we are aware of the uncertainty in properties arising from tools, human actions, concrete age and other factors. This uncertainty may have a strong influence on results, especially on impacts on concrete. In order to take this effect into consideration we studied the robustness of our optimization point as a last step with a Monte Carlo analysis using LS-OPT. A variability of physical concrete parameters given for the Benchmark was introduced to evaluate the results variability.

In this paper, to be concise enough and to also give enough precision, we will not explain all the three cases performed in the Benchmark. But we will only present in details the results for VTT Punching (Modeling, Results and Fitting Approach).

VTT Punching Modeling

VTT Punching test is composed of two parts:

- A missile with a steel dome and a concrete cylinder with a steel skin, with a total mass of about 50 kg. This missile impacts the slab at 135 m/s.
- A concrete slab of 200 x 200 x 25 cm hold by a UPN Steel part, reinforced by a square mesh of longitudinal rebars on each side of the slab.

This test is modeled by a 3D half model; the goal is to use one of the symmetry axes to limit the number of elements without forcing a distortion mode.

The supporting frame is not explicitly modeled but is taken into account with Boundary conditions. Z-translation is blocked on lines (front and rear face) at 5 cm from edge. Y-translation is only blocked on the lines parallel to the horizontal edge and X-translation is only blocked on the lines parallel to the vertical edge. The symmetry axis is the YZ plane, all nodes in this plane are blocked in X-translation and Y, Z-rotations.

Concrete is modeled by under integrated constant stress solid element (one integration point per volume). Reinforcement is modeled by Hugues-Liu with cross section integration beam elements. The ratio between slab and missile element size guarantees a good behavior during the contact.

The UPN Steel part, surrounding the concrete slab, is explicitly modeled by Belystchko fully integrated shell element and is merged into the concrete part.

The missile for the VTT Punching test is explicitly modeled. Light-weight concrete and steel dome are modeled using under integrated constant stress solid elements (one integration point per volume). Steel pipe and steel plate are modeled with Belytschko fully integrated shell elements merged into the concrete solid.

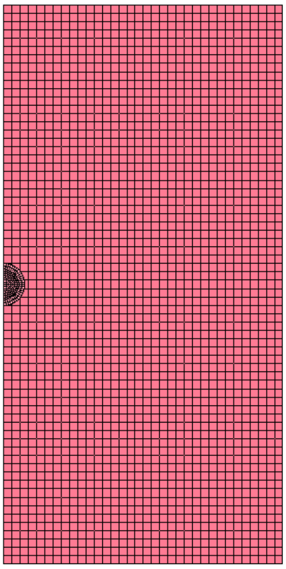

Figure 1 : *Top View*

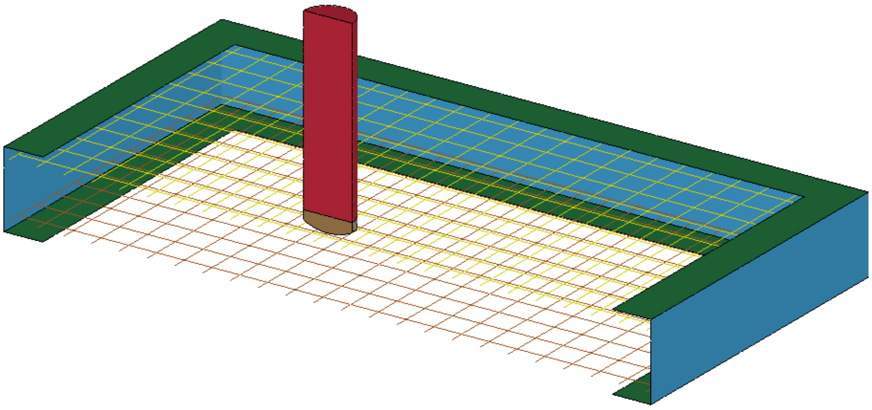

Figure 2 : *View of rebars, missile and UPN Steel part*

The constitutive law of concrete is a *MAT_CONCRETE_DAMAGE_REL3 also called *MAT_72R3 able to model the behavior of a concrete subjected to high triaxial stress and high strain rate effects. This constitutive model is particularly adapted to this kind of simulation because the missile impacts the target with a high kinetic energy (47 kg at 135 m/s) and because the missile is almost undeformable.

The constitutive law for concrete is built using the model generation parameter capability, based solely on standard unconfined compression strength.

