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A QUICK SEISMIC ASSESSMENT METHOD FOR JACKET TYPE OFFSHORE STRUCTURES BY COMBINING PUSH-OVER AND NONLINEAR TIME HISTORY ANALYSES

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ABSTRACT

Several offshore structures are located in seismic regions, and to upgrade their seismic behavior it is required to evaluate their seismic vulnerability. It is believed that the most reliable type of analysis for seismic evaluation is Nonlinear Time History Analysis (NLTHA), however, this type of analysis is very time consuming. Therefore, some quick procedure for seismic evaluation is greatly acknowledged in professional practice. This paper presents a quick procedure by combining the Push Over Analysis (POA) and the NLTHA. Some POA are preformed first to identify the more critical members of the structure, based on the range of their plastic deformations. Then the NLTHA is performed, focusing on the critical members, to obtain their vulnerability with higher reliability. To show the efficiency of the proposed method, an offshore structure of jacket type, installed in Lavan oil field in Persian Gulf in 1970 has been considered. It is 304 feet high, and has a deck of 96 feet by 94 feet, and a total weight of over 290 million pounds. By using the 3-components accelerograms of 100 earthquakes, covering a wide range of frequency content, all normalized to various PGA levels, several NLTHA have been performed, in which the interaction effect of surrounding water has been considered by added mass and equivalent damping. In these analyses stress and strain values, particularly plastic strains in critical members, have been of the main concern. Numerical results show that combining POA and NLTHA is a quick and reliable seismic evaluation method. Furthermore, the results show that although the vulnerability of the jacket structure is not very high, the level of damage is not the same for different members, and is dependent on their location in the structure and also its geometric orientation and load bearing situation.

Introduction

Offshore structures, particularly oil and gas platforms, are among vital structures all over the world, and many of them are located in seismic regions. Regarding the adverse effects of

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damage to these structures subjected to earthquake it is important that their seismic design is performed by very high reliability. Reliability of a system is generally defined as having an expected level of performance under a given environmental and working condition for a certain period of time, is usually expressed as a probability value.

Several studies have been performed on the reliability of offshore structures, of which some have dealt with seismic analysis, and a few of them are briefly reviewed here. Nadim and Gudmestad (1994) seem to be among the first researchers who have worked on reliability of an engineering system under a strong earthquake with application to offshore platforms. Venkataramana and his colleagues (1998) have performed a study on the earthquake response and reliability analysis of offshore structures in which they have studied two structure models: (i) a jacket-type offshore structure and (ii) a tension-leg-platform, and have used the Kanai-Tajimi spectrum as the ground acceleration model in a frequency-domain random-vibration approach. They have claimed that the responses of tension-leg-platforms are highly dependent on the frequency parameter.

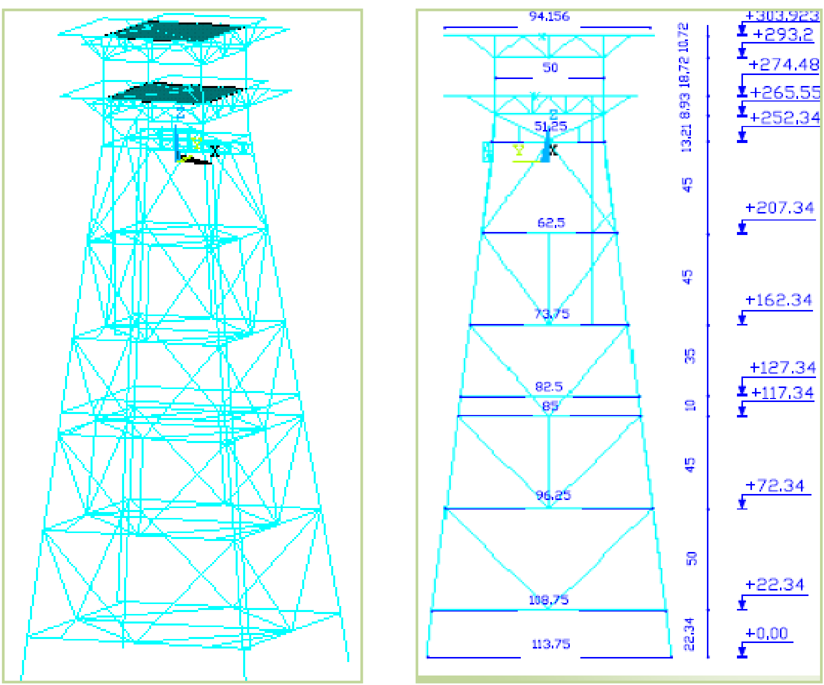
Zhuang and his colleagues (1999) have also studied the seismic reliability offshore jacket platforms by means of nonlinear pushover failure analysis. Jin and his colleagues (2002) have also worked on reliability of offshore jacket platforms subjected to seismic action by a stochastic approach. They have reported that the responses of the platform considering the pile-soil-structure mutual interaction were less than those of a fixed platform with 6 times the diameter, and that the dynamic reliability index of offshore platforms was high and the failure probability was very low. Recently, Finagenov and Glagovsky (2005) have performed a study on the assessment of reliability of offshore marine hydraulic structures under seismic impacts by both deterministic and stochastic approaches, in which the soil-structure-interaction has been taken into account with more precision.

