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Sensitivity analysis of a numerical welding simulation model

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Résumé :

La Simulation Numérique du Soudage (SNS) repose sur des calculs thermomécaniques par Eléments Finis, visant à déterminer l'état thermique et mécanique du matériau suite à une opération de soudage. En particulier, l'état de contraintes résiduelles est un résultat important pour l'estimation de la durée de vie des composants soudés. Les modèles utilisés dans cette approche nécessitent la caractérisation de nombreux paramètres d'entrée (propriétés thermiques et mécaniques du matériau, paramètres procédé, ...), à différentes températures. Ces paramètres, issus de la littérature ou d'essais expérimentaux, sont souvent mal connus. L'impact de ces incertitudes sur l'estimation des contraintes résiduelles est peu maîtrisé. L'article vise à présenter le travail réalisé à EDF autour de ce thème à travers un cas d'étude : le modèle numérique d'une maquette issue du réseau NeT. Une analyse de sensibilité est menée afin de quantifier l'impact de chaque entrée incertaine sur la variabilité du résultat estimé : plusieurs problèmes méthodologiques sont abordés, depuis la quantification de l'incertitude affectant les variables d'entrée jusque la visualisation de tels résultats.

Abstract:

Numerical welding simulation (NWS) is a finite element method based on the definition of a thermo-mechanical model. It aims to assess residual stresses from welding, which is a major issue in estimating life time of welded components. Modeling welding operation requires the characterization of material input data at different temperatures. Such data are very poorly known at high temperatures and contain uncertainties. Currently, their impact on the residual stresses left by a welding operation is difficult to assess. This paper aims at presenting the current research work at EDF in this framework, through an illustration on a numerical model of a welded specimen. A global sensitivity analysis is performed in order to rank the input variables according to their influence on the residual stresses: several methodological issues are mentioned, from the uncertainty quantification to the need of specific visualization tools.

Key words: numerical welding simulation, sensitivity analysis, thermo-mechanical model, visualization, uncertainties

1 Introduction

The formation of residual stresses is inevitable in any welding operation. Residual stresses introduced in the welded regions, due to the nonlinear thermal processes during welding, can have detrimental effects, such as stress corrosion cracking, hydrogen-induced cracking and reduced fatigue strength. A better knowledge of this phenomenon is crucial in estimating life time of welded components.

The recent development of strong computing power allows nowadays simulating a complex welding assembly by the finite element method (FEM). Numerical simulation becomes a particularly interesting tool to predict residual stresses and distortions resulting from a welding process. However, due to the scarcity of experimental data and the limitations of measurement technology, many of the material parameters involved in the kinetic laws cannot be estimated with sufficient accuracy, in particular at high temperatures.

Uncertainty analysis has therefore to be used in order to assess the effects of variability in material

parameters on the welding residual stresses. As an essential step, global sensitivity analysis aims at ranking the most influential inputs on the output variability [1]. Asserin et al. [2] have shown the efficiency and usefulness of such an approach on some welding thermomechanical models when the model output variable of interest is several scalar values (e.g. displacement at some specific points). Some recent works on other application domains have considered the full spatial map of model output variables in a global sensitivity analysis process [3]. The results particularly emphasized the relevance of the additional information (in addition to the expert and model knowledge) brought by the spatial maps of sensitivity indices. These sensitivity maps allow for spatially identifying the most influential inputs, for detecting zones with input interactions and for determining the zone of influence for each input.

A major issue to care about in this kind of analysis is the quantification of the input uncertainties, as the result realism strongly depends of the input modeling: for each variable, marginal probabilistic density have to be fitted to data or extracted from expertise knowledge, and potential dependence structure between variables have to be chosen, determining how important is the probability of joint events. In some particular case, as the material properties at different temperatures, probabilistic modeling must also respect some physical laws (as inequality constraints).

In this paper, we show a recent work of EDF on this subject. Section 2 describes the study case, based on an accurate thermal and mechanical numerical model, partially validated by experimental data. Section 3 summarizes methodological elements for uncertainties treatment: first it presents the main issues in the uncertainty quantification, then the principles of Global Sensitivity Analysis and finally the methods for information visualization in uncertainty and sensitivity analyses, which have been applied on a previous preliminary study. Results on the complete model will be detailed during the oral presentation.