The constitutive law of steel elements is a *MAT_PIECEWISE_LINEAR_PLASTICITY able to model the behavior of steel with a complex plasticity curve and to include strain rate effects. Engineer values are changed into true values up to striction and then interpolated using a swift law. Without stress-strain curves for different strain rates, a simple way to take into account strain rate effects is to add a Cowper-Symonds law.

Rebars are not merged to the concrete elements; the interaction is modeled by a coupling method based on a constrained approach. Junctions between two longitudinal rebars are merged.

Two types of contact are used to model the interaction between missile and slab:

- *CONTACT_ERODING_SINGLE_SURFACE deals with the contact between missile and solid concrete and the auto contact of the missile on itself. This contact is based on penalty method with a segment based option for contact detection (instead of node based) to avoid penetration.

- *CONTACT_ERODING_NODES_TO_SURFACE deals with a possible contact between reinforcement nodes and missile segments (if erosion leads to such a possibility).

VTT Punching Results

With default parameters of *MAT_72R3 generated by LS-DYNA, we found a solution with a perforation of the slab. During the shock, a high confined zone appears just behind the missile; this zone is quickly much damaged and loses its resistance. A cone-shaped shear surface leads to high distorted elements and then to the cone cracking when elements reach the erosion criteria. At the end of simulation, the slab is totally damaged in a larger cone surrounding the perforated area; we also notice a damaged zone near the junction with UPN Steel Part.

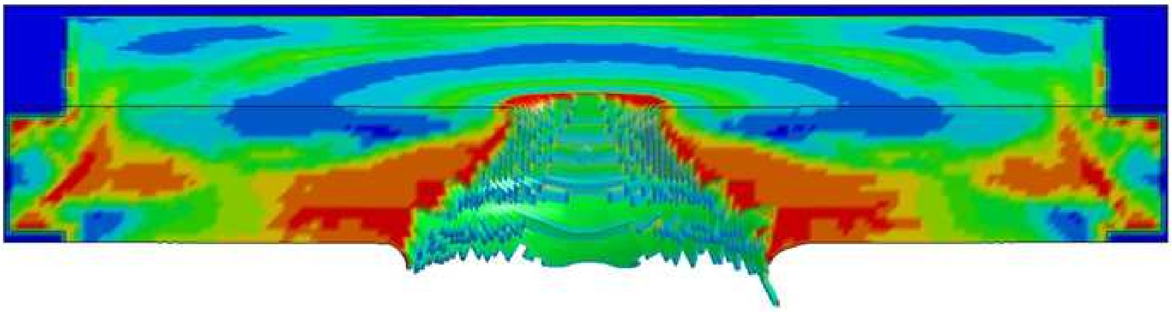

Figure 3 : *View of slab damaging at the end of simulation*

Figure 4 : *Experimental View of an horizontal cross-section of the slab*

If we compare our numerical results with the experimental results, we can see that we have a damage zone similar to the experiment. The damage cone is clearly present with a similar shape excepted for the scabbing area behind the rear longitudinal rebars. Indeed, this scabbing area is larger in the experiment probably because our simulation can't model the decohesion between reinforcement and concrete.

The concrete inside the missile is much damaged and plastic strain is important in the steel dome, there is a small barrel effect at the junction between concrete and steel. If we compare our numerical results with the experimental results we notice a similar shape effect.

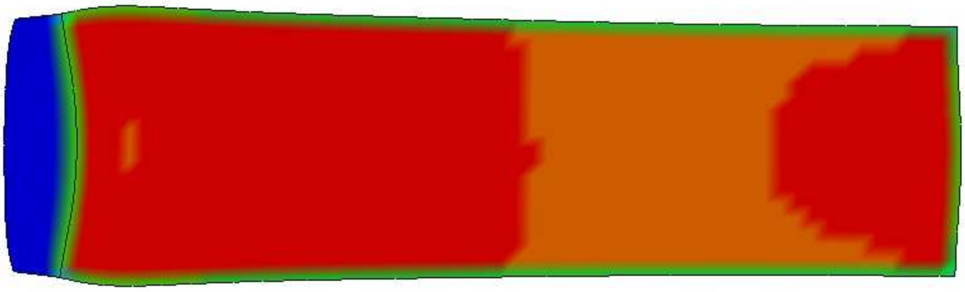

Figure 5 : *View of missile at the end of simulation*

Figure 6 : *Experimental View of missile*

Finally, with the default parameters of *MAT_72R3, we found a solution with a realistic behavior and a damage globally representing the experiment. But if we analyze the residual velocity of the missile after perforation, we have in simulation 47 m/s whereas this velocity is about 36 m/s in experiment. Therefore, our simulation overestimates the residual velocity and need an optimization run to better fit the experimental results.

