General Approach for Concrete Modeling: Impact on Reinforced Concrete

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Abstract

In the world of Numerical Simulation, concrete modeling is one of the most complicated aspect engineers have to carry out. In fact, damage and failure occurring during concrete deformation are very complex processes difficult to reproduce with material models. And to make matters worse, material information available for concrete is often much reduced, leaving engineers profess structure performance without sufficient data.

LS-DYNA® has several material laws to model concrete behavior, and other modeling choices like hourglass treatment and boundary conditions are crucial. All these possibilities lead to a problem of "engineering dependence" for simulation results. This paper offers a general modeling approach for concrete modeling, where the main goal is to try to understand the ins and outs of different modeling to be able to have an overall view of a problem.

This general modeling approach will be showed with the example of an impact on a reinforced concrete structure, setting up DoE study investigating material models, Boundary Conditions and Hourglass aspects, and using LS-OPT® to perform Sensitivity Analysis and Optimizations assessing concrete behavior.

Introduction

The dynamic behavior of Concrete is one of the most common and difficult problem of simulation in Nuclear, Defense and Civil fields. In most cases, the data available for modeling problems is much reduced; engineers are obliged to predict the behavior with non sufficient information. Due to this lack of experimental sample based input parameters, the result of simulation becomes "engineer dependent", leading to much different results than people doing the same modeling problem.

The main goal of this paper is to present a general modeling approach for concrete modeling to reduce these differences due to the modeling choices. The aim is to investigate all the modeling aspects using a modern method made possible by the more easily access to efficient computing resources: a probabilistic approach. In fact the use of DoE studies, Sensitivity and Monte-Carlo analysis makes possible to observe problems in a more general and complete point of view, leading to a good understanding of the ins and outs of the different modeling choices.

In the modeling process of concrete cases, the first things the user has to face are the mesh size and the boundary conditions. These choices have non negligible consequences in terms of behavior, hourglass phenomenon and results accuracy, that is why the user have to choose them with a special care.

LS-DYNA software has several advanced constitutive models developed to simulate concrete material; most of them have an automatic generation parameters capability to help user during input phase. However, these sets of parameters automatically generated are based on reference experimental data that could not match very precisely with concrete properties in some cases. Therefore, engineers have to be careful about this point and must investigate these models with sensitivity analysis and optimizations to be sure behavior is as closer as possible the real one.

In addition, for every experimental data, we are aware of uncertainties in properties arising from tools, human actions, concrete age or other factors. This may have a strong influence on results, that is why it is recommended to perform robustness studies to evaluate the results variability due to these uncertainties.

Here are the several steps of the proposed general approach for concrete modeling:

- First analysis and tests
    - Boundary conditions,
    - Hourglass treatment,
    - Mesh size.
- Results with automatic parameters generation for several material model
    - Behavior on unitary sample tests,
    - Results on the real case.
- Fitting approach
    - Sensitivity analysis on automatically generated parameters,
    - Optimization of material parameters (if experimental results available).
- Robustness analysis
- Final result

All the calculations presented here are performed with LS-DYNA solver, coupled with LS-OPT software for the probabilistic part of the studies (DoE studies, Monte Carlo Analysis, Robustness and Optimizations).

In this paper, an example of this general approach for concrete modeling will be explained. The main goal is to show several important aspects and results with the example of an impact on reinforced concrete.

First analysis and tests

VTT Punching General Presentation

The test case presented is the VTT Punching test case from the IRIS_2010 Benchmark (an international OECD benchmark initiated by IRSN and CNSC). VTT Punching test is composed on two parts:

- A missile with a steel dome and a concrete cylinder with a steel skin, with a total mass (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 symmetry plane to limit the number of elements without forcing a distortion mode.

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. This UPN is hold by rolls applying a pressure.

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.

