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Fatigue Damage Analysis of Offshore Structures using Hot-Spot Stress and Notch Strain Approaches

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Abstract. In offshore structures, the consecutive environmental and operational loading lead to an ever-changing stress state in the topside structure as well as in the substructure, which for offshore jacket-type platforms (called of fixed offshore structures) commonly used, result in fatigue damage accumulation. A wide variety of codes and recommended practices provide approaches in order to estimate the fatigue damage in design phase and remaining life in existing structures. In this research work, fatigue damage accumulation analyses applied to an offshore jacket-type platform using hot-spot stress and notch strain approaches are presented. These analyses are performed using wave information from the scatter diagram collected in North Sea. The wave loads used in this analysis were obtained using the Stokes 5th order wave theory and Morrison formula. The jacket-type offshore structure under consideration has a total height of 140.3 meters, a geometry at mud line of 60×80 meters and composed by tubular elements.

Introduction

Due to their location and function, offshore structures have undergone a significant improvement over the years converging in innovative solutions and materials to tackle the problems. With constant and/or variable cyclic loading from the environment, namely, environmental loads, this kind of structures are subject to fatigue damage accumulation resulting in the appearance of fatigue cracks leading to a reduction in their service life.

Several research studies to evaluate fatigue damage accumulation in offshore structures for oil & gas extraction and to support wind turbine towers have been proposed [1-4]. Michalopoulos and Zaaijer [1] have developed studies to assess the fatigue damage based on simplified approaches applied to offshore wind support structures accounting for variations in an offshore wind farm caused by wind and wave loading. Siriwardane et al. [2] proposed an accurate fatigue damage model for offshore welded joints subjected to variable amplitude loading. This new model is based on damage transfer concept using only the S-N curve given in the standard codes of practice. Kajolli and Siriwardane [3] have proposed a new approach for estimating fatigue life in offshore steel structures based on a sequential law as well as in the hot-spot stress approach accordingly DNVGL-RP-C203 code [4]. Conti et al. [5] proposed a fatigue assessment of tubular welded connections with the structural stress approach and considering the Dang Van criterion. A comparison with traditional hot-spot stress approach was made and showed that the proposed methodology is consistent with the existing approach and enables the consideration of the

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beneficial effects of compression in legs, which was already observed in tubular joints tested under compression.

The fatigue design of offshore steel structures is normally made based on recommendations from the DNVGL-RP-C203 code [4]. The fatigue life may be calculated based on the S-N fatigue approach under the assumption of linear cumulative damage Palmgren-Miner method [6]:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} = \frac{1}{\bar{a}} \sum_{i=1}^{k} n_i \cdot (\Delta\sigma_i)^m \leq \eta. \tag{1}$$

where, D is the accumulated fatigue damage, $\bar{a}$ is the intersection of the design S-N curve with the log N axis, m is the negative slope of the S-N curve, k is the number of stress blocks, n_i is the number of stress cycles in stress block i, N_i is the number of cycles to failure at constant stress range $\Delta\sigma_i$, and η is the usage factor (1/Design Fatigue Factor). The DFF parameter (Design Fatigue Factor) to be used in fatigue design and analysis is based on classification and accessibility to the structural component [7].

Alternatively, a simplified fatigue analysis based on a long-term stress range distribution may be presented as a two-parameter Weibull distribution, which is also presented in the DNVGL fatigue design code [4]:

$$D = \left(\frac{n_0}{a}\right) \cdot q^m \cdot \Gamma\left(1 + \frac{m}{h}\right) \leq \eta. \tag{2}$$

where, n_0 is the number of occurrences, q and h the Weibull distribution scale and shape parameters, respectively, and Γ the gamma function.

In this study, fatigue damage accumulation analyses based on traditional and simplified probabilistic fatigue methodologies using notch strain and hot-spot stress approaches, respectively are presented and applied to an offshore jacket-type platform. In this way, the wave characterization aiming at simulating and posteriorly achieve the structural response is required. Wave measurements in the North Sea were made to obtain the scatter diagram, which correlates wave periods, wave height, and the number of occurrences. The wave loads to be applied in elements of the structural model were obtained using the fifth order Stokes wave theory [8] and the Morison's formula [8].

