Computers and Structures 191 (2017) 51–61

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Numerical effects on notch fatigue strength assessment of non-welded and welded components

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ARTICLE INFO

Article history:
Received 25 May 2016
Accepted 13 June 2017

Keywords:
Finite element analysis
Notch stress approach
Linear-elastic computation
Element type
Shape function
Mesh refinement

ABSTRACT

Local fatigue strength assessment based on threshold values obtained by linear-elastic notch stress calculation is commonly utilized due to its applicability to complex geometries with an acceptable effort. As the result of a finite element computation is affected by the element type and mesh refinement, this paper investigates the numerical influence on the notch stress based fatigue strength assessment of non-welded and welded components. Based on extensive finite element studies employing the software package Abaqus it is concluded that quadratic shape functions with a number of sixteen for non-welded parts and twelve elements over a semicircle for welded joints should be at least applied to minimize the numerical impact.

1. Introduction

Nowadays, the finite element method has become one of the most common techniques for numerical analysis due to a feasible practicability in a wide range of engineering applications, such as static, dynamic or coupled non-linear analysis. Lightweight structures involving high-strength materials and recent manufacturing processes are today's challenges in the design process in order to reduce consumption of non-renewable resources and noxious emissions. To fulfil these needs, numerical analysis significantly supports the understanding of local characteristics, such as complex stress states or effects of manufacturing processes on material properties, leading to an improved dimensioning compared to common procedures based on analytical approaches. The significance of the finite element method as well as an overview for macro- and microscale applications and their basic principles are presented in [1]. Thereby, the fatigue assessment of cyclically loaded components is major task in mechanical engineering applications. A review of local fatigue approaches for non-welded and welded structures is provided in [2]. Among these, one frequently used method is the notch stress approach, taking the linear-elastic computed stress at the notch area as fatigue-related parameter. In [3], an overview of classical and recently unified formulations to assess the fatigue resistance of notched components is given. Herein, one fundamental method to consider the effect of stress concentration at notches on fatigue is introduced as stress averaging concept by Neuber [4]. Thereby, the average stress $\bar{\sigma}$ at the root of a notch is evaluated by averaging the stress distribution in depth $\sigma(x)$ over a material dependent microstructural support length ρ^*, see Eq. (1).

$$\bar{\sigma} = \frac{1}{\rho^*} \cdot \int_0^{\rho^*} \sigma(x) dx \tag{1}$$

Utilizing the averaging stress hypothesis for a computed stress distribution, a feasible assessment of the notch fatigue strength is enabled [5]. For a simplification of this method in order to avoid the integration procedure, Neuber has discovered and formulated the concept of fictitious notch rounding, which is applicable to plane and antiplane stress fields, see [6]. Here it is suggested to evaluate the averaged notch stress $\bar{\sigma}$ at the real notch exhibiting a radius ρ_r without an averaging procedure by analysing a substitute notch with a fictitiously enlarged notch radius ρ_f, see Eq. (2).

$$\rho_f = \rho_r + s\rho^* \tag{2}$$

The support factor s is dependent on the loading mode, on the multiaxiality condition as well as on the applied strength criterion. Recommended values for the application are presented in [4]. As stated in [6], additionally the notch opening angle has a remarkable influence exhibiting different values of the support factor s for the three basic V-notch shapes. An application of the fictitious

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http://dx.doi.org/10.1016/j.compstruc.2017.06.009
0045-7949/

notch rounding concept to sharp V-notches in order to evaluate the microstructural support factor for different failure hypotheses is shown in [7,8]. Furthermore, the practicability of the elaborated method for V-notches under in-plane shear [9] and in-plane mixed mode loading [10] is highlighted. The utilization of the averaging approach for a local fatigue assessment of welded joints by incorporating numerous specimen types and different failure locations is shown in [11]. Recently, modern fatigue design concepts, such as the extended stress intensity factor [12] and the local strain energy density approach [13] are developed. The applicability for non-welded and welded notches is presented in [14,15] and some aspects on the advantages by utilizing these methods are given in [16]. However, due to their engineering feasible and widespread practicability, stress gradient dependent notch fatigue assessment models are common as reliable approaches [17]. For instance, the fatigue support number n can be evaluated according to Eq. (3) by considering the microstructural support length ρ^* as well as the relative stress gradient χ' of the stress distribution in depth $\sigma(x)$ at the notch of the root.