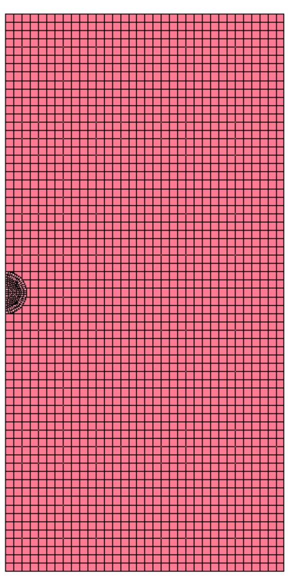

Figure 1 : *Top View*

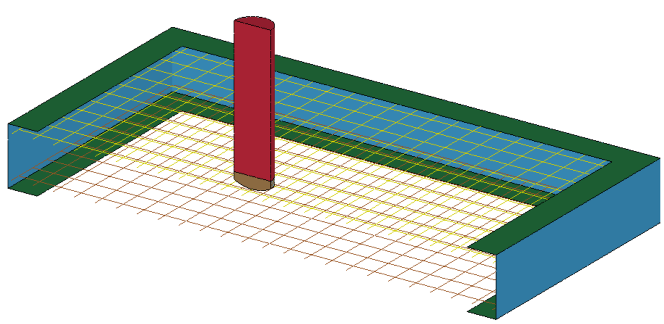

Figure 2 : *View of rebars, missile and UPN Steel part*

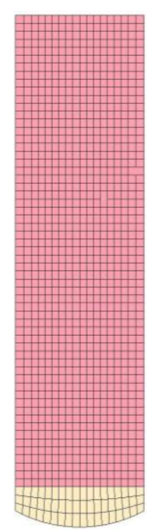

Figure 3 : *View of missile*

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).

Discuss and Tests about Boundary Conditions, Hourglass and Mesh Size

A DoE study performed in parallel on a simple impact on concrete beam test case (bending without perforation) has shown that the modeling of boundary conditions could have a significant impact on the Hourglass energy present in the model. In fact, the more boundary conditions are binding, the more Hourglass energy is important in the model, leading to possible non physical results. It seems advisable to model boundary conditions with a hypothesis the nearest possible to the reality: ideally, a BC are never “perfect”, so an applied pressure is often better than a big set of *BOUNDARY_SPC. However, sometimes, apply a pressure is not possible (because of complex geometry or a lack of information) and the best solution is to do some *BOUNDARY_SPC on a most possible reduced set of nodes to avoid Hourglass problems.

Regarding to this observation, we choose for the VTT Punching test case to model the supporting frame with some *BOUNDARY_SPC on only one line of nodes. 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.

Following the first tests about boundary conditions, some tests have been performed about the mesh and the Hourglass treatment. Several mesh sizes and several types of Hourglass methods were tested for the VTT Punching case and the simple impact on concrete beam test case. The results showed that, in the two cases, stiffness Hourglass methods are most efficient than the viscous one to reduce Hourglass energy. However, in the VTT punching case, we noticed stiffness method lead to the impossibility for concrete slab to reach the erosion criteria (see Figures below).

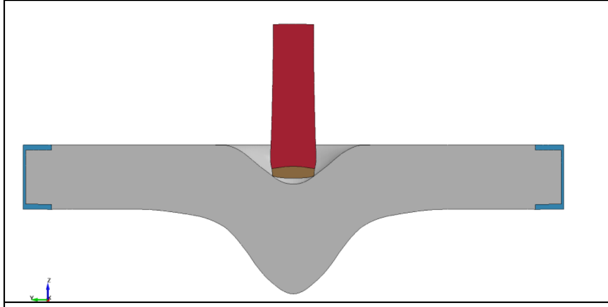

Figure 4 : *VTT Punching result with Stiffness Hourglass method*

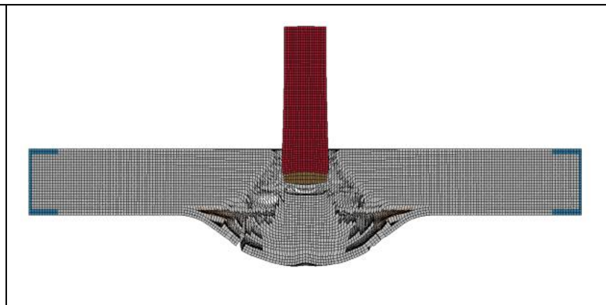

Figure 5 : *VTT Punching result with Viscous Hourglass method*

Concerning the mesh size, results are not very mesh-dependent for a non perforation test (models have regularization schemes) but for a perforation test like the VTT Punching case, a fine mesh is crucial to obtain a good erosion cone and spalling area.