It is seen that in spite of several studies on seismic reliability of offshore structures, the cases in which the sever earthquake and the nonlinear behavior of the structure have been taken into consideration are very few. It is believed that the most reliable kind of analysis for seismic design is Nonlinear Time History Analyses (NLTHA). However, this type of analysis is very time consuming. Therefore, some quick procedure, which is based on the NLTHA, for seismic evaluation is greatly acknowledged, particularly for professional practice in engineering offices. On this basis, recently the authors have performed a study on the seismic evaluation and reliability assessment of offshore structure, and have proposed a method for this purpose (Karimiyan, 2008). The results of that study and the proposed quick evaluation method are briefly presented in this paper. The suggested evaluation method is based on combining the static and dynamic analyses and using them in two phases. The static or Push Over Analysis (POA) is preformed first to recognize the more critical members of the jacket, based on the range of their plastic deformations. Then the dynamic or NLTHA is performed to obtain more precisely the amount of vulnerability of critical members.

To show the efficiency of the proposed method an offshore structure of jacket type, which is 304 feet high, and its members are all of tubular section, has been considered. By using the 3-components accelerograms of 100 earthquakes, covering a wide range of frequency content, all normalized to some specific levels of peak ground acceleration, several NLTHA have been performed to find out the effect of earthquake intensity on the vulnerability of the jacket structure. In these analyses the stress and strain values, particularly plastic strains in critical members, have been of the main concern. The variations of maximum stress and strain values in critical member versus different features of the input earthquakes have been studied to find out which feature, including frequency content, spectral intensity, duration, energy, and so on, has the dominant effect on the seismic vulnerability of the jacket structure. In the following section of the paper the studied jacket structure is introduced, and then the results of its seismic evaluation and reliability assessment by using the combined POA and NLTHA procedure are presented and discussed briefly.

Introducing the Jacket and its features

The studied offshore platform is of the jacket type, and has been installed in Lavan oil field in Persian Gulf in 1970. It is 92.63 meter high, and has a deck of 29.3 meter by 28.6 meter , being carried on four inclined legs of 0.9 meter diameter. The total weight of jacket and deck is over 290 million pounds (more than 131,000 tonf), and its structural members are all of tubular sections. The material of the jacket structure is high-strength steel with specific gravity of 7850 kgf/m3, modulus of elasticity of 2.1E10 kgf/m2, and yielding stress of 3600E4 kgf/m2, giving a yielding strain of 0.171%. Fig. 1 shows the geometric features of the jacket and platform, and its natural periods and frequencies up to 11 modes.



Mode No.	Period (Sec)	Freq. (Hz)
1	2.4139	0. 41426
2	2.3382	0.42767
3	1.3343	0.74945
4	0.7612	1.3137
5	0.76039	1.3151
6	0.6999	1.4286
7	0.69676	1.4352
8	0.6704	1.4916
9	0.6614	1.5119
10	0.6047	1.6535
11	0.6041	1.6552

Figure 1. The geometric features of the jacket and platform structure and its natural periods and frequencies up to 11 modes

It can be seen that there is just slight difference between the frequencies of the 4^{th} and higher modes up to the 11^{th}. This means that the structure has several closely-spaced modes, and this make its modal analysis a very deliberate one, in which using the ordinary modal combination methods like SRSS is not adequate, particularly since the third mode of the structure is a torsional mode.

