STRUCTURAL MECHANICS APPLIED TO MOORING COMPONENTS DESIGN

Arnaldo F. Camarão[1], Marcos V. Pereira[2], Fathi A. Darwish[2] and Sérgio H. Motta[3]
[1] GEP / ArvinMeritor CVS
Av. João Batista 825, Osasco / SP, CEP 06097-900, Brazil
arnaldo.camarao@arvinmeritor.com
[2] Department of Materials Science and Metallurgy / Catholic University of Rio de Janeiro
Rua Marquês de São Vicente 225, Rio de Janeiro / RJ, CEP 22453-900, Brazil
marcospe@dcmm.puc-rio.br and fathi@dcmm.puc-rio.br
[3] Technology Division / Brasilamarras
Rua Eng. Fábio Goulart 40, Niterói / RJ, CEP 24050-090, Brazil
shamotta@brasilamarras.com

Abstract

The objective of this work was to develop a methodology for assessing the structural integrity of mooring components for offshore applications. Finite element calculations were performed in order to determine the stress levels in studless and stud chain links as well as to evaluate the critical regions of the links. A study was also developed based on the concept of critical volume associated with the material volume susceptible to a certain critical crack size. The results showed that the studless chain links present a higher critical volume than that related to the stud chain links, fact that confirms the beneficial effect of the stud. According to the crack assessment procedure the critical crack length is smaller for the stud chain links. However, the critical association between volume and crack size turns the studless chain links more susceptible to brittle fracture than the stud chain links.

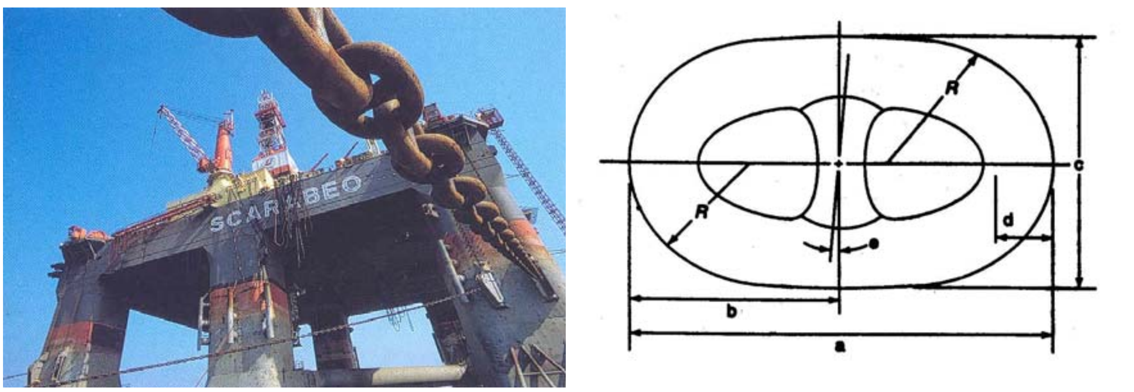
Introduction

Oil exploration in the world has nowadays large fields in offshore areas and these are responsible for increasingly greater percentages of worldwide production. The continuous expansion of petroleum deepwater activities over 2000 m depth demands an increasing attention to the design of mooring systems, as shown in Fig. 1A. The failure of a single component in a mooring line of an offshore oil exploitation platform can produce incalculable environment damage as well as human and material losses. Production offshore units have a relative long operational life (about 20 years), during which they are submitted to the ocean adverse environment loading produced by the combination of wind, waves and currents. This complex loading history can promote the nucleation and propagation of cracks in components of mooring lines and it is well known that the presence of defects in elements of such lines means a critical situation that can lead to catastrophic failures. For this reason, methodologies for assessing the structural integrity of mooring components are considered to be of fundamental importance.

Material Selection and Chain Link Production

The material selected for this work was an R3 grade structural steel largely used for fabricating offshore mooring chains. According to API 2F [1], the R3 chain links present yield and tensile strength of 570 MPa and 720 MPa, respectively. The steel was received in the form of hot rolled round bars of circular cross section of a nominal diameter of 76 mm.

The circular bars were bent in conformity with the typical (studless or stud) chain link geometry before they were butt flash welded [2]. A stud chain link, as an exemplification, is presented by Fig. 1B. Following the welding procedure, the chain links were quenched (900ºC for 90 minutes) in water and then tempered (620ºC for 90 minutes).



(A) (B)

FIGURE 1. Mooring system in an offshore floating structure (A) and an R3 grade stud chain link geometry [1].

