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HIGH-CYCLE FATIGUE OF MILD AND HIGH-STRENGTH STEEL COMPONENTS FOR OFFSHORE ENERGY APPLICATIONS

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Abstract

The present paper investigates high-cycle fatigue of steel components, using advanced numerical methods supported by appropriate testing. The research work is part of a national research program (acronym SIRENES), that aims at improving the structural performance of offshore floating platform, installed in deep-water locations. The current study extends the work performed by the research team in previous European research projects and focuses on a hybrid tension-leg-platform (TLP), suitable for combined offshore wind and wave energy exploitation. The paper presents a robust and effective numerical methodology, which is capable of predicting the fracture initiation and propagation in steel components due to cyclic loading. The methodology predicts the position of the crack tip, the direction of the crack propagation and the crack growth rate in steel components. The numerical model employs appropriately modified cohesive elements to predict accurately and computationally efficiently the crack growth rate in the high-cycle fatigue regime, taking into account cyclic loading and damage accumulation. A dedicated experimental program is also conducted, using compact-tension specimens made of mild-strength S355 and high-strength S700 grade steel, to calibrate the developed numerical model and verify the numerical results.

Keywords: high-cycle fatigue, fatigue crack growth, compact tension specimen, cohesive zone model, high-strength steel, offshore structure.

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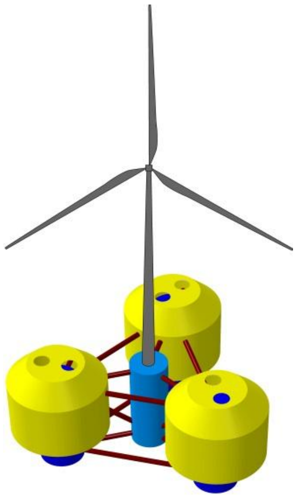
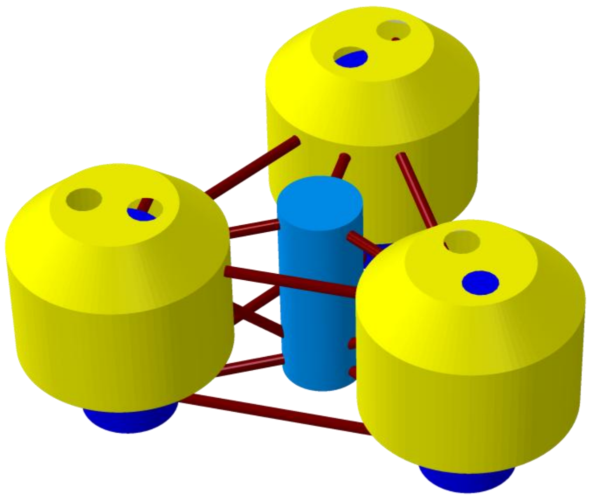
1 INTRODUCTION

During the last decade, the rapid expansion of offshore platforms for renewable energy exploitation has introduced significant challenges concerning their structural integrity and cost-efficient design [1]-[3]. A critical aspect of these structures is the strength of welded joints connecting the primary tubular members. These joints are particularly susceptible to concentration of local high stresses and strains at critical locations, commonly referred to as "hot spots" [4]. Under repeated loading conditions, these high local stresses can cause fatigue cracking and progressively deteriorate the structural integrity of the welded connection, potentially leading to fracture and compromising the long-term reliability and safety of the platform. Therefore, a comprehensive understanding of stress distribution and mitigation strategies are if immense importance for enhancing the durability and operational performance of offshore renewable energy structures.

The present research is part of national research program SIRENES, which focuses on improving the structural performance of offshore floating platforms deployed in deep-water environments. It builds upon prior investigations carried out by the research team in the framework of relevant European projects [5, 6], specifically targeting on the development of a hybrid tension-leg platform (TLP), as shown in Figure 1a, designed for the integrated harnessing of offshore wind and wave energy. The TLP constitutes the basis of the present study; it adopts a triangular configuration, as shown in Figure 1b, consisting of a central cylindrical column supporting the wind turbine tower and three corner cylinders interconnected by tubular braces. The three corner cylinders are capped with oscillating water columns (OWCs), which are designed to trap and compress/decompress the air repeatedly, resulting in wave energy production through a pair of air turbines installed in each OWC.



