FATIGUE ANALYSIS OF LAZY-WAVE STEEL RISERS

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Abstract. *A lazy-wave configuration appears as an alternative to steel catenary free hanging risers in deepwater oil exploitation since this configuration can reduce loads and increase fatigue life. However, many design cycles must be done to obtain a feasible configuration for the riser. In each design cycle, several geometric configurations must be analyzed. If a lazy-wave solution is considered, there are many parameters to be varied to achieve the best configuration resulting on thousands of geometric configurations to be analyzed, considering both extreme and fatigue loading conditions. So a very great number of analyses must be carried on. Among those configurations many are not geometrically possible and others don't meet some design restrictions such as top angle limits, tension ranges and curvature radius values, reducing the total number of cases to be considered. This paper presents the methodology used in fatigue analyses of a lazy-wave steel riser, considering a pre-selected group of configurations. It aims to analyze and approve configurations according to some pre-defined fatigue criteria, such as fatigue life at TDP. The inputs for these analyses are configurations that are geometrically possible and approved by static and dynamic analyses under extreme loads. The simplified fatigue models that were developed are presented and a case study is performed focusing on its results and the "best" configuration choice.*

Keywords*: Fatigue, risers, Lazy-Wave.*

1. Introduction

As any other structure submitted to cyclic loads, steel risers will be susceptible to failure due to a fatigue process. Therefore, considering that an oil exploitation unit has a desired production life between 20 and 30 years, the risers have to be designed to ensure a greater fatigue life.

When an offshore oil exploitation is considered it's clear the importance of a correct fatigue life estimation since a riser collapse will lead to significant environmental and economical losses.

As offshore oil production has moved to deeper water, steel catenary free hanging risers could be no more feasible, due to high top loads and fatigue damage. A lazy-wave configuration appears as an alternative to reduce loads and increase fatigue life as can be seen in Jacob et al. (1999). However, in each design cycle, several geometric configurations must be analyzed (Roveri et al. 2005). There are many parameters to be varied to achieve the best configuration, for instance, the total length, the length of each segment and the floaters data, resulting on thousands of geometric configurations to be analyzed, considering both extreme and fatigue loading conditions. So a very great number of analyses must be carried on.

This paper presents a parametric methodology implemented on a computer tool, to be used mainly in the first design cycle of a lazy-wave riser. The main purpose here is to discuss the fatigue analysis and its results performing a case study.

2. Purpose and Sequence of Analysis

Given the riser data (material data, diameter, thickness, etc.), the top vertical coordinate D and the horizontal projection H of the riser, a lazy-wave configuration is considered, in this work, to be composed by three segments of lengths L_1, L_2 and L_3 as in Fig. 1. The second segment, of length L_2 has floaters with external diameter D_f, length L_f and pitch S_f (Fig. 1). At a first glance, it is not easy to determine the combinations of ranges for those parameters that make the lazy-wave feasible from a geometric viewpoint, that is, the configurations in which the whole riser is in tension.

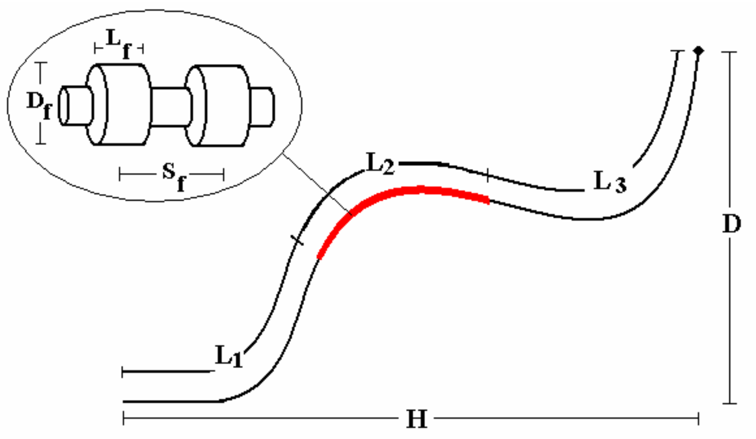

Figure 1 . Lazy-wave configuration and floater data (in detail)

To help this process it was implemented a parametric analysis in which all the parameters, L_1, L_2, L_3, D_f, L_f and S_f, were varied within a pre-defined range of values. This analysis tries to build a lazy-wave for each one of the parameters value combinations, resulting on a set of possible geometric configurations. For each one of those possible configurations a set of design criteria is applied to select the approved ones.

