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A Review of Fundamental Approaches for Fatigue Analysis of Welded Steel Joints

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ABSTRACT

Fatigue damage occurs in welded steel joints under cyclic loads. These joints are particularly vulnerable to fatigue due to high stress concentrations. Today, with the developing numerical analysis software, fatigue life calculations are carried out with different methods based on the fatigue life and the stresses that will occur in the elements. These methods, which may differ from each other, examine the stress distributions occurring under different loading conditions and the initiation, development and collapse of the damage occurring in the element. Fatigue analysis methods are divided into two groups as local and global approaches. In global methods, the critical stress that will occur on the entire structure is considered, while local geometry and local parameters are examined in local methods. This study presents fatigue analysis methods of welded steel joints.

Kaynaklı Çelik Birleşimlerin Yorulma Analizinde Kullanılan Temel Yaklaşımların Gözden Geçirilmesi

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ÖZ

Çevrimsel yükler altında kaynaklı çelik birleşimlerde yorulma hasarı meydana gelmektedir. Bu birleşimler, yüksek stres konsantrasyonları nedeniyle özellikle yorulmaya karşı hassastır. Günümüzde gelişen sayısal analiz yazılımları ile yorulma ömrü hesapları, yorulma ömrü ve elemanlarda oluşacak gerilmelere bağlı olarak farklı yöntemlerle gerçekleştirilmektedir. Birbirinden farklılık gösterebilen bu yöntemler, farklı yükleme koşulları altında meydana gelen gerilme dağılımlarını ve elemanda meydana gelen hasarın başlamasını, gelişmesini ve göçmesini inceler. Yorulma analizi yöntemleri lokal ve global yaklaşımlar olarak iki gruba ayrılır. Global yöntemlerde tüm yapı üzerinde oluşacak kritik gerilmeler dikkate alınırken, yerel yöntemlerde yerel geometri ve yerel parametreler incelenmektedir. Bu çalışma kaynaklı çelik birleşimlerin yorulma analizi yöntemlerini sunmaktadır.

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1. Introduction

The fatigue phenomenon was firstly concerned by a German Engineer August Wöhler in the 18th century in a way of examining the failure reasons of steel profiles utilized in the railroad network (Schijve, 2009). Although there does not exist a certain study to lay down the theoretical basis of fatigue damage in the 19th century, the first attempt in associating fatigue formation with the crack issue became in the 20th century (Mann, 1970). The steel structures such as railroads, crane bridges, offshore tribunes, and steel frame structures are subjected to cyclic stresses during their service lifetime (Fricke, 2003). Cracks and damages caused by these stresses over time are called “fatigue”. The fatigue problem plays an important role in the design as it usually causes sudden damage and collapses without warning (Macdonald, 2011). Thus, the fatigue phenomenon is considered dependent on two fundamental concepts “stress” and “fracture” (Caputo and Fabrizio, 2015). In the fatigue analysis of steel structures, the fatigue life of each structural element constituting the structure should be determined. In this regard, the welding issue, which is utilized widely in the connection of separate structural and/or mechanical components, has a big importance in the evaluation of fatigue-related damage (Radaj et al., 2006; Yucel and Talaslioglu, 2022). In fact, the main reason behind its importance arises from the higher stress concentrations in the welding regions (Mashiri et al., 2004). Particularly, the seam-welded joints, which are obtained in a way of melting any external material throughout a continuous weld line, are mostly utilized in the welded structures rather than the spot-welded joints. Thus, there are two commonly used approaches namely the stress and stress changes number (S-N)-based approach and fracture mechanics-based approach (Doshi and Vhanmane, 2013). The first approach calculates the fatigue strength of steel structural elements over S-N curves obtained experimentally. The second approach considers the crack propagation in the element that is subjected to fatigue loadings by fracture mechanics.

Yıldırım (2015) proposed design curves in the fatigue analysis of welds improved with tungsten inert gas dressing. Fischer et al. (2016) published a review article on the fatigue analysis of welded joints based on two different approaches. The first approach is notch stress intensity factor and the second approach is the strain energy density approach. In the study, the verifications performed with these analysis methods are presented. Pedersen (2016) carried out the fatigue analyzes using the notch stress approach. It was determined that the reference S-N curves were in good agreement with the experimental results. Wei et al. (2018) conducted a review of the fatigue calculations of tubular steel elements. The finite element model applications are also included in the study in which different fatigue analyzes are explained. A review on the fatigue life prediction models of welded joints was given in the study of Kang and Luo (2020). Meneghetti and Campagnolo (2020) reviewed fatigue assessment of welded joints by using the peak stress method. With this method, which requires analysis with finite element models, 2 and 3 dimensional linear elastic models can be solved, and the crack initiation point can be determined. Braun and Wang (2021) reviewed the effects of weld toe grinding and weld profiling on the fatigue life of welded steel elements. As a result of the study, a new S-N curve was proposed. Skriko et al. (2021) in a way of being experimentally investigated the fatigue behavior of welded joints. In the study, the ultra-high-strength steel beam structures loaded longitudinally were discussed. The fatigue analyzes of these elements were carried out with stress-based methods given in various design codes and guidelines.

