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SEISMIC RELIABILITY OF MARINE PLATFORMS WITH MECHANICAL DAMAGE

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SUMMARY

PEMEX has over 200 marine platforms and handles over 2.1 millions of oil barrels per day. Given the strong dependency of the national economy on the oil income, it is crucial to adequately protect these structures. In this paper a formulation to assess the global reliability of marine platforms including mechanical damages is proposed. Mechanical damages are dents, out of straightness, localized corrosion and cracking in some joints.

The study is based on a typical marine platform located on the Bay of Campeche, Mexico. In such structure the following analyses are performed:

1. Joints prone to fatigue failure are identified through a spectral analysis.
2. Damage magnitude is varied for dents, out of straightness and corrosion in order to identify the joints and members whose damages influences the most on the global reliability.
3. Global reliability index against earthquakes is estimated through an approximated reported expression [3]. The approximation is based on the base shear load and capacity of the platform.
4. A time-dependent global failure probability expression is developed to consider the presence of mechanical damage at the time of the earthquake. Previously reported (De Leon and Heredia, 2001) time-dependent probability distributions of damage magnitude for dents as well as out of straightness.

The formulation may be used to improve the practice and codes for Design and Assessment of Marine Platforms in Mexico.

INTRODUCTION

PEMEX (Petróleos Mexicanos) has an infrastructure for hydrocarbons exploitation on the Bay of Campeche, Mexico of more than 200 offshore jacket platforms and 1900 Km. of submarine pipelines. With these facilities it handles about 2.1 million of oil barrels per day and a gas production of 1500

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million of cubic feet per day. These production volumes rank the Bay of Campeche as one of the most important production regions in the world.
By considering the importance of these structures, it becomes crucial to make sure that they stay within the reliability thresholds stated in the code [1, 11] while they operate. Given the potential occurrence of earthquakes on the zone, an adequate seismic reliability should be provided to the platform design as a way to fulfill the safety measures to withstand earthquakes.
In order to account for the uncertainties associated with the seismic actions, as the base accelerations are unknown, as well as those related to the mathematical models to calculate the remaining strength of the damaged members, a structural reliability framework is applied. The failure probability is estimated, in this paper, in terms of the Cornell index which, in turn, depends on a reserve of strength defined through an expression typically used [3] to assess offshore jacket platforms.
The types of mechanical damages commonly observed on some members of offshore platforms are denting, out-of-straightness, corrosion and fatigue cracks. The first two types of damages are modeled through a set of relationships bending-axial load-curvature fitted to represent the remaining member capacity for any magnitude of damage [12]. The corrosion effect, commonly considered trough a reduction on the member thickness, it is indirectly included by an equivalent denting. The fatigue damage is modeled through a reduction on the steel yielding stress, according to the surfaces concept. In a previous work [9] the details of these models are described and the corresponding spectral fatigue analyses are usually performed to formally consider fatigue damage [5].
Finally the damage states producing the most significant reduction on the platform global reliability are identified and the damage level of damaged members with the major reduction on safety, are selected. Also, from inspection reports the occurrence probability of the above described mechanical damages are considered, as published earlier [4].

DESCRIPTION OF THE PLATFORM

The studied structure corresponds to a drilling platform installed in 1979 on the Bay of Campeche. It is a steel jacket structure built on a water depth of 45.1 m and it consists on superstructure, substructure, piles and typical accesories. Both, the superstructure and substructure have two longitudinal frames and four transverse frames. The superstructure contains two decks and the substructure has five horizontal frames. A typical longitudinal frame of the substructure is shown in Fig. 1. The corner piles penetrate 102 m under the marine soil whereas the others go up to 76 m. under the marine bottom.