The offshore jacket-type platform under consideration has a height of 140.3 meters (an elevation of 27 meters above sea level and a water depth of 113.3 meters) and geometries at mud line and top side interface of 60×80 meters and 24×80 meters, respectively. All members of the offshore structure were built using tubular elements of S420 structural steel [9,10].

Hot-spot and Notch Stresses Approaches

The fatigue design codes have suggested the use of nominal, hot-spot and notch strain approaches to find the most efficient S-N design curve of a considered structural detail. In Figure 1, it can be seen the nominal, hot-spot and notch stresses in a tubular welded joint [5]. Very often, the notch stress due to the local weld geometry is excluded from the stress calculation [4,6]. In this situation, hot-spot stresses are assumed to generate design S-N curves.

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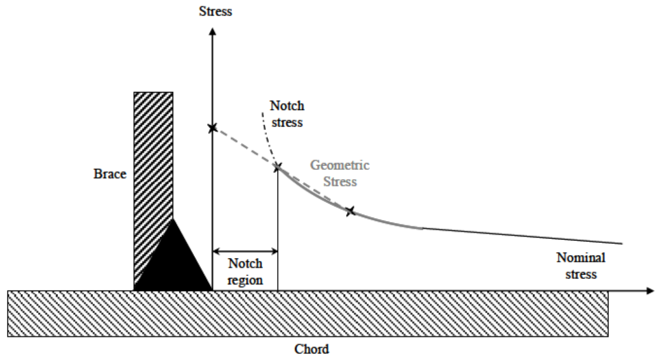

Fig. 1. Notch region and geometric hot-spot stress definition [5].

Hot-spot Stress approach

The fatigue damage assessment for tubular welded joints according to DNVGL-RP-C203 code is based on hot-spot stress approach instead of a nominal and notch stress approaches.

The design value of geometrical (hot-spot) stress, σ_{hs}, should be determined as follows [4,6]:

$$\sigma_{hs} = SCF \cdot \sigma_{nom}. \tag{3}$$

where, σ_{nom} is the nominal stress and SCF is the stress concentration factor calculated by Efthimiou' formulas for tubular welded joints based on geometrical parameters and loading modes (axial, in plane bending, out of plane bending) [4]. Once the stress concentration factors for axial, in-plane-bending and out-of-plane bending are obtained, the hot-spot stresses according DNVGL-RP-C203 code [4] are determined based on a superposition of the stress concentration factors at 8 different points for different loading modes at the weld toe around the tubular joint correlated with the nominal stresses. Alternatively, the hot-spot stresses can be evaluated by a finite element simulation and considering the stress distribution through a two-point linear regression at $t/2$ and $3/2t$ distances from the weld toe, where t is the thickness of the tubular element under consideration [11].

Notch Stress approach

Notch stress is commonly referred as local- or peak stress, which occurs at the weld toe or at critical point in a holed plate. This stress include the notch effect of a structural detail which occurs along the notch zone until the beginning of the weld toe.

The design value of local (notch) stress, σ_{loc}, should be determined as follows [4,6]:

$$\sigma_{loc} = SCF \cdot \sigma_{nom}. \tag{4}$$

where, σ_{nom} is the nominal stress and SCF is the stress concentration factor. The notch stress approach have a counterpart notch strain approach that is advantageous when some level of plasticity could appear. In case of fully elastic behavior both notch stress and strain approaches are equivalent.

Proposed Fatigue Methodologies Based on Hot-Spot and Notch Strain Approaches

In Fig. 2 and 3, the fatigue methodologies based on hot-spot and notch strain approaches are presented. The hot-spot stresses, around of weld toe of the tubular joints, are obtained using the Efthymiou equations with aims to determine the stress concentration factors (SCF), which are correlated with the nominal stresses for different loading conditions according to the DNVGL-

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RP-C203 code. Simplified fatigue method proposed in the same standard is used in the proposed fatigue procedure presented in Figure 2. The second proposed fatigue methodology based on notch (local) strain approach uses the Neuber rule and Ramberg-Osgood description as well as the Coffin-Manson relation with objective to evaluate the strain amplitude and number of cycles [12,13].