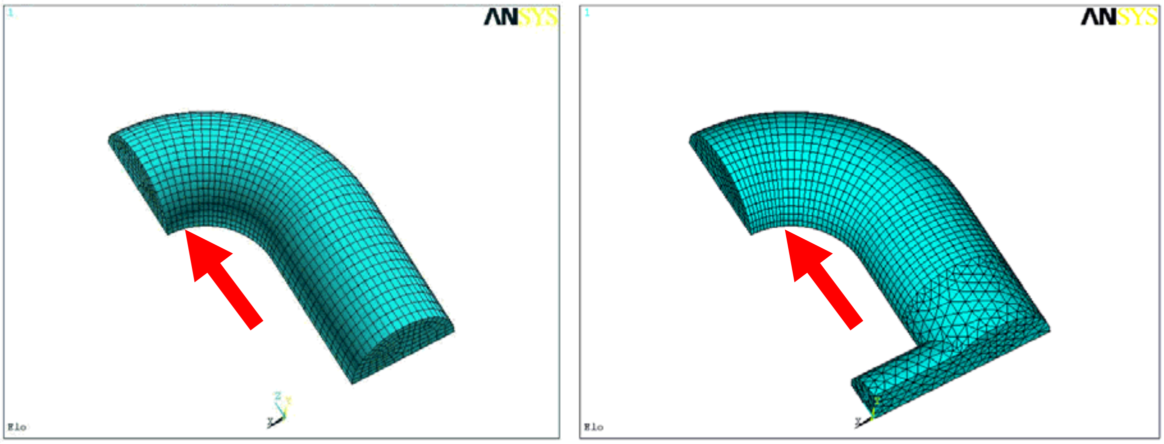
Model

The geometry of studless and stud chain links were designed in accordance with ABS recommendation [2]. For a circular section with diameter *d*, the length (*a*) is equal to 6*d* for both links and the maximum width (*c*) is 3.35*d* (studless link) and 3.6*d* (stud link), as presented in Fig. 1(B). For the presented simulations a simplified model was adopted considering the width for both links equal to 3.3*d*, as proposed by Papazoglou *et al.* [3].

Elastic models for studless and stud chain links were developed making use of 3D solid finite element. In order to simplify the analysis, three planes of symmetry were considered, as shown in Fig. 2. The numerical simulations were performed with ANSYS 5.6 [4] finite element code. The elements SOLID 92 with 10 nodes (3 degrees of freedom per node) and SOLID 95 with 20 nodes (3 degrees of freedom per node) were selected for the simulations. The final meshes were defined after a convergence study.

A pressure distribution applied at the contact area between the chain link and the other mooring line components was adopted to simulate the loading condition, as shown in Fig. 2. The pressure value was assumed to be equivalent to the total load acting in the region. An angle of 25 degrees with the axial direction was selected to represent the contact area between the chain link and the mooring line according to Papazoglou's model [3], which recommends this angle for simulating offshore chain link connection in axial loading.

In the proposed model symmetry boundary conditions were applied to the three planes of symmetry. The elastic model proposed did not capture local plastic deformation normally observed in mechanical components. Considering that the localized plastic deformation promotes stress redistribution, the stresses predicted by the proposed model presented values higher than the actual ones.



(A) (B)

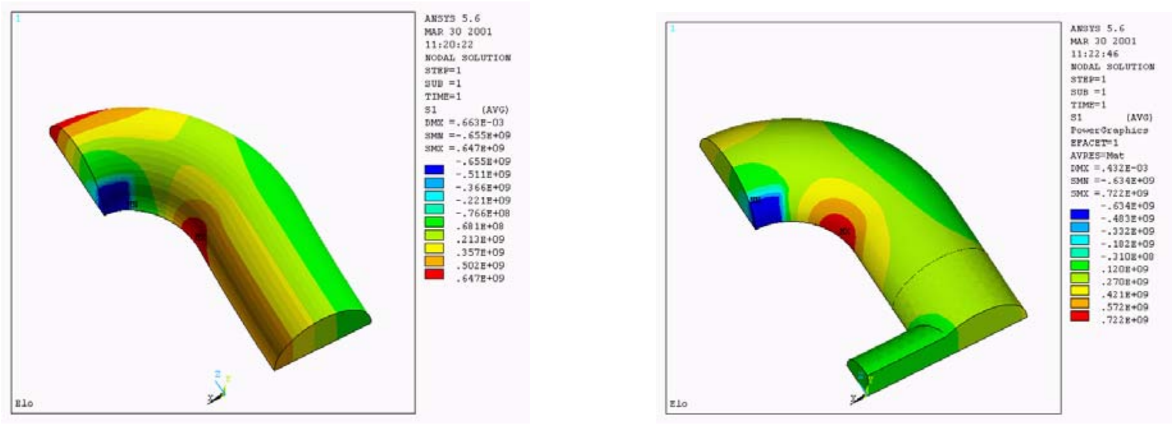
FIGURE 2. Geometries and meshes adopted for the analyses of the studless (A) and stud chain links (B).

