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Global sensitivity analysis in welding simulations—What are the material data you really need?

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ABSTRACT

In this paper, the sensitivity analysis methodology is applied to numerical welding simulation in order to rank the importance of input variables on the outputs of the code like distorsions or residual stresses. The numerical welding simulation uses the finite element method, with a thermal computation followed by a mechanical one. Classically, a local sensitivity analysis is performed, hence the validity of the results is limited to the neighbourhood of a nominal point, and cross effects cannot be detected.

This study implements a global sensitivity analysis which allows to screen the whole material space of the steel family mechanical properties. A set of inputs of the mechanical model—material properties that are temperature-dependent—is generated with the help of latin hypercube sampling. The same welding simulation is performed with each sampling element as input data. Then, output statistical processing allows us to classify the relative input influences by means of different sensitivity indices estimates.

Two different welding configurations are studied. Considering their major differences, they give a different ranking of inputs, but both of them show that only a few parameters are responsible for the variability of the outputs. To illustrate the pertinence of the overall process, for the first of the two configurations, two series of computations are performed: one for a complete sample and one for its reduced version—where all the secondary parameters are set to mean values. They match perfectly, showing a substantial economy can be done by giving mean values to the rest of the inputs.

Sensitivity analysis has then provided answers to what we consider one of the probable frequently asked questions regarding welding simulation: for a given welding configuration, which properties must be measured with a good accuracy and which ones can be simply extrapolated or taken from a similar material? That leads us to propose a comprehensive methodology for welding simulations including four sequential steps: a problem characterization, a sensitivity analysis, an experimental campaign, simulations.

1. Introduction

Control of mechanical effects of welding is a very difficult problem a lot of manufacturers have to solve, especially in the transport and the nuclear fields.

The finite element method has been proved to be an effective tool for the welding simulation. The high increase in computer power allows nowadays simulating a complex welded assembly with a personal computer, in order to predict, from the conception stage, if mechanical behaviour is acceptable.

On the other hand, increasing processes complexity demands more and more accurate adjusting. Numerical simulation, when sufficient precision can be reached, is expected to become an important tool because it can considerably reduce the cost of developments. For example, it allows optimizing parameters for special processes as for example in [1] and even allows virtually investigating new processes, without experimental work [2]. Now, it permits to predict mechanical welding effects like residual stresses and distortions. Hence, numerical simulation has to fulfil growing requirements.

However, running a welding simulation requires inputs like mesh geometry, boundary and initial conditions, material properties and process parameters. The simulation generates several outputs, including spatial distributions of displacements and

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residual stresses in the seam. Among the aforementioned inputs, material properties are numerous.

This leads to one of the key problems of welding simulation. During a welding process, as temperature varies over a wide range, material properties vary strongly. Hence, material properties need to be inputted as arrays of 5–10 values for various temperatures instead of a single value. The number of input material parameters can rapidly reach high values, typically 50–100.

It is quite difficult to use material data published in the technical literature: firstly, it is sometimes difficult to find data for a given material apart from a few which are the most used; secondly, they are rarely characterized over a sufficiently wide temperature range. At high temperature, near the solidus temperature, most of these parameters are impossible to measure. Furthermore, some mechanical models involve parameters which are not present in classical data banks. On the other hand, for one given material, the full characterization is very expensive, often difficult or even sometimes impossible. For instance, it can take years to characterize a specific material without anyway knowing if all these data are significant.

To avoid this problem, numerical simulations are commonly done using available material data complemented with extrapolated values at high temperature and/or data given for a supposed similar material. This is not necessarily a bad method, because—as shown in this paper—for a given problem family, some material properties are not very significant. The problem is to know what is permitted, i.e. what inaccuracy is induced by these practices.

Sensitivity analysis (SA) of these numerical models gives a rigorous answer to this question: it permits to notify what material properties need to be precisely determined and whether it is possible to use a "mean value" or a "probable value" for some other properties.