Results with automatic parameters generation

LS-DYNA software has several advanced constitutive models developed to simulate concrete material behavior, the most usual ones are currently *MAT_PSEUDO_TENSOR (*MAT_16), *MAT_CONCRETE_DAMAGE_Release3 (*MAT_72r3), *MAT_WINFRITH_CONCRETE (*MAT_84) and *MAT_CSCM (*MAT_159). Most of them have automatic generation capability of concrete law parameters. Indeed, LS-DYNA is able to provide, starting from a first reduced set of physical parameters (unconfined compressive strength Fc, unconfined tension strength Ft…) a second larger set of parameters by internally fitting experimental reference results.

Starting from the Fc, a good thing to do is to reproduce by simulation the unitary tests (unconfined compression and tension tests, confined compression tests, tri-axial tests…) to better understand the behavior of each automatically generated law.

For example, the Figures below show the stress-strain curves for each law (16, 72r3, 84 and 159) corresponding to an uniaxial compressive sample test with a compressive strength Fc = 30 MPa. This type of comparison can point the exact behavior of each law with their strengths and weaknesses in order to be able to choose the best law for each type of application. For example, we can notice on these curves that the material model 84 has no softening in compression, this should be problematic in our case (punching mode with perforation).

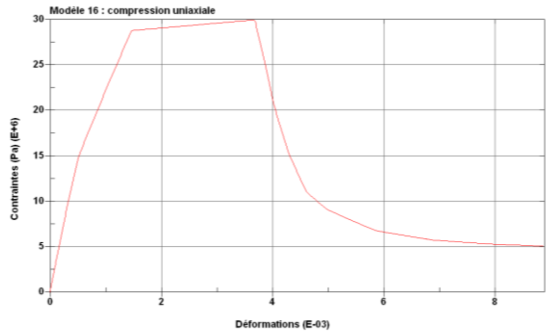

Figure 6 : *Uniaxial Compressive Sample Test for material model 16*

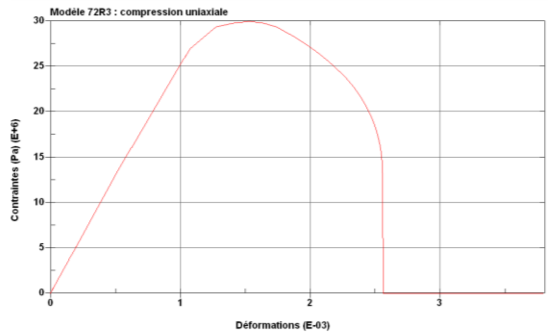

Figure 7 : *Uniaxial Compressive Sample Test for material model 72r3*

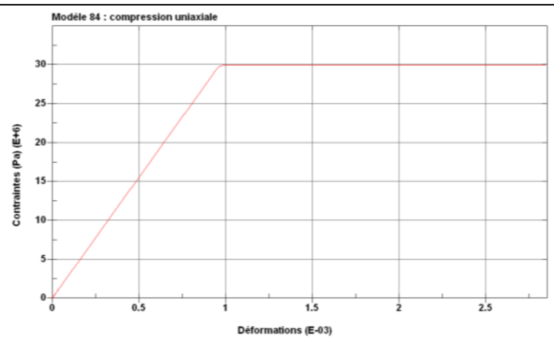

Figure 8 : *Uniaxial Compressive Sample Test for material model 84*

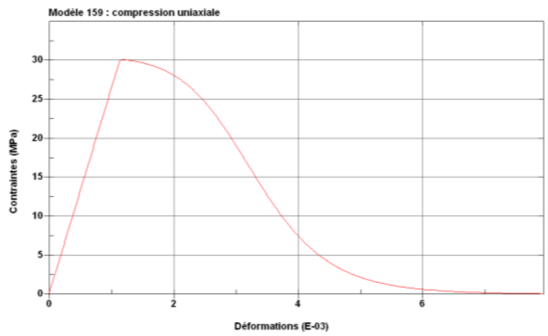

Figure 9 : *Uniaxial Compressive Sample Test for material model 159*

After ensuring each law is correctly generated and seems to have the expected behavior (Fc, Ft are the ones expected, etc…), we ran the real model of VTT Punching with the four constitutive model. The goal is to examine from a qualitative and quantitative point of view each result.

The following table shows final missile speed calculated with each model with automatically generated parameters in comparison to the experimental one. This table also compares the area from simulation with the experimental spalling area.

