Engineering Journal issn: 0125-8281

Article

Effects of Redundancy in Bracing Systems on the Fragility Curve Development of Steel Jacket Offshore Platform

Md Samdani Azad[1,a], **Wonsiri Punurai**[1,b,*], **Chana Sinsabvarodom**[2,c], **and Pornpong Asavadorndeja**[3,d]

1 Department of Civil and Environmental Engineering, Faculty of Engineering, Mahidol University, Thailand
2 Department of Marine Technology, Norwegian University of Science and Technology, Norway
3 Synterra Co., Ltd., Thailand
E-mail: [a]mdsamdani.aza@student.mahidol.ac.th, [b]wonsiri.pun@mahidol.ac.th (Corresponding author), [c]chana.sinsabvarodom@ntnu.no, [d]p.asavadorndeja@synterra.co.th

Abstract. Steel jacket offshore platforms are typically employed for use in shallow to moderate water depths. During platform operations, there have been some historical accidents completely damaging the diagonal members of the bracing systems due to explosions, fire accidents and dropped objects. Different locations of damaged bracings demonstrate different levels of risk for safety and integrity of the structures. This research illustrates the effects of redundancy in the bracing systems for steel jacket offshore platforms. Assessments have been carried out using the nonlinear pushover analysis method and formations of nonlinear hinges of different members were noted. Redundancy in different positions has been considered to investigate the consequences. Reserve strength ratio (RSR) and damage strength ratio (DSR) of the global structure were also evaluated to understand the importance of different local members. From the collapse data of local failures, fragility curves for the global structures were estimated. The results demonstrated that the position of damage can be a great concern which affects the overall performance of the structures.

Keywords: Jacket platform, redundancy analysis, plastic hinges, fragility curve.

ENGINEERING JOURNAL Volume 23 Issue 1
Received 12 June 2018
Accepted 24 October 2018
Published 31 January 2019
Online at http://www.engj.org/
DOI:10.4186/ej.2019.23.1.123

1. Introduction

Offshore structures are employed for several different reasons especially in energy industries, such as for support structures of offshore wind turbines and petroleum exploration. Although there are noteworthy developments of renewable energy, demand for oil and gas all over the world is still high. Apart from onshore extraction, extrication of oil and gas in offshore areas is also becoming common to cope with the present demands. It has become a challenge for structural engineers to design safe and robust marine structures for the uncertain behaviors of such structures. Redundancy or complete damage of structural members are salient issues and an offshore structure could be disposed due to collapse. Redundancy can be defined as the creating of an alternative load path due to some local damages in the structure [1]. The term redundancy is used when complete damage of any local member or some local members occurs. It is important to check whether the acting loads are being transferred to foundations if any local member is fully damaged or partially damaged. These types of damage often occur due to unforeseen events or accidental actions. The accidental actions include ship impacts, explosions or dropping of objects.