(a)



(b)

Figure 1. Schematic representation of the prototype hybrid platform [5]: (a) overall view, (b) triangular configuration of the platform.

In particular, the present work examines the high-cycle fatigue of steel components, commonly used for components in offshore tubular steel structures. An efficient numerical methodology is adopted and described briefly in the following section. The methodology is capable of predicting accurately the fatigue crack growth rate of compact tension [C(T)] specimens in the high-cycle fatigue regime, taking into account the damage accumulation under cyclic loading. The finite element model is capable of predicting the position of the crack tip, the direction of the crack propagation and the crack growth rate in steel components. The numerical results are compared with experimental results obtained by fatigue crack growth (FCGR) tests of C(T) specimens made of mild and high-strength steel. The tests have been performed at the facilities of the University of Thessaly (Laboratory of Mechanics and Strength of Materials).

2 DESCRIPTION OF THE NUMERICAL MODEL FOR HIGH-CYCLE FATIGUE

A finite element model is developed in ABAQUS/Standard [7], which represents a Compact Tension specimen model, depicted in Figure 2a. The geometric properties of the C(T) specimen follow the ASTM E647-00 standard [8], while Figure 2b shows an actual test specimen tested in this project. The thickness of the C(T) specimen is equal to 10 mm. A 2-mm-long crack is induced to the test specimen, as shown in Figure 2b, prior to the fatigue crack growth test by a pre-cracking cyclic loading. The 2-mm pre-crack is also considered in the numerical model, as shown in Figure 2a (red solid line), in the vicinity of the notch.

The numerical model consists of linear plane-strain elements with reduced integration (CPE4R) with length equal to 0.5 mm, while the total number of elements in the model is 23,474. Two rigid surfaces are developed with surface-to-surface contact interaction to simulate the pins of the experimental set-up. Furthermore, a spring element with very small stiffness is added connecting the reference points of the rigid surfaces, in order to alleviate convergency issues until the rigid surfaces establish contact with the specimen.

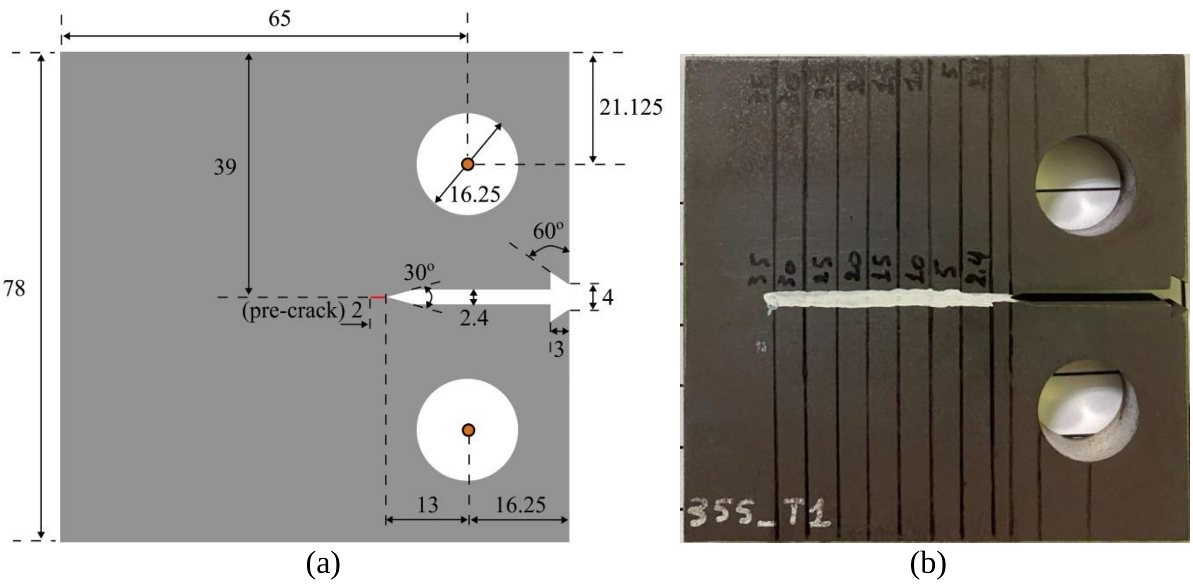


Figure 2. (a) Finite element model, (b) test C(T) specimen, following the ASTM E647-00 standard [8]; the dimensions are in mm.