This process is shown in Fig. 2. First the "neutral" analysis is run, its results are then verified against a set of design limits for tension, top angle, etc. In the sequence the static analysis is run only for the configurations that were approved in the "neutral" analysis and so on for dynamic, internal and fatigue analyses. The "best" configuration can be found among the possible configurations.

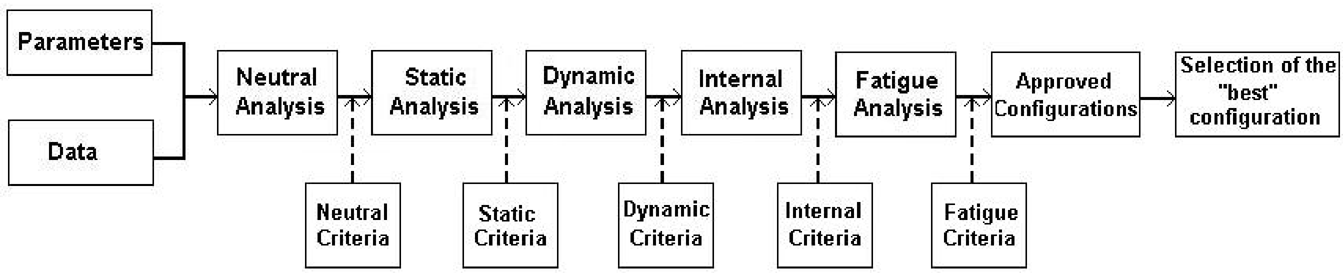

Figure 2 . Flow chart of the analyses

To make feasible all the process in a short time, simplified models were employed. The simplifications made, however, do not invalidate the comparison between the configurations, the mainly assumptions are briefly discussed in the following.

A neutral configuration is a geometric configuration assumed by the riser when it is submitted only to gravity and hydrostatic loads and it is considered geometrically feasible if it is in tension for the whole length. Given the riser data and its vertical and horizontal projection, it is completely defined by a set of values for the parameters L_1, L_2, L_3, D_f, L_f and S_f. The possible configurations obtained are then verified against a set of design values. The configurations that meet those criteria are the approved neutral configurations.

In the static analysis the approved neutral configurations are submitted to a set of static load cases each one including a current velocity profile and a floating unit offset. The results for all possible configurations are compared once more against a set of design limits, which are not necessarily the same as for the neutral analysis, resulting on the approved static configurations.

In the dynamic analysis only the configurations approved in the static analysis are considered. Besides currents and offsets, the load cases now include also extreme waves and floating unit motions (RAO). The model that was adopted for the dynamic analysis considers the riser firstly as a perfectly flexible cable ringed at the top and at the static touchdown point and the motion as a small perturbation of the static configuration around which it is linearized. The dynamic equations are made discrete by means of a finite element model. The problem is then solved in the frequency domain. The viscous damping is linearized iteratively, maintaining the same dissipated energy as in the nonlinear model. Later the bending stiffness effect and the touchdown motion are incorporated by means of a boundary layer model. The results are verified against a set of some dynamic design criteria to select the feasible configurations.

In the internal analysis it is verified the stress level along the riser for all the configurations that were approved on the dynamic analysis. It is made again a selection; being approved the configurations for which a predefined design value is not surpassed.

In the fatigue analysis it is verified the fatigue life for all the configurations that were approved in the previous analyses (neutral, static, dynamic and internal). A set of fatigue load cases are required, they include besides RAO, currents, offsets and waves in order to represent the environmental conditions responsible for the fatigue damage. In each hotspot it is adopted the cumulative damage Palmgren-Miner rule and a S-N curve. The fatigue life must surpass a pre-specified design value, that in general is 10 times greater than the fatigue life wanted, e.g 250 years for a production unit with 25 years of operational life.

The static and dynamic models are better explained in Silveira et al. (2005) and Tanaka et al. (2005) respectively. The fatigue model is presented in the next item.

