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RESEARCH ARTICLE

MULTIAXIAL AND UNIAXIAL FATIGUE ANALYSIS OF A MOORING CHAINS FOR AN OFFSHORE FLOATING WIND TURBINE

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Abstract

This paper presents the fatigue study (uniaxial fatigue and multiaxial fatigue) of mooring chains for a floating wind turbine (FWT). The operating principle of a floating offshore wind turbine (FOWT) and general information on uniaxial and multiaxial fatigue are presented, together with a reminder of the standards governing fatigue in the offshore sector. Uniaxial fatigue damage and service life calculations are carried out for various loading conditions and sea states. The finite element method is carried out using ANSYS software in order to estimate the best mapping of stresses and strains on the structure of the mooring chain. Finally, a simulation was also carried out using usingMatlab software to calculate the damage and multiaxial fatigue life. Comparison of the two analyses shows that uniaxial fatigue analysis minimises long-term damage and that multiaxial fatigue should be preferred for estimating the durability of offshore structures under extreme loading.

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Introduction:

In the exploitations of marine energy and resources, floating structures have emerged as an economically and environmentally preferable alternative to bottom-fixed structures, particularly in deep water [1].The utilization of renewable energy has great significance to reduce CO2[2]. With continued declines in the costs of solar, wind, and related technologies, variable renewable-energy sources, will gradually but steadily transition from being marginal, to becoming the major electricity sources in 2050according to DNV [3].Offshore wind energy emerges as a crucial cornerstone in the global transition toward renewable energy sources. Floating wind turbines, in particular, present exciting new prospects for harnessing offshore winds, thereby expanding the scope of wind energy.Over recent years, offshore wind power has gained prominence in the global renewable energy market due to its abundant reserves, minimal environmental impact, renewable nature, and enhanced stability[4]. Statistics reveal a significantsurge in the global offshore wind power sector over the past decade, with an average annual growth rate of 36%[4].Wind energy in deeper waters is better for energy harvesting, with steadier and higher wind speeds, compared to shallow waters. To date, most current offshore wind turbines are fixed to the seabed, which is unfeasible for water depths over 60 m[5].Deep waters hold significant untapped power potential, and FOWT offer advantages such as reducing visual impact from the shore in comparison to fixed platforms, higher theoretical wind power potential, and towing procedures for easier maintenance and deployment, among others.However, these FOWTs manage to stay upright on the sea surface through a highly specialized mooring system (Fig.1). Mooring

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chains are key components for floating platforms, connecting the floating structures to their foundations on the seabed, which serve as anchors. Failure of these components induced by fatigue can be catastrophic in economic and environmental terms. The minor and major chain failures from year the 2001 to2011 point out that the mooring chain failure probabilities are much higher than the intended design failure probabilities[6],[7].Many authors has studied the fatigue behaviour of the mooring chain. Zarandi et al [8] did an experimental and numerical fatigue analysis of a studless mooring chain. The effects of corrosion on fatigue of mooring chain have been addressed previously byLone [6], [9]. He developed a reliability formulation for mooring chain fatigue, taking into account the effects of mean load and degradation due to corrosion.Zarandi [8], Martinez[10],and Mendoza[11]alsoanalyzed the effect of corrosion of mooringchain.Moreover, a multiaxial fatigue analysis of a mooring chain hadalso been performed by Martinez et al. [10]using Dang Van critical plane approach[12],[13].

None of these do, however, consider a comparative study of the fatigue behaviour of studlinkmooring chain using uniaxial fatigue approach given by standards[14] and the multiaxial fatigue criteria[12],[13]. Thus, the study presented in this paper aims to compare the fatigue damage and fatigue life prediction given by uniaxial fatigue approach and multiaxial fatigue one. The potential influence of corrosion was not taken into account in this study.The first part of the paper presents the materials and methods used to correctly dimension offshore wind turbines. The finite element model is described, together with the geometric mesh implemented using ANSYS software. The various mechanical characteristics essential for sizing the mooring chain are described. Fatigue analysis of mooring chains is then presented in order to show the different modes of failure that are discriminating for this type of structure. In parallel, the uniaxial and multiaxiale fatigue design criteria for the structure are developed, while presenting the various mechanical loading cases impinging on the wind turbine structure. Finally, the last part compares the results generated by the different loading cases in relation to the two design criteria.

Material and Methods:

The mooring chain

Nowadays, major offshore floating wind turbine projects are emerging and offshore wind is considered as an energy in constant development. The offshore wind sector is promising and offers good prospects for the development of renewable energies. As onshore wind power reaches its point of maturity, offshore wind power has many advantages for the wind energy sector:

Sea winds encounter few obstacles in their path. The offshore wind turbine can thus produce more electricity than an onshore wind turbine. With the establishment of offshore wind farms (Fig.1), a country with a large coastal area exposed to winds such as can compensate for a land area less conducive to the installation of wind turbines [1].

However, these wind turbines manage to stand upright on the sea surface thanks to a very suitable mooring system (Fig.1).The mooring system consists of an anchor, a mooring line and mooring connectors. The mooring chains (Fig.2) are part of this framework; they are key components for floating platforms. They connect floating structures (floating offshore wind turbines, ships etc.) to their foundations on the seabed, which serve as anchors [4]. The failure of these components can be catastrophic in terms of the economic and environmental impacts. However, mooring failures have been regularly occurring much earlier in their service lives than expected, with almost 50% of the reported failures happening in the first 3 years of 20-year design lives [15].