A modified cohesive zone element is employed, in order to simulate cracking during the high-cycle fatigue performance in the C(T) specimen, and it is implemented in ABAQUS/Standard using an external user-element "UEL" subroutine. The cohesive zone elements are developed in the vicinity of the crack-tip parallel to the direction of the pre-crack (red solid line), as shown in Figure 2a. The subroutine calculates the cyclic response of two-dimensional linear cohesive zone elements, as reported in [9]. This cohesive zone model is assumed to follow a mixed mode traction-separation law, which is capable of simulating: (a) softening when the current separation is greater than the maximum separation during the loading history, (b) unloading-reloading when the separation is within the cohesive interaction region and the current separation is smaller than the maximum separation, (c) contact when the normal separation is negative, and (d) complete failure when the separation is outside of the cohesive interaction region.

Furthermore, the cohesive zone model is enhanced in order to accumulate cyclic "damage" during repeated loading. The numerical methodology is capable of identifying the cohesive element with the maximum accumulated damage, determining the corresponding node of the crack tip and predicting the direction of the crack propagation. Subsequently, the subroutine traces element paths around the crack tip evaluating the J-integral, the stress intensity factor range, and the corresponding crack growth rate. In the following, the model calculates the number of cycles required to propagate the crack through the length of the cohesive element at the crack tip. This is achieved by setting the damage parameter equal to the complete failure of the cohesive element. The calculation of the necessary cycles for the crack propagation by one element length at the vicinity of the crack tip is based on experimental data of a fatigue crack growth test, and more specifically by using ΔK-da/dN data of C(T) specimen after the pre-cracking procedure. This constitutes a very efficient cycle-skipping methodology, capable of providing directly the number of cycles required for the complete failure of the critical cohesive element and the subsequent extension of the crack along one element length, without simulating the complete loading history of the C(T) specimen. The formulation of the modified cohesive element and its implementation with the cycle-skipping methodology are described in detail in [10] and [11].

3 NUMERICAL RESULTS

Figure 3 shows the evolution of the crack length (α) with respect to the loading cycles (N), using the present numerical methodology. The numerical model considers a mild steel S355 material with Young's modulus equal to 207 GPa and Poisson's ratio equal to 0.3. The numerical results show satisfactory agreement with the corresponding experimental data, which corresponds to load ratio $R = F_{min}/F_{max}$ equal to 0.1 and maximum applied load F_{max} equal to 10 kN. The numerical methodology calculates accurately the stress intensity factors (ΔK) used for the calculation of the J-integral. Therefore, the model results in accurate prediction of the necessary cycles needed to propagate the crack through the length of a cohesive element.