2 Study case: numerical model of a welded 316L plate

The European Network on Neutron Techniques Standardization for Structural Integrity (NeT) is working on experimental and numerical techniques and standards in order to characterize residual stresses in structural welds [4]. NeT Task Group 4 (TG4) was formed in order to study the case of a chamfered plate in AISI 316LN austenitic stainless steel, whose slot is filled with three superimposed weld passes, made using the tungsten-inert-gas welding process.

The study conducted at EDF deals with the welding numerical simulation applied to the NeT TG4 specimen. It consists of carrying out thermal-mechanical calculations, implemented with *Code_Aster*, thanks to finite element methods in order to pin down the thermal and mechanical state of the material. For instance, with the aim of estimating the life expectancy of welded materials, residual stresses after the welding process are particularly important. Various parameters are needed to conduct the simulations (thermal and mechanical properties of the material, process parameters ...) and have to be given for different temperatures until the melting threshold. These parameters are afterward validated by comparing the simulation results to the deformation, residual stresses and temperature measurements obtained during experimental trials.

The welding process is simulated thanks to a volume heat flow of double ellipsoid type. A dozen thermocouples enabled the calibration of the different parameters of this flow. They are located near from the slot, where temperature gradients are high (about 100°C/mm). For the whole experimentation, several TG4 specimens were manufactured following the dimensions shown in FIG. 1. SALOME¹ software has been used to build the mesh and the geometry according to their general arrangement.

¹ Salome-Meca is a platform based on Salome, that includes Code_Aster, OpenURNS, pre- and post-treatment tools: <http://www.code-aster.org/V2/spip.php?article347>

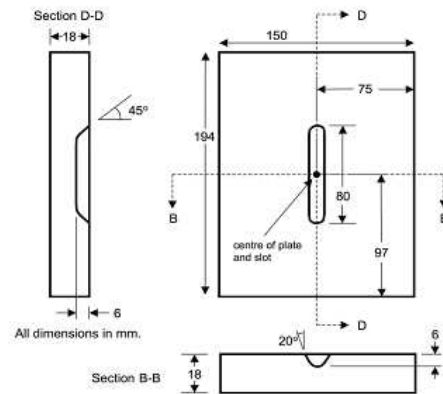


FIG. 1: General arrangement of NeT TG4 specimen

In an effort to keep the match between the specimens and the simulation models, the construction of the mesh has been parameterized thanks to a python script which could be loaded on SALOME. This allowed us to conduct thermal simulations on three different models with meshes and geometries fitting perfectly to the experiment specimens.

Moreover, given that the thermocouples are in zones with high temperature gradients, it was relevant to place points on the meshes on the exact thermocouple positions for each specimen.

Our study is divided in two parts: the thermal analysis, decoupled from the second part, the mechanical analysis. The first one is dedicated to the calculation of the temperature evolution during the welding simulation. The obtained temperature field is used during the mechanical analysis to evaluate the material stresses and deformations.

For symmetry reasons, meshing only half a plate is sufficient and permits a significant time saving. Both analyses are operated on the same mesh and an implicit formulation is used. The mesh is made of quadratic elements and counts about forty thousand nodes.