This paper presents a review of the fatigue assessment methods for the welded steel joints, which are utilized in the connection of steel structural components, due to the limited work in the welding-related fatigue analysis for the steel structural systems. While S-N-based analyzes were examined in the first four sub-titles, the fracture mechanics approach was examined in the last sub-title.

2. Nominal Stress Approach

The most widely used approach among fatigue analyzes is the nominal stress approach. In this approach, the stress is calculated on the considered section by ignoring the local stress concentrations in the weld area. However, macro-geometric effects are considered, and elastic behavior is assumed. In many codes, the analysis is completed using the detailed classification of basic joints along with S-N curves. Since this detail classification depends on the element geometry, loading conditions and crack location, the element to be analyzed must be compatible with the detail given in the relevant code. In the analysis with the finite element method, the stresses measured at 1-1.5 plate thickness from the stress concentration region (e.g., weld toe) are considered as nominal stress.

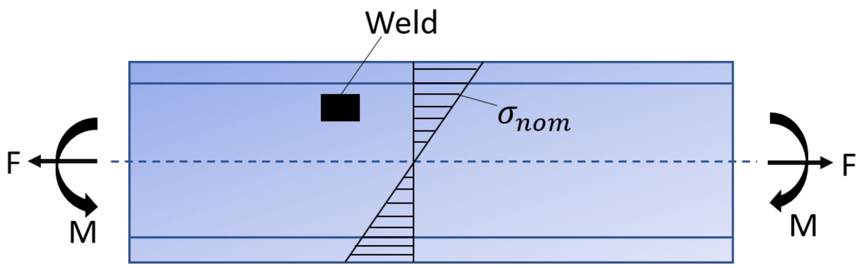


Figure 1. Nominal stress in a beam.

The nominal stress that will occur in a beam element is exemplified in Figure 1. The nominal stress is calculated with the elementary structural mechanics' theories on the numerical model with linear elastic behavior defined. Nowadays, these numerical models are usually constructed with finite element software (Bashiri and Alshoaibi, 2020). Each stress variation scenario is determined by the defined loadings, and the stress distribution on the model is obtained by static analysis. The fatigue life of the structure is determined by evaluating these obtained stress values in the S-N curves given before. As mentioned in the introduction, the method of S-N based analyzes is based on fatigue life evaluation with these curves.

3. Hot Spot Stress Approach

In the hot-spot stress approach, stress concentration effects in a particular hot spot are considered. However, non-linear stresses occurring in the weld itself are ignored. This stress calculation is performed on the surface of the element and using designated reference points (Figure 2). Therefore, in this method, the thickness of the base plate element affects the results of the stress analysis. In this method, which is generally used when the geometry is not suitable for the nominal stress calculation, stress calculations are done with finite element models. There are several codes regarding loading assumptions, stress calculation and extrapolation, and hot-spot stress concentration factor formulations (Van Wingerde et al., 1995). Uncertainties in extrapolation and limitation of damage to surface crack are the main weaknesses of this method. In addition, the designer must accept that fatigue damage will not occur at the root of the weld element or at defects within it (Hobbacher, 2016)