3. Fatigue Model

The fatigue model needs as input the called load cases, which are a set of environmental conditions as floating unit offsets, currents and waves. Each one of these load cases has a occurrence probability and represents the sea states during the riser operational life, a scheme is presented on Fig. 3. For an adequate statistical representation more than ten load cases are commonly used. The floating unit second order movement is not considered in this model.

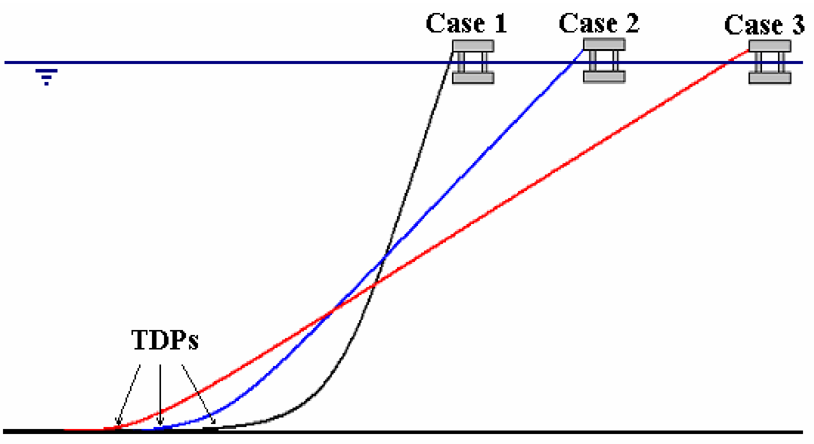

Figure 3 . Representation of sea states for the fatigue model

For the fatigue analysis the chosen hotspots were the static TDPs (touchdown points), for all load cases (Martins, C.A., et al. 1999). Among them, it was chosen the worst case, with less fatigue life. To calculate the damage at each sea state was used a S-N curve (DNV, 2001):

$$\log N = \log \bar{a} - m \log \Delta\sigma \tag{1}$$

being N the predicted number of cycles to failure for stress range $\Delta\sigma$, m the negative inverse slope of S-N curve and $\log \bar{a}$ the intercept of logN-axis by S-N curve.

Since the dynamic pipe wall stresses (σ_z) are calculated from the dynamic bending moments and the dynamic tension variations, the stress ranges are obtained from the global riser analysis:

$$\sigma_z = \frac{T_w}{A} \pm \frac{M}{2I}(D_0 - t) \tag{2}$$

where T_w is the wall tension, A is the cross-sectional area, M is the bending moment, I is the moment of inertia, D_0 is the outside diameter and t is the pipe wall thickness.

Once it was obtained the damage for each load case it is adopted the Palmgren-Miner rule:

$$D = \frac{n_1}{N_1} + ... + \frac{n_j}{N_j} = \sum_{k=1}^{j} \frac{n_k}{N_k} \quad (3)$$

where D is the cumulative damage, n_k is the number of cycles for the load case k and N_k is the number of cycles to the failure for the case k obtained from the S-N curve.

Equation (3) is used to obtain the cumulative damage at each TDP and so to add the effect of all the cases. The estimated fatigue life is equal to the inverse of the annual damage generated by the fatigue loads. The procedure used here agrees with that suggested in DNV (2001) and API (1998).

4. Case Study

The parametric analysis was applied to a lazy-wave steel riser focusing on the fatigue analysis results. This riser is assumed to be installed in a 1255m water depth. It was carried an analysis where only the segment lengths L_1, L_2 and L_3 (Fig. 1) where varied. The floaters data were kept constant and the riser is supposed to be attached to a semi-submersible platform. The used RAO is for operational draft of 27.5m.

4.1. Riser Data

Material: API 5L X-65 steel
Thickness: 2.54 cm
Ultimate strength: 530.72 MPa
Specific weight in water: 0.85 kN/m
Vertical projection (D): 1248m
External diameter: 45.72 cm
Yield strength: 448.32 MPa
Specific weight in air: 3.82 kN/m
Horizontal projection (H): 2340m
S-N curves: B1, C, E (DNV, 2001)

4.2. Floaters Data (see Fig. 1)

Length (L_f) : 1.30m
Pitch (S_f) : 2.00 m
Diameter (D_f) : 1.37m
Density: 501 kg/m^3

4.3. Parameters Range

The following range for the segment lengths were considered, given a total of 3150 neutral configurations:
400m < L_1 < 3000m – divided in 21 cases
1m < L_2 < 2000m – divided in 10 cases
1m < L_3 < 2500m – divided in 15 cases

5. Analysis Results

Among all the configurations considered in the "neutral" analysis, only 582 were geometrically feasible. With all the geometric configurations in hands, it is easy to select those that meet some design specifications but here no design specifications were chosen. Then the 582 feasible configurations were submitted to the static analysis.