The assessments of offshore jacket platforms can be illustrated from the outcomes of nonlinear analyses, consideration of redundancy for different local elements, robustness and fragility curve fitting. Refachinho et al. [1] reported that robustness is a variable for different damage conditions and found that design codes should have more specific guidelines to quantify robustness. Reserve strength ratio and damage strength ratio were illustrated to discuss robustness and redundancy. Paliou et al. [2] developed a general method to evaluate the system reliability of structures and emphasized the reliability and redundancy of offshore structures. Awall et al. [3] found that the modal behavior of steel truss bridges is variable for different damaged chord conditions. The axial stresses of different members were tested considering intact conditions and different redundancy conditions to evaluate the performances and damage severity of the steel bridges. Some researchers focused on the nonlinear assessments of offshore platforms. Nguyen and Sinsabvarodom [4] showed that plastic hinges first formed in the diagonal bracings which are in-plane of applying loads. This implies that the first failure of the bracings occurred due to its compression. The offshore jacket platform was modeled as a space frame system and the support condition was fixed. Three different types of bracing systems (X-bracings, V-bracings and single bracings) were adopted to make a comparative study of the seismic performances among the models. The jacket was modeled in SAP2000 to develop the capacity curve through performing pushover analysis. The jacket platform with X-bracings demonstrates best performance while the single bracing is susceptible to highest damage levels. El-din and Kim [5] demonstrated that retrofitting with buckling-restrained braces provides enough strength and ductility as required by the API RP 2A. The effect of buckling restrained bracing (BRB) depends on the configuration of the bracing: the strength increased in the BRB-retrofitted jacket structures was found to be three times greater than the conventional structure with K-bracing, while it was only 41% in the structure with V-type bracing. According to the assessment criteria, it is required to satisfy the collapse prevention limit states of the structure under extreme earthquake conditions. Some researchers [6] considered nonlinear static analyses considering pile soil interaction to assess real fixed jacket platforms. Golafshani et al. [7] showed the legs of jacket behavior are force control behavior at first and second level, while its response is deformation controlled behavior at higher levels. The response from bracings exceeded the collapse prevention level at the fourth level while it just passed the life safety level at other levels of the jacket platform. Building codes can be used to develop numerical and applicable criteria for seismic assessments of jacket structures. Redundancy of a jacket platform was found at low levels, which leads to a significant occurrence to the structure. Failure of one member in a structure can provide immediate reduction of structural strength and then it may collapse without warning. The assessments of offshore structures are generally done considering the wind and wave loads as there are no established procedures to perform seismic analyses. There are international standards for assessments of offshore structures, comprising ISO19900 [8], ISO19902 [9], API RP2A-WSD [10] etc. Presently, API is developing standards for offshore structures subjected to hurricanes, earthquakes and storm loadings. Global criteria for seismic assessments of jacket platforms are presented in the API standard, but there are no numerical or specific criteria in order to assess the structures. Return periods for collapse prevention in API RP 2A [11] and FEMA [12] are 1000 and 2500 years respectively. The return period of API should be reviewed because it was observed that the expected mean life time of the jacket is greater than design life. The approaches and methodologies for building standards can be used in appropriate and efficient ways for seismic assessments of jacket platform structures if the standards are reviewed properly and modified following the design criteria of offshore structures. The fragility curve is a convenient way to express the structural performance substantially with respect to the intensity measure of loads. A fragility curve [13] is generated by lognormal distribution of failure data points from pushover analysis. Fragility curves can also be developed using the outcome of incremental dynamic analyses and multiple strip analyses [14, 15]. From the analysis, the probabilities of different damage states are calculated. After that the maximum likelihood method [16] or method of moments [17] is employed to estimate the fragility curves. The linear regression method [18] can also be used to estimate the fragility curve parameters i.e. mean and standard deviation. Zeinoddini et al. [19] conducted endurance wave analyses for developing the fragility curve of a fixed offshore platform. A probabilistic load model has been incorporated for the assessment.

The aim of this paper is to study the assessments of offshore jacket platforms for different redundant conditions in order to estimate fragility curves from pushover analyses results. This method provides efficient computational time in comparison with dynamic time history analyses. An approximation in estimating fragility curves has been reported in this study. The jacket platform has been adopted from Punurai et al. [20]. Pushover analyses are conducted for different redundant conditions to observe the force-displacement behavior following the procedure of El-din and Kim [5]. The local members are monitored at different damage states for corresponding base shear values and ultimate capacity of each models are evaluated. Reserve Strength Ratios (RSR) and Damage Strength Ratios (DSR) are estimated from design force and ultimate capacity in order to understand the importance of different damaged members. Force thresholds for different damage states are noted. The base shear values at the different damage state are found in local members. These values for each damage states are considered to evaluate the fragility curves for demonstration of structural performances.

2. Methodology

2.1. Structural Model Descriptions

The jacket platform used in this study has been designed for shallow water depth of approximately 65.53 meters [20]. The configuration of the steel jacket platform consists of a 4-legged structure with containing pile inside. The jacket platform has been modeled using 2 by 2 square grids. The overall dimensions are 8 m by 8 m at top elevation and 21.76 m by 21.76 m at the mud line. The total height is 83.21 meters. Two types of bracing are used: horizontal bracings and vertical bracings. The horizontal bracings are installed at each level parallel to the horizontal plane. The vertical bracings are provided as single bracings till the bottom level. At the bottom level, these are placed as K-bracings to impart more stiffness and to reduce buckling. The jacket support/foundation is modeled as fixed support conditions. The full scale model of the jacket is illustrated in Fig. 1(a). The jacket platform has been modeled in commercial software "SAP2000" as shown in Fig. 1(b) and the water depth and jacket height are included in Fig. 1(c).