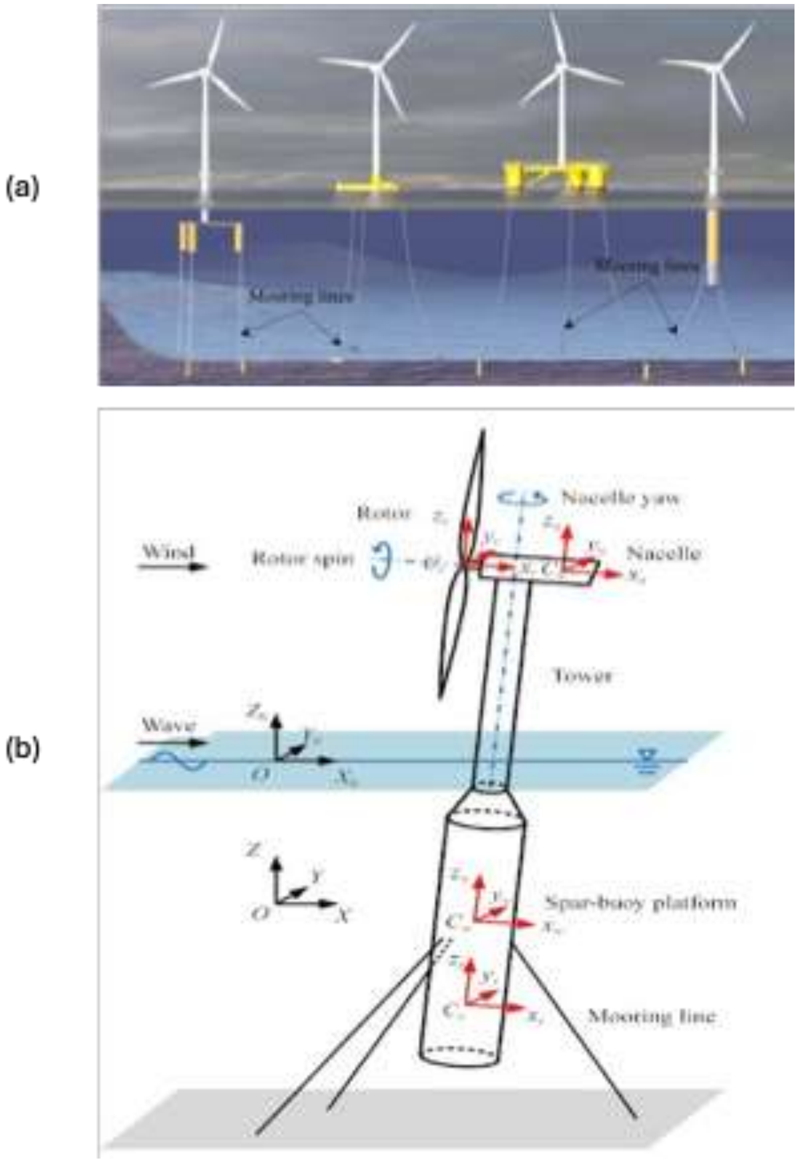


Fig. 1:- Wind turbines (a) with mooring chains and the illustration of wind and wave action (b) on it[5].

Fig. 2:- Picture of a mooring chain.

In general, mooring chains are an integral part of the mooring system (Fig.1and Fig.2). They ensure the mooring of offshore floating structures such as wind turbines and have to deal with various environmental factors including the hydrodynamic factor responsible for the degradation of the chain in fatigue. Generally, it exists different types of chain, which can be classified into two families (Fig.3): studless chain (welded link chain) and studlink chain. The latter is used in this study.

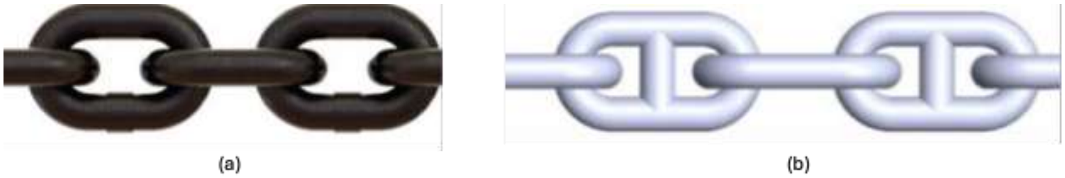


Fig. 3:- a) Studless chain, b) studlink.

Originally studs were added to chain to stiffen the links, preventing them from severely deforming when overloaded. They have an added advantage in that they prevent chain from knotting up when twisted, thus avoiding problems when the chain is retrieved with a windlass. Most chain of this type is used on larger vessels, offshore mooring systems or used as a ground chain for a mooring system.

Material properties

Mooring chains are made of steel and according to the codes and regulations, they are classified according to the steel grade [16]. Offshore mooring chain can be obtained in several grades from R3, R3S, R4, R4S to R5. Among them, R5 has the highest strength. The mechanical data of the materials are given in table 1.

Table 1:- Mooring chain materials properties.

	Grade	E (MPa)	υ	σ_y (MPa)
Mooring Chain	R5	560000	0.3	760

Constant amplitude multiaxial and uniaxial fatigue sizing methods

Fatigue is a process (succession of mechanisms) which, under the action of time-varying stresses or strains due to vibrations, wind gusts, wave changes the local properties of a material (Fig.4). These can lead to cracking and eventual failure of the structure. Fatigue is characterised in particular by a range of stress variation that may be well below the material's yield strength. Regarding the mooring chains, we have the fatigue due to tension-tension load (tension-tension fatigue) and the fatigue due to out-of-plane bending (OPB). However, mooring chains used for floating offshore wind turbine are submitted to alternating tension force due to wave. Then, tension-tension fatigue is used.

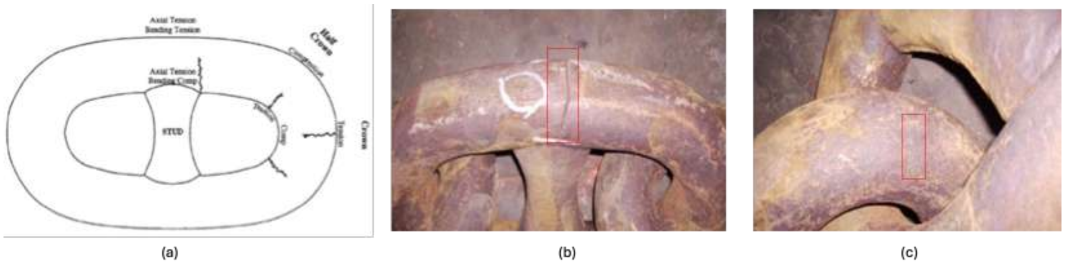


Fig. 4:- Possible fatigue crack location on studlink chain: (a) Crack at the weld, (c) Fatigue cracks at the crown [17].