Seismic Evaluation of the Jacket Structure

For seismic evaluation of the jacket structure two types of analyses including a set of Push Over Analysis (POA) and a set of Nonlinear Time History Analysis (NLTHA) were performed. The main purpose of the POA was identifying the more critical members of the structure for the NLTHA to decrease the volume of the NLTHA outputs, which can be very large if all members of the structure are taken into consideration. In these analyses the strain-stress relationship of the jacket material was assumed to be elastic-perfectly plastic as shown in Fig. 2.

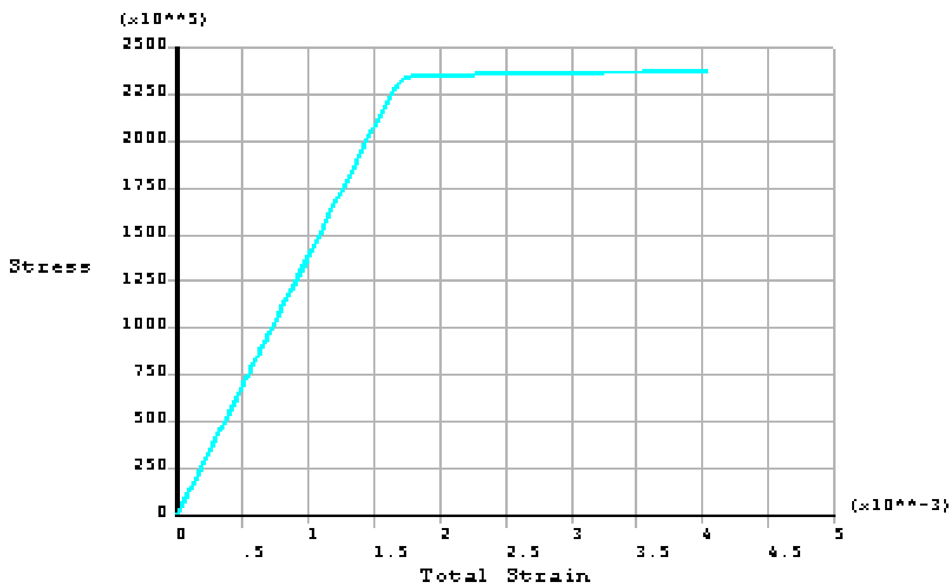


Figure 2. The stress-strain curve of the jacket structure material

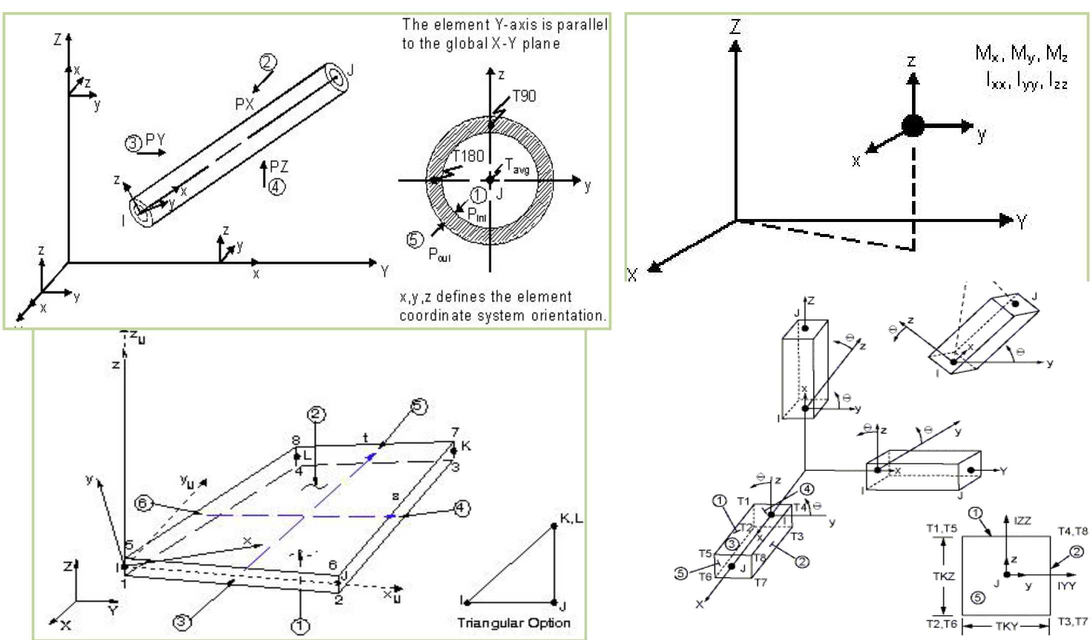
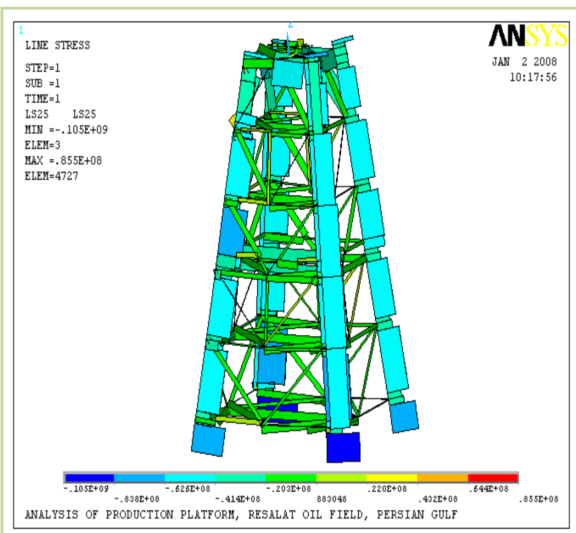