For static analysis eight load cases were considered, with vessel offsets of 5% water depth aligned to centenary current profiles. Figure 4 shows a scheme of the current directions adopted for each load case.

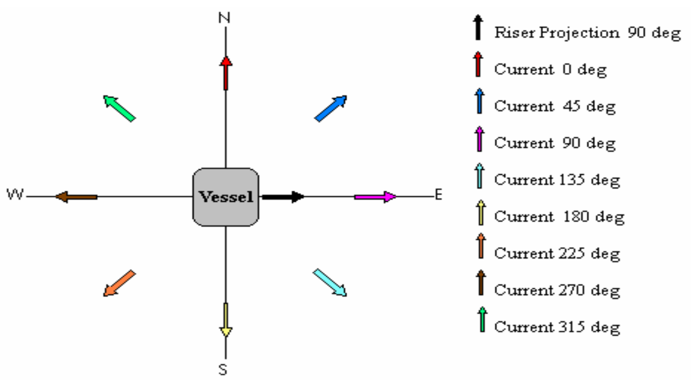

Figure 4 – Scheme of static load cases

As all the feasible configurations were submitted to the static analysis, 4656 cases were statically analyzed, resulting 293 possible configurations.

For dynamic load cases it was used the same logic as for the static load cases, decennary waves were aligned to centenary currents and centenary waves were aligned to decennary currents. Vessel offsets were 3.5% of water depth aligned to the current profiles.

For dynamic analysis 16 load cases were considered for each configuration, resulting 4688 cases. After this analysis there were 252 possible configurations. Considering a design criteria - for the top angle - of 30 degrees there were 182 configurations approved for next analysis.

In internal analysis, von Mises equivalent stress is calculated for all configurations, approved in the previous analysis, at the touchdown region and at the top including both static and dynamic loadings. In this analysis no design criteria were chosen so we still have 182 configurations for the fatigue analysis. For each approved configurations in the internal analysis, they were considered 85 fatigue load cases (see tab. 1).

After the fatigue analysis, 121 configurations were possible but considering a design fatigue life of 200 years and DNV E curve, it results in 50 approved configurations. Fatigue life presented in the following figures is the result obtained for each configuration calculated for the TDP.

