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Partial safety factor calibration from stochastic finite element computation of welded joint with random geometries

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ABSTRACT

Welded joints are used in various structures and infrastructures like bridges, ships and offshore structures, and are submitted to cyclic stresses. Their fatigue behaviour is an industrial key issue to deal with and still offers original research subjects. One of the available methods relies on the computing of the stress concentration factor. Even if some studies were previously driven to evaluate this factor onto some cases of welded structures, the shape of the weld joint is generally idealized through a deterministic parametric geometry. Previous experimental works however have shown that this shape plays a key role in the lifetime assessment. We propose in this paper a methodology for computing the stress concentration factor in presence of random geometries of welded joints. In view to make the results available by engineers, this method merges stochastic computation and semi-probabilistic analysis by computing partial safety factors with a dedicated method.

1. Introduction

Welded joints are usually used in various structures such as bridges or marine and submarine structures and are regularly submitted to cyclic stresses. It is then necessary to assess their fatigue bahaviour. Fatigue analyses of welded structures are therefore one of the key issues addressed for steel structures (see the review in [1]). One of the key input parameters is the amplitude of the applied local stress. When considering the S–N approach, the knowledge of this stress allows computing the fatigue lifetime expressed with a number of cycles N thanks to the S–N or Wöhler curves. Nevertheless, the required local stress is generally unknown unlike the applied nominal stress on the structure. We therefore need methods to compute the local stress on the structure from the nominal stress. One way is to calculate the stress concentration factor; this factor has the advantage of simply linking the local stress with the nominal stress using a simple relationship.

It is also now well known that the geometry of the welded joints affects significantly the local stresses and therefore the service lifetime of welded joints. For T-joints, it is influenced by global imperfections such as misalignments of the two welded components [2,3], as well as by local parameters such as the radius in weld toe, the width, the height or the angle at weld toe [4–6]. In the present study only the latter local imperfections are considered. The welded process mainly generates the local geometry of the joint such as the technology used, the operator and the protocol (number of welding passes). The quality of the welding is generally controlled to verify that some geometrical parameters (angle, radius) stay between an upper and a lower bounds but the real value is generally not registered.

In view to analyze and quantify the role of the geometry, the first issue is to get real geometries of welded joints (here T-weld joints). The French company DCNS used a laser process measurement named WISC [7] shown in Fig. 1 in order to get real values of the geometrical parameters and their variations. The statistical analysis of these measures was done in [8] and provided probability distribution functions (PDF) for the main parameters which best describe the geometry and play a major role for stress computation.

The second issue is to develop a tractable numerical method that is able to deal with random geometries of the welded joint.

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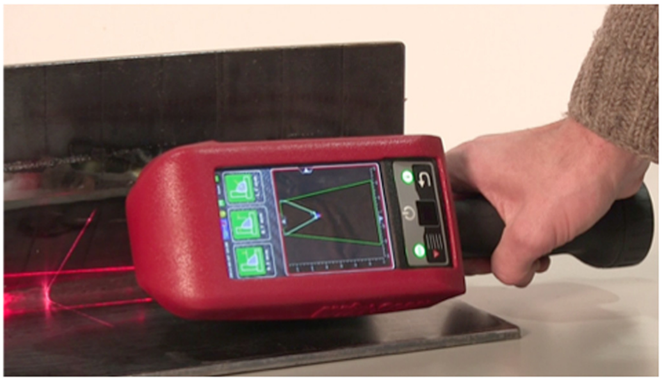

Fig. 1. Laser process measurement WISC used by DCNS.

The consideration of random geometries with classical Finite Element Model (FEM) implies a remeshing of the geometry for the different geometrical configurations that are to be accounted for in an uncertainty quantification purpose. This task may be intractable and the idea is to skirt the issue of remeshing. Several methods were developed to this aim: a first class of methods consists in using a stochastic transformation of a deterministic reference domain [9] and a second class of methods relies on the re-formulation of the problem on a fictitious domain that includes all realizations of the geometry [10–12]. These latter methods based on fictitious domain differ by the representation of the geometry and the associated discretized problem; in this paper we use the method named XSFEM (eXtended Stochastic Finite Element Method) presented in [11]. This method takes advantage of XFEM (eXtended Finite Element Method) by using level-sets theory to describe the boundaries and SFEM (Stochastic Finite Element Method) by introducing random variables on the Finite Element theory. This method allows developing an approximation of a variable of interest (e.g. displacement or stress) in a stochastic space. Nevertheless, this approximation may need for intrusive programming in the computation code which limits its use in structural engineering. The present paper suggests using a least-squares method for the stochastic approximation of the stress concentration factor. This method only requires samples of the factor which are obtained here from a post-processing of the XFEM approximation, the XFEM being preferred to the FEM for remeshing consideration as stated above. The overall method that combines XFEM and least-squares method is called RXFEM (for Regressive eXtended Finite Element Method) and the results are compared with analytical approximations available in the literature [5,13–15]. The final objective of this paper is to provide a deterministic analytical formulation of the stress concentration factor based on the reliability analysis from the approximation given by RXFEM: one of the most elegant ways is the partial safety factor format.