Dang Van multiaxial fatigue criterion

The Dang Van criterion in its version of 1973 is the first multiaxial fatigue criterion that was introduced in the French industry. It was originally presented through considerations established at the microscopic scale, even if the criterion uses macroscopic stresses which are the alternating part of the shear stress $\tau_{ha}$and the hydrostatic pressure p [13], [12]. The fatigue damage function E of the criterion gives a maximization of the damage indicator Eh, defined on the material plane which unit normal vector is h:

$$E_h = \underset{t}{Max}\left\{ \frac{\tau_{ha}(t) + \alpha . p(t)}{\theta} \right\} \qquad (1)$$

Where $p(t) = \frac{I_1(t)}{3} = \frac{\sigma_{11}(t) + \sigma_{22}(t) + \sigma_{33}(t)}{3}$, the hydrostatic pressure,$I_1(t)$ is the time dependent first invariant of the stress tensor,$\tau_{ha}(t)$ is the alternating shear stress acting at time t on the material plane; it is obtained by determining the smallest circle surrounding to the load trajectory [18].
The plane where E_h is maximal is the so-called critical plane. It allows the criterion to express the material fatigue damaging affect generated by the multiaxial loading cycle.The fatigue function of the criterion is thus written as:

$$E_{DV} = \underset{h}{Max}(E_h) \qquad (2)$$

The fatigue function of the criterion is equal to unity when the fatigue limit of the material is reached by the analyzed multiaxial stress cycle. This fatigue function (E_{DV} =1) is also checked for particular material fatigue limits as those related to fully reversed tension fatigue limit (σ_{-1}, R = -1), fully reversed torsion fatigue limit (τ_{-1}, R = -1). This allows to calibrate the criterion, i.e to determine the two parameters α and θ that are involved within the damage indicator formulation.

$$\begin{cases} \alpha = 3\left(\frac{\tau_{-1}}{\sigma_{-1}} - \frac{1}{2}\right) \\ \theta = \tau_{-1} \end{cases} \qquad (3)$$

When a structure in service is subjected to periodic multiaxial loading, it is highly likely that this loading will cause damage or even failure of the structure, even if it is below the material's yield limit, provided it is applied a sufficient number of times. To quantify this fatigue damage in multiaxial loading, we use fatigue criteria.

When applied to a multiaxial stress cycle, a fatigue criterion allows us to position any stress cycle relative to the material's endurance limit (or relative to its fatigue limit at N cycles). It expresses, through the value of its fatigue function E, the more or less damaging nature of the applied stress cycle.

The multiaxial fatigue post-treatment tool developed on Matlab software and validated by Camara[19] is used to assess the fatigue damage and then the fatigue life of the mooring chain. The obtained results are compared with those provided by uniaxial fatigue analysis according to DNV standard[14].

Uniaxial fatigue analysis according to the DNV standard[14]
The calculation of uniaxial fatigue damage for the mooring chain under different sea states is performed using the DNV-OS-E301 standard [14]. The sea state is the description of the sea surface influenced by wind and swell. A sea state is characterized by a significant wave height (Hs) and a peak period (Tp). The scatter diagram provides the probability of occurrence for a pair of significant wave height (Hs) and peak period (Tp). The METCenter[20] document provides a simulated sample distribution of the pair (Hs; Tp) for a 50-year period for a Hywind-type wind turbine.

By considering the number of measurements taken for each sea state and the total number of measurements during the given period, we can calculate the probabilities of occurrence [14] for each sea state using the following formula (4).

$$P_i(\%) = \frac{N_i^m}{N_n^m} x\ 100 \qquad (4)$$

WherePi (%) is the probability of occurrence, N_i^mrepresents the total number of measurements taken for sea state i, and,N_n^m represents the total number of measurements taken for all sea states.
According to the DNVGL-OS-E301 standard [14], the number of stress cycles in each sea state is given by the relationship (5).

$$N_i = f_i\ .P_i.T_D(5)$$

Wherefi is the frequency in hertz, which is equal to the inverse of the peak period T_p for a given sea state i:
$f_i = \frac{1}{T_{Pi}}$(6)

$T_D$is the theoretical life duration of the mooring component, measured in seconds. It has been set to 10 years in this study (10 years = 315360000 seconds); N_i is the number of stress cycles for a given sea state i.

Following the variations in sea states, the mooring chain is alternately under tension and at rest, implying that it is subjected to repeated tensile loading. Thus, we will conduct a simplified study of tension-tension fatigue in accordance with the DNV-OS- E301 standard [14] and the DNV - RP C203 standard [21]. Fatigue analysis of a component or structure depends on the intrinsic fatigue characteristics of the material constituting the component (S-N curve). These fatigue characteristics are represented in the form of an S-N curve (Stress-Number of cycles).

For mooring chains, according to the DNVGL-OS -E301 standard, the S-N curve (Fig.5) is given by the following relationship:

〖Log[n〗 _c (s)] = 〖Log(a〗 _D) − mLog(s) (7)

Wheren_c (s) is the number of stress ranges (number of cycles); s denotes the stress range (double amplitude) in MPa,it is computed by dividing thecorresponding tension ranges (table 4) by the nominal cross-sectional area A of the component (A = $2\frac{\pi d^2}{4}$ for chain [14]where d is the chain diameter) ; a_D represents the intercept parameter of the S-N curve and m the slope of the S-N curve.