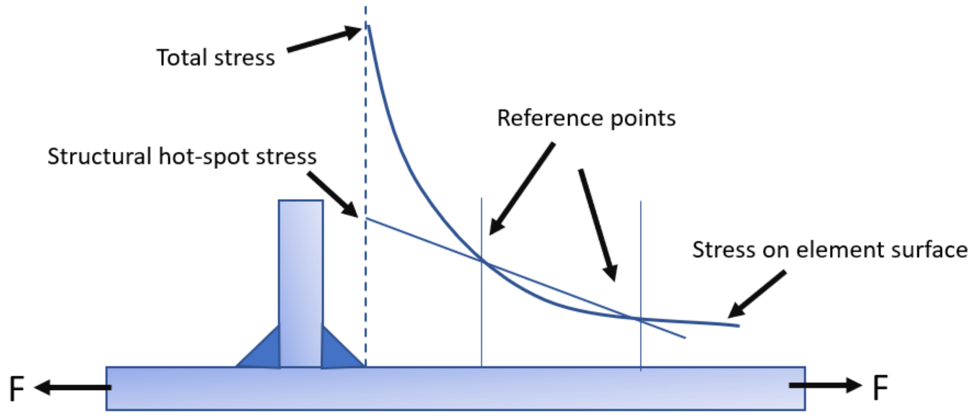
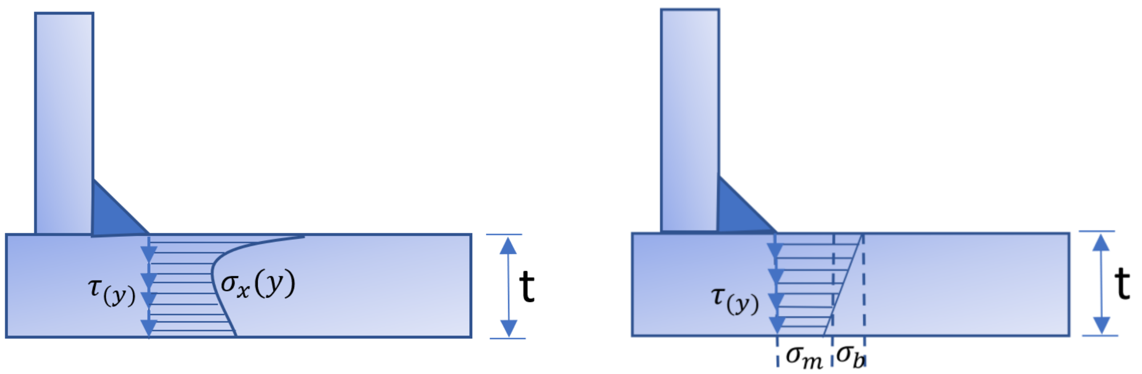


Figure 2. Definition of structural hot-spot stress (Hobbacher, 2016).

4. Equivalent Structural Stress Method

The irregularities in the geometry along the weld line and the variation in the thickness of parent plates cause to be concentrated on the stresses in the certain location of the welded structural system. The use of the finite element method for the simulation of welded structural systems, unfortunately, fails to obtain a consistent stress distribution due to being completely dependent on the meshing attribution. Nevertheless, in order to predict more accurately the fatigue lifetime for the welded structural system, the best reasonable approach is to be regularize accordingly the stresses of finite element considering the notch and thickness effects. In this regard, the equivalent structural stress analysis approach which is based on summing the membrane and bending stresses taking into account parent plate thickness has been widely used for the evaluation of multi-principal axial stresses (Dong, 2001; Dong and Hong, 2003). In this method which is mesh-insensitive, stresses are calculated at the weld toe, not at a distance from the weld, and a single S-N curve is sufficient without the need to classify the weld joint.



(a) (b)

Figure 3. (a) Local stress distribution and (b) corresponding structural stress distribution (Dong, 2001).

In this study, the structural stress calculation is illustrated by the model given in Figure 3. Figure 3a shows a stress distribution at which the stress peak occurs. Figure 3b shows the corresponding structural stress distribution. Total stress consists of membrane (σ_m) and bending stress (σ_b). In Figure 4, for the model with plate thickness t, an example of calculating the structural stresses in the A-A section is done. Structural stress components σ_m and σ_b should meet the equations (1) and (2) by applying the equations of equilibrium between section A-A and section B-B where the stresses are calculated by the finite element models (Dong, 2001).

$$\sigma_m = \frac{1}{t}\int_0^t \sigma_x(y)dy \tag{1}$$

$$\sigma_m \frac{t^2}{2} + \sigma_b \frac{t^2}{6} = \frac{1}{t}\int_0^t \sigma_x(y)y dy + \delta \int_0^t \tau(y)dy \tag{2}$$

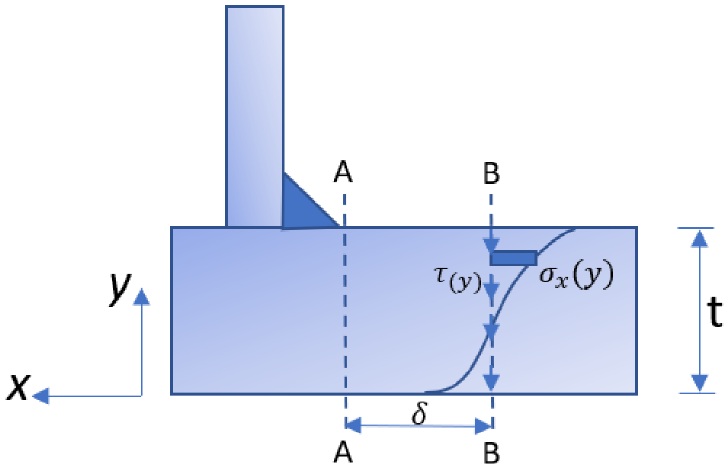


Figure 4. Structural stress calculation example (Dong, 2001).