Figure 3. The features of elements used for modeling the offshore structure

The foundation piles have been modeled using a length of 6 times their diameter. It is worth mentioning that experimental studies have shown this length to be around 5.8 times the pile diameter. For both of POA and NLTHA the ANSYS computer program was employed, and the elements used in this computer program for modeling various members of the off-shore include: SHELL181 for modeling the deck of the structure, MASS21 for modeling the facilities and equipment installed on the deck, PIPE20 for all legs of the jacket structure, and BEAM4 for beam members surrounding the deck. The features of these elements are shown in Fig. 3.

Push Over Analyses (POA)

The POA was preformed to recognize the more critical members of the jacket, based on the range of their plastic deformations. For this purpose a concentrated load was applied at the master joint of the top level of the upper platform, once in one main direction (X) and once in the other main direction (Y). Since the jacket structure is slightly asymmetric the POA were repeated for opposite directions (–X and –Y) as well. Among the POA results the ultimate strength and yielding displacements of the jacket structure in two main directions are of great interest. These values are shown in table beside Fig. 4.



POA case	Yielding Force (lb)	Yielding Disp. (ft)	Stiffness (lb/ft)
Push (X)	88,499,185	1.760	50,278,384
Push (-X)	92,158,817	1.840	50,076,738
Push (Y)	84,579,280	1.715	49,316,160
Push (-Y)	86,261,183	1.753	49,213,052

Figure 4. Stress values in the structure's elements due to static loads, and the ultimate strengths of the structure obtained by POA

The closeness of stiffness values in X and –X, as well as Y and –Y directions show the satisfactory precision of the performed POA. The close values of frequencies of the first two modes of the jacket structure, given in Table 1, is also confirmed by the close values of stiffness in the two main directions of X and Y, which are around 50,175,000 lb/ft and 49,260,000 lb/ft respectively (the difference is less than 2%). It is worth mentioning that although the stiffness values of the jacket structure and its natural vibration periods at X and Y directions are close, the yielding forces in these two directions are different, as shown in Table beside the figure (the difference is around 5.5%). This can be to some extent due to the difference in the dimensions of the jacket structure at the two main directions, and partially because of the non-uniform distribution of vertical gravity loads on the legs of the jacket structure, which results in a slight difference in the values of normal stress in the legs cross-sections in the static conditions as shown in Figure 4.

As it is seen in Figure 4, the stress values are a little higher in a part of the two left legs (according to the figure) and also in one of the piles. These slightly higher stress values in some members under vertical load can cause the start of plastic deformation in these members, when the structure is pushed in one direction some step(s) earlier than the counterpart members in the other side of the jacket, when the structure is pushed in the opposite direction. The higher normal stress values in one of the right piles (according to the figure) for which the stress level is shown in dark blue in the figure, is also effective is the conditions of this pile for being the more critical leg of the jacket structure as discussed hereinafter.