Table 1. Fatigue Load Cases

Case	Current at sea surface		Offset		Wave 1 (JONSWAP)			Wave 2 (JONSWAP)			Occurrence (%)
	speed (m/s)	direction (deg.)	%WD	direction (deg.)	direction (deg.)	Hs (m)	Tp(s)	direction (deg.)	Hs (m)	Tp (s)	
1	0.15	135	0.25	21.0	45	3.25	16.30	153	1.20	5.80	0.02
2	0.15	135	0.46	1.8	0	5.25	15.53	7	1.43	8.40	0.06
3	0.35	90	2.01	56.8	45	4.75	14.22	24	2.24	7.90	0.10
4	0.25	225	0.67	10.1	45	6.75	13.70	------	-----	-----	0.02
5	0.35	135	1.55	71.1	45	4.25	12.67	23	1.44	5.84	0.43
6	0.25	225	1.23	310.1	0	3.25	12.11	353	1.40	6.01	0.43
7	0.35	180	0.65	237.8	45	3.25	11.96	22	1.09	5.78	0.41
8	0.45	180	0.93	232.5	0	2.75	11.80	353	1.14	5.77	1.21
9	0.35	225	1.43	276.5	0	2.25	11.80	298	1.07	5.78	0.70
10	0.45	180	1.90	209.0	0	1.75	11.73	211	1.11	5.93	1.05
11	0.35	90	2.25	61.7	45	3.75	11.69	38	1.48	6.14	0.45
12	0.45	180	1.81	221.2	0	1.75	11.66	260	0.97	5.48	1.89
13	0.35	180	0.30	187.8	45	2.75	11.59	16	1.15	6.08	0.72
14	0.35	180	1.14	214.1	0	2.25	11.46	272	1.06	5.62	0.45
15	0.45	180	1.54	265.2	0	2.25	11.37	349	1.16	6.18	1.91
16	0.45	180	1.66	226.8	0	2.25	11.32	342	1.05	6.75	1.05
17	0.45	225	2.19	267.2	0	1.75	11.28	278	0.84	5.52	1.11
18	0.35	135	1.78	70.4	45	3.25	11.18	27	1.28	6.19	0.49
19	0.45	135	0.78	126.7	0	2.25	11.15	312	1.30	5.83	0.51
20	0.45	180	1.04	84.4	0	2.75	11.09	1	1.48	6.15	0.74
21	0.45	180	2.00	208.5	0	1.25	11.09	206	0.93	5.36	1.50
22	0.45	180	0.84	237.7	45	2.25	11.08	7	1.13	6.47	0.47
23	0.45	180	1.04	247.6	0	2.25	10.97	5	1.06	5.96	1.17
24	0.45	135	1.83	86.6	45	2.75	10.88	26	1.11	5.49	0.76
25	0.45	225	2.21	235.7	0	1.25	10.79	254	0.88	5.85	2.54
26	0.55	225	2.90	267.9	0	1.25	10.60	271	0.80	5.64	1.07
27	0.45	135	0.98	118.9	45	2.25	10.55	23	1.06	5.76	1.01
28	0.55	135	1.94	165.3	45	1.75	10.52	229	1.11	6.62	0.72
29	0.45	180	1.50	232.1	0	1.75	10.40	339	0.81	5.60	1.38
30	0.55	180	2.40	223.4	315	1.25	10.17	230	0.92	5.25	1.77
31	0.45	225	1.46	254.7	0	1.75	10.12	343	0.81	5.75	1.85
32	0.45	180	1.64	236.2	315	1.75	9.76	297	0.76	5.36	1.31
33	0.45	180	1.91	226.3	315	1.75	9.75	231	0.95	5.14	0.78
34	0.45	225	1.91	267.6	0	1.25	9.66	336	0.76	6.31	1.01
35	0.45	225	2.28	260.8	315	1.75	9.65	316	0.87	6.20	1.17
36	0.45	180	2.28	265.1	315	2.75	9.61	310	1.26	6.11	0.78
37	0.45	135	2.18	72.6	0	1.75	9.61	359	0.85	6.68	1.33
38	0.35	135	0.34	183.4	45	1.75	9.47	35	0.83	5.30	0.45
39	0.45	225	1.95	273.5	312	2.25	9.43	311	1.13	6.58	1.07
40	0.45	180	0.67	215.4	45	1.75	9.39	29	0.98	6.51	0.72
41	0.45	225	2.09	236.7	0	1.25	9.29	349	0.77	6.48	1.27
42	0.45	135	1.65	80.9	0	1.25	9.15	347	0.75	7.16	0.98
43	0.45	180	2.40	223.4	315	1.25	9.02	306	0.66	7.12	1.29
44	0.35	225	1.90	276.4	315	1.25	8.93	305	0.67	6.51	1.35
45	0.35	225	1.25	273.5	315	1.75	8.91	345	0.90	6.72	0.45
46	0.55	180	3.55	252.3	270	2.75	8.89	269	1.13	5.35	0.53
47	0.55	180	2.54	243.0	225	1.75	8.67	245	0.90	5.06	0.59
48	0.45	225	0.85	170.7	315	1.25	8.64	329	0.68	5.44	0.92
49	0.55	180	1.59	180.2	270	1.25	8.63	254	0.59	5.21	0.59