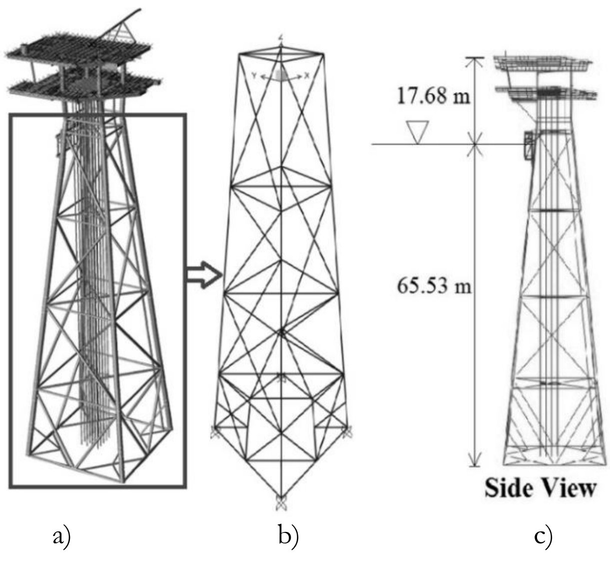
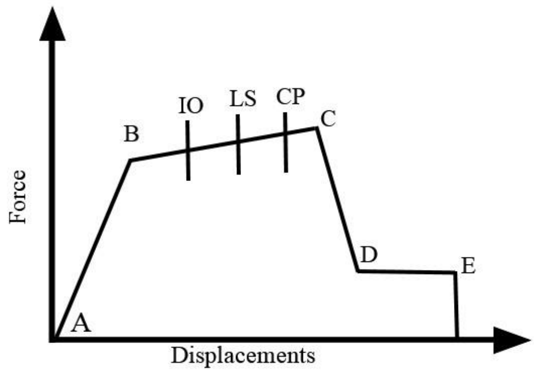


Fig. 1. Offshore Platform: a) Full scale model; b) Modeled in Sap2000; c) Model including real dimensions.

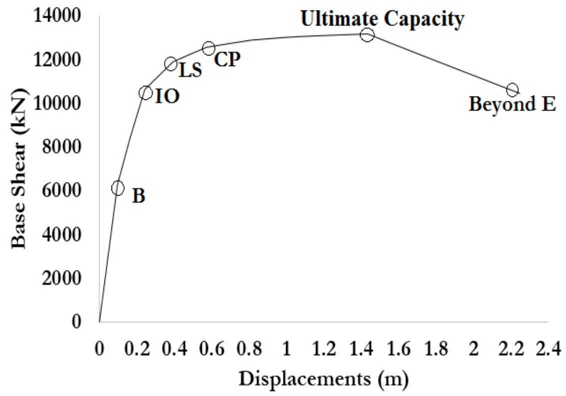
DOI:10.4186/ej.2019.23.1.123

2.2. Pushover Analysis

Pushover analyses have been conducted to determine the force-displacement relationships and the performance levels of the structural models. Pushover analysis is classified as two types, known as force control and displacement control. Force-controlled analyses are suggested as per API-2A WSD [9] for wave forces. Displacement control analyses are performed in this study to see the collapse of local members as well as global structural performance. Pushover analyses are performed using uniform acceleration of loads up to a certain level of displacements. An outline of a typical pushover curve [11, 21] is shown in the following Fig. 2 (a).



a) Pushover Curve from FEMA356



b) Pushover curve from Undamaged model

Fig. 2. Typical force displacements curve as per FEMA356.