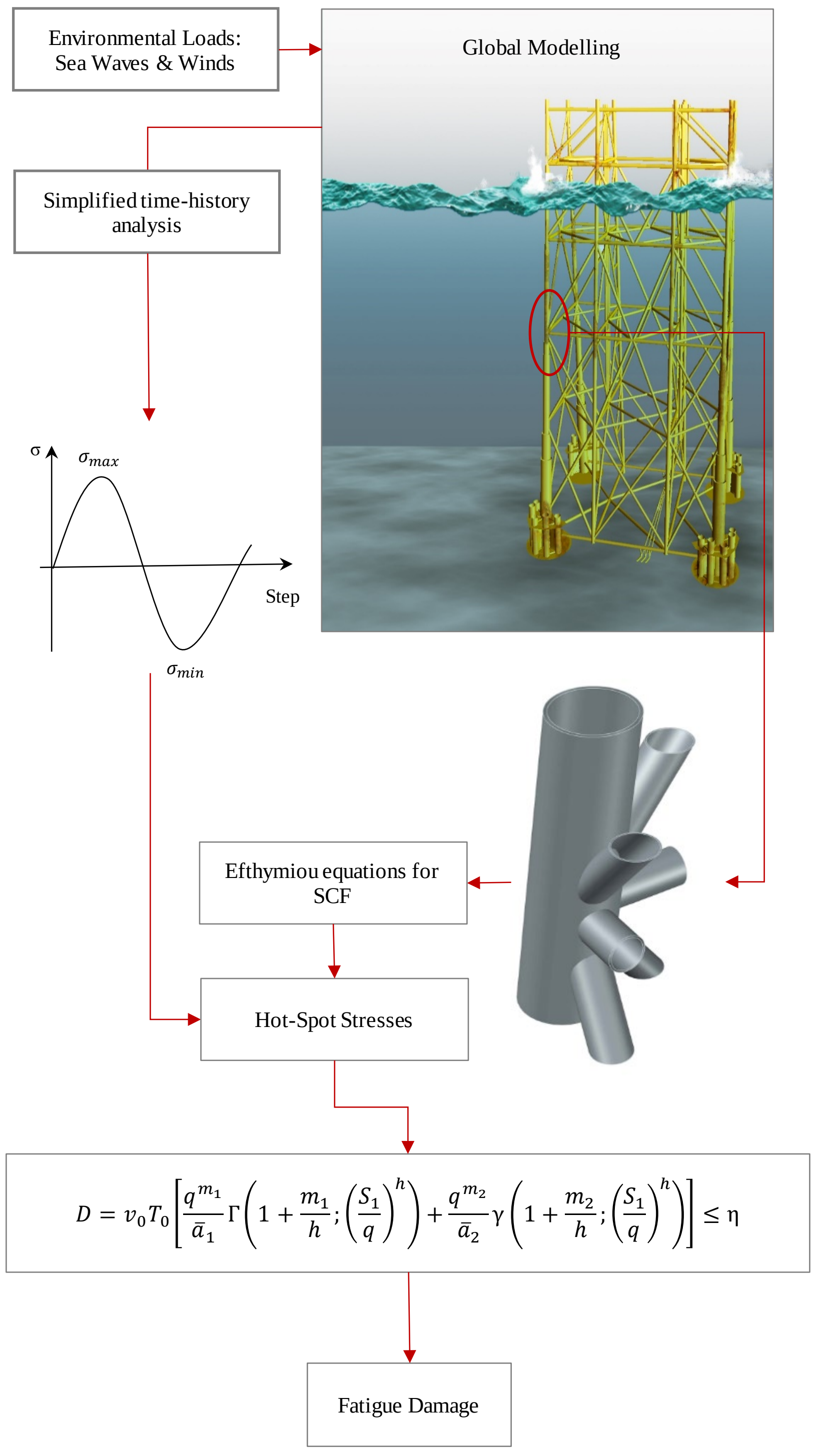


Fig. 2. Hot-spot stresses methodology workflow.