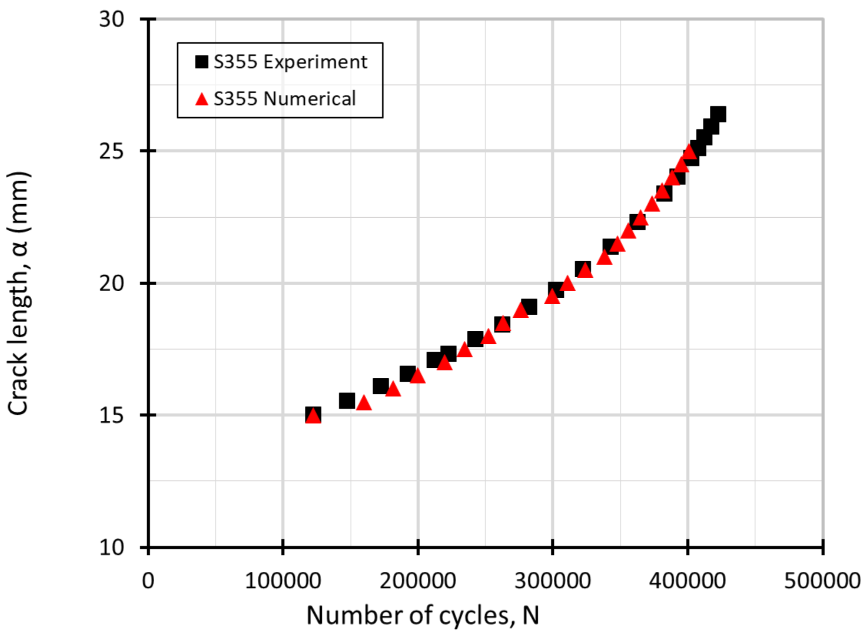


Figure 3. Calculated crack length with respect to the number of loading cycles compared to experimental data for S355 steel and R=0.1.

The crack propagation of the C(T) specimen with load ratio R=0.1 is also presented in Figure 4, with five different snapshots representing the stages of the specimen fatigue life. Figure 4a refers to a crack increase (Δα) equal to 0.5 mm, which corresponds to deletion of the first cohesive element. This occurs at loading cycle (N) 159,964. In the following, Figure 4b-Figure 4e demonstrate the propagation of the crack by 1.5 mm, 4.5 mm, 7.5 mm and 10 mm, which correspond to loading cycle number 219,696; 299,622; 364,724 and 401,060; respectively. The figure shows the von Mises stress distribution and in particular the stress concentration at the vicinity of the crack tip. The results show that the maximum stress near the crack tip increases, as the crack length also increases. The length of the pre-crack at the beginning of a fatigue crack growth test and the crack path at the end of the test for the C(T) test specimen of Figure 3 are shown in Figure 5a and Figure 5b, respectively.