5. Effective Notch Stress Approach

In this approach, which assumes linear elastic behavior, the notch stress is equal to the total stress at one notch root. The repetitive local yielding approach is used to represent crack initiation (Radaj et al., 2006). The true weld root is replaced with an effective version to consider the variations due to the shape of the weld and the nonlinear material behavior at the notch root. For structural steel, the effective notch radius is assumed to be 1 mm. Effective notch stresses can be determined by the finite element method and evaluated by using a single S-N curve. Weld toe angle, leg length and undercut effects can be evaluated in this method (Hobbacher, 2016). Rounding of weld toe and root and recommended rounding of a butt weld are given in the Figure 5.

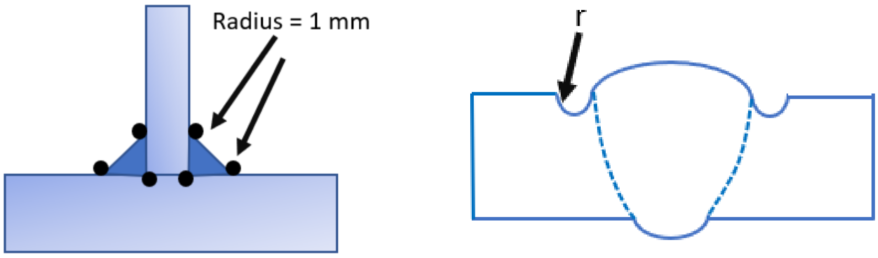


Figure 5. (a) Rounding of weld toe and root and (b) Rounding of a butt weld (Hobbacher, 2016).

6. Fracture Mechanics Approach

The fracture mechanics approach is the method used to monitor crack development due to fatigue loads. This crack development cannot be defined in approaches using S-N curves. Stress field is considered, not stress concentrations and stress inside the crack is described by stress intensity factor:

$$K = Y.\sigma_0.\sqrt{\pi.a} \quad (3)$$

where Y is the correction factor, σ_0 is the stress, and a is the crack size.

The crack initiation and the progression of this crack to the fracture are examined. Crack development follows the rule known as the Paris-Erdogan law (Paris and Erdogan, 1963):

$$\frac{da}{dN} = D.\Delta K^n \quad (4)$$

where D is the crack growth constant, n is the material factor, N is the number of stress cycles and ΔK is the difference of stress intensity factor. The crack growh curve is given in the Figure 6 (Fuštar et al., 2018).

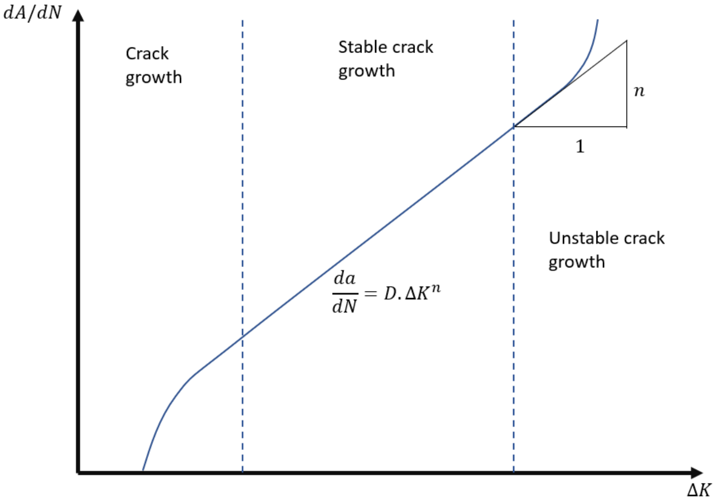


Figure 6. Crack growth curve (Fuštar et al., 2018).

7. Conclusion

In this study, the different fatigue analysis methods are summarized. One can examine these methods, each of which has different features, under two main headings as S-N curve and Fracture mechanics methods. The analysis methods in which fatigue behavior caused by cyclic loading are examined with S-N curves require evaluation with the existence of an experimental S-N curve. The most commonly used of these methods is the nominal stress approach, which accepts macro-geometric effects and elastic behavior and neglects local stresses. In the hot spot stress approach, where local stress concentrations are taken into account, the stress calculation is completed by using reference points on the element surface. In the equivalent structural stress approach, where stresses are calculated independently of the finite element mesh size, the stresses are separated as membrane and bending stresses. In the effective notch stress approach, stresses are calculated on the notch with a radius of 1 mm at the root and toe of the weld. The fracture mechanics approach is used to examine crack development as a result of fatigue damage.

Statement of Conflict of Interest

The authors have no conflicts of interest to declare.

Author's Contributions

The authors declare that they have contributed equally to the article.

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