Several studies regarding the influence of material properties in welding simulation are available [3–10], but none of them can be considered as SA. Indeed, these parameter studies are only based on the comparison of results in terms of stresses and/or displacements of simulations considering different kinds of material property evolutions with temperature. These authors have studied the influence of the thermo-mechanical material properties for various welding cases, with different materials and models of material behaviour. Several papers seem to show that the distortions are mostly affected by thermal expansion and Young's modulus.

A study in which design variables are optimized to obtain minimum welding residual stresses can be found in [11]. Let us mention [12,13] whose results tend to show that for the studied cases the distortions are mostly affected by thermal expansion and, to a lesser extent, by Young's modulus and yield strength. Schwenk [13] adds that Poisson's ratio and the strain hardening have no noticeable influence on the calculated distortions and they can therefore be described by a master curve corresponding to the general alloy group. Moreover, this study shows that Young's modulus and the yield strength at high temperature do not have to be measured and can be taken from the literature.

Sensitivity analysis is also useful to solve inverse problem as in design optimization. A very detailed review of design sensitivity analysis methods can be found in [14] and a lot of later SA works covering various applications including welding can be found. The paper [15] reviews methods for optimization of computational welding mechanics (CWM) which is related to sensitivity analysis. Many of these approaches need to solve the adjoint problem, or involve partial derivatives which may be computed numerically by varying each input variable within a small interval around a nominal value and determining the corresponding effect on the output variable. However, few of these works deals with welding modelling and influence of material properties is not explicitly studied.

In welding simulations, the works cited above are based on local SA, which is of limited use for several reasons: (i) the validity of the results is limited to the neighbourhood of the studied material(s); (ii) in consequence the results of a local SA in welding simulation do not provide for an exploration of the rest of the material space of the input factors, i.e. it is improper, on the basis of a local SA, to make general recommendations on which material properties are necessary to know to perform an accurate simulation; (iii) local SA can be used to assess the relative importance of input factors only if the output behaviour is proved to be linear.

Global SA avoids these problems. In the two last decades, the work of searchers like Morris [16], Helton [17], Saltelli [18], Kleijnen [19], Iooss [20] helped to promote the use of global SA. Practical aspects of global SA and its applications can be found in the following books [21–24]. This methodology takes into account the entire variation range of all inputs, and tries to apportion the output variation between them. This technique has been successfully used in a large variety of domains. An application of global SA to general design that may be of interest is [25], this work being also related to the method of design of experiments (DOE) that is an approach that has been used to devise simplified formulas for input–output relations from finite element simulations.

In this work, complete methodology of the global SA is successfully applied to welding simulation. The input space concerns only the mechanical properties and is extended to all steel materials. This leads to a quantitative classification of the most important parameters. Due to simulation time constraints, in order to use this technique, it was necessary to develop specific sample techniques and choose a relatively light problem.

The present paper is organized as follows. In Section 2, the mathematical modelling of mechanical effects of welding is discussed, firstly with the thermal model and secondly with the elasto-viscoplastic mechanical model. In Section 3, we describe the global sensitivity analysis by computations of correlation coefficients between input and output variables and we propose a technique for generating latin hypercubes samples with a monotonic dependence. Samplings and statistical analysis were realized with the SSURFER toolbox [26] developed within the R Software [27]. In the last part of this work, the global SA is performed on two different welding studies.

2. Finite element model

The welding thermo-mechanical problem is solved by the finite element method. In welding problems, the thermal history has a notable influence on the mechanic behaviour because firstly, temperature is directly responsible to the thermal expansion which gives strains and then stresses, and secondly temperature affects mechanical properties like Young's modulus or the yield strength. On the other hand, the reverse effect is negligible: the heat produced by mechanical non-linearities like plasticity is very low compared to the one delivered by the welding source. Effect of deformation on the thermal boundary conditions is also neglected. This kind of problem is said to be weakly coupled.

According to this fact, practitioners generally simulate welding in two steps: first the thermal field time evolution is computed solving the time-dependent heat conduction equation; second, the mechanical equilibrium equations are solved for each time step, the thermal field, which had been previously computed for this time, token as a thermal load. For the mechanical problem,