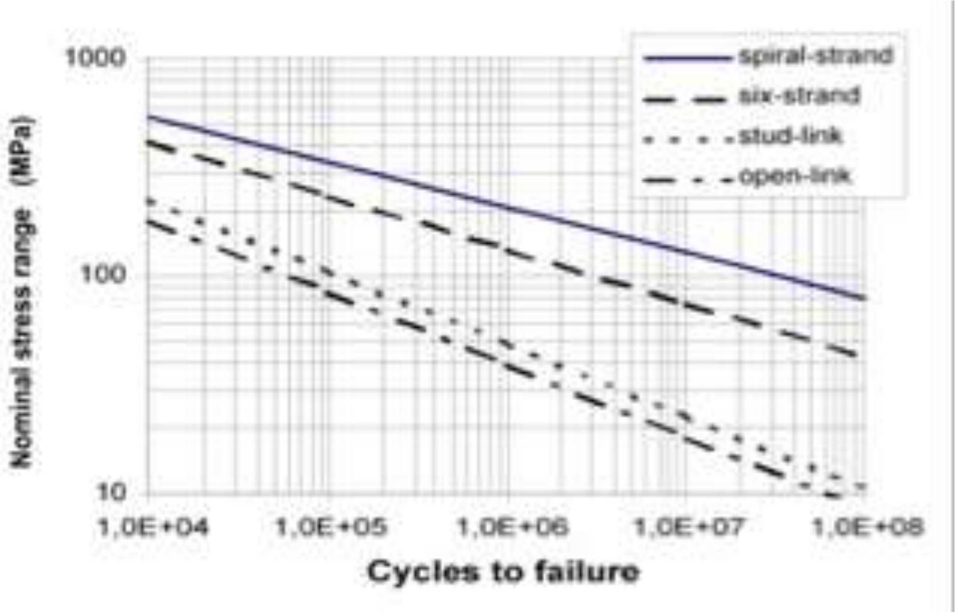


Fig. 5:- Design S-N curves [14].

According to the DNVGL - OS - E301 standard [14] and DNV RP C203[21], for a given sea state i, the fatigue damage di is obtained from the following relationship:

$d_i = \frac{Ni}{n_c(s)} = \frac{N_i \times S^m}{a_D}$(8)
For studlink chains[14], the parameters of the S-N curve area_D = $1.2\ x\ 10^{11}$ and m = 3.

Specific cases of this numerical study
In order to compare the damage obtained with uniaxial fatigue to that obtained with multiaxial fatigue; we made a certain assumption to simplify the study. Conducting a study in variable amplitude multiaxial fatigue proved to be

tedious; therefore, we considered a sea state with waves that present identical heights and peak periods. The following three sea states had been chosen (Table 2).

Table 2:-Sea states used**.**

Sea states	H_s (m)	T_p(s)
1	0.5	6.5
2	1.5	7.5
3	7.5	12.5

Based on this assumption, each sea state will have a 100% probability of occurrence, meaning that for sea state 1, we are certain to encounter waves with the following characteristics (Hs = 0.5m and Tp = 6.5 seconds).

In the absence of data related to the tension induced by each sea state (lack of actual ΔTi values), we conducted a fatigue sensitivity study. This sensitivity study aimed to determine the damage in uniaxial fatigue as well as in constant amplitude multiaxial fatigue, and thus compare the predictions of standards (uniaxial fatigue) with the multiaxial fatigue criteria (Dang Van criterion) to determine the more conservative approach, i.e., the one that ensures safety. Two loading cases had also been studied.To achieve the objectives, we proposed different tension loading cases for each chosen sea state in our study. Thus, six cases had been studied.

Table 3:-The six cases studied.

Cases	Tension variation ΔT_i(in tons)	Sea states	T_p(s)
Case 1	100	1	6.5
Case 2	100	2	7.5
Case 3	100	3	12.5
Case 4	75	1	6.5
Case 5	75	2	7.5
Case 6	75	3	12.5

Results and Discussions:

Finite Element Model andflowchart of the multiaxial fatigue post-treatment tool

Finite Element Model

The finite element analysis of the stud link chain is carried out on ANSYS software in order to have a better mapping of the stresses on the mooring chain structure, which will be used for the fatigue analysis purpose.Thestudlink chain geometry used is given in Fig 6 and table 4.

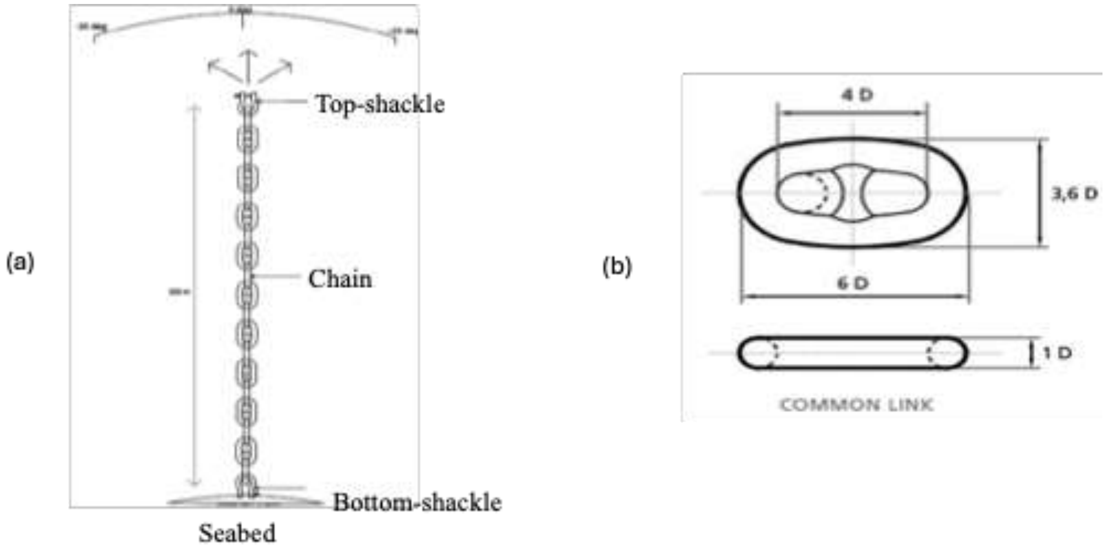
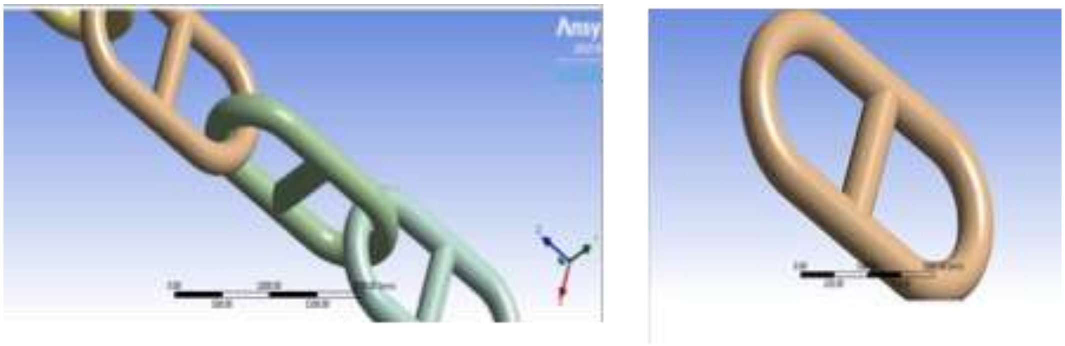