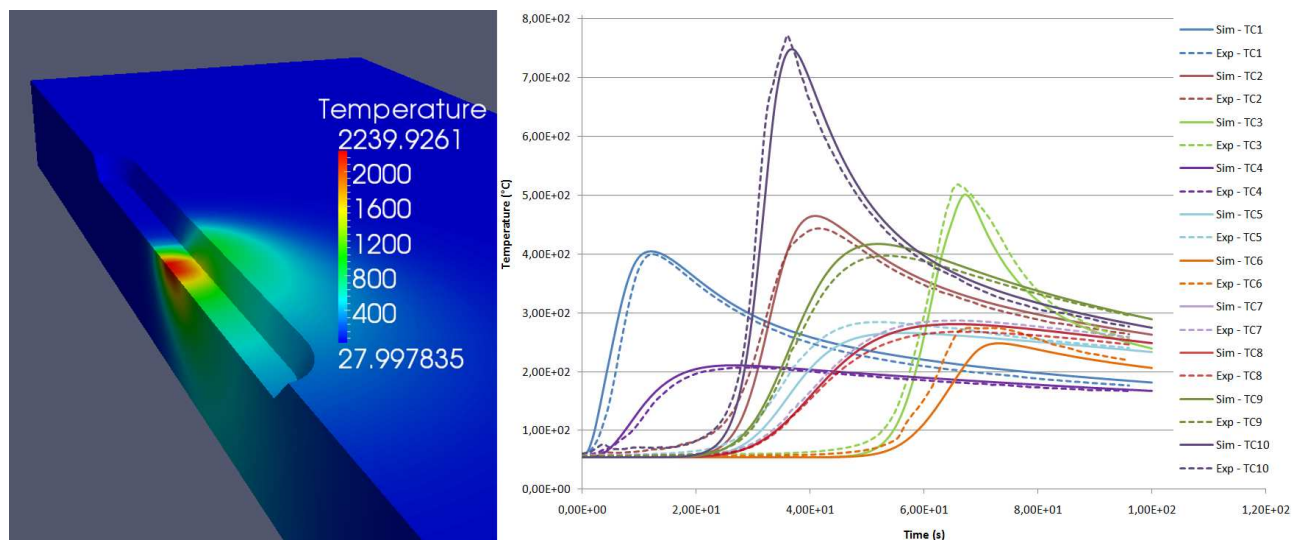


FIG. 2: Temperature field (°C) - Temperature evolution on different thermocouples: experimental and numerical results (continuous line for simulation, dotted line for experiment)

Once the heat input calibration is done, that is when the simulation results match the experimental temperature evolution on the different thermocouples as shown in FIG. 2, the objective becomes the calculation of residual stresses. During the mechanical analysis, an elastoplastic constitutive relation of Von Mises with isotropic non linear strain hardening is assigned to the plate. At the end of a simulation that last about thirty hours, residual stresses on specific lines of the plate are plotted. The FIG. 3 displays the stress measurement lines and a result of transverse stress (MPa) according to z position.

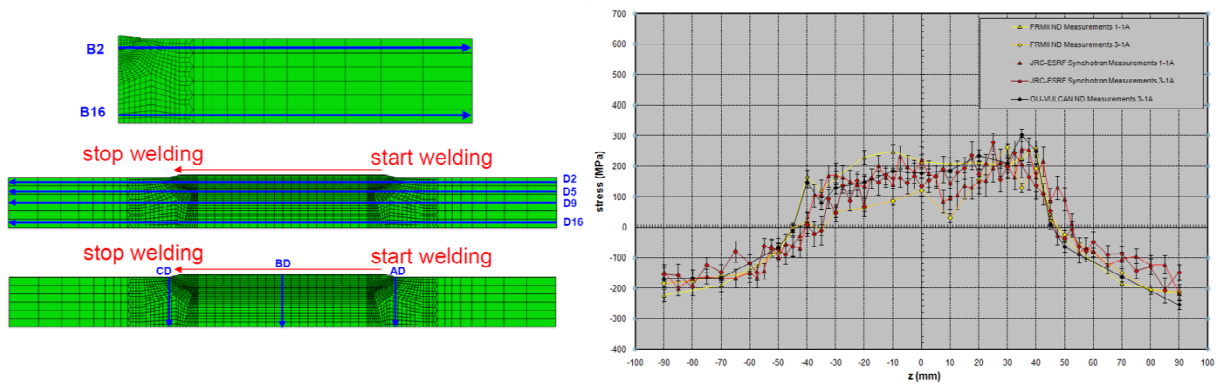


FIG 3 : Measurement lines - Transverse stress measurements on line D2

3 Uncertainty treatment and sensitivity analysis

The objective of this part of the work is to take into account uncertainties on the nominal values of some inputs of the model, to propagate them through the model and to assess the variability of the result according to the randomness of each variable. Uncertain inputs are modeled by random variables: marginal distributions and dependence structure have to be set. Usual and robust method of uncertainty propagation is Monte-Carlo sampling: depending on the quantity of interest (here, some sensitivity indices) and on the high calculation cost of the physical model (about 30 hours per run on a cluster), the Global Sensitivity Analysis method choice is impacted. Finally, special tools for visualization of such results for spatial output variables are used.