Fitting Approach

To fit the experimental residual velocity, a strategy has been developed to identify which variables can affect this velocity and then to optimize them. This strategy consists of 2 stages: a phase of sensitivity analysis to identify important variables, followed by a phase of optimization of these variables.

This fitting approach is performed with the software LS-OPT version 4.1.

If we analyze residual velocity evolution during the calculation, we can notice that the final velocity of the missile is achieved very quickly after impact, so we can reduce the computation time to 3 ms, allowing us to perform a very large number of calculations and significantly improve LS-OPT efficiency.

For our sensitivity analysis, we choose 8 variables used in concrete and steel constitutive models:

- Management of highly damaged concrete in compression: a_{1f} and a_{2f} from *MAT_72R3.
- Management of damaged concrete in tension: b_1 and b_2 from *MAT_72R3.
- Strain rates effects in missile steel: cm and pm parameters from Cowper-Symonds law.
- Strain rates effects in reinforcement steel: cf and pf parameters from Cowper-Symonds law.

Variable	**Lower Bound**	**Upper Bound**
a_{1f} (Mbar)	0.3	0.7
a_{2f}	5	200
b_2	- 8	2
b_3	0.01	2
cm (µs^{-1})	$1e^{-5}$	$3e^{-4}$
pm	1	10
cf (µs^{-1})	$1e^{-5}$	$3e^{-4}$
pf	1	10

Figure 7 : *Table of variables and bounds*

For this Metamodel-based Monte Carlo analysis, we choose 300 simulation points for 8 variables, so we could use a neural network metamodel able to model accurately all types of response evolution. A sampling type "space filling" and a metamodel "Radial Basis Function Network" have been selected for this study.

The studied response is the residual missile velocity at the end of the calculation (at t = 3 ms). We also asked the history of this velocity in order to assess its evolution in the LS-OPT Viewer.

At the end of a LS-OPT study, the first thing to check is the metamodel accuracy to validate the results from a numerical point of view. As we can see on the picture below, RMS and Sqr PRESS errors and R^2 coefficient are good (RMS and PRESS about 0 and R^2 close to 1), this ensure that the metamodel is a good approximation of responses.