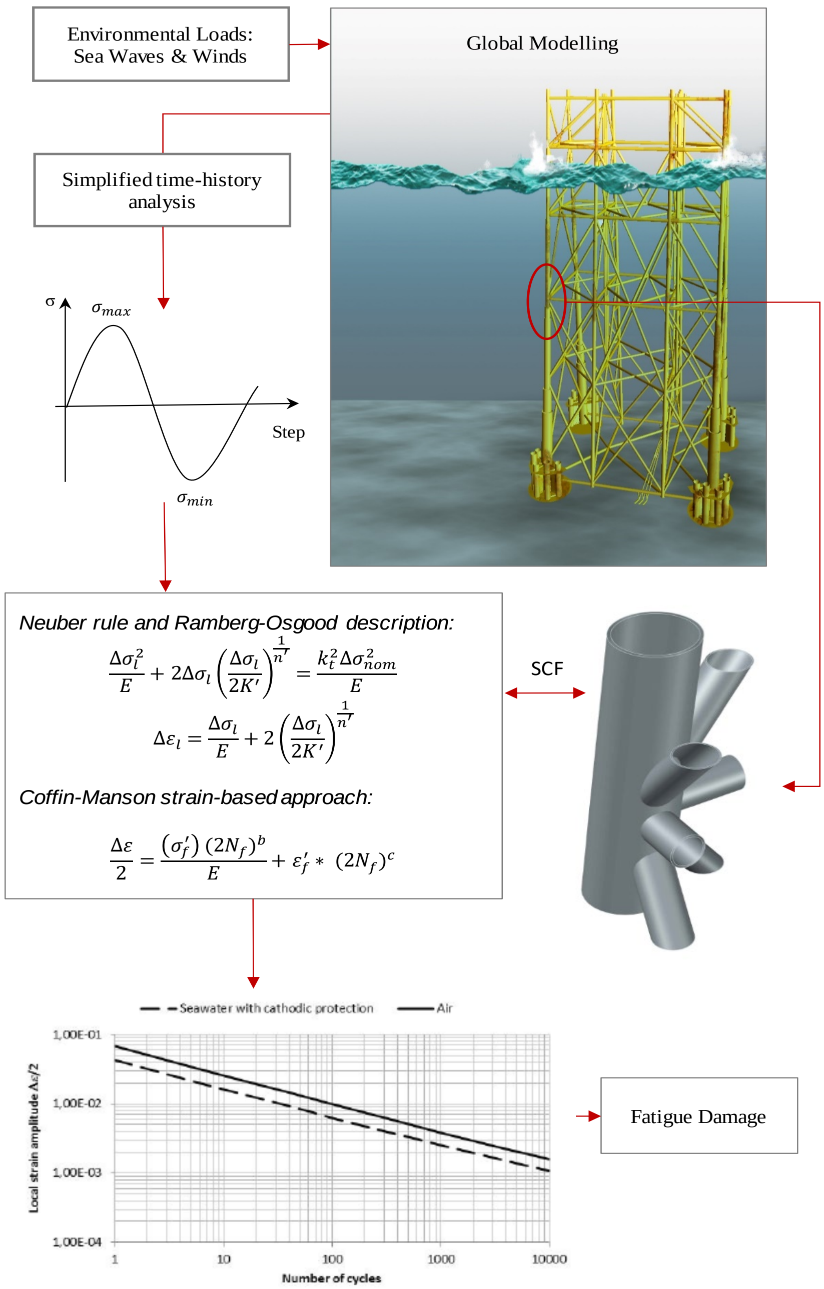


Fig. 3. Notch (local) strain methodology workflow.

Application and Results

The offshore jacket-type platform under consideration has a total height of 140.3 meters – an elevation of 27 meters above sea level and a water depth of 113.3 meters. The geometries at mud line and top side interface are equal to 60×80 meters and 24×80 meters, respectively, and all members are built in tubular elements of S420 structural steel [9,10]. The offshore structure is composed by horizontal bracing at elevation -108.9 m, -73 m, -44 m, -15 m, +8 m, and +24 m. In Fig. 4 and 5, an overview of the offshore jacket-type platform under consideration and the critical joint can be seen [9,10].