RESERVE OF STRENGTH, CORNELL INDEX AND FAILURE PROBABILITY

The structural reliability C is estimated in terms of the global failure probability p_{fg}:

$$C = 1 - p_{fg} \tag{1}$$

The failure probability may be defined as the probability that, at a given time, the demand is larger than the resistance. Formally, this probability is formulated in terms of the joint distribution of the demand and the resistance or in terms of their marginal distributions if they are independent [2, 6]. Given the difficulty to get complete information to build the joint distribution, usually the formulation resorts on the

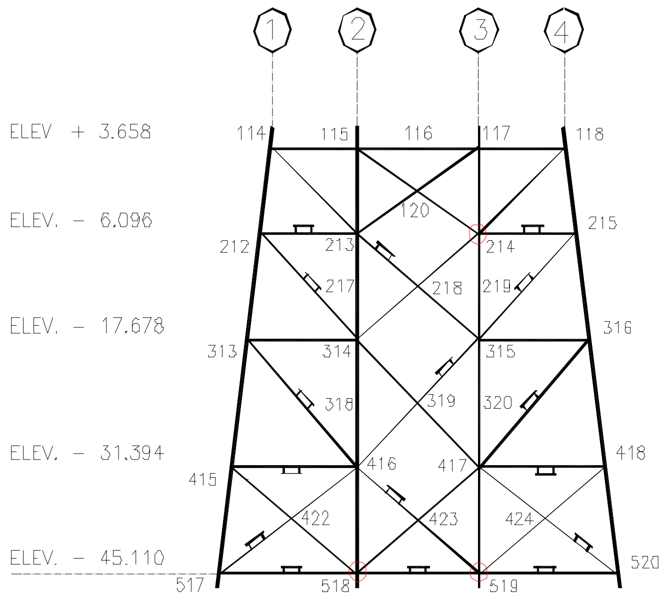


Figure 1. Substructure longitudinal frame, marking the critical fatigue joints [10].

first two statistical moments of the demand and resistance, namely, the mean and standard deviation.

In this paper, the only limit-state considered is the collapse event where the actual base shear force exceeds the corresponding resistance. In addition, an approximate relationship between the platform reserve of strength *RSR* and its Cornell index β, is followed to calculate the global failure probability. This formulation has the shortcomings of not considering other failure modes as joint fatigue, bracings buckling, etc. or service limit-states as excessive deformations or vibrations.
The global failure probability is related to the Cornell index through:

$$p_{fg} \approx \Phi(-\beta) \tag{2}$$

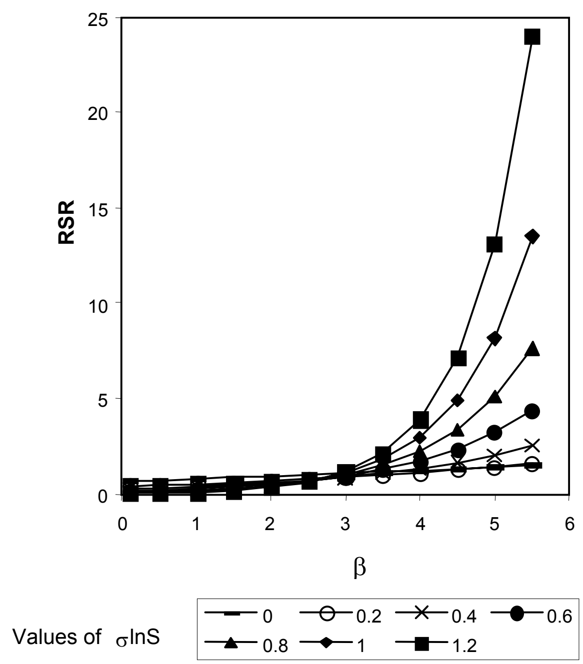
The relationship between RSR and β has been calibrated for the seismic biases and uncertainties on the Bay of Campeche and it is:

$$RSR = \frac{B_S}{B_R} 0.95 \exp(\beta\sigma - 2.57\sigma_{\ln S}) \tag{3}$$

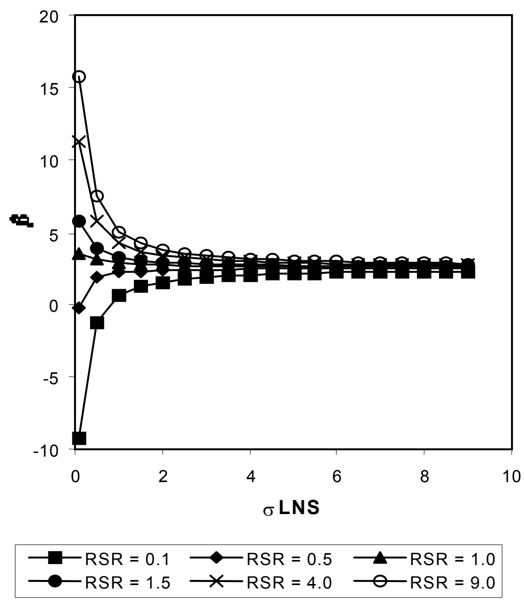
Where:
RSR= reserve strength ratio or global safety factor
σ = total uncertainty in the platform due to the seismic load and the resistance
σ_{lnS}= uncertainty on the seismic lateral load
B_S = Mean bias of the seismic lateral load
B_R = Mean bias of the platform lateral resistance
It has been suggested [3] σ = 1.21, σ_{lnS}= 1.2, B_S = 1.0 and B_R = 1.4