In the first part, the main computational principle of RXFEM is shown for the case of random geometries with a focus on the accurate computation of local stresses. In the second part, we recall the theoretical background of the calibration of partial safety factors and its extension in case of full probabilistic expression for a semi-probabilistic formulation. Its application to the stress concentration factor K_t is then presented. It is shown that the approximation gives close results to existing analytical formulations [5]. A sensitivity analysis, using the total Sobol indices, is also proposed that allows to highlight the most influential random variables on the reliability computation [16,17].

In the last part, we apply this methodology on two geometries of welded joints in view to illustrate the calibration of partial safety factors and show the potential extension to industrial cases.

2. Backgrounds of XFEM and SFEM methods for random geometries

The resolution of problems governed by random variables became more and more important during the last three decades [18]. To solve this family of problems, SFEM was developed in the early 1990s [19] and is still improved to deal with specific questions in solid and fluid mechanics. It is more and more considered even for industrial applications for non-linear transfer of random variables especially when quadratic response surfaces are not adapted [20,21]. In this paper we consider linear elastic problems with random geometry. In this part, we give some basic knowledge about the coupling of XFEM and SFEM methods for the resolution of this family of problems to simulate random geometries of a domain (see [22] for details).

2.1. Stochastic problem with random geometry

We consider the linear elastic problem defined on a random domain $\Omega(\xi)$ represented in Fig. 2 where ξ is a finite set of d random variables that constitutes a parameterization of the geometry of the random domain $\Omega(\xi)$. Let $(\Xi, \mathcal{B}, P_\xi)$ be the associated probability space where $\Xi \in \mathbb{R}^d$ and P_ξ is the probability measure of ξ.

The problem is governed by the following equations:

$$\begin{aligned} &\text{div } \bar{\bar{\sigma}} + \vec{f} = \vec{0} \quad \text{in } \Omega(\xi), \\ &\bar{\bar{\sigma}} = C : \bar{\bar{\varepsilon}} \quad \text{in } \Omega(\xi), \\ &\vec{u} = \vec{0} \quad \text{on } \Gamma_1, \\ &\bar{\bar{\sigma}}.\, \vec{n} = \vec{F} \quad \text{on } \Gamma_2(\xi). \end{aligned} \tag{1}$$

where $\vec{u}$ is the displacement, C is the Hooke tensor, $\bar{\bar{\sigma}}$ is the Cauchy stress tensor, $\bar{\bar{\varepsilon}} = \overline{\overline{\text{grad}}}_{sym}\vec{u}$ is the strain tensor, $\vec{n}$ the orthonormal external vector on the border of the domain $\partial\Omega(\xi)$ and $\partial\Omega(\xi) = \Gamma_1 \cup \Gamma_2(\xi)$ with $\Gamma_1 \cap \Gamma_2(\xi) = \varnothing$. The surface and volume load densities $\vec{F}$ and $\vec{f}$ are here considered deterministic for simplicity but the extension to stochastic loadings is straightforward.

In order to deal with a parametrized domain, we introduce the eXtended Finite Element (XFEM) method [23] that does not require the mesh to conform with the geometry and consequently avoids remeshing. XFEM is a method based on classical finite element method and was devoted to deal with crack propagation without any remeshing. This is achieved by using level-sets that implicitly define the crack both in terms of contour and discontinuity of stresses on the domain. For simulating geometries of welding joints, only the description of the contour is required.

We define a virtual deterministic domain B that includes all possible realizations of the domain $\Omega(\xi)$. The first step is the meshing of domain B. Using XFEM requires defining implicitly the border of the domain by level-set functions. To that aim we introduce a distance function $\phi: B \times \Xi \to \mathbb{R}$:

$$\phi(X, \xi) = \pm \text{dist}(X, \partial\Omega(\xi)). \tag{2}$$

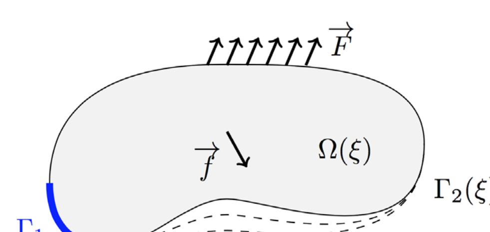

Fig. 2. Model finite element method problem.