Figure 2(b) illustrates the pushover curve obtained from the analysis for the undamaged model. By applying Eq.(1) and (2), one can find the reserve strength ratio (RSR) using the ultimate capacity of the undamaged (intact) and damaged structure. As per API [9], there is a direct relationship between the ultimate capacity of structure and RSR. RSR can also be considered as safety factor as it is the ratio of ultimate capacity of force and design force. The RSR value can be calculated as follows:

$$RSR(Intact) = \frac{\text{Ultimate capacity of structures (Intact)}}{\text{Design Environmental Loads}} \tag{1}$$

$$RSR(Damaged) = \frac{\text{Ultimate capacity of structures (Damaged)}}{\text{Design Environmental Loads}} \tag{2}$$

After calculating RSR, the damage strength ratio (DSR) is calculated as it is a measure of redundancy.

$$DSR = \frac{RSR\text{(Damaged)}}{RSR\text{(Intact)}} = \frac{\text{Safety Factor (Damaged)}}{\text{Safety Factor (Undamaged)}} \tag{3}$$

The formations of nonlinear hinges are checked and the locations are also noted. The damaged conditions are considered in terms of redundancy of the vertical bracings at each level. For each case, one member was considered completely damaged. The analyses are done considering the damaged condition of vertical bracings. The locations of damaged members at different levels are depicted in Fig. 3.

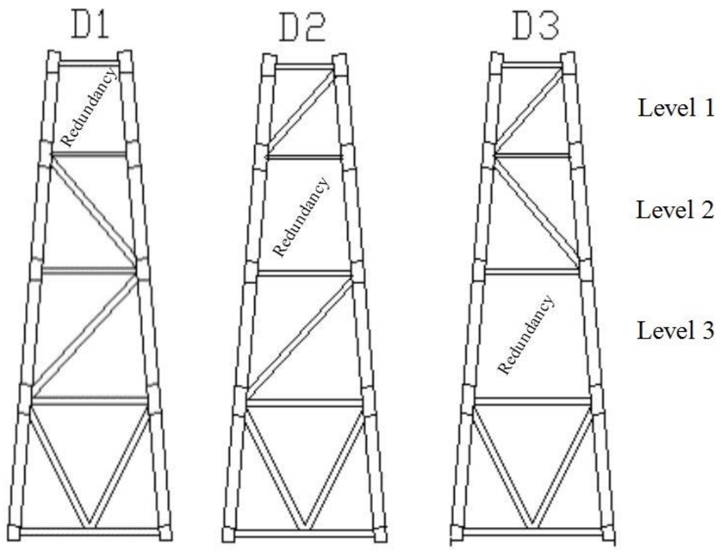


Fig. 3. Damage locations of local members in various positions of the Jacket.

There are 3 different redundancy conditions, consisting of D1, D2 and D3. The specifications of D1, D2 and D3 follow the different levels of the jacket platform. Different levels are classified from the top of the jacket towards the downwards to the seabed. The top level is considered as Level 1. The following level towards the seabed is contemplated as Level 2 and the next level along the depth of sea is Level 3. When a vertical bracing is completely damaged at Level 1, the specification of the model has been considered as D1. In the case of a damaged vertical bracing at Level 2 and Level 3, the models are specified as D2 and D3. The models with redundancy (complete damage of a single vertical bracing) under the different loading direction for pushover analysis are specified as:

- D1+x: D1 model and the pushover loading is along positive x-direction.
- D1-x: D1 model and the pushover loading is along negative x-direction.
- D2+x: D2 model and the pushover loading is along positive x-direction.
- D2-x: D2 model and the pushover loading is along negative x-direction.
- D3+x: D3 model and the pushover loading is along positive x-direction.
- D3-x: D3 model and the pushover loading is along negative x-direction.

2.3. Fragility Curve development

The analytical fragility function has been developed to represent the base shear data, which is obtained from the nonlinear static analyses. Fragility functions are influenced by the number of data points from pushover analyses. The relationships between the base shear forces and top displacements of the jacket structures imply the levels of damage state. The specifications of damage states/nonlinear hinges are illustrated briefly in Table 1. The higher states of damages result in the reduction of local stiffness, which provides flatter slopes in pushover curves, due to the occurrence of nonlinear hinges at the local members or local connections. The data points are collected in such a way that there must be at least one member reaching a certain damage state. As shown in Table 1, the first data point is noted when at least one member crosses the elastic limit and this limit has been depicted as "B". The following damage states (IO, LS, CP and E) are determined in similar ways afterwards. The initiation of different damage states has already been reported in Figure 2(b). The fragility curve is developed under the lognormal cumulative distribution function, which has been widely using in engineering problems for environmental load design. The formulation of the lognormal probability density function (PDF) and cumulative density function (CDF) are given in equations 4 and 5, respectively.