In this work, as suggested in the code developed for design and assessment of the platforms on the Bay of Campeche, [11], the *RSR* is defined as the ratio between the ultimate lateral platform capacity and a reference load, considered to be the 200 years return period earthquake. This reference load is obtained for the specific spectrum as proposed in the code [11].

A parametric analysis of Eq. (3) is performed to assess the sensitivity of the *RSR* respect to the probabilistic parameters involved. The results are shown in Fig. 2.

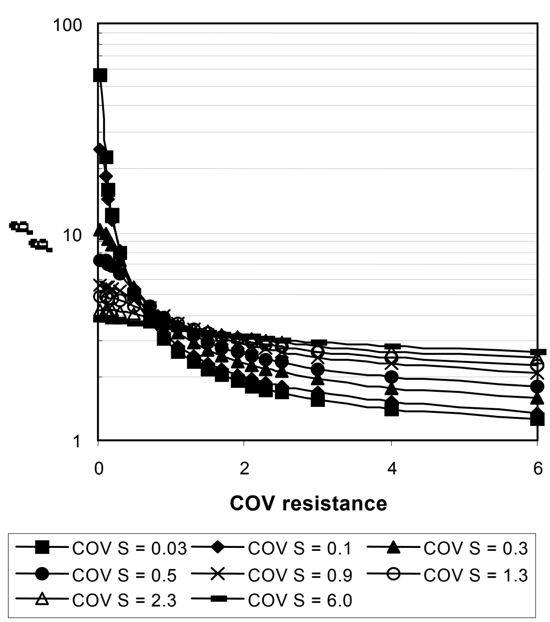


a)



b)

Figure 2. Parametric analysis of *RSR*. (a) *RSR* for several values of β and σ_{lnS}, if σ_{lnR} = 0.15. (b) β for several values of *RSR* and σ_{lnS} if σ_{lnR} = 0.15.



c)

Continuation of Fig. 2. Parametric analysis of *RSR* (c) β for several load and resistance *COV* if *RSR* = 6.4

According to fig. 2a), which is plotted for a resistance uncertainty σ_{lnR}= 0.15, β varies very little for σ_{lnS} < 0.2 whereas, for σ_{lnS} > 0.4 β has large variations for β > 3. The relevance of the load uncertainty σ_{lnS} deserves to be highlighted. For a new structure with β = 4.5, an *RSR* = 7.17 is required if σ_{lnS} = 1.2; however of σ_{lnS} = 0.2, the *RSR* requested would be 1.25. There is, therefore, an economical benefit for acquiring new knowledge about the expected seismic load to reduce σ_{lnS}.

From fig. 2b) it is observed that, for σ_{lnS} > 2, the variation of β is not significant for any *RSR*. Also, for σ_{lnS} < 1, β is very sensitive for any *RSR*.

In fig. 2c) it is shown that β is very sensitive for COV_R (coefficient of variation of the resistance) < 1 and COV_S (coefficient of variation of the seismic load) < 1 whereas, for other cases, its variation is small.

ULTIMATE RESISTANCE ANALYSIS INCLUDING DAMAGE

The reduction on member capacity for denting and out-of-straightness damages was previously described. For corrosion, in a previous work [8] was proposed the expression:

$$\delta / D = 1/2(1 - \cos\pi \frac{A_{corr}}{A}) \tag{4}$$

where: δ = equivalent denting depth, *D*= diameter of tubular section, A_{corr} = corroded transverse section and *A* = total cross section area.