50	0.45	225	2.91	253.0	270	2.25	8.53	274	1.03	5.20	1.37
51	0.35	225	1.73	285.0	270	1.25	8.53	247	0.60	4.77	0.64
52	0.45	180	2.74	224.1	270	2.25	8.33	248	1.01	4.87	0.78
53	0.35	225	1.40	244.4	270	1.75	8.32	257	0.79	5.30	0.47
54	0.45	180	2.65	228.8	270	1.75	8.31	210	0.93	5.04	0.62
55	0.45	225	2.21	254.8	270	1.75	8.25	273	0.80	5.64	1.15
56	0.45	180	2.37	230.1	270	1.75	8.21	249	0.96	5.27	3.34
57	0.45	225	1.94	248.9	270	1.25	8.09	269	0.70	5.26	1.27
58	0.45	225	2.60	245.6	270	1.25	8.00	212	0.88	5.31	0.86
59	0.45	180	2.43	234.3	270	1.25	7.91	251	0.84	5.59	3.47
60	0.45	180	2.85	198.2	225	2.75	7.70	204	1.05	4.55	0.51
61	0.45	180	3.61	213.7	225	2.25	7.67	209	1.11	5.11	2.38
62	0.55	180	2.45	234.6	225	1.25	7.62	243	0.75	5.30	0.59
63	0.35	225	1.58	241.9	225	1.75	7.58	209	0.84	5.23	0.99
64	0.55	225	2.55	277.7	225	1.25	7.56	230	0.88	6.21	0.76
65	0.45	225	2.03	277.3	225	1.75	7.50	219	0.92	6.22	0.55
66	0.45	180	2.79	219.9	225	1.75	7.33	219	0.97	5.13	5.52
67	0.55	225	3.43	305.5	225	2.75	7.30	297	0.17	17.10	0.02
68	0.45	225	1.84	255.1	225	1.25	7.26	225	0.81	5.61	0.66
69	0.35	180	2.49	198.7	180	2.25	7.24	192	1.08	4.62	0.84
70	0.45	180	2.57	204.4	225	2.25	7.01	19	0.64	13.12	0.78
71	0.55	180	2.80	221.2	225	1.25	6.97	228	0.86	5.48	4.90
72	0.45	180	3.57	218.2	225	2.25	6.91	341	0.89	12.68	0.70
73	0.45	180	2.11	206.8	270	1.75	6.87	358	0.73	13.16	0.66
74	0.45	180	2.45	196.2	180	2.25	6.71	4	0.62	13.22	0.62
75	0.55	180	2.61	185.1	180	1.75	6.67	192	0.95	4.46	1.35
76	0.55	180	2.75	214.0	270	1.25	6.67	354	0.78	12.71	1.38
77	0.45	180	2.20	198.7	225	1.75	6.43	13	0.70	12.85	1.85
78	0.45	180	2.70	207.1	225	1.75	6.19	331	0.81	11.66	2.67
79	0.45	180	2.06	213.6	225	1.25	6.03	11	0.78	11.64	2.96
80	0.55	180	2.96	200.6	180	1.75	6.02	0	0.70	12.30	1.83
81	0.45	180	2.34	212.4	225	1.25	5.97	329	0.76	11.23	4.72
82	0.55	180	2.52	199.1	180	1.25	5.94	209	0.82	6.70	0.72
83	0.45	180	2.96	207.0	180	1.75	5.81	294	0.82	10.32	0.66
84	0.55	180	2.80	199.2	180	1.25	5.60	357	0.76	11.13	2.03
85	0.45	180	1.99	194.6	180	1.25	5.22	304	0.75	10.48	0.80

Attempting to find values that could guide the lazy-wave riser design the following figures were made. Figure 5 shows the parameters of the possible configurations after the fatigue analysis. The configurations were ordered by ascendent fatigue life, as in all the following figures. The purpose here was to verify the dependence on fatigue life of each segment length. Only a dependence on the second segment length (with floaters) was clear. Also from the figure, a shorter range for L_1 and L_3 could be chosen.