Numerical Simulations

Numerical simulations were developed to determine the stress distribution promoted by the axial loading in the studless and stud chain links with a diameter of 76 mm. Concerning the material's properties, the yield strength, tensile strength, elastic modulus and Poisson's coefficient were selected equivalent to 570 MPa, 720 MPa, 200 GPa and 0.29, respectively. The maximum loading condition for both mooring chain geometries was assumed equal to 1.5 MN, which represents the maximal probabilistic environmental loading for period of ten years on a drilling offshore platform [5].

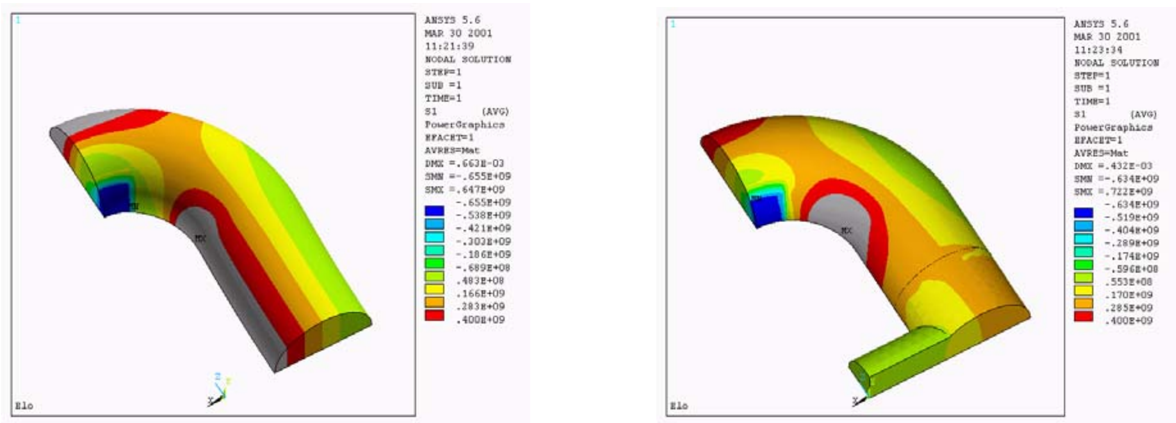
The maximum principal stress (σ_1) distributions for the mooring chain links are presented by Fig. 3. It can be observed that the stud chain link presents a higher value of σ_1 than the studless link. However, the amount of material subjected to higher stresses is smaller. This observation is reinforced by Fig. 4, where the grey regions represent areas where the stress value is higher than 400 MPa. The chain link volumes related to maximum principal stresses higher than 400 MPa, as well as higher than 200 MPa, are presented in Table 1. These volumes are considered critical volumes in the sense that critical crack length can be associated to these values of stress.

The simple observation of Table 1 reveals that there is no significant difference between the critical volumes of studless and stud chain links associated with maximum principal stresses higher than 200 MPa. However, considering maximum principal stresses higher than 400 MPa, the critical volume of studless chain links is about three times the critical volume related to the stud chain links.



(A) (B)

FIGURE 3. Maximum principal stresses for studless (A) and stud chain links (B).



(A) (B)

FIGURE 4. Maximum principal stresses smaller than 400 MPa for studless (A) and stud chain links (B).

TABLE 1. Critical volumes of the chain links subjected to maximum principal stresses.

	σ_1 > 200 MPa		σ_1 > 400 MPa	
	studless link	stud link	studless link	Stud link
Critical volume / m^3	2.7×10^{-4}	2.3×10^{-4}	6.3×10^{-5}	2.0×10^{-5}

Crack Assessment

Considering the maximum principal stresses calculated by the finite element approach, three different regions (critical regions) of the studless and stud chain links were subjected to a crack assessment related to brittle fracture of the mooring component. Two of these regions were located in the base material (sections A and B) while the third one was situated in the weld region of the link (section WL). The critical regions and respective positions of brittle fracture analysis are presented in Fig. 6.