(PDF) $$f(x)=\frac{1}{x\cdot\beta\cdot\sqrt{2\pi}}\exp-\frac{\left(\ln\left(x/\theta\right)\right)^{2}}{2\beta^{2}} \tag{4}$$

(CDF) $$P\left[X\leq x\right]=F_{x}\left(x\right)=\int_{-\infty}^{\infty}f(x)dx \tag{5}$$

$$P\left[X\leq x\right]=\Phi\left(\frac{\ln x-\ln\theta}{\beta}\right) \tag{6}$$

$$P\left[IM=x\right]=\Phi\left(\frac{\ln\left(x/\theta\right)}{\beta}\right) \tag{7}$$

Equation (4) depicts the probability density of event x. Here, event x is the base shear. From this equation, the probability of failure of any event can be evaluated. Equation (5) illustrates the summation of probability of failure for each events. The cumulative probability of failure can be obtained from this equation for different events. Here, θ is the lognormal mean value and β is the standard deviation of ln(x). The equation of cumulative distribution can be written as Eq. (6) and (7) using a standard normal cumulative distribution function, $\Phi(.)$. Here $P(IM=x)$ is the probability that base shear (event) with *IM*=x causes a different damage stage in the local members. IM is the intensity measure which can be the base shear, acting force, height of waves and spectral acceleration. In the study, base shear has been considered as IM.

Table. 1. Data-point collection from nonlinear hinges as shown in Fig. 2.

Non-linear Hinge type/Damage States	Data point	Remarks
B	Datapoint-1	When reaches nonlinear limit
IO	Datapoint-2	Immediate Occupancy
LS	Datapoint-3	Life Safety
CP	Datapoint-4	Collapse prevention
E	Datapoint-5	Dropping of Hinge

3. Result and Discussion

The nonlinear behavior of steel jacket offshore structures can be investigated by using pushover analyses. Pushover curves for different models are delineated in Fig. 4 and the formations of nonlinear hinges for undamaged conditions are illustrated in Fig. 5. Moreover, first nonlinear hinge (Damage state) formations for all damaged models are illustrated in Fig. 6. It should be noted that the formation of nonlinear hinges/damage states in certain local members depend on the amplitude of forces at that level and the availability of local members which will face damage due to buckling at the same level of redundancy. The first damage will be observed in the vertical bracings which are already reported in Nguyen and Sinsabvarodom [4] and the same phenomena can be noticed in this research as shown in Fig. 6. The initiations of plastic hinges at different force levels are dependent on mode of failure of local members. The mode of failure is comprised of either compression (Buckling) or tension (Yielding). These facts are dependent on the horizontal direction (+x and -x) of loading. The initiation of damage due to yielding requires higher force amplitudes than that of buckling and it is explained briefly through the following Fig. 5. The amplitude of forces is higher at the higher levels i.e. it increases along the height in a triangular pattern. According to this, the amplitude of pushover loads are as follows: Level 1 > Level 2 > Level 3. According to Fig. 4, the linear behavior within state (B) implies the undamaged condition with the base shear around 6000 kN. The value of base shear in state "B" is higher for D1+x model because the first nonlinear hinge occurs in the local member at Level 2. According to the consideration of D1+x, one vertical bracing member is completely damaged at Level 1. The remaining vertical bracing at the same level is subjected to yielding due to the direction of loading. In such cases, higher amplitude of forces will initiate damage. Before reaching that force level, a vertical bracing at Level 2 faces the first damage state due to compression (Fig. 6). For other damaged models, the elastic force limits (B) are lower than for the undamaged condition. The elastic force limit (B), immediate occupancy (IO) and the following force levels (LS, CP, E) are lowest in model (D1-x) compared with all other models. The base shear for initial damage in the first plastic hinge in state (B) of model (D1-x) is approximately 50 percent in comparison with the undamaged model. Due to the reverse direction of loading, the remaining vertical bracing at Level 1 is subjected to compression which initiates the damage state due to buckling. Moreover, the intensity of force amplitudes are highest as discussed before. For this reason, the force amplitudes decrease radically for the D1-x model. The corresponding forces for other damage states (IO, LS and CP) are significantly lower (approximately 50%) considering the undamaged model. D1-x is found as the most severe condition among all models. The behavior of D2+x is similar to the D1-x model. The corresponding base shear values for different damage states of D2+x is slightly higher than D1-x, but still significantly lower than for the undamaged model. From Fig. 6, it can be observed that the first hinge (damage state) occurs at Level 2 and redundancy is also present in Level 2. That is why required force amplitudes are considerably lower in D2+x too. It shows better performance considering D1-x as the damage occurs at Level 2 where force amplitudes are lower than Level 1. The load capacity of D2-x is superior to the previous damaged specimen (D2+x). From the same figure, it can be observed that the first damage occurs at Level 1 but that redundancy exists at Level 2. It means that the level shifts, because the remaining vertical bracing at Level 2 is subjected to yielding due to the direction of loading (-x). These two reasons are responsible for better performance of D2-x. The pushover curves of (D3+x) and (D3-x) models can be considered with better performance compared to D1 and D2 specimens, though less base shear capacity is found contrasting the undamaged condition in model 1. The corresponding base shear values for different damage states can be noted in Table 2. The reasons for different force thresholds of different damage states and different pushover curves are due to different directions of loading. This different direction of loading creates compression or yielding of local members. It depends on whether the member faces failure due to buckling or yielding and also on story levels which have already been discussed.