3.1 Uncertainty quantification

Main uncertain variables in welding simulation model are material properties. For instance, Young modulus is involved at each step of the simulation, at different temperatures. Classical tables in the literature give a quite good estimation of such material properties at ambient temperature, and the uncertainty quantification can be classically estimated. It remains more complicated at high temperatures, where the uncertainty becomes more important. Moreover, the main difficulty here is to correctly model the uncertainty at high temperature, respecting also the fact that Young's modulus evolution is monotonous with the temperature: sampled value at low temperature must be higher than the value at high temperature. A first solution is to set the relationship between Young's modulus and temperature: the value at ambient temperature is random and the curve is deduced for the other temperatures. It implies to introduce a strong hypothesis on the shape of the relationship between these two quantities. A second solution is to determine a statistical dependence that respects the inequality constraints between the two variables [6]: such method does not introduce a functional link between variables, and allows setting different uncertainty estimation for each temperature.

3.2 Global sensitivity analysis

Global Sensitivity Analysis (GSA) methods (Sobol, 1993 [5]; Saltelli et al., 2000[1]) aim to apportion model output variability into input variables and their interactions. Results of GSA are particularly relevant for model calibration, model validation, decision making process, i.e., any process where it is useful to know which variables mostly contribute to the output variability.

A first class of GSA methods is qualitative and is called the "screening", as it aims to deal with a large number of input variables (from tens to hundreds). An example of screening method is the Morris' method (Morris, 1991 [8]). With a few model evaluations, it allows a coarse estimation of the main effects but misses out interactions among input variables.

The second class of GSA methods are the popular quantitative methods, mainly based on the decomposition of the model output variance (which leads to the so-called variance-based methods and Sobol' sensitivity indices). It allows computing the main and total effects (called first order and total Sobol' indices) of each input variable, as interaction effects. However, the estimation procedures are more expensive in terms of number of required model evaluations. Then, variance-based methods can only be applied to model with a small number of input variables (no more than several tens). Depending on the model shape properties

(linearity, monotonicity, continuity...), several indices and related estimation techniques can be used to determine which inputs are the most influential on the output. The choice of the method will also strongly depend on the computational cost of the model.

3.3 Visualization tools

Regarding their capacity to summarize rich and complex information, visualization tools are very important in statistical studies. Several types of visualization exist, depending on the information that have to be emphasized and the dimension of the involved problems.

When the model output is a scalar variable, classical tools are used to represent its uncertainty: boxplot, histogram, kernel density, etc. These ingredients fulfill most of the needs and are implemented in almost every statistical softwares.

In sensitivity analysis studies, we may want to access to relationships between output and inputs, capturing potential interactions between inputs. For scalar variables, scatterplots (see FIG. 4) and cobweb plots (see FIG. 5) may be sufficient (Saltelli et al., 2000 [1]).

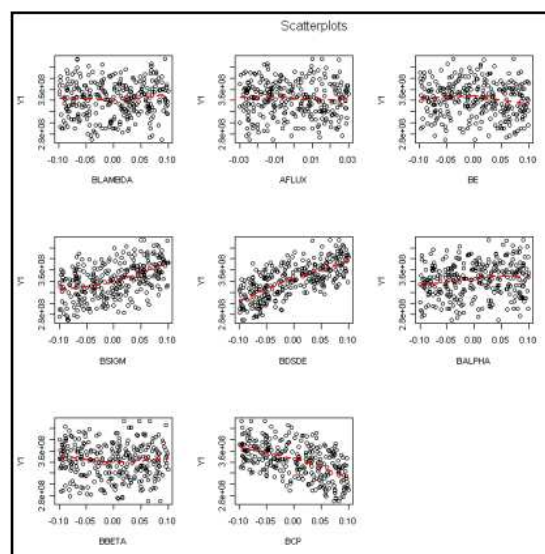


FIG. 4: Example of scatterplots between 5 variables – Each dot represents a sample: shape of the dots cloud indicates a first idea of the relationships between the two variables.