As the main use of POA in the seismic vulnerability assessment approach, proposed in this paper for the jacket structure, the results of the POA were used to identify the more critical members of the structure based on their plastic deformation, using the value of 0.00171 for the plastic strain (see Fig. 2). On this basis, the more critical member were identified for different cases of the POA, related to (X), (-X) and (Y) and (-Y) directions. Some members experienced plastic deformation in all of these 4 states. These members, shown in Fig. 5-a, were considered as the most critical members of the jacket structure, however, as it can be seen in this figure, these members are just of beam, leg, and pile types, and does not include diagonal members between beams and legs in various levels. The final selection of critical members of the jacket structure which includes members of all different types, including legs, beams, horizontal diagonals, and diagonals between legs, consists totally of 20 members as shown in Fig. 6-b.

(a) Critical beams and leg columns (b) The most critical member

Figure 5. The more critical members of the jacket structure yielded or ruptured in all 4 states of the POA in (X), (-X), (Y) and (-Y) directions (a), and the final selection of most critical member (b)

By identifying those members which are among the critical members in at least two cases of four POA cases the most critical member(s) were realized. As expected, it happened that element No. 1, which is the pile with higher stress values under gravity loads as shown in Fig. 5-b, was among the more critical members in two cases of four POA cases, due to combination of compressional stresses under gravity and lateral loads.

Nonlinear Time History Analyses (NLTHA)

The NLTHA were performed by using the 3-components accelerograms of 100 earthquakes, covering a wide range of frequency content, all normalized to the same Peak Ground Acceleration (PGA) level. Three values of 0.3g, 0.65g, and 1.0g were used for the PGA level to find of the effect of earthquake intensity on the behavior of the jacket structure. The interaction effect of surrounding water was considered by added mass and equivalent damping. In these analyses the stress and strain values, particularly plastic strains in critical members, identified by the POA, were of the main concern. To decrease the volume of the NLTHA outputs the stress and strain values at only four locations in the section of critical members (say at 0, 90, 180, and 270 degrees in the tubular section) were calculated.

Table 1. The 29 accelerograms which were able to create plastic deformation or rupture cases in the jacket critical structural members, and the number of plastic and ruptured locations

No.	Earthquake Name	No. of plastic locations (Np)	No. of ruptured locations (Nr)	Np + Nr	No.	Earthquake Name	No. of plastic locations (Np)	No. of ruptured locations (Nr)	Np + Nr
1	Chi-Chi 9	92	54	146	16	Birjand	56	14	70
2	Bajestan	77	40	117	17	Duzce	55	21	76
3	Chi-Chi 4	72	42	119	18	Imperial	54	14	68
4	Boshrueh	70	38	108	19	Northridge 3	52	23	75
	Turkey	68	29	97	20	Ferdows	52	21	73
6	Erzincan	68	28	96	21	Gheshm	51	14	65
7	Northridge 2	64	38	102	22	Chi-Chi 10	49	19	68
8	Sedeh 2	63	34	97	23	Tehran	49	12	61
9	Imperial	60	32	92	24	Tehran 23	47	21	68
10	Bandarabbas	60	26	86	25	Abaregh	45	7	52
11	Imperial	60	26	86	26	Deyhook	43	16	59
12	Chi-Chi 2	60	26	86	27	Chi-Chi 3	38	2	40
13	Khash	57	30	87	28	Rudbar	37	8	45
14	Rayen	57	27	84	29	Bandar	34	2	36
15	Sedeh	57	25	82					

The number of locations in the sections of structural members, in which the strain value exceeded the yielding level in each time history, was chosen as the main damage criterion in the NLTHA. Since 4 locations in each section were considered to experience plastic deformation, and this could be the case at either end sections of each member the maximum number of locations having the potential of plastic deformation or rupture could be 8 in each member.

Depending on the level of applied PGA, in some of these locations the strain value exceeded the rupture level (which was the strain value of 0.0034 for steel material based on Von Mises plasticity criterion). Assuming that these locations were just in the critical members the number of these locations were obtained for all 100 accelerograms with the PGA value of 1.0g, which showed that just 29 accelerograms were able to create plastic deformation or rupture cases in the jacket critical structural members, as shown in Table 1.