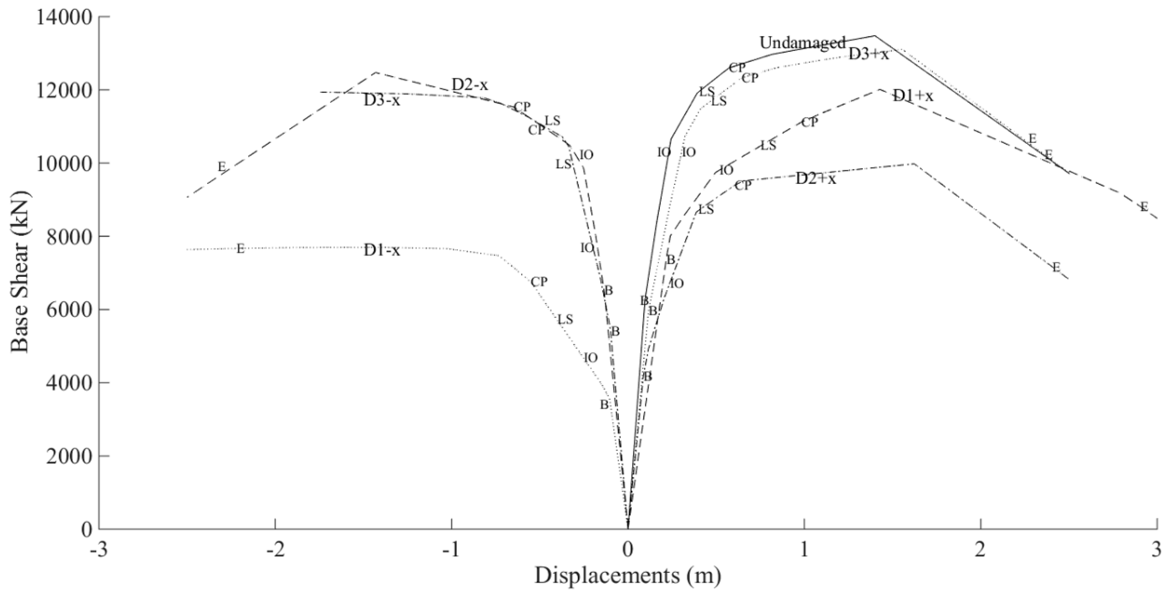


Fig. 4. Pushover curves for all models.