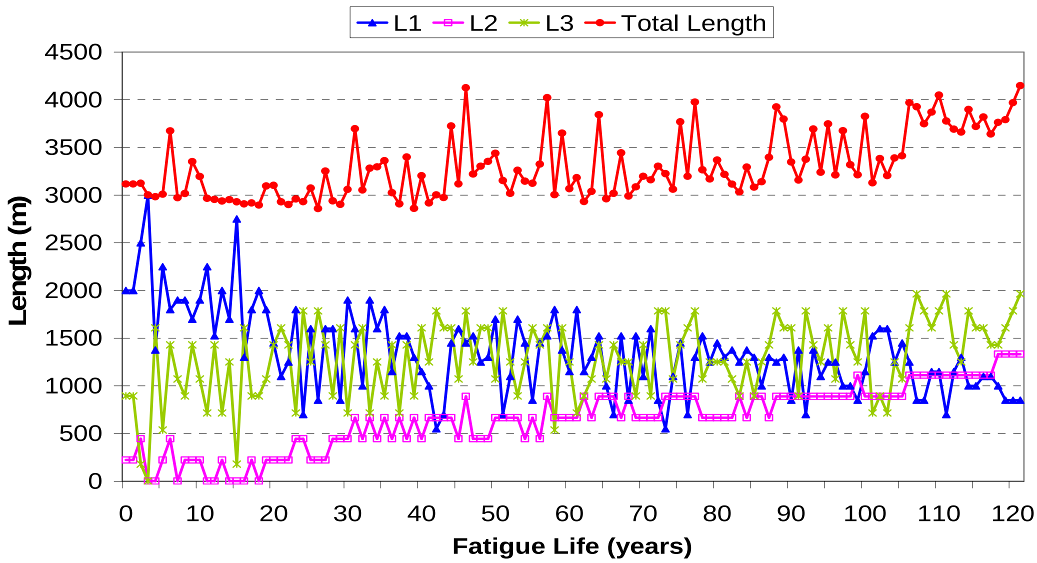

Figure 5 – Parameters of the possible configurations after fatigue analysis

Figure 6 shows the comparison among the results obtained with three SN curves, commonly used in risers design (DNV, 2001). The B1 curve is used for non-welded sections, C is for circunferencial butt weld dressed flush and the worst case is verified for the E curve that is for circunferencial butt weld made at site. Using a design limit of 200 years and E curve, 71 configurations were reproved while 53 and 43 were reproved for C and B1 curves respectively. The graphics were shortened because the others configurations had too great fatigue lives.

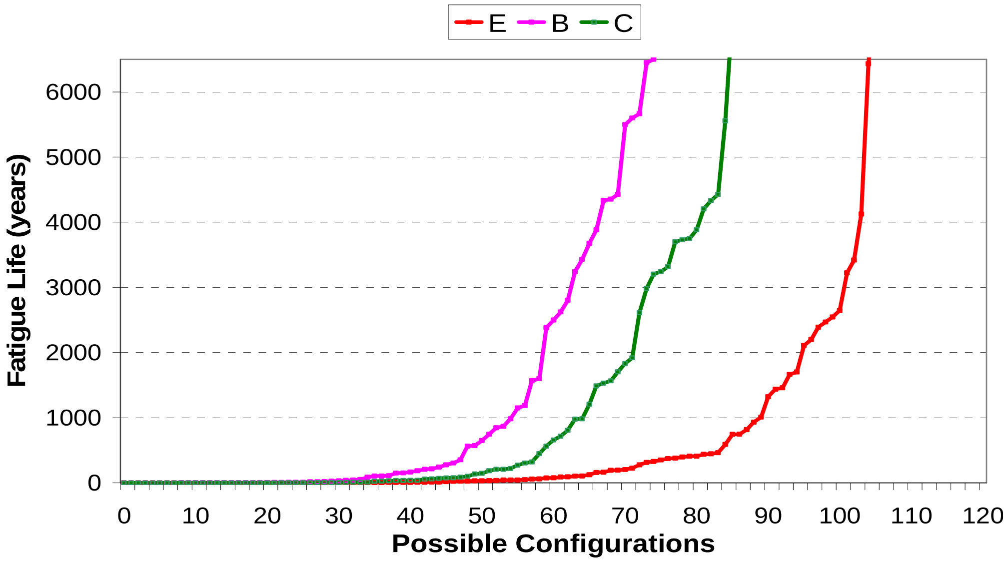

Figure 6 – SN curves comparison

The purpose of Fig. 7 is to show the relation between fatigue life and segment lengths ratio. In the first graphic it can be seen that for a ratio greater than 0.30 the fatigue life will be greater than 200 years. Being L_t the total length of the riser, at the second graphic a fatigue life greater than the design criteria is reached for a ratio greater than 0.25. The fatigue lives at Fig. 5, 7 and 8 were obtained with E curve.