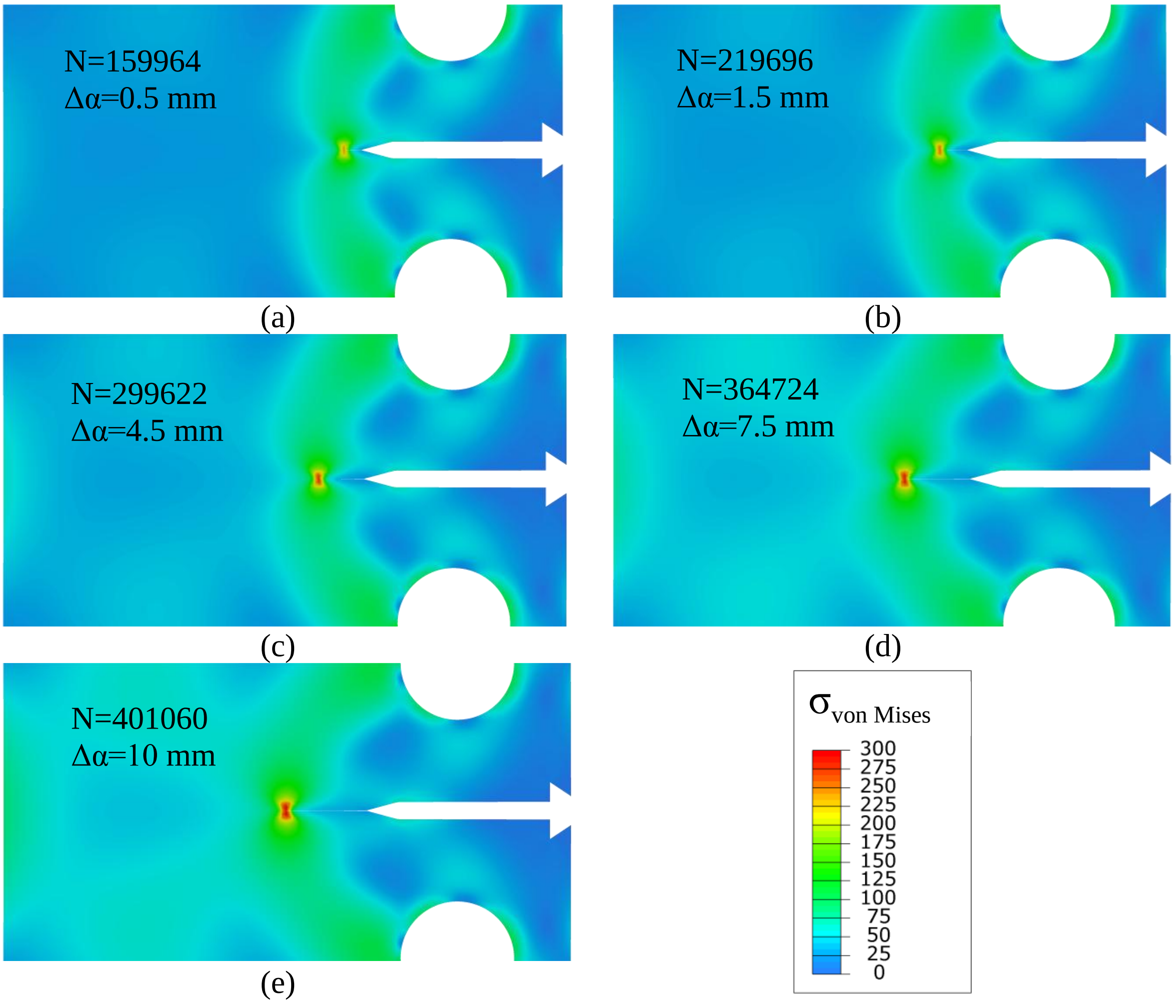
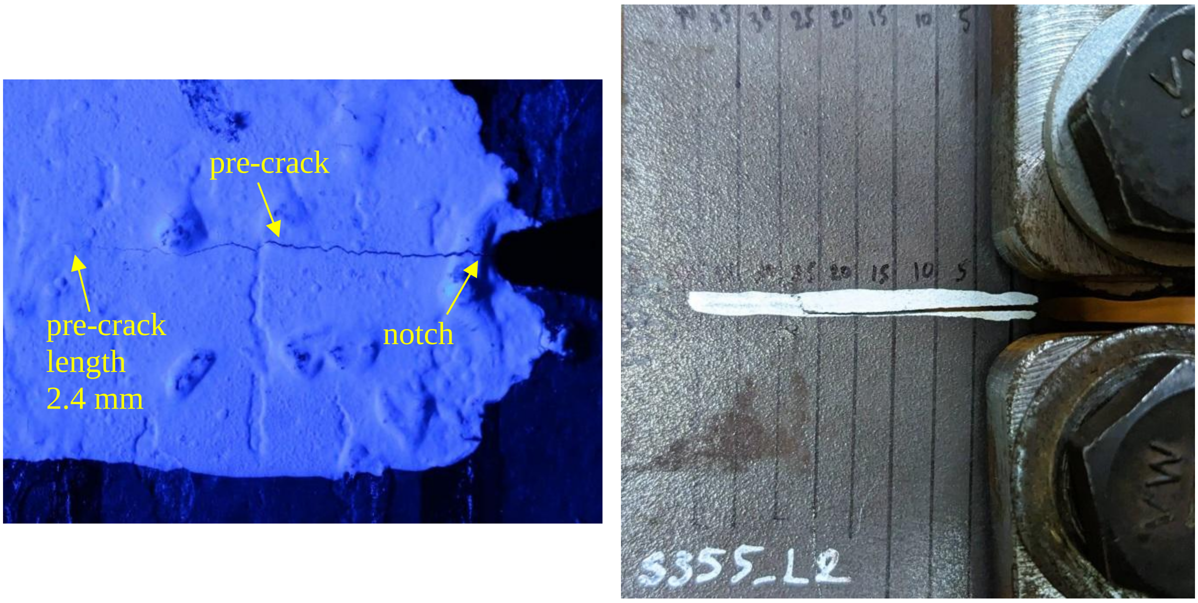


Figure 4. Crack propagation and stress distribution at the vicinity of the crack tip for S355 steel and R=0.1.