$$n = 1 + \sqrt{\rho^* \chi'} \tag{3}$$

In [18] it is suggested to estimate the considered support length by $\rho^* = (\Delta K_{th}/\sigma_{tf})^2$, whereby ΔK_{th} is the threshold stress intensity range and σ_{tf} the alternating tension/compression fatigue strength of the base material. In this work, an alternative stress gradient approach is utilized, which is introduced in [19]. The concept is incorporated in a frequently applied numerical post-processor to assess the fatigue strength of automotive components based on finite element results [20]. A detailed illustration of the method is subsequently, in the course of the fatigue assessment for non-welded components, given. To ensure a proper estimation of the fatigue life, it is of utmost importance to evaluate the local stress and strain conditions accurately. It is well known that the element type, mesh density and quality essentially affect the numerical results. Recent studies focussing on beams [21], plates [22] and more complex structures [23] reveal an excessive underestimation of the numerically computed stress state in case of coarse mesh sizes. Furthermore, the aspect ratio of the elements, especially in highly-stressed regions, affects the numerical notch stress results significantly, see [24]. Although recommendations for mesh generation [25] and mesh criteria for stress analysis exist [26–30], the numerical effect on the notch fatigue strength assessment is still not comprehensively quantified. Adaptive re-meshing procedures [31] are basically applicable to improve the accuracy of the numerical results and save calculation time, like presented in [32,33] for hexahedral meshes, but however, in engineering applications such methods are often not used and the notch fatigue strength assessment is performed on the basis of the initial mesh. In addition, the superconvergence patch recovery (SPR) technique enables an advanced finite element based method to evaluate the peak stress and local stress gradient accurately even for coarse meshes [34,35]. As the SPR method is up to now not thoroughly implemented in industrial applicable finite element packages, the current paper focuses on the following numerical settings and their effect on linear-elastic notch stress computations:

- Mesh density, respectively element size and its impact on calculation effort.
- Element type including hexahedral/tetrahedral with linear/quadratic shape functions and exact/reduced integration type.
- Consequence on evaluated fatigue strength assessing non-welded and welded parts.

The work is basically structured in three major parts, consisting of the analysis for non-welded components and welded joints as well as a final discussion. All numerical computations are performed by the aid of the software package *Abaqus* [36] only applying pre-defined element types and formulations without any user-specific modifications.

2. Non-welded components

In order to validate the numerically computed results, a model involving a notch geometry, which exhibits an exact analytical solution, is required. Fundamental work by Neuber [37] provides analytical formulae for numerous notch geometries under multiple loading conditions. Within this work, a round specimen including a hyperbolical notch under tension loading is analyzed, see Fig. 1.

Based on this geometry, the following working tasks are executed to assess the numerical effect on the notch fatigue strength assessment for non-welded components:

- Evaluation of reference value for surface notch stress and stress gradient in depth by analytical formulae as defined in [37].
- Numerical analysis incorporating different mesh densities, element types, and, in case of the relative stress gradient, additional evaluation procedures.
- Notch fatigue strength assessment by means of a relative stress gradient based approach and comparison of analytical and numerical results.

2.1. Analytical notch stress calculation

For the analytical assessment, an oblate spheriodal coordinate system u, v, and w is used, which is converted to the Cartesian system x, y, and z according to Eq. (4).

$$\begin{aligned} x &= d\sinh(u)\cos(v) \\ y &= d\cosh(u)\sin(v)\cos(w) \\ z &= d\cosh(u)\sin(v)\sin(w) \end{aligned} \tag{4}$$

A detailed derivation of the complex stress condition is illustrated in [37]. The final normal stresses σ_u, σ_v, and σ_w under tension loading can be calculated as shown in Eq. (5).

$$\begin{aligned} \sigma_u &= \frac{1}{h^2}\left\{D\tanh^2(u) + B\frac{\cos(v)}{\cosh^2(u)} + C\left[-2-\alpha+\frac{1}{\cosh^2(u)}\cos(v)\right]\right\} \\ &\quad + \frac{\cos(v)}{h^4}[-D+B+C\cos^2(v)] \\ \sigma_v &= \frac{1}{h^2}\left[-D\frac{\cos(v)}{1+\cos(v)} + (\alpha-1)C\cos(v)\right] + \frac{\cos(v)}{h^4}[D-B-C\cos^2(v)] \\ \sigma_w &= \frac{1}{h^2}\left\{D\left[-\tanh^2(u)\frac{\cos(v)}{1+\cos(v)}\right] - B\frac{\cos(v)}{\cosh^2(u)} + C[\alpha-1 \right. \\ &\quad \left. - \frac{1}{\cosh^2(u)}]\cos(v)\right\} \end{aligned} \tag{5}$$

The corresponding shear stresses τ_{uv}, τ_{uw}, and τ_{vw} are calculated by Eq. (6).

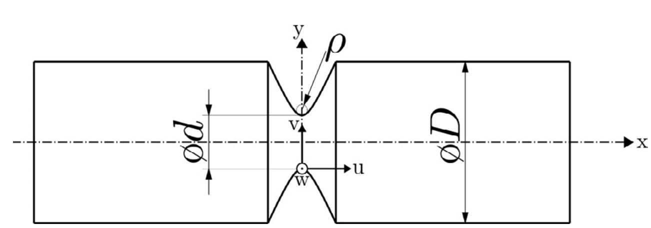

Fig. 1. Geometry of non-welded round specimen with hyperbolic notch.