The crack assessment was performed on the basis of the BS 7910 Procedure [6], making use of equation (1), and the CTOD Design Curve Approach [7], based on equations (2) and (3):

$$\bar{a}_{\max} = 24764\, d^{3.25}\, S_y^{0.5}\, (SCF\, T)^{-1.5}\, \delta_c \qquad (1)$$

$$\bar{a}_{\max} = \frac{\delta_c E S_y}{2\pi \sigma^2} \qquad \text{if} \quad \frac{\sigma}{S_y} \le 0,5 \qquad (2)$$

$$\bar{a}_{\max} = \frac{\delta_c E}{2\pi(\sigma - 0,25 S_y)} \qquad \text{if} \quad \frac{\sigma}{S_y} > 0,5 \qquad (3)$$

where:

$\bar{a}_{\max}$ = critical crack length; T = load applied to the link; d = nominal diameter of the chain link; δ_c = critical CTOD of the material; S_y = yield strength of the material; E = Young modulus; SCF = stress concentration factor and σ = elastic stresses acting at the crack tip.

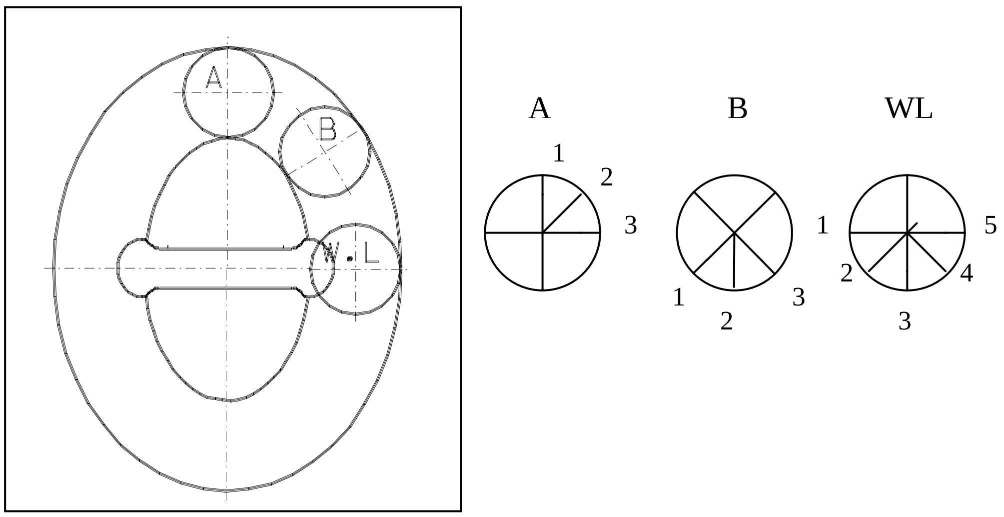


FIGURE 6. Critical regions and respective positions of brittle fracture analysis in studless and stud chain links.

For the evaluation of the critical crack sizes, the values of d, S_y, T and E were the same values adopted for the numerical stress analysis. The SCF was defined as the ratio between the maximum principal stress at the analysed position and the nominal stress (165 MPa). The values of δ_c was considered as 0.12 mm and 0.20 mm for the weld region and base material, respectively, according to API recommendation [5]. Finally, the values of σ were assumed as the values of σ_1 at each position. Table 2 presents the values of critical crack lengths according to BS 7910 document, $(a_{max})1$, and CTOD Design Curve approach, $(a_{max})2$, for studless and stud chain links.

TABLE 2. Critical crack lengths evaluated to studless and stud chain links.

Position of analysis	Studless Chain Link				Stud Chain Link			
	σ_1 / MPa	*SCF*	$(a_{max})1$ / mm	$(a_{max})2$ / mm	σ_1 (MPa)	*SCF*	$(a_{max})1$ / mm	$(a_{max})2$ / mm
A1	636	3.9	11.1	12.9	412	2.5	21.2	23.6
A2	556	3.4	13.5	15.4	372	2.3	24.7	27.7
A3	211	1.3	57.9	> 76	191	1.2	67.2	> 76
B1	647	4.0	10.8	12.6	722	4.5	9.1	11.0
B2	437	2.7	19.4	21.6	462	2.9	17.9	19.9
B3	133	0.8	> 76	> 76	120	0.7	> 76	> 76
WL1	485	3.0	10.0	11.2	186	1.2	41.9	62.9
WL2	391	2.4	13.8	15.4	262	1.6	25.1	31.7
WL3	162	1.0	51.6	> 76	286	1.8	22.0	26.6

Discussion of Results

Table 2 indicates that the smallest values of $(a_{max})1$ and $(a_{max})2$ concerning the base material of the studless chain link are located at the positions A1 and B1, where the *von Mises* stresses are 636 MPa and 613 MPa, respectively, according to Paiva *et al*. [8]. Both stresses are higher than the yield strength of the material (570 MPa) due to the linear-elastic analysis carried out at the numerical simulations, which could not predict any plastic deformation. Therefore, the calculated critical crack lengths at the positions A1 and B1 should be considered as conservative brittle fracture parameters in virtue of the linear elastic approach.

