Development of numerical tools for endurance based fatigue and fatigue crack propagation

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Motivation

Ageing infrastructure is driving the need for improved numerical models that accurately provide lifetime predictions of welded steel structures. Some of the structures managed by project partners, for example train bridges and craneway girders, date back to the 1960s. The need for adequate integrity assessment of the ageing infrastructure in Europe is high on the strategic research agenda for maintenance and asset management. More accurate lifetime assessment tools will help owners make more intelligent, informed decisions concerning operations, maintenance, and repair, as well as life time extension, with the ultimate goals of supporting safety and maximizing the value of industrial assets.

For welded steel structures, fatigue is the main mode of failure. Traditionally, steel structures are designed for fatigue based on the endurance approach, also known as S-N approach. Basic assumption is that the structure is in a pristine condition, i.e. no cracks are present. Design stresses are generally based on nominal stresses extracted from simplified models or analytical calculations. The quality of numerical predictions of fatigue life (in the high-cycle regime) depends on accurate knowledge of local stress ranges at critical locations. Such knowledge cannot be obtained from highly simplified models of a large scale welded structure.

Imperfections unavoidably arise during the manufacturing and construction stages. Some of these may further develop into a fatigue crack due to operational loads. Figure 1 gives illustrative examples of observed cracks in complex steel structures managed by industrial partners of the SafeLife project. Structures remain in operation until a critical crack length – most often empirically based – is reached. For accurate assessment of structures that contain fatigue cracks, fracture mechanics based analyses have to be performed. There is a need for numerical tools that allow simulation of multi-axial, non-planar fatigue crack growth in large-scale three-dimensional models.

Figure 1 Illustrations of crack formation in complex welded steel structures: crane-way girder at AM (left) and railway bridge at Infrabel (right)

Objectives

The general goal of this project is to develop new and robust numerical tools for endurance based fatigue design and simulation of fatigue crack propagation. These tools will be combined with load and condition monitoring data to enable the more accurate lifetime prediction of fleets of quasi identical welded steel structures, such as railway bridges, crane-way girders and jacket offshore platforms.

Three main objectives have been defined for this PhD project:

1. Development of coupled beam-shell based global finite element models for each of the selected industrial assets. Development of submodels of the most fatigue critical joints for determination of local stress ranges. Figure 2 shows an example of a finite element model of an overhead crane girder that has been developed in the project.

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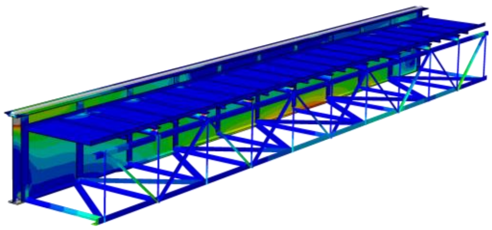

Figure 2: Finite element model of an overhead crane girder

2. The development of an endurance based numerical framework for fatigue assessment of welded joints. The framework needs to include non-linear damage accumulation models to allow better representation of the damage evolution under variable amplitude load spectra .
3. To evaluate damage evolution and assess lifetime of structural components that contain crack-like defects, a fracture mechanics based approach for three dimensional fatigue crack growth under multi-axial loading conditions needs to be developed.

Approach

Two Python based frameworks have been developed, one for endurance based fatigue and one for X-FEM based fatigue crack propagation to achieve objectives 2 and 3. Both the endurance framework and the fatigue crack propagation framework require a finite element (sub)model constructed with solid elements as input. The submodel is driven by a global model that is built using beam elements and/or shell elements. The purpose of the global finite element model is the simulation of the overall deformations of the structure and the corresponding nominal stresses for different load cases. This means that the structural details do not need to be modelled explicitly, decreasing the time spend on modelling. Based on the stresses resulting from the analysis of the global model, potential fatigue critical locations can be identified. The structural details that are identified as fatigue critical are then modelled in detail by means of a submodel to obtain an accurate stress solution near these critical locations.

The endurance based fatigue framework combines the results of the submodel with a fatigue spectrum and a relevant S-N curve to determine the fatigue life. For welded joints, an automated hot spot stress routine was developed and implemented in the framework. The hot spot stress approach was developed to deal with singularities that occur at geometric discontinuities such as welds in finite element models. It allows extraction of local stresses that can be used with designated S-N curves. The application of this methodology for a large number of welds is however time intensive, therefore an automated routine was developed. The framework also implements non-linear cumulative fatigue damage models to overcome the deficiencies exhibited by the conventional Miner linear damage accumulation rule.

When cracks are present in the structure, the fatigue crack propagation framework can be used. Simulating crack propagation using conventional FEM necessitates continuous re-meshing and leads to unrealistic needs for computer power and computing time when applied for large scale structures. Therefore the framework developed in the scope of this work is based on the extended finite element (X-FEM) approach. It allows simulation of a crack along an arbitrary path without remeshing. Figure 3 shows a comparison of experimental and numerical data for a CT specimen loaded with a constant amplitude.

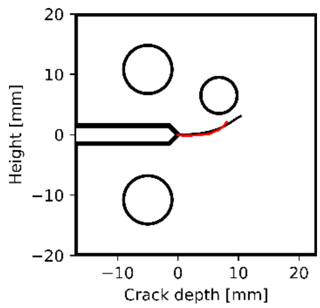

Figure 3: Fatigue crack propagation simulation (black) vs experimental data (red) for fatigue crack growth in a 3D CT specimen.

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