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Novel hot spot stress calculations for welded joints using 3D solid finite elements

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ABSTRACT

This paper presents a novel numerical method through which less mesh-sensitive local stress calculations can be achieved based on the 3D solid finite element, adhering strictly to the original definition of hot spot stress. The traction stress, which is defined at 0.5t and 1.5t away from the weld toe, was calculated using either a force equivalent or work equivalent approach, both of which are based on the internal nodal forces on the imaginary cut planes. To confirm the validity of the proposed method, 5 typical welded joints widely used in ships and offshore structures were analyzed using 5 different solid element types and 4 different mesh sizes. Finally, the methodology was applied to the more complicated pontoon-column connection part of a semi-submersible RIG under a realistic wave load, and the performance of the proposed method was compared with the traditionally used surface stress extrapolation method.

1. Introduction

Ship and offshore structures are composed of complicated connections of stiffened plates, which are joined together by welding, inevitably producing structural discontinuities. Regardless of the structure,

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the structural discontinuity causes stress concentrations, eventually increasing the possibility of premature fatigue cracking starting either from the weld toe or root. Unlike other mechanical structural parts, the welded joints possess considerable uncertainties due to the presence of welds, such as geometric irregularity, material heterogeneity and potential residual stress. The majority of those uncertainties may not be overcome in a deterministic manner because they are difficult to identify during the design stage; hence, they are handled as unknown factors treated by a safety margin, e.g., using the SN curves of the mean minus two standard deviations. In addition to those uncertainties mentioned above, the stress that is combined with design SN curve needs to be defined with clarity, to maintain the consistency between the SN curve and stress analysis. Traditionally, the so called nominal stress approach has been used widely, especially in civil engineering, which simplifies the design stress calculation procedure by taking the local stress concentration effect into account at the specimen level, i.e., SN curve. This leads to weld classification, e.g., Class B, C and D in BS5500 [9]. On the other hand, classification of the weld geometry is unclear, and the definition of nominal stress is not straightforward when the analyzed structure is of a complex geometry. In line with the rapid development of numerical methods in the stress calculation procedure, such as the finite element method, the calculation of local stress considering the local stress concentration effects became the daily life of engineers. Therefore, rather than leaving the stress concentration effect into many SN curves, a single unified SN curve is used by taking the stress concentration effect out of the SN curve with a concrete definition of the local stress that may be obtained using the finite element method. The fundamental philosophy of local stress, normally called hot spot stress or structural stress, is that it includes the local stress concentration effect induced by the local structural discontinuity, such as weld attachment, but without an extra stress concentration induced by the presence of a notch, such as the weld toe. In addition, this hot spot stress includes the global stress concentration as well. Although there appears to be some consensus as to how the hot spot stress is defined near the weld discontinuity, different researchers proposed different methodologies for calculating the hot spot stress, eventually leading to different fatigue life estimations even with the same structural component under the same loading. According to the recommendation of the IIW (International Institute of Welding), the hot spot stress is defined as the stress at the weld toe that excludes the nonlinearly varying peak stress component, as illustrated by Fig. 1 [8,10]. The definition is based on the stress distribution through the thickness of the plate under consideration.

Although the definition in Fig. 1 is shared by the regulatory bodies of the marine community, such as ship classification societies, the practical procedure to calculate the hot spot stress is not shared. Sticking to the original definition, the hot spot stress can be obtained by linearizing the stress distribution through the plate thickness direction provided that the stress distribution through the thickness, including nonlinearly varying peak stress, is estimated correctly. One of the practical procedural difficulties of hot spot stress calculations related to the original definition is that the nonlinearly varying peak stress is difficult to obtain because it requires a relatively fine mesh division, e.g. three elements through the thickness direction. To simplify the calculation procedure, an extrapolation method using the surface stresses has been proposed [6,13,14,10,11]. This method is based on the premise that the extrapolation to the weld toe of the two surface stresses picked at two distinct locations away from weld

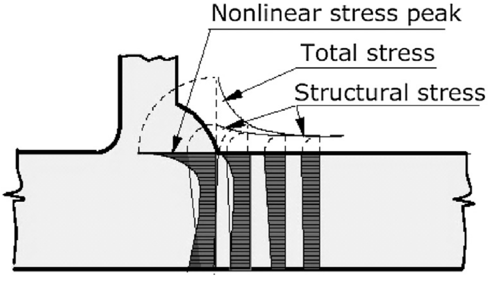

Fig. 1. Definition of the hot spot stress according to the IIW.