As one might expect, the most critical region of studless chain link is related to the welded joint (position WL1), which shows the smallest predicted values of $(a_{max})1$ and $(a_{max})2$. The fact that smallest values of critical crack lengths are associated with the weld region is caused by the recommendation that this region has the smallest CTOD value allowed to the whole chain link [5] as well as by the presence of relatively high stresses. On the other hand, the crack assessment performed at the positions A3 and WL3 by CTOD Design Curve approach, as well as at the position B3 by both methodologies, leads to crack sizes larger than the link diameter. It means that the loading condition selected for this crack assessment does not promote the brittle fracture of the studless chain link at the positions A3, B3 and WL3.

Another important observation with regard to Table 2 is that the crack assessment carried out on the studless chain link by means of the BS 7910 procedure is more conservative than that related to the CTOD Design Curve approach, on the basis that the first methodology predicts values of critical crack lengths, (a_{max})1, which are smaller than the second one, (a_{max})2.

One can observe from Table 2 that the smallest values of the critical crack sizes concerning the whole stud chain link are related to position B1, in which the *von Mises* stress has a value of 681 MPa [8]. The argument that the numerical analysis was carried out making use of a linear-elastic model might be adopted once more to explain the calculation of *von Mises* stresses higher than the yield strength of the material.

The analysis of Table 2 shows that the welded joint is not the most critical region of stud chain link regarding the possibility of brittle fracture, on the basis that this region does not present the smallest predicted values of critical crack lengths. The presence of a stud modifies the link geometry and restricts the bending in the welded region; this restriction of bending results in a reduction of the stress intensity. On the other hand, bending acts together with tension in region B, a fact that gives to this region the highest calculated values of the maximum principal stresses and, consequently, the smallest values of (a_{max})1 and (a_{max})2.

The crack assessment carried out on the stud chain link at the position A3 by CTOD Design Curve approach, as well as at the position B3 by both methodologies, leads to crack sizes larger than the link diameter, similar to the studless chain link. For this reason, it is assumed that the mentioned positions will not present brittle fracture considering the present loading condition. As discussed earlier, the analysis of Table 2 evidences that the crack assessment evaluated by means of the BS 7910 procedure gives more conservative values of critical crack sizes in comparison to that predicted by CTOD Design Curve approach.

Table 3 summarizes the evaluation of structural integrity carried out on R3 grade chain links with a nominal diameter of 76 mm. The critical volumes and minimum critical crack lengths (a_{max}) for the base material (BM) and weld region (WL) are given as functions of the maximum principal stresses which act on the mooring components.

TABLE 3**.** Critical volumes and minimum critical crack lengths of the chain links subjected to maximum principal stresses.

σ_1 / MPa	Studless Chain Links			Stud Chain Links		
	Critical volume / m^3	a_{max} / mm		Critical volume / m^3	a_{max} / mm	
		BM	WM		BM	WM
> 200	2.7 x 10^{-4}	10.8	10.0	2.3 x 10^{-4}	9.1	22.0
> 400	6.3 x 10^{-5}	10.8	10.0	2.0 x 10^{-5}	9.1	22.0

Table 3 shows that the minimum critical crack length (9.1 mm) related to the brittle fracture assessment of both chain links corresponds to the base material of the stud chain link. However, the minimum critical crack length of the studless chain link (10.0 mm) is associated with a larger critical volume of material under high tensile stresses and, therefore, this critical combination turns the studless chain link more susceptible to brittle fracture than the stud chain link.

Conclusions

A structural integrity analysis of studless and stud chain links was performed. The results of the finite element stress analyses as well as the critical crack length assessment lead to the following conclusions:

- The critical volume related to the maximum principal stresses higher than 400 MPa of the studless chain links is about three times the critical volume corresponding to the stud chain links.
- Considering the studless chain links, the welded joint seems to be the critical region concerning brittle fracture, due to the fact that this region has relatively high stresses and the smallest critical CTOD value allowed to the whole chain link.
- With regard to the stud chain links, the welded joint is not a critical region for brittle fracture occurrence. The presence of a stud reduces the stress state acting in this region. The critical region is located close to the curvature of the chain link, where the smallest values of critical crack length were predicted.
- The crack assessment carried out on mooring chain links by BS 7910 leads to more conservative results than that performed by CTOD Design Curve approach. Premature maintenance may occur taking into account critical crack sizes predicted on the basis of the first approach.

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