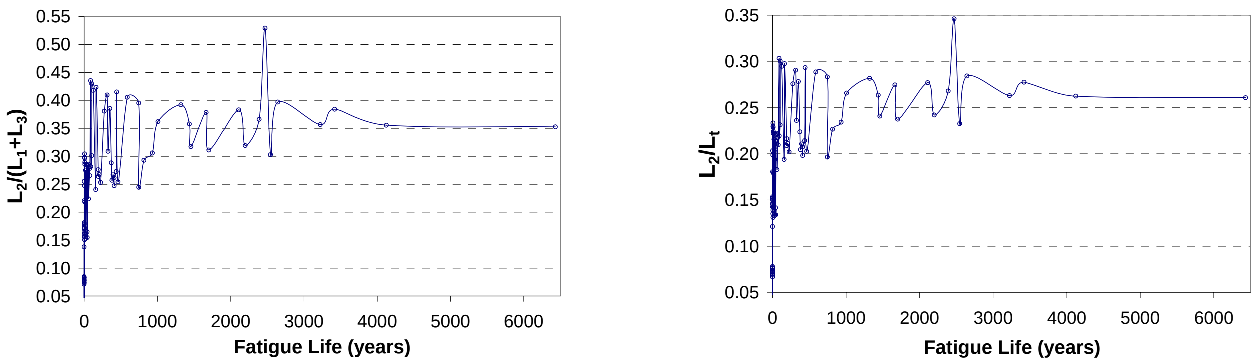

Figure 7 – Relation between fatigue life and segment lengths

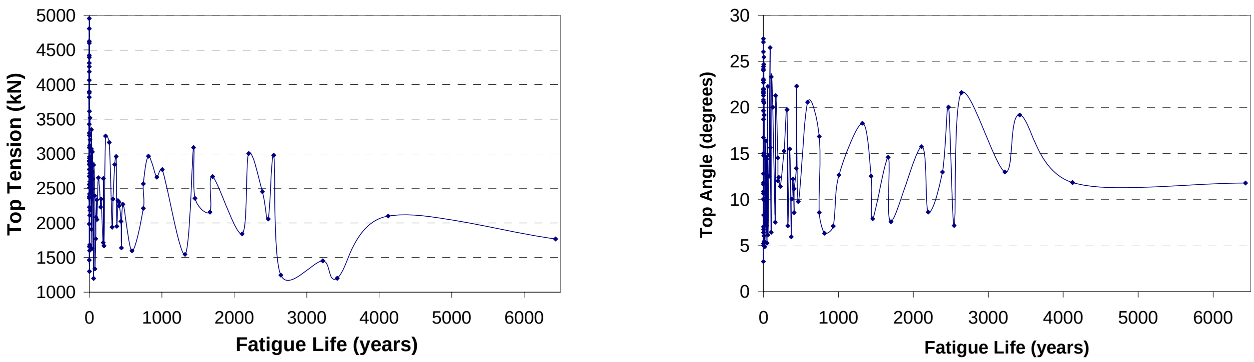

Figure 8 – Results for top tension and top angle

Figure 8 was made attempting to identify a relation between fatigue life and top tension or top angle values for the neutral configurations, what could be useful to establish design criteria and earlier reprove not promising cases. A clear relation wasn't identified but it can be observed that configurations with top tension greater than 3500 kN aren't promising.

The machine used to run all analyses was a 2.4 GHz Pentium 4 with 1 Mbyte RAM. After chosen the parameters range, all the analyses took about 45 processing hours to be run. The fatigue analysis alone was responsible for 24 processing hours.

Based on the, for instance, minimum damage criteria, a configuration could be selected to be studied at a more advanced level, using a software that executes time domain analysis.

6. Conclusions

A clear dependence on segment 2 length was verified for the riser fatigue life, for example, for a L_2 greater than 1000 m the fatigue life was greater than 6500 years. For global results such as top tension and top angle it wasn't found a clear relation with fatigue life. As expected, when the riser is welded fatigue life decreases substantially.

If desirable, the analysis can be redone using a finer mesh, but the range of possible values for the lengths of each segment will be known in advance. The approved configurations can now be studied with more accurate methods, and other problems, like VIV fatigue and riser installation, must be addressed, but the number of configurations to be analyzed will be significantly reduced.

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9. Responsibility notice