Fig. 6:- Example of studlink anchor chain.

Table 4:- Geometric parameters of the modelled mooring chain.

Chain diameter, D (mm)	Length of the chain 6*D (mm)	Width of the chain 3.6*D (mm)
152	912	547.2

3D finite element model of the stud link chain (Fig.7) had been developed using Ansys software to access the stress state the mooring chain experienced under the dynamic load induced by the waves and the wind.



(a) (b)

Fig. 7:- The studlink anchor mooring chain modelled: (a) mooring chain; (b) common link.

Tetrahedral solid elements are utilized to mesh the numerical models of the studlink anchor chain of the mooring chain in order to realise their stress-strain response analysis (Fig. 9). In areas where contact and discontinuity may create stress concentrations, an analysis is conducted to choose the appropriate mesh size in these stress concentration zones (Fig. 8 and Fig. 9).

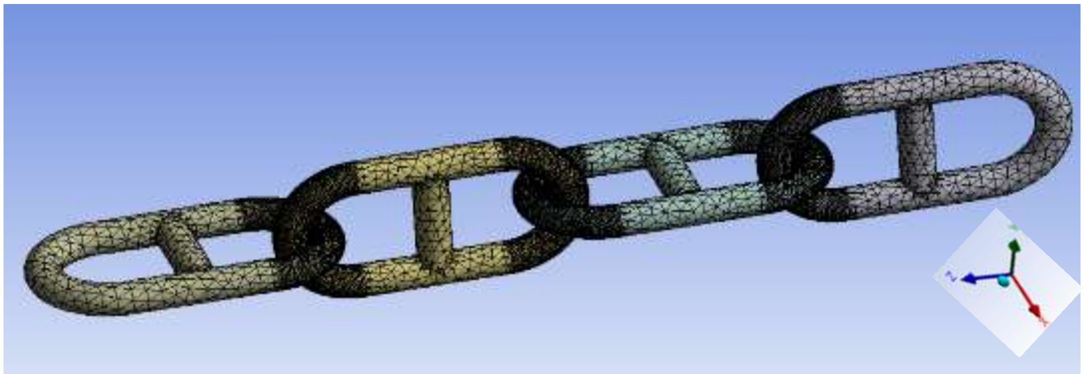
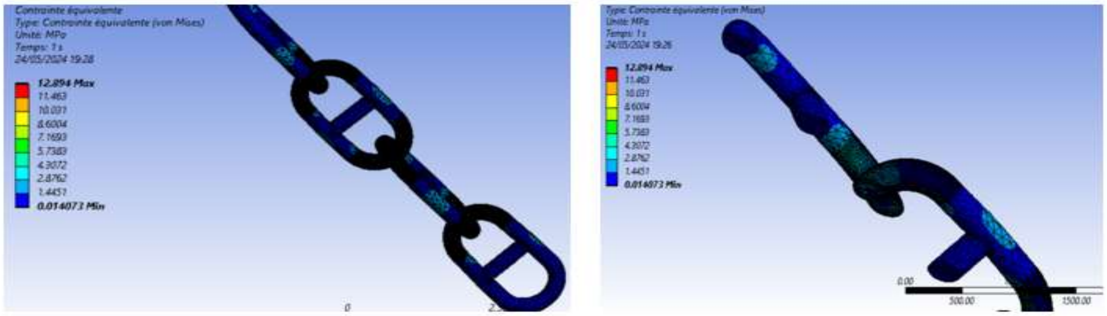


Fig. 8:- The stud link mooring chain meshing.

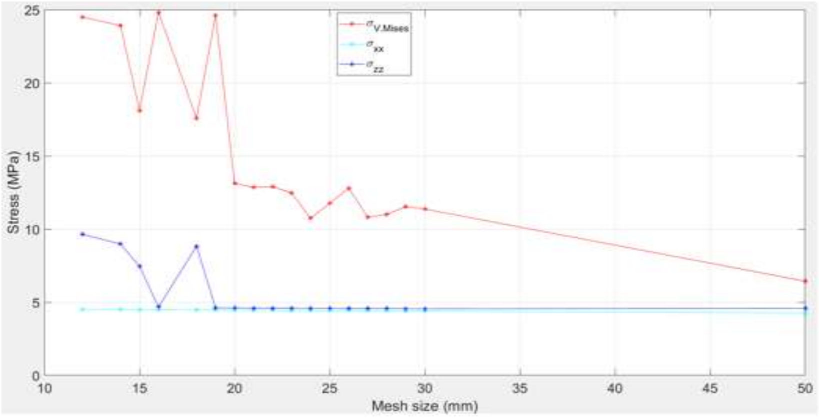
Figure 9 shows the variation of stresses (σ_{xx}, σ_{zz}, and Von Mises) as a function of mesh refinement (mesh size). It had been observed that between a mesh size of 50 mm and 30 mm (coarse mesh), the Von Mises equivalent stress is not constant. Indeed, it increases as the mesh size decreases. From 30 mm to 20 mm mesh size, the stresses stabilize. Below a mesh size of 20 mm, we observe a sawtooth variation. We deduce that the mesh size leading to a realistic stress value for this study is between 20 mm and 30 mm. Thus, the following mesh sizes are chosen:

- 22 mm in contact and discontinuity zones
- 100 mm outside stress concentration zones.