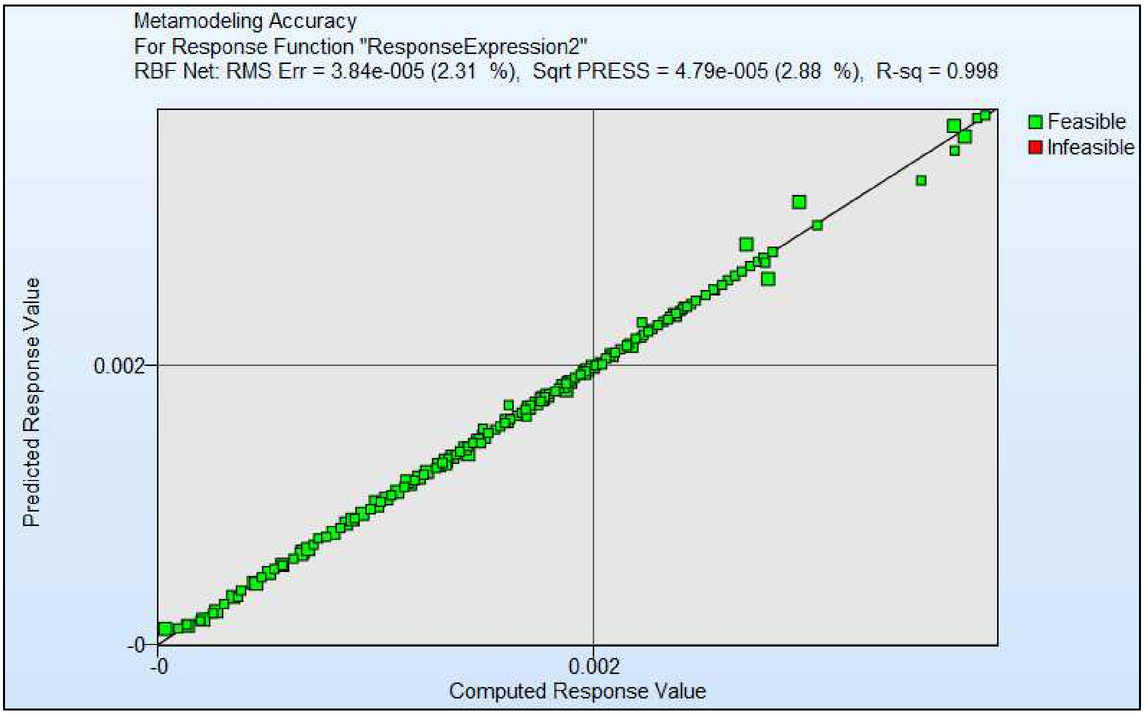

Figure 8 : *Metamodel Accuracy*

Secondly, analyzing the ANOVA and GSA/Sobol Sensitivity diagrams, we can see good 90% Confidence intervals which allows us some conclusions about sensitivity. We notice that only one variable has a significant effect on the residual speed of the missile. In fact this parameter a1f focuses 96% of the response expansion.