Similarly, other studies, [13], Skallerud and Amdahl proposed the expression:

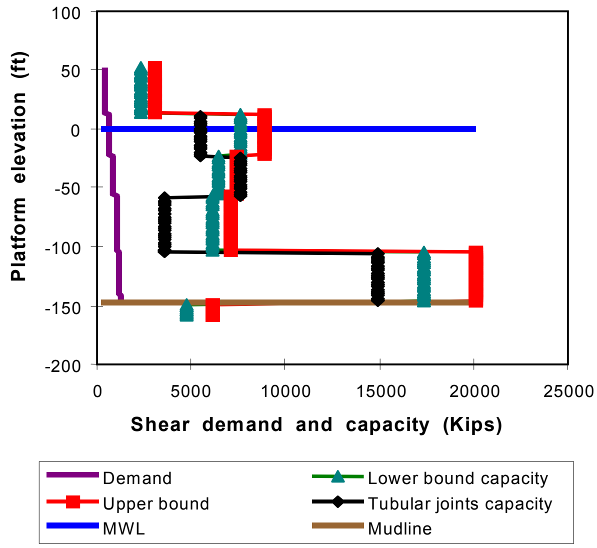
$$P_C = P_k(1 - \frac{A_{crack}}{A}) \tag{5}$$

where: P_C = remaining capacity of cracked joint, P_k = capacity of intact joint, A_{crack} = cracked area and *A* = full cross section area.

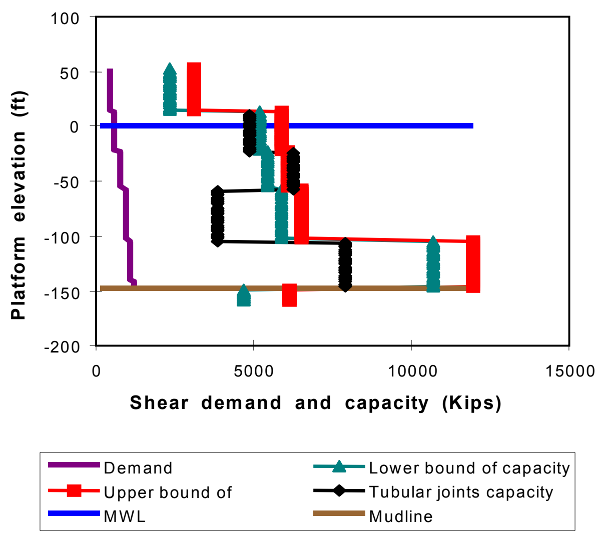
A commercial computer software [14] is used to determine the seismic loading, period and modal shapes by following a standard spectral mode method. Rigid base, shear deformations, rotational inertia negligible and mass concentrations at the superstructure level and between the substructure levels are assumptions made to simplify the analysis. The ultimate capacity of the components is calculated by considering the following failure modes:

a) simultaneous plastic hinges at both ends of the columns at any bay without restrains,
b) buckling or yielding of the diagonal bracings or joint collapse at the bracings end (a lower bound is calculated as the load making the weakest member to fail and an upper bound is based on the post-yielding and post-buckling strength of all members on the bay.
c) Simultaneous yielding of all piles.

Figure 3 shows the shear force demands and the component capacities for the longitudinal a) and transverse b) directions for the undamaged platform.



a)

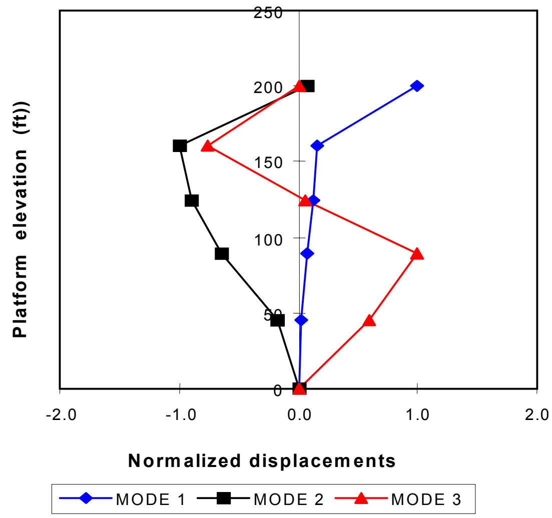


b)

