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Validation of the weakest link approach and the proposed Weibull based probability distribution of failure for fatigue design of steel welded joints

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ABSTRACT

The paper describes validation process of a proposed application of the weakest link concept to fatigue life evaluation of steel welded joints. The weakest link concept was used to evaluate failure probability and the resulting fatigue lives of typical welded joints under the constant amplitude uniaxial loading.

The validation of this approach involved comparison between the modeling results and experimental results. Investigation concerned butt- and double T-joints manufactured from three steel grades, the latter of which being of two thicknesses. Two assumptions for the approach have been tested: (i) applicability to joints of different geometry and (ii) ability to predict the effect of decreased fatigue life in joints with higher plate thickness. The results revealed appreciable effect of geometry on cumulative distribution function of failure, changing the kurtosis of failure distribution.

1. Introduction

Welded joints are extensively used in the construction of steel structures, pipelines and automotive parts. In many structures welded joints are used to join elements of a critical importance to safety [1–4]. Because of the microstructure and geometry of welds they are particularly prone to failure when exposed to variable loading. This effect has its origin in the joining process, specific due to the presence of steep temperature gradient over a very limited area, accompanied by the introduction of a filler material. The resulting welded joint produces stress concentration which eventually reduces the fatigue strength of the structural element.

These are the reasons why the welded joints require specific approach to fatigue analysis.

There are several groups of approaches to fatigue life determination of welded joints. Depending on the damage parameter used, they can be divided into the groups of the nominal stress approach, the structural stress approach, approaches based on the linear fracture mechanics and others. Each method has its inconvenience which comes mainly from two features: (i) the selected damage parameter is representative only in pre-defined conditions; (ii) ambiguity in selection of the fatigue curve appropriate for the joint and additional fatigue influencing factors.

The oldest and probably the most frequently used concept in case of noncomplex structures is the nominal stress approach. This approach has its place in several rules and recommendations, i.e. [5–7]. The idea behind it is to predict the lifetime on the basis of nominal normal stress in a sectional area in close vicinity to the joint, i.e. treating it as non-existent. This facilitation is accompanied by the inconvenience of selecting the S-N curve appropriate for lifetime predictions. Each (from the many S-N

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curves) is ascribed to a specific geometry which requires the designer to carefully review the welded element and its working conditions. Additional effects, e.g. misalignment and volume effect, are covered by conversion factors of a value that should be tailored to acting conditions.

Another group is the group of the structural stress approaches. The definition of structural stress includes only the geometry as stress raising effect and disregards the nonlinear stress peak at the notch root. Damage parameter used in the widely spread hot-spot approach [6,8] is a stress value extrapolated from reference points onto the weld toe (Fig. 1). Like in the nominal stress approach, lifetime prediction is based on references to several S-N curves, different between geometries. Additional effects are covered also by the conversion factors.

Approaches based on the linear fracture mechanics use stress intensity factor range tailored to individual notch type by a number of correction factors. Lifetime is determined on the basis of crack propagation law [9]. In case of these methods, most of the inconvenience comes from the complicated determination of stress intensity factor and the fact that widely available solutions are for the 45^o toe angle only. The presented approaches were analyzed in [10].

In paper [11] different approach was proposed. In the non-local theory it can be found that fatigue durability of elements with steep stress gradient (i.e. welded joints) is not directly related to the maximum notch stress only [12–16]. Here, lifetime is predicted on the basis of stresses in a specified material volume of the welded joint. In this way, conversion factors covering the weld geometry do not apply since the effect of misalignment or plate thickness (volume effect) is reflected in the analyzed volume. The needed stress tensor components are generated as standard output requests in the finite element codes. This application of the weakest link concept takes into account the effect of geometry and volume in the calculation of fatigue failure probability [17,18]. The welded joint is divided into a number of stressed ‘links’ having their contribution to the calculated fatigue life. Contribution of each ‘link’ is weighted by an introduced S-N curve, representative for common steel welded joints. The developed model allows to determine fatigue life at the desired level of failure probability P_f, on the basis of two-dimensional Weibull distribution.

The paper describes validation of the above approach across a range of cases; from different geometry to different steel grades.

2. Application of the proposed Weibull based probability distribution of failure to the weakest link concept

In the assumptions underlying the classical weakest link concept it can be found that each material contains defects, statistically distributed throughout the material volume. Thus, for larger volume the probability of finding a critical (bigger) defect is higher. Material behavior is modeled in the same way as a known from reliability theory serial system along with its main features: (i) increasing the number of sub-areas (i.e. links) results in higher probability that the entire system will fail; (ii) damage of one sub-area/link causes damage of the entire system.

In the proposed approach fatigue life is determined at the chosen level of failure probability P_f which cumulative distribution function is:

$$P_f(N) = 1 - P_s = 1 - \exp\left(-\frac{1}{V_0}\int_V \left(\frac{\log N}{H}\right)^p dV\right), \tag{1}$$

where:

P_s – survival probability, –,
V – volume, mm^3,
V_0 – referential volume, mm^3,
N – number of cycles, –,
H – scale parameter, –,

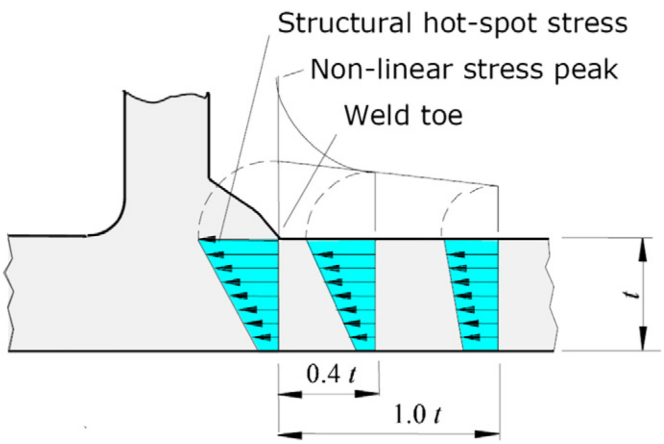

Fig. 1. Definition of structural hot-spot stress [8].