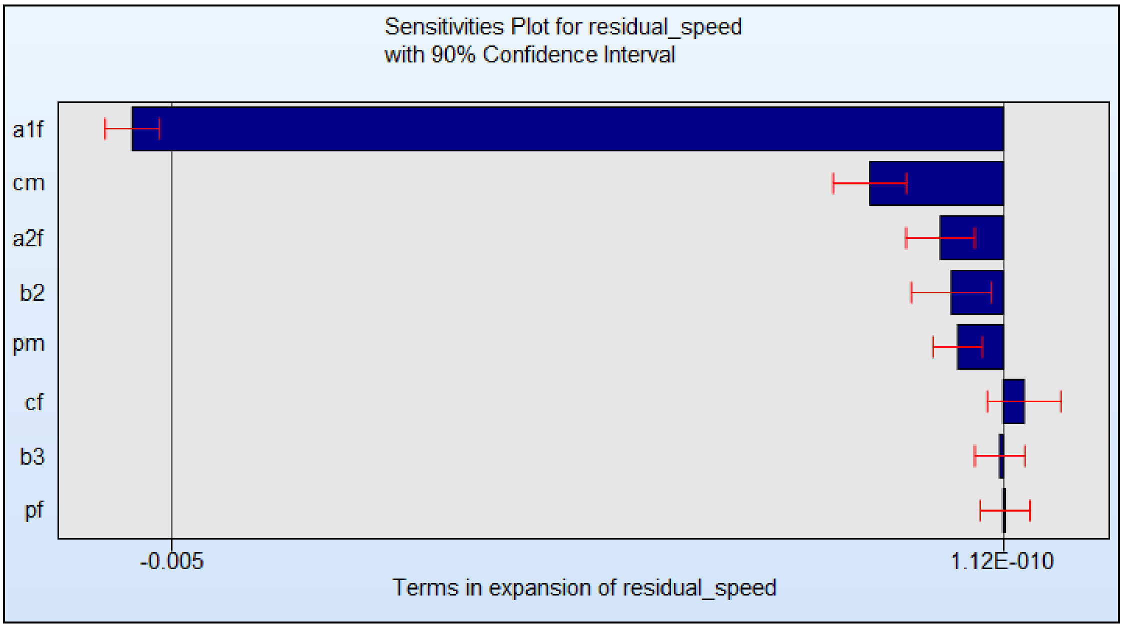

Figure 9 : *ANOVA for residual_speed*

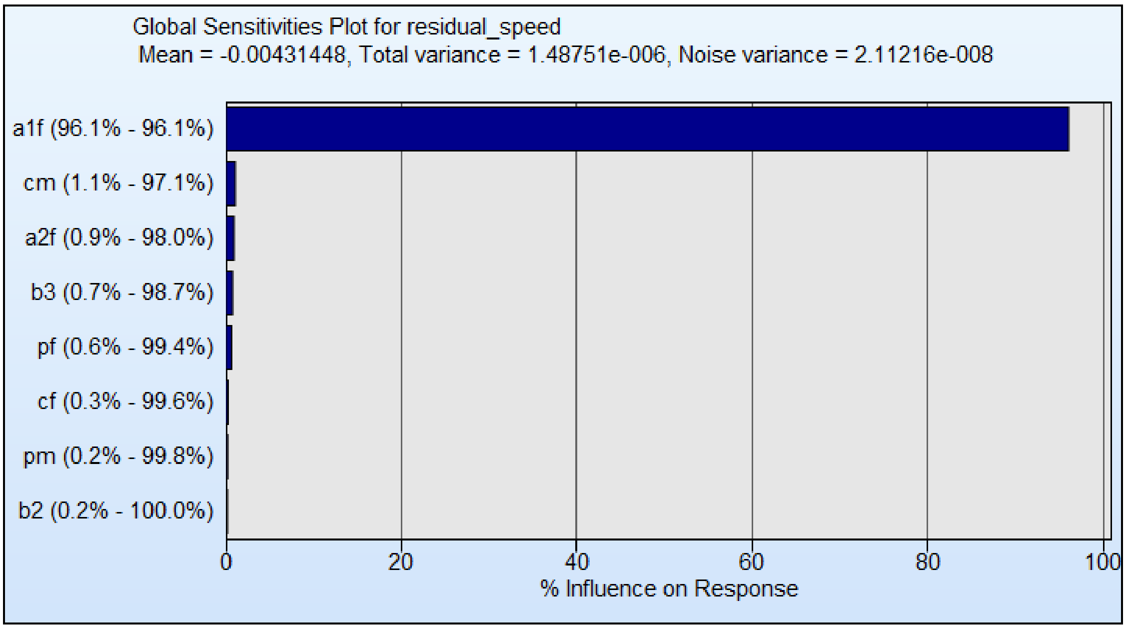

Figure 10 : *GSA/Sobol for residual_speed*

Results of this Monte Carlo analysis show that only concrete parameters managing with compression have an effect on residual speed. Tension parameters and strain rate effects in steel are less significant. This study allows us to reduce the variables of our future optimization to only one parameter: a_{1f}.

For the optimization stage, the aim is to fit the simulation value to an experimental result taken at 36 m/s. Metamodel and Sampling types are still chosen with Neural Network and Space Filling with 100 simulation points for 1 variable (a_{1f}). Single stage strategy was done for this Metamodel-based optimization.

Metamodel Accuracy results were similar to the previous study with good values for R^2, RMS and PRESS.

In the Metamodel Surface diagram of LS-OPT Viewer, we can display the error between simulation and experiment in relation to a_{1f} (see Figure 11). We notice a very accurate fit between simulation points and metamodel confirming good results found in Metamodel Accuracy diagram. However, this kind of results is normal because curve behavior is simple with only one global optimum and no local optimums. The optimized point given by LS-OPT for a1f gives a residual speed of 36.3 m/s, really closed to the experimental value (36 m/s).

This fitting approach is very interesting to calibrate tools or directly fit experiment in simulation. It brings the advantage to reach a good understanding of parameters influence on the response and then quickly optimize on a reduced set of parameters. However, even if this method is useful when we have only basic input material data, this will never replace the only rigorous method: a fit of experimental curves on small sample tests data characterizing concrete behavior.