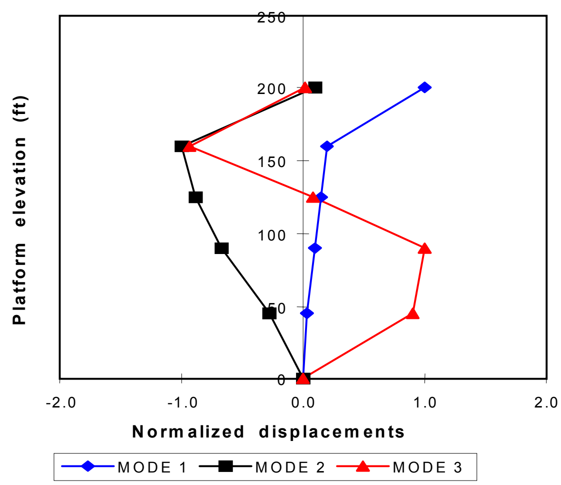
Figure 3. Shear demand and capacity for undamaged platform. (a) Longitudinal direction (b) Transverse direction.

It is observed that the transverse direction is critical for most of the bays and that the joint capacity for the 3rd. bay is significantly lower for both directions.

The first three modal shapes are shown in Fig. 4 for the undamaged platform in longitudinal a) and transverse b) directions.



a)



b)

Fig. 4. Modal shapes for undamaged platform. (a) Longitudinal direction (b) Transverse direction.

RESULTS

Near of 100 ultimate resistance analysis were performed for the platform transverse direction under different damage conditions. Damage states were modeled according to the occurrence probability and intensity of these damages as estimated in previous works where the corresponding probability distributions were determined for typical platforms on the Bay of Campeche. Denting and out-of-straightness were taken from De León and Heredia, 2001 [4] and joints cracking from Ortega and De

León, 2003 [10]. The maximum damage intensities were $\delta/D = 0.16$ for denting, $\Delta/L = 0.02$ for out-of-straightness and $A_{crack}/A = 0.30$ for joint cracking.

The global Cornell index β was estimated for seismic loading of the platform under given damaged conditions. The variations of the conditional reliability β for specified damage levels on specified bays, for out-of-straightness and denting, are shown in Figure 5. These damages were simultaneously applied on 1, 2 or 3 members where 3 damage levels were assumed, the same level for each member. Damage location was varied in the following way: out-of-straightness on bays 1 in Fig. 5a), 2 in Fig. 5b), 3 in Fig. 5c) and 4 in Fig. 5d); denting on bays 1 in Fig. 5e), 2 in Fig. 5f), 3 in Fig. 5g) and 4 in Fig. 5h).