Considering the summation of ‘number of plastic locations’ and ‘number of rupture locations’ as the damage criterion the first 15 earthquakes out of the 29 ones mentioned in Table 3 can be selected as the most damaging earthquakes for the jacket structure. On this basis the accelerograms of these earthquakes were scaled once to 0.65g and once to 0.30g for more cases of the NLTHA. On the other hand, paying attention to the results of the NLTHA for various critical members, shown in Figure 5, it could be realized that in each case each of these elements experienced some different level of damage. On this basis, depending on the number of locations of plastic deformation or rupture happened, which was between 0 and 8, a damage percent was defined for each critical structural member.

Furthermore, to categorize the damaged members from a statistical point of view five levels of damage were considered as follow:

1. 0%, which means that the member has remained elastic,
2. More than 0% and less than 25%, which means that just in one location the strain value has exceeded the yielding level in the member end sections,
3. Equal to or more than 25% and less 50%, which means that the number of locations where the strain values has exceeded the yielding level in the member end sections has been 2 or 3,
4. Equal to or more than 50% and less 75%, which means that the number of locations where the strain values has exceeded the yielding level in the member end sections has been 4 or 5,
5. Equal to or more than 75%, which means that the number of locations where the strain values has exceeded the yielding level in the member end sections has been 6, 7 or 8.

A sample of the results obtained by this categorization is shown in Fig. 6, which relates to element No. 1 (see Fig. 5-b) as the most critical element of the jacket structure.

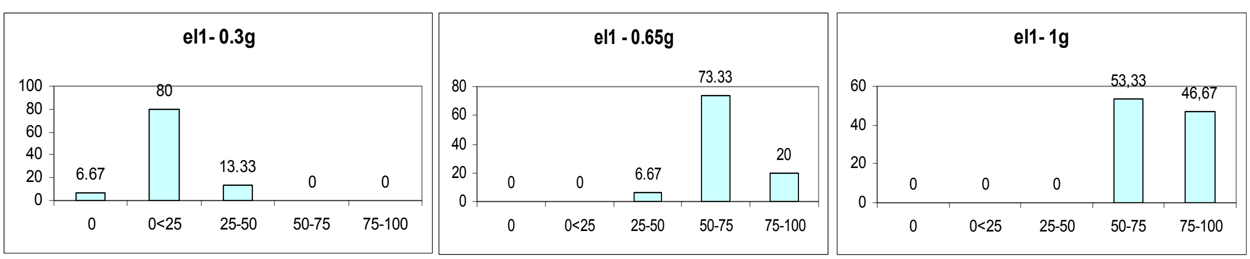


Figure 6. Damage percent of element No. 1 for various PGA levels obtained by the NLTHA

It is seen in Fig. 6 that the damage level of element No. 1, which based on the five aforementioned damage categories has almost normal distribution for PGA values of 0.3g and 0.65g, increases with increase in the PGA level. If the number of rupture cases is considered as the damage index, by using the results shown in Table 1 for the rupture cases, and using the five aforementioned categories, the rupture probability density function can be obtained as shown in Figure 7 for element No. 1, which shows that the rupture probability in this element has an almost normal distribution, and also shows that the damage level of this element increases with increase in the PGA level. Similar results, obtained for other members of the jacket structure, can not be presented here because of lack of space and can be found in the main report of the study (Karimiyan, 2008).

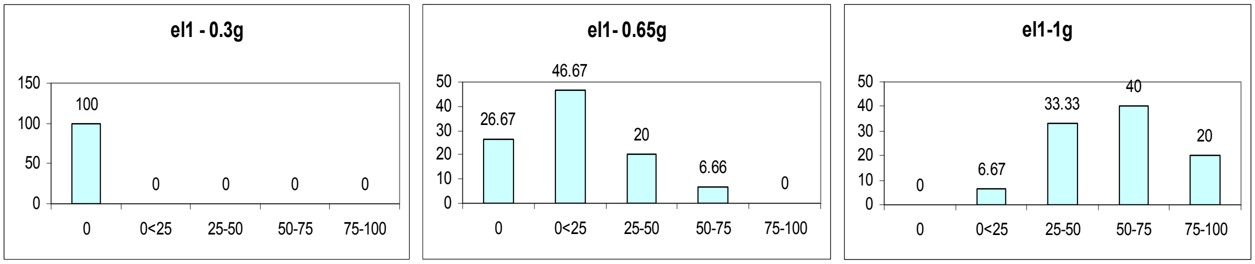


Figure 7. Rupture percent of element No. 1 for various PGA levels obtained by the NLTHA