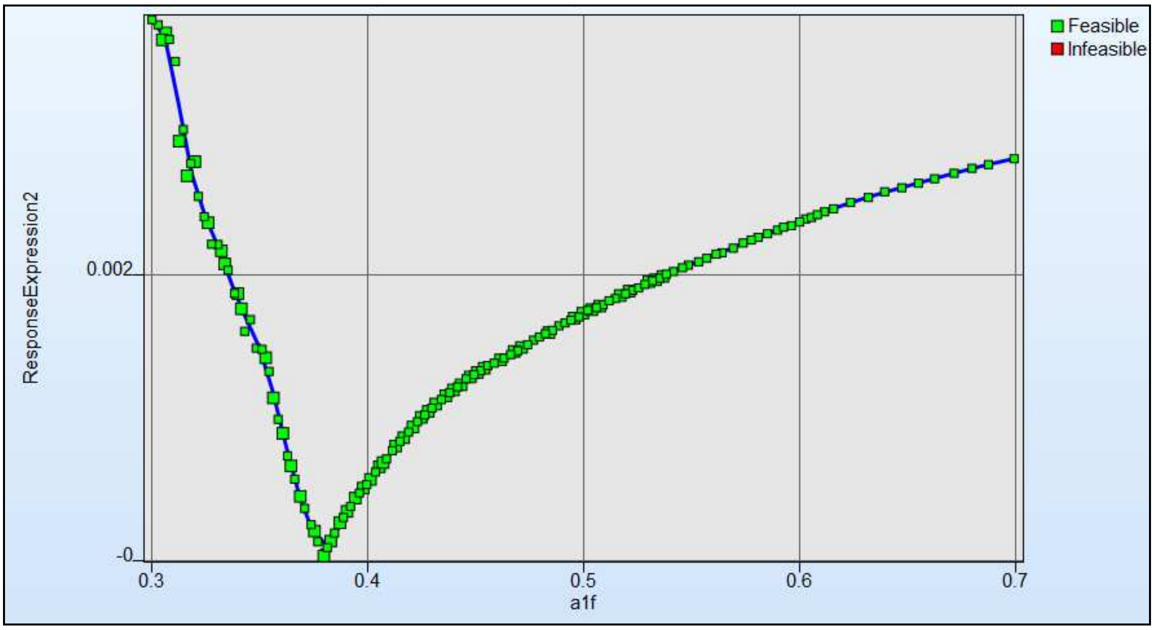

Figure 11 : *Simulation/Experiment Error VS a1f*

Finally, a complementary Monte Carlo analysis on physical parameters (Concrete resistances, Poisson's ratio…) was used to investigate process uncertainty and variations of material data.

Therefore, to assess the robustness of our optimal point, a sensitivity analysis on physical concrete parameters (ft, ρ and ν) was performed. Variable boundaries taken into account were extracted from testing materials provided for the Benchmark.

Variable	**Lower Bound**	**Upper Bound**
Ft (MPa)	3.9	4.3
ν	0.18	0.21
ρ (kg/cm^3)	2.3	2.37

Figure 12 : *Table of variables and bounds*

The Figure 13 shows the stochastic contribution diagram and presents the standard deviation of residual speed according to the different variables. We notice a huge response deviation due to these variables, for example the uncertainty on ft can change the velocity of about 6 m/s, which is 16% of the optimal response. Moreover, if we sum all deviations, we can see that the variation can reach 10 m/s.

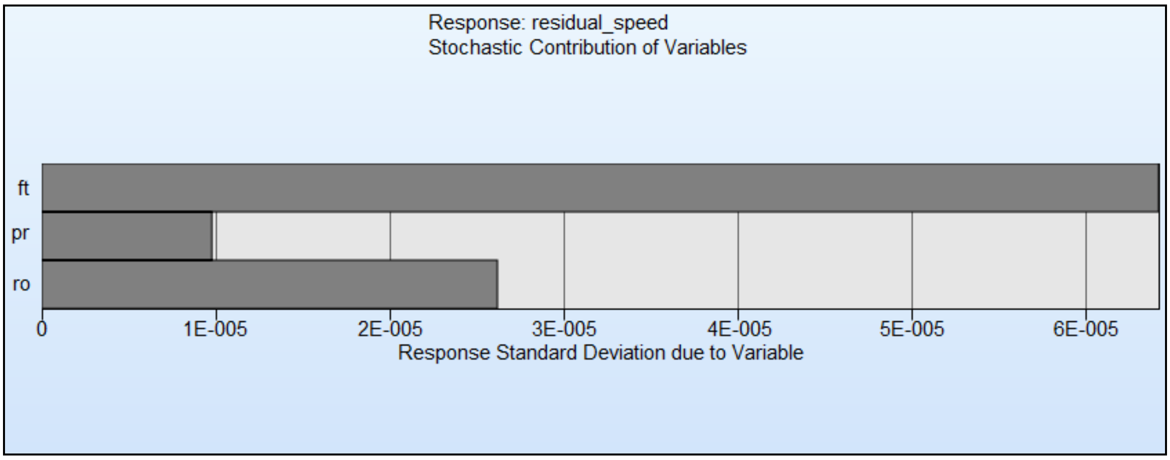

***Figure 13 :** Standard Deviation for residual_speed*

The optimal solution obtained after the optimization run has limited significance. Considering the natural variability of concrete parameters (two concretes are never identical and tools accuracy is sometimes doubtful) affects a change of 25 % on the response, the optimal solution found before is not robust; we cannot expect to get a result with high accuracy.

Conclusion

This paper, based on a work realized for an international OECD benchmark initiated by IRSN and CNSC, aimed to present a fitting approach using LS-OPT to simulate high velocity impacts on reinforced concrete slabs. Indeed, without sufficient test data (only basic material input) to fit constitutive model before the complete simulation, we developed an appropriated method using optimization and sensitivity studies:

- Automatic parameter generation capabilities can be used to create an acceptable set of parameters for concrete constitutive models starting from uniaxial compressive strength.
- Sensitivity analysis on this set of parameters leads to an identification of variables affecting the results (reduced set of parameters).
- Optimization of this reduced set to fit experimental results.
- Monte Carlo analysis on given material data to evaluate the robustness of optimal solution.

References

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