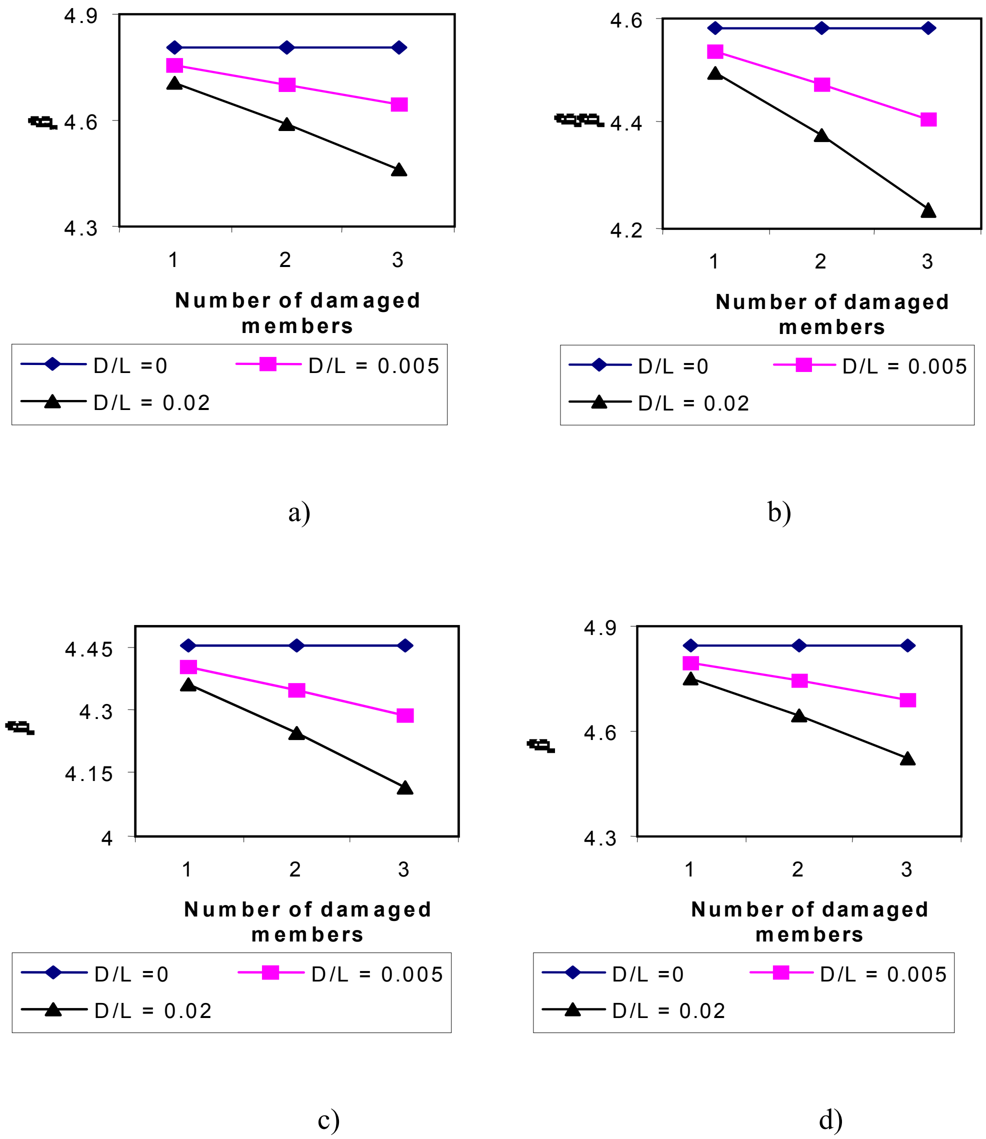
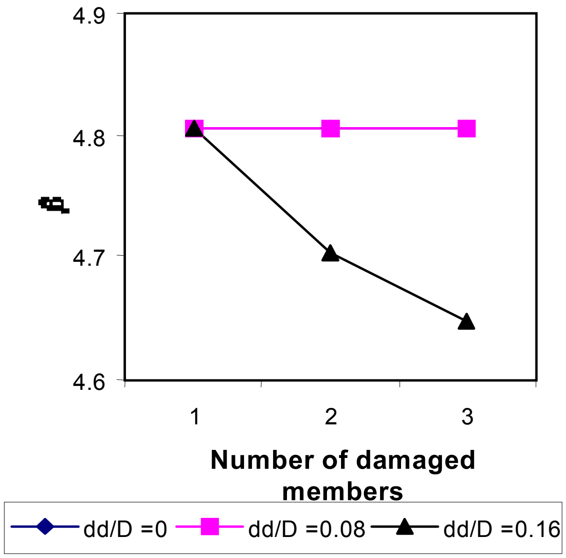
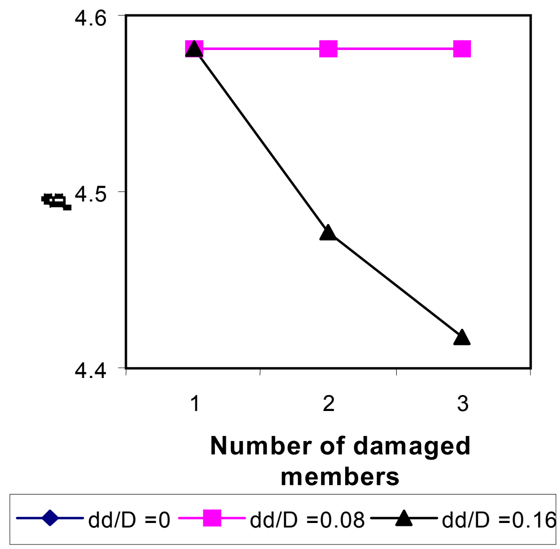


Figura 5. Variation of global β for several damage states, (a) out-of-straightness bay 1, (b) out-of-straightness bay 2, (c) out-of-straightness bay 3, (d) out-of-straightness bay 4.



e)