The fatigue analysis of the offshore jacket-type platform was made considering the wave loads and ignoring the wind loads. The fatigue damage due to wind loading when compared to wave loading is so small that it is not considered in the analysis. Morrison forces according to 5th order Stokes wave theory for several water depths and for a wave with 14.5 m height can be seen in Fig. 6. Permanent loads will not contribute to fatigue damage and were also excluded from the analysis. The stress ranges from each wave force based on wave scatter diagram were obtained using the SESAM software. In this analysis 2304 load cases resulting from the 12 wave directions, 8 wave heights with corresponding periods, and 24 steps in the wave were considered. The dynamic response of the offshore structure was made using the SESAM software (see Fig. 7 to 9).

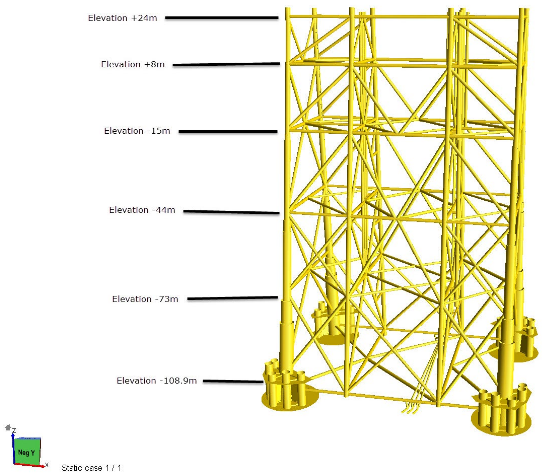


Fig. 4. Overview of the offshore jacket-type platform.

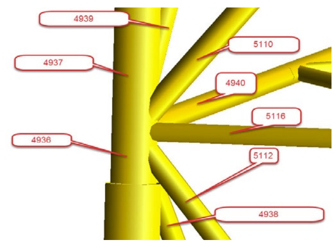


Fig. 5. Critical joint at elevation -44 m.

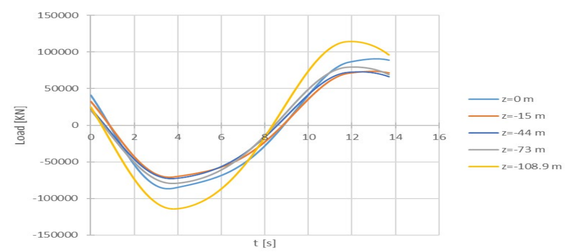
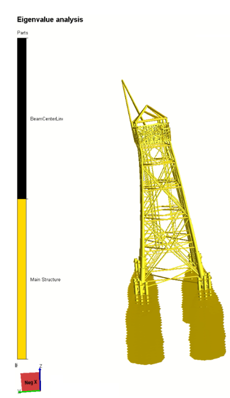
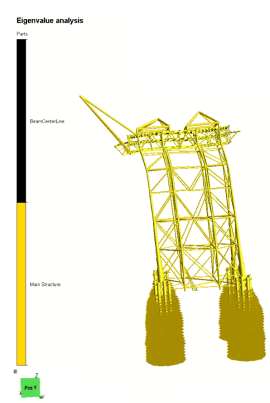


Fig. 6. Morrison force (14.5 m wave height).



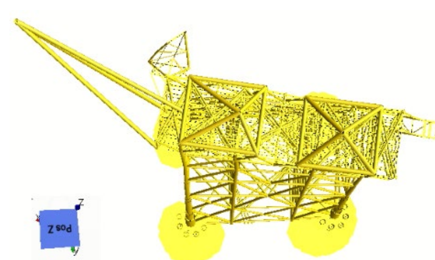
Global sway in North/South-direction

Fig. 7. Vibration mode 1: Period 3.18 seconds.



Global sway in East/West-direction

Fig. 8. Vibration mode 2: Period 2.99 seconds.



Global twisting about vertical axis

Fig. 9. Vibration mode 3: Period 1.90 seconds.