The resulting mesh is shown in Fig.8.



(a) : Equivalent stress mapping



(b) : variation of stresses

Fig. 9:- Equivalent stress mapping and variation of stresses as a function of mesh size.

Flowchart of the multiaxial fatigue post-treatment tool

Multiaxial stress states are observed on the mooring chain especially in stress concentration zones. A multiaxial fatigue post-treatment tool is thus implemented on Matlab software using the Dang Van multiaxial fatigue criterion (critical plane approach). The fatigue post treatment tool developed and validated by Camara[19]is use to analyse the chain behaviour from the fatigue point of view. The flowchart of the iterative process is given in Fig. 10.

Convergence of the approach is progressive and proceeds by reducing the domain [N1, N2] of the solution sought at each iteration:

- If E(N)> 1, N_1 takes the value of N that of N_2 is unchaged;
- If E(N)< 1, N_2 takes the value of N that of N_1 is unchaged.

The value of N corresponding to E(N) = 1 by linear interpolation of the two points
(N_1, E_1) et (N_2, E_2) is given by :

$$N = N_1 + \frac{(N_2 - N_1)(1 - E_1)}{E_2 - E_1} \quad (9)$$

The process is stopped when the absolute difference between E(N) and the unit value is deemed sufficiently small (e.g. 10^{-4}). Convergence is very rapid, since only the criterion's calibration constants α(N) and θ (N) are modified from one iteration to the next, while all the stress components of the cycle analyzed remain identical. Extended in this way to the field of limited endurance, multiaxial fatigue criteria are transformed into tools for determining multiaxial fatigue life.Thismultiaxial fatigue post treatment tool was validated in [19].

Loading

The displacement along z-axis of the lower link of the chain (part B, Fig.11) is blocked. An external load T is considered upon the upper link of the chain. Let ΔT_i be the range of the tension or the variation of the tension for a given sea state:

$$\Delta T_i = T_{i,\max} - T_{i,\min} \quad (10)$$

We consider that the mooring chain works in repeated traction, that is to say that the external stress due to waves varies between T_{max} and T_{min} (null). Thus, we obtain:

$$\Delta T_i = T_{i,\max} \quad (11)$$

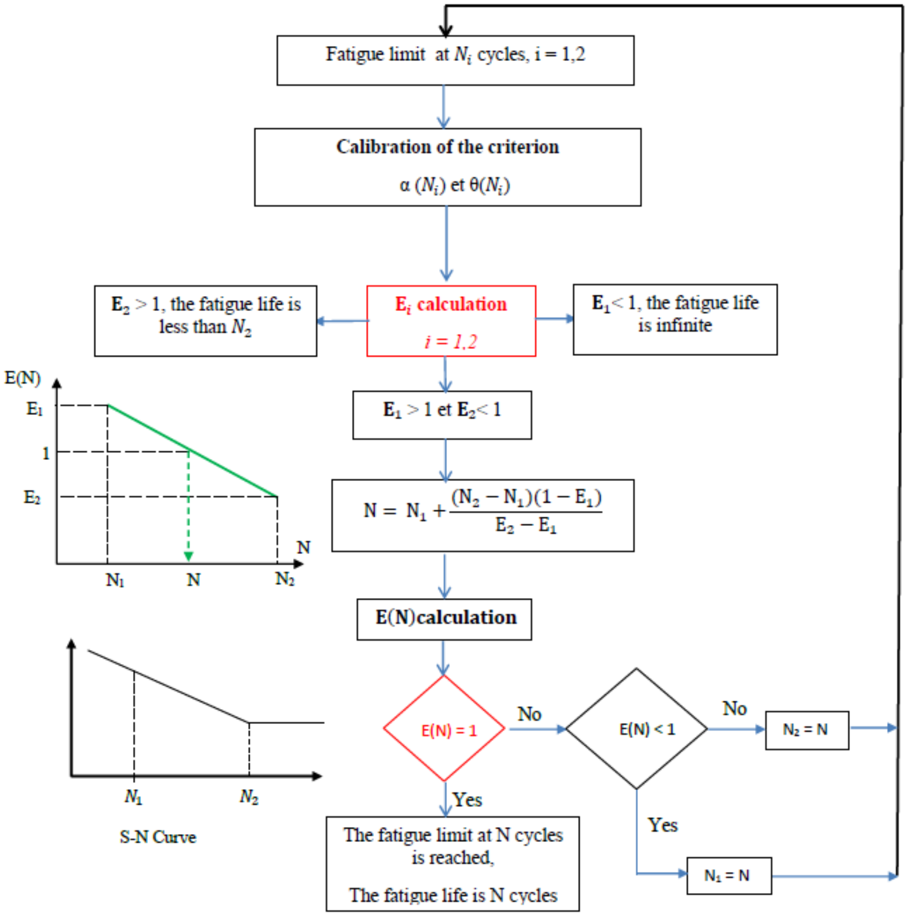


Fig. 10:-Flowchart of the iterative procedure for assessing fatigue life with Dang Van criterion.

Two values of $T_{i,max}$ are considered in this analysis (Table 3).