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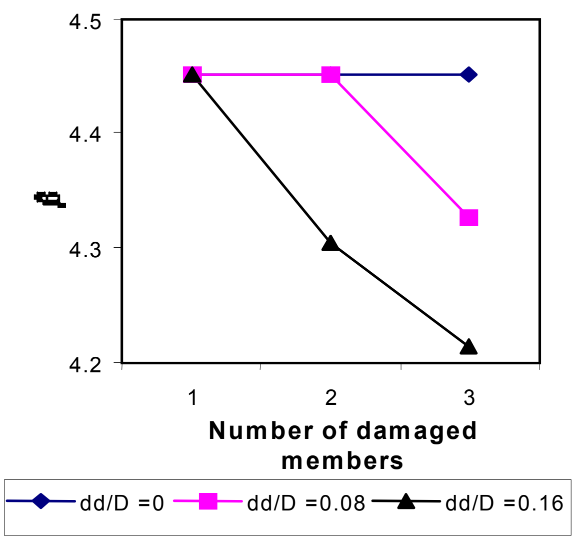

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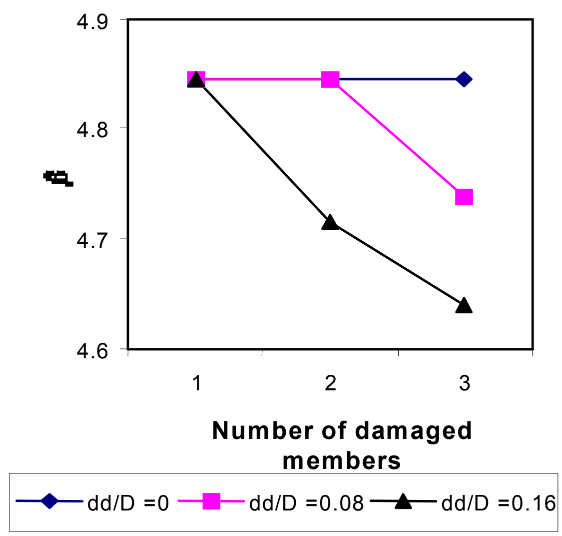

h)

Figure 5 Continuation. Variation of global β for several damage states (e) denting bay 1, (f) denting bay 2, (g) denting bay 3 and (h) denting bay 4.

It is observed that denting damage does not reduces significantly the global reliability index β, whereas the out-of-straightness damage applied at the bay 3, has the strongest reduction on reliability, specially if it is applied with maximum damage level to 3 members.

Joint cracking is applied, with 3 damage levels, to individual joints located at one given bay, either 1, 2 , 3 or 4. Results are shown in Fig. 6. It is observed that, again, bay 3 shows the highest susceptibility to this type of damage.

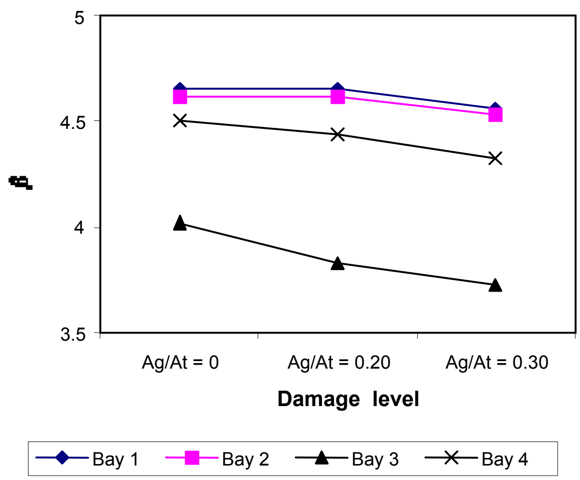

Figure 6. Variation of global β for several joint damage conditions.

CONCLUSIONS AND RECOMMENDATIONS

The current code [11] specifies that the considered platform, with high consequences and vertical restraints type *K*, should have an *RSR* = 1.9, which corresponds to a β = 3.4. For the worst damage condition, β is 3.7 approximately and the platform may be considered, therefore, adequate for seismic loading.

The loading uncertainty has a strong influence on the global reliability.

Denting damage does not significantly influence the global reliability.

Joint cracking influences the most the platform global reliability.

For future work, damage conditions should be considered combined (joint cracking + out-of-straightness) and the corresponding occurrence probabilities should be included to get the unconditional reliability index. Also, potential failure paths with several joints having fatigue damage need further study.

The present work may be used to support optimal planning for inspection and maintenance of offshore platforms on the Bay of Campeche.

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