Furthermore, the fatigue performance of a C(T) specimen made of S700 high-strength steel material is also investigated, using the model described in Section 2 and presented in Figure 2a. The Young's modulus of the material is equal to 210 GPa (nominal value) and the Poisson's ratio is equal to 0.3. The present model is based on experimental data ΔK-da/dN data of C(T) specimen with load ratio R=0.1 and maximum force F_{max} equal to 10 kN. Figure 6 presents the progression of the crack length (α) with respect to the loading cycles (N). The numerical methodology calculates accurately the stress intensity factors (ΔK) compared to the experimental values, resulting in good agreement with the experimental results in terms of crack length extension with respect to the loading cycles.



(a) (b)

Figure 5. C(T) specimen made of S355 steel showing: (a) the pre-crack length (2.4 mm), (b) the crack path at the end of the test.

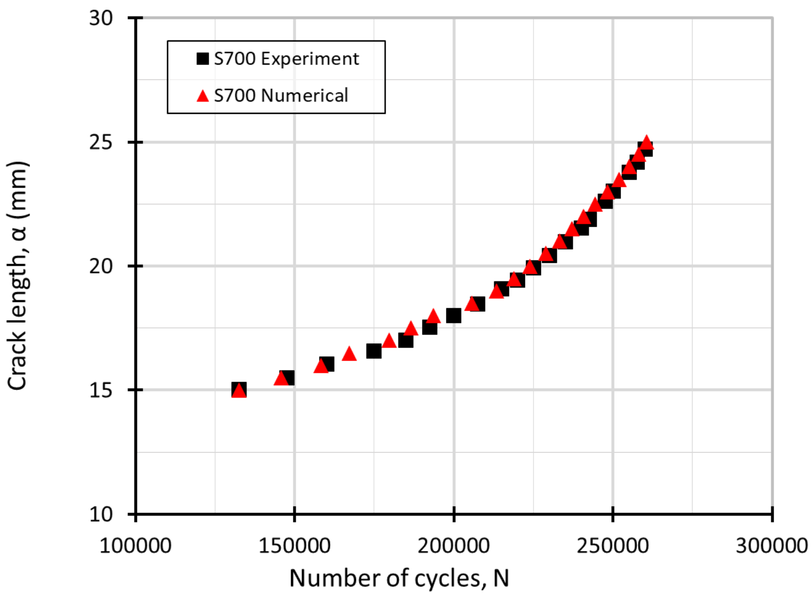


Figure 6. Calculated crack length with respect to the number of loading cycles compared to experimental data for S700 steel and R=0.1.

It should be emphasized that "cycle-skipping" is an important feature of the present numerical methodology, and constitutes a major challenge for the use of cohesive elements in high-cycle fatigue applications. The "cycle-skipping" algorithm calculates the necessary cycles for the critical cohesive element to fail and sets the damage parameter of the element equal to 1.0. It should be noted that the simulated cycles both C(T) numerical models are 40, while the actual cycles related to the experimental tests are 401,060 and 260,552 for the mild-strength and the high-strength test specimen, respectively. This indicates the computational efficiency of the current numerical methodology.

4 CONCLUSIONS

Motivated by the structural integrity of offshore energy production platforms, the present work focuses on the numerical simulation of high-cycle fatigue in steel components. A robust and efficient computational framework is developed to simulate crack propagation, employing an enhanced version of cohesive elements. The calibration of the numerical model requires standard crack growth rate test data (ΔK-da/dN) or Paris' law parameters. The elements are capable of simulating quite accurately and efficiently the crack growth rate in the high-cycle fatigue regime, accounting for fatigue damage accumulation under cyclic loading conditions and using an efficient cycle-skipping technique, based on J-integral calculations that determine the stress intensity factor and estimate the loading cycles needed for the crack to extend along one cohesive element length. The numerical model automatically predicts the crack tip location, its propagation direction, and the corresponding crack growth rate. The numerical results are in good agreement with laboratory tests in both S355 and S700 steel C(T) specimens in terms of crack length increase with respect to the number of loading cycles.

5 AKNOWLEGMENTS

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