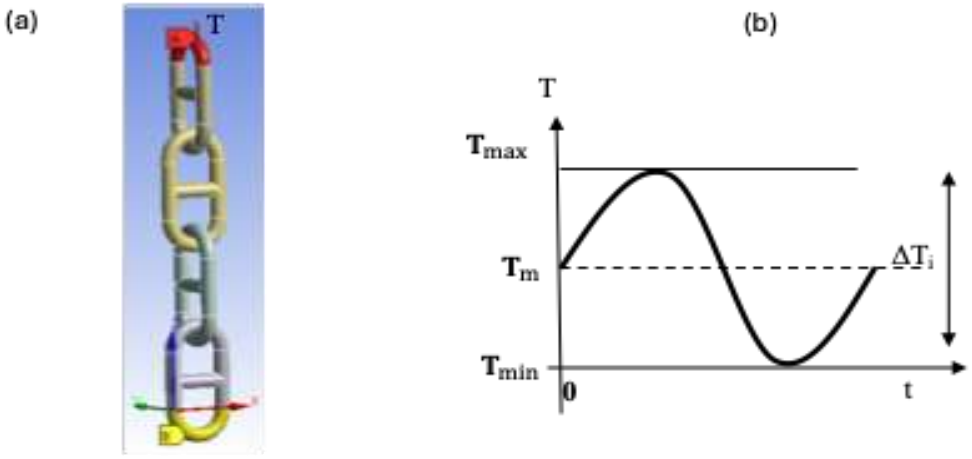


Fig. 11:- Constant amplitude load and boundary condition: (a) Applied force illustration upon the mooring chain; (b) variation of loading.

This uniaxial loadTi, maxapplied to the chain leads to a multiaxial stress stateup on the chain (Fig.12) because of the stress concentration zones but also the contact zones.

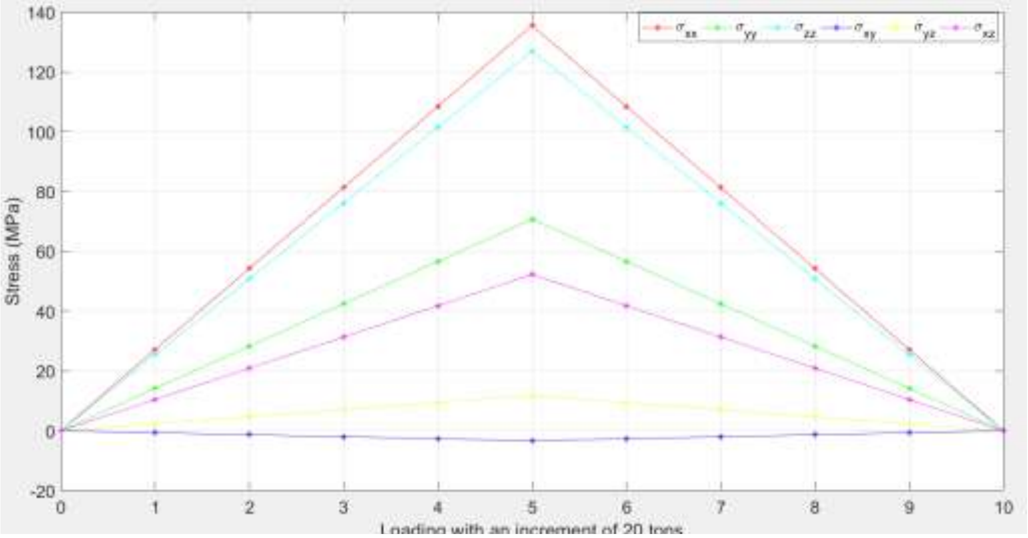


Fig. 12:-Multiaxial stress state for the critical node in the case where the external load vary from 0 to 100 tons and back to 0 ton.

Uniaxial and multiaxial damage and fatigue life assessment

The obtained results (Fig. 13. and Fig. 14.) show that damage values are generally higher in multiaxial fatigue. For the 6 cases studied, there is only 1 case (load of 100 tons and sea state 1) where the uniaxial fatigue damage value is slightly higher than that in multiaxial fatigue; otherwise, for the other 5 cases, the damage is much higher in multiaxial fatigue.

These damages have led to significantly lower predicted lifetimes in multiaxial fatigue compared to uniaxial fatigue. Indeed, the multiaxial stress state (Fig. 12.)is generally more severe for fatigue endurance than the uniaxial one used in uniaxial fatigue (according to standards). In the case of a multiaxial stress state, all components of the stress tensor are likely to contribute to damage, explaining why damages are more significant in multiaxial fatigue. Since fatigue life is inversely proportional to fatigue damage, we obtain a much shorter fatigue life with the multiaxial fatigue approach (Fig.14.).