Model	Final missile speed (m/s)	Error VS Experiment	Spalling area (m^2)	Error VS Experiment
Experiment	33.8	-	1.055	-
16	74.1	**119 %**	0.124	**88 %**
72R3	32.4	**4 %**	0.960	**9 %**
84	No perforation	**-**	-	**-**
159	38.15	**13 %**	0.243	**76 %**

Figure 10 : *Comparison between simulation and experiment for final missile speed and spalling area*

As expected for this case, material models 16 and 84 gave non acceptable results. For this type of application, material models 72r3 and 159 gave more accurate results even if the spalling area for material 159 is quite far from the experimental one. Anyway, from a qualitative point of view, these two materials gave the good behavior (Figure below shows final damage of the slab).

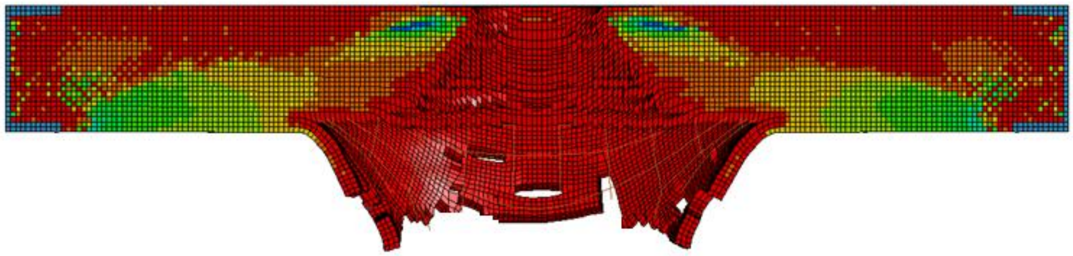

Figure 11 : *View of final damage of the slab (material 72r3)*

In this case, materials 72r3 and 159 are probably able to fit the experimental results if they are optimized.

Material model fitting approach

A good approach consists in doing a sensitivity analysis on several parameters previously automatically generated by LS-DYNA to see if they can be optimized. If some parameters are identified as significantly affecting the result, they are good candidates to be taken as variable for an optimization. If no experimental results are available, this sensitivity study can bring knowledge of the behavior and effects of a change in the input on the result (then we have a probabilistic result).

The example given here is a sensitivity analysis followed by an optimization of the final missile speed for the material model 159. This fitting approach is performed with the software LS-OPT version 4.2.

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 5 variables used in the 159 constitutive model for concrete:

- Management of fracture energy in compression, tension and shear: Gfc, Gft and Gfs.
- Management of brittle and ductile damage (softening): B and D.

Variable	Lower Bound	Upper Bound
B	50	150
Gfc	0.005	0.1
D	0.05	1
Gft	5.10^{-5}	1.10^{-4}
Gfs	5.10^{-5}	1.10^{-4}

Figure 12 : *Table of variables and bounds*

For this Metamodel-based Monte Carlo analysis, we choose 50 simulation points for 5 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).

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 R² 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.