The fatigue methodologies presented in Figures 2 and 3 were used and the results are presented in Fig. 10. The fatigue methodology based on hot-spot stress approach (Fig. 2) was applied considering the stress concentration factors and geometrical dimensions of the critical joint at elevation -44 m determined using the DNVGL-RP-C203 recommendations (see Table 1). The design fatigue S-N curve for tubular joints in a seawater environment with cathodic protection according to DNVGL-RP-C203 code was used. In the other hand, for the fatigue methodology based on notch (local) strain approach, the cyclic properties of S420 steel based on

DNVGL-RP-C208 standard [14] as well as Coffin-Manson strain-life properties from ref. [15] (the strain-life parameters used in this analysis correspond to S355 structural steel) were used (see Table 2). In both methodologies, the Palmgren-Miner linear damage rule was used to determine the fatigue damage using the usage factor of 0.1 and service life of 50 years. In Figure 10, the summary of fatigue damage obtained for both analyses considering extreme waves from the scatter diagram called W73 (smallest wave height and most number of occurrences) and W80 (biggest wave height and less number of occurrences).

Table 1. Stress concentration factors and geometrical dimensions for members of the critical joint.

	Location	SCF_{BAL}	SCF_{IPB}	SCF_{OPB}	SCF_{UOPB}	Diameter [m]	Thickness [m]
Chord	5110	1.6009775	1.2990365	1.8363963	2.5436804	1.2	0.04
	5116	2.9490646	1.3706252	2.5918459	2.9185857	1	0.03
	5112	1.3688033	1	1.0828665	2.1077958	1.1	0.025
Brace	5110	1.8233236	1.6235408	2.6893376	-	1.2	0.04
	5116	3.4089698	2.1717246	3.7857918	-	1	0.03
	5110	1.7857226	1.5148	2.9438576	-	1.1	0.025
Chord	4939	1.8318157	1	1.1413502	2.9810327	1.2	0.035
	4940	5.4295072	2.3804706	5.6410504	5.762028	1.32	0.055
	4938	1.6207604	1	1.2818332	3.2921516	1.1	0.025
Brace	4939	1.7222647	1.4198678	3.3873849	-	1.2	0.035
	4940	4.5199659	2.4921638	4.9807336	-	1.32	0.055
	4938	2.0016058	1.6093898	4.5979906	-	1.1	0.025
Chord	4936	-	-	-	-	2.3	0.095
	4937	-	-	-	-	2.3	0.095

BAL – Balanced axial load; IPB – In-plane bending; OPB – Out-of-plane bending; UOPB – Unbalanced out-of-plane bending.

Table 2. Monotonic, cyclic and Coffin-Manson parameters of the S420 structural steel.

E GPa	f_u MPa	f_y MPa	K' MPa	n' -	σ'_f * MPa	b * -	ε'_f * -	c * -
210	561.2	426.3	690	0.1	952.2	-0.089	0.7371	-0.664

* Strain-life parameters of the S355 structural steel used in this study.

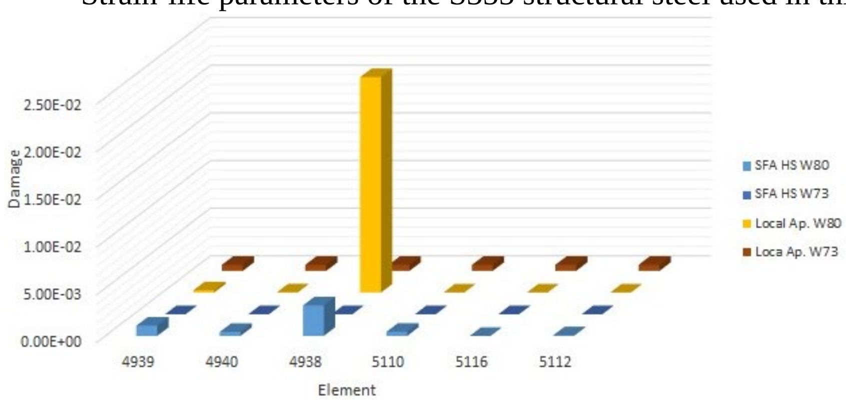


Fig. 10. Summary of fatigue damage obtained for both analysis.

Conclusions
All fatigue damage obtained in both analyses are inferior to the limit imposed to the usage factor of 0.1. The fatigue damage estimated using the methodology based on the notch (local) strain approach according to the Neuber rule and Ramberg-Osgood description shows a significantly higher damage value when compared with the methodology based on hot-spot stress approach. Experimental strain-life tests for the low- and high-cycle fatigue regimes are recommended.

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