Dominant Earthquake Feature in the Vulnerability of the Jacket Structure

Based on the results of several cases of the NLTHA, performed on the jacket structure, it is possible to find out which parameters of ground excitation have more correlation with the vulnerability of the jacket structure. The amount of vulnerability can be stated in terms of:

- The number of locations in structural members which experiences plastic deformations
- The number of failure cases in structural members based on the ultimate strain of the structural material
- The dissipated energy due to plastic deformations in structural members

On the other hand, the parameters of ground excitation can be any combination of the following ones:

- The energy of the record components (E_x, E_y, E_z) or their summation,
- Maximum spectral acceleration values of each component (S_{ax}, S_{ay}, S_{az}) or their summation,
- The spectral acceleration values of each component at the fundamental period(s) of the structure (S_{a1}, S_{a2}, S_{a3}, …), or their summation.

Samples of relation between the number of plastic locations in the critical member of the structure, as the damage index, and the summation of modal spectral values of the first three modes ($S_{a1} + S_{a2} + S_{a3}$) in each of the main directions x, y, and z as the earthquake parameter are shown in Figure 8.

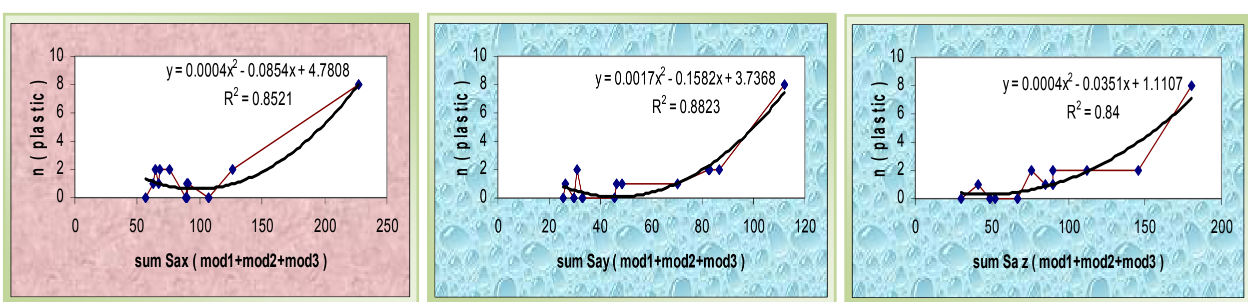


Figure 8. Correlation between damage index and $S_{a1} + S_{a2} + S_{a3}$ in each main direction

It is seen in Fig. 8 that there is a good correlation between the number of plastic locations in the critical members of the structure and the summation of spectral values of earthquake. On this basis, it can be suggested to use the summation of modal spectral responses of the structure as the earthquake feature for obtaining the damage of the structure subjected to that earthquake.

Conclusions

As the concluding remarks it can be said that combining POA and NLTHA is a quick and reliable seismic evaluation method. From the 100 earthquakes used in the study, covering a wide range of frequency content, and duration and spectral characteristics, less than 30% could be damaging for the considered jacket structure, even by using a PGA level of 1.0g. This means that, in an overall view the reliability of the seismic design of the jacket structure is relatively high. However, the level of damage is not the same for different members. This implies that the reliability level of seismic design is not the same for all jacket structural members. The importance factor of members, which depends on its location and orientation and load bearing situation, has also great effect on the reliability assessment. The NLTHA results also show that that none of the earthquake characteristics alone, can be the dominant factor. Instead, a combined factor in which various features are taken into account can be suggested. In this regard the summation of spectral acceleration responses of the jacket structure in its first three modes ($S_{a1} + S_{a2} + S_{a3}$) for each component of earthquake excitations show the best correlation with the level of damage in the structure, however further research is needed to better address this issue.

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