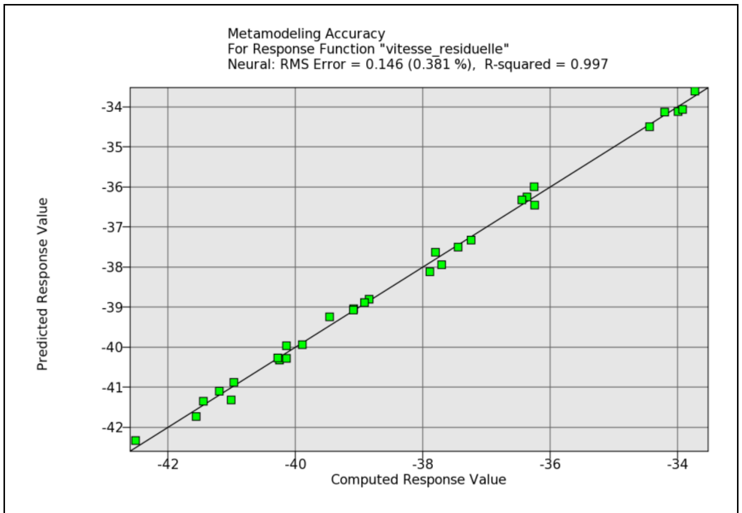

Figure 13 : *Metamodel Accuracy*

Secondly, analyzing the ANOVA diagram, we can see good 90% Confidence intervals which allows us some conclusions about sensitivity. We notice that the fracture energy have a significant effect on the residual speed of the missile. In fact, these parameters have a direct effect on the energy absorbed by the concrete slab, so on the final missile velocity.

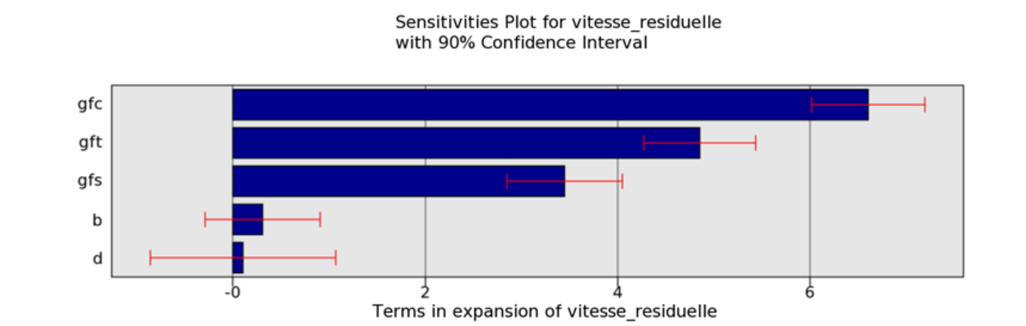

***Figure 14 :** ANOVA for final missile velocity*

Results of this Monte Carlo analysis show that each of the fracture energy parameters can probably be used for optimization. To have the best chance to fit the experimental value, we choose to take the Gfc parameter as variable for the optimization.

For the optimization stage, the aim is to fit the simulation value to an experimental result taken at 33.8 m/s. Metamodel and Sampling types are still chosen with Neural Network and Space Filling with 30 simulation points for 1 variable (Gfc). 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 Gfc (see Figure 14). We notice an accurate fit between simulation points and metamodel confirming good results found in Metamodel Accuracy diagram. The optimized point given by LS-OPT for Gfc gives a residual speed of 33.75 m/s, really closed to the experimental value (33.8 m/s).