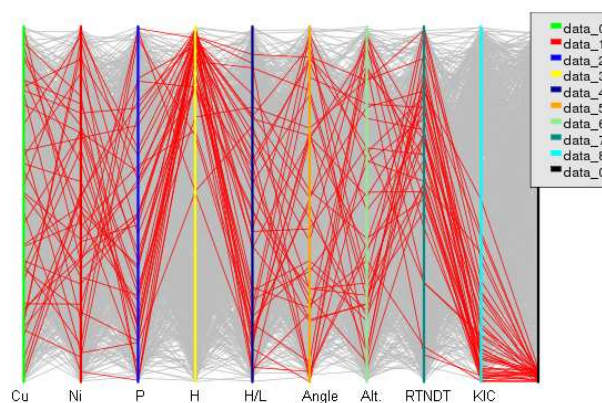


FIG. 5: Example of cobweb plot – Each vertical line represents an input variable, the right one is the output variable. Each sample is represented by a polygonal curve linking each sampled input and the result output. Interactions can be highlighted for some range of output values (red lines).

When the output variable is spatially distributed, as residual stresses on a mesh, such graphical tools cannot be computed and visualized for each point of the mesh. A previous preliminary study on a simplified welding model [7] allowed us to test specific tools to visualize sensitivity indices on a continuous colored

map based on the meshed structure (FIG. 6). Such maps show which are the main influential input variables : the variability of the thermal source Q has almost no impact on the estimated residual stresses (sensitivity index near to zero), whereas some other material properties as yield stress σ_Y have very important influence on the final stress state, in a positive or negative way, following traction and compression areas.

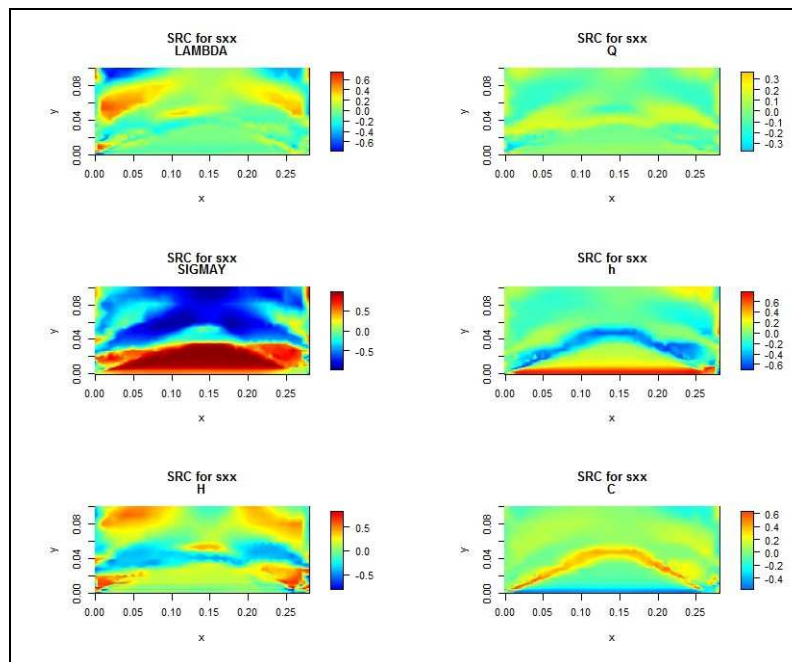


FIG. 6: Sensitivity indices maps for longitudinal residual stresses: each map gives the spatially distributed influence of one input variable.

4 Conclusion

Calibration and validation of a complex thermomechanical model remain a difficult and important issue in numerical welding simulation. Modeling uncertainty on input variables can help to better understand the model behavior, conditionally to a good probabilistic model. Global sensitivity analysis allows selecting most influential variables on the variability of the interest result: calibration efforts can afterwards be concentrated only on a fewer parameters. The use and the choice of these methodologies can require HPC tools and specific care for visualization of the results, which is a crucial point for an easier interpretation.

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