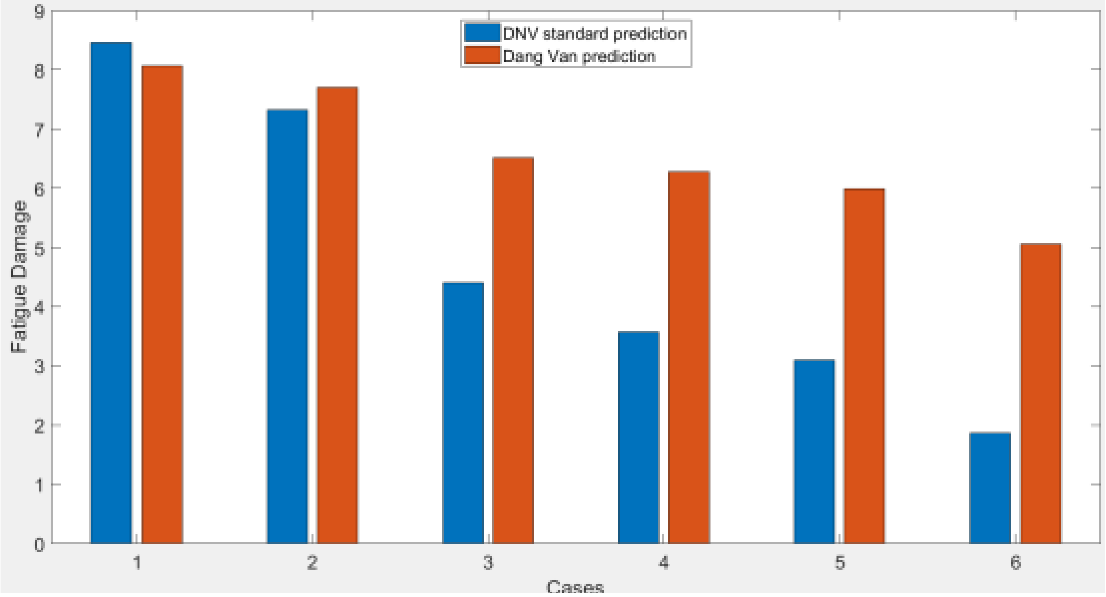


Fig. 13:-The evolution of fatigue damage (uniaxial and multiaxial) as a function of the 6 loading cases.

Thus, based on the obtained results, the uniaxial fatigue life (provided by the DNV-OS-E301 standard) is approximately 5 times longer than the predicted fatigue life obtained with the Dang Van multiaxial fatigue criterion. However, in practice, fatigue resistance is generally assessed based on standards (DNV, VDI[22], Eurocode[23], etc.), and very often mooring chain failures occur much earlier than anticipated during their service life. In other words, observations of the fatigue performance of mooring chains indicate that fatigue cracks appear about 6 times sooner (20 years/3 years) than expected[15].This means that the actual fatigue life is much closer to the predictions obtained with multiaxial fatigue (Dang Van multiaxial fatigue criterion prediction).

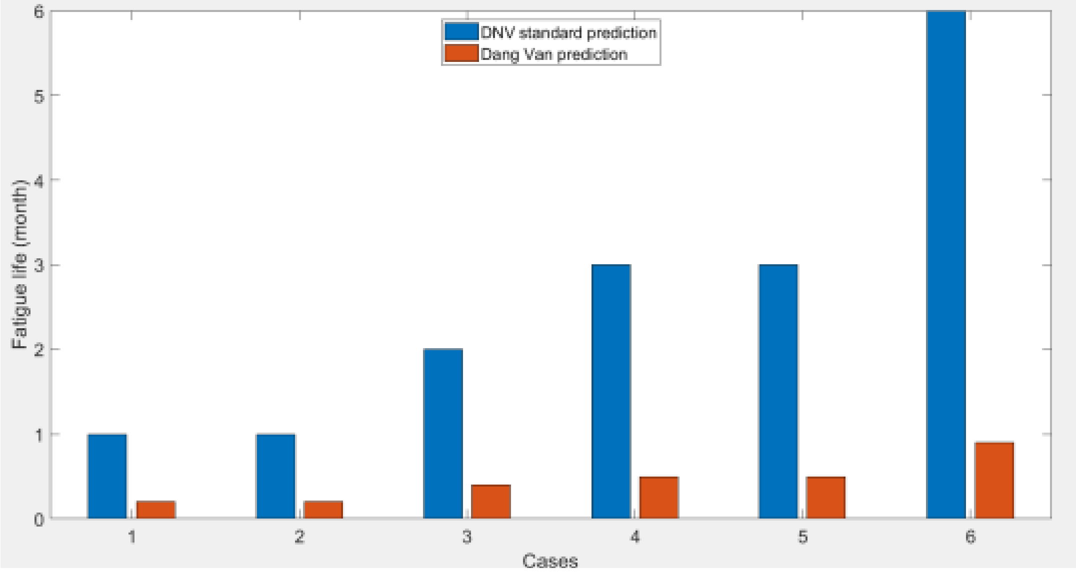


Fig. 14:-The evolution of fatigue life (uniaxial and multiaxial) as a function of the 6 loading cases.

The fatigue life obtained with multiaxial fatigue appears to correspond to the actual fatigue life of the mooring chain corroborating the Martinez et al [10]findings . Unlike, the prediction made with uniaxial fatigue seems to underestimate the damage and overestimate the fatigue life expectancy.

Conclusion:

A mooring chain is submitted to the effects of temperature, marine growth, corrosion but also and mostly the dynamic load due to waves. All these effects are applied simultaneously on the mooring chain and wear it down throughout its life. In this article, only the fatigue effect of the dynamic load on the mooring chain was studied. The study of fatigue under tension-tension with a cycle of stress assumed to have constant amplitude was carried out to determine the prediction of the DNV standard and the multiaxial fatigue approach. The comparison of damage and fatigue life given by the critical plane approach in multiaxial fatigue (Dang Van criterion) with the simplified damage and fatigue life calculation methods proposed by standards was conducted. The current models are not very adequate, as triaxiality of stress states is not well considered in the procedures recommended by standards (DNV standard). However, multiaxial stress states are frequently encountered in mooring chains in service, particularly in stress concentration zones. This study shows that the fatigue life calculation methods proposed by standards are not particularly suited for multiaxial stress state. Therefore, the use of multiaxial fatigue criteria remains to this day the approach leading to fatigue life closer to reality, both in uniaxial stress states and multiaxial stress states, when the stress states experienced by the material and the fatigue characteristics of the material are well identified.

It is important to note that the Dang Van criterion does not take into account other factors such as corrosion, which can also affect fatigue life.Thecorrosion effect is properly addressed by current S-N design curves or design practice[9]. Therefore, the next step of this study will be to take into account this effect of the corrosion in the uniaxial and multiaxial fatigue analysis of the mooring chain. For this purpose, the extended S-N curve formulation developed by Lone[9] will be used.

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Declaration of Conflicting interest
The authors have nothing to disclose.

Data availability statement
The authors confirm that the data supporting the findings of this study are available within the article. Raw data that support the findings of this study are available from the corresponding author, upon reasonable request.

Author contribution statement

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