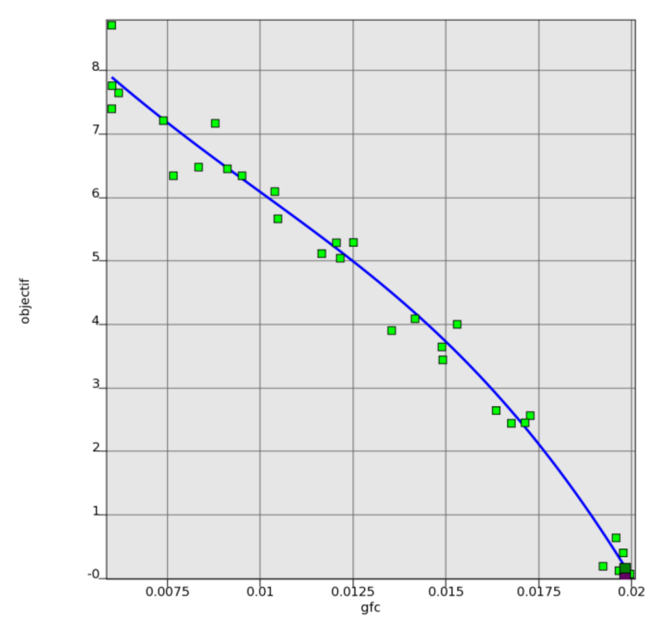

***Figure 15 :** Simulation/Experiment Error VS Gfc*

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.

Robustness Analysis

In a last step, a complementary Monte Carlo analysis on physical parameters can be used to investigate process uncertainty and variations of material data. In this paper, to vary a little bit the object of the LS-OPT studies, we present here the sensitivity analysis performed for the material model 72r3.

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 16 : *Table of variables and bounds*

The Figure 15 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 (25 %).

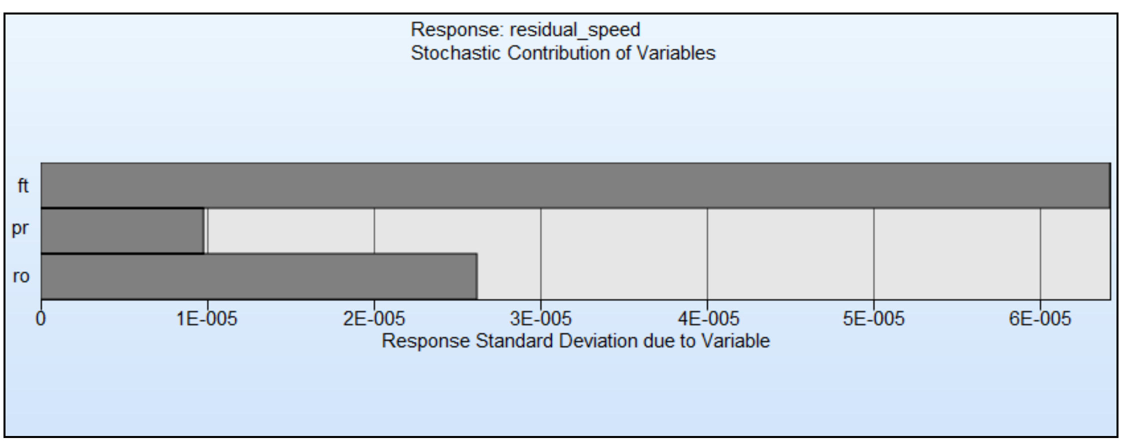

Figure 17 : *Standard Deviation for residual_speed*

The analysis of this last sensitivity about important physical parameters shows that the optimal solution obtained after the optimization run has limited significance. Considering the natural variability of concrete parameters (two concretes are never identical and testing facilities accuracy may be unknown) 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 general approach for concrete modeling with the example of an impact on a reinforced concrete slab.

LS-DYNA has several material laws to model concrete behavior (a set of parameters can be automatically created from basic input), and the choice of other modeling parameters like hourglass treatment and boundary conditions is crucial. All these possibilities lead to a problem of “engineering dependence” for simulation results that our approach tries to deal with. The main goal is to better understand the ins and outs of different modeling to be able to have an overall view of a problem from a more probabilistic point of view.

This general modeling approach was showed with the example of an impact on a reinforced concrete structure, setting up DoE study investigating material models, Boundary Conditions and Hourglass aspects, and using LS-OPT to perform Sensitivity Analysis and Optimizations assessing concrete behavior.

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