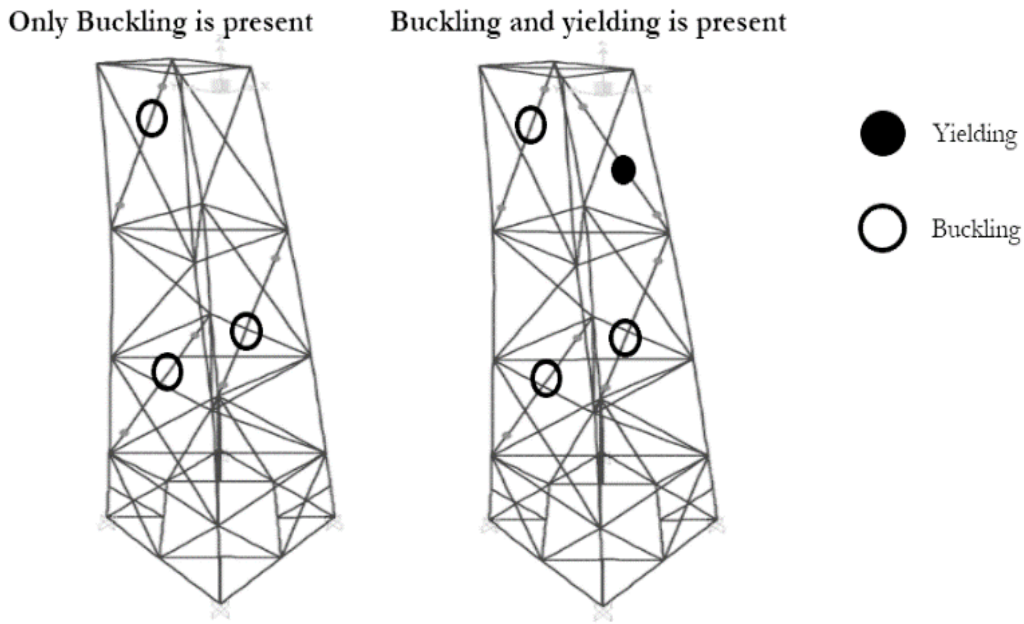


Fig. 5. Nonlinear hinges in undamaged model.

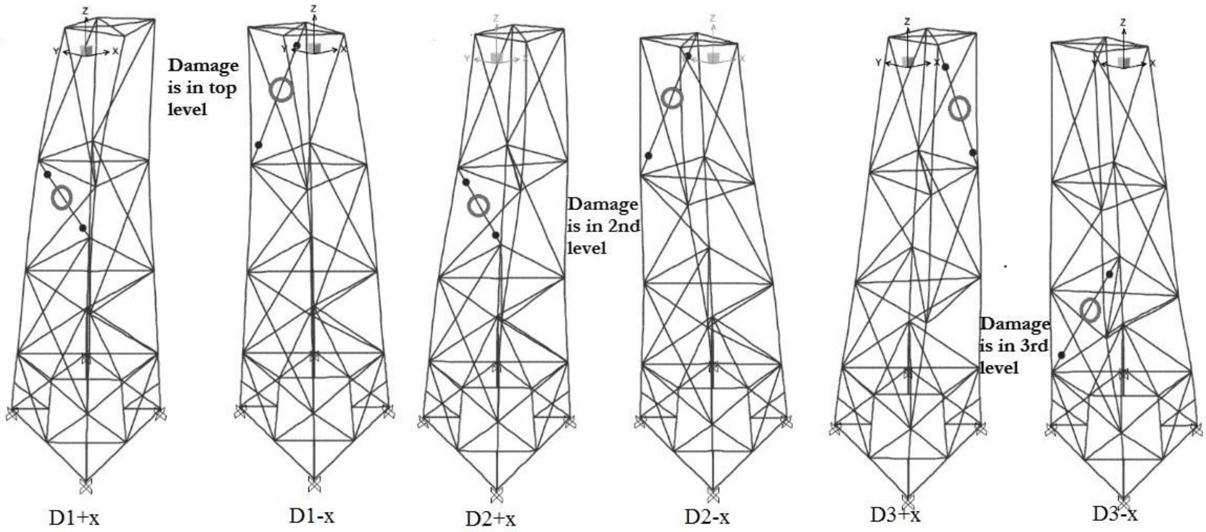


Fig. 6. Nonlinear hinges in damaged models.

Table. 2. Formation of the nonlinear hinges for different models.

Condition	B		IO		LS		CP		E	
	Base shear (kN)	Disp. (m)	Base shear (kN)	Disp. (m)	Base shear (kN)	Disp. (m)	Base shear (kN)	Disp. (m)	Base shear (kN)	Disp. (m)
Undamaged	6249.85	0.096	10691.46	0.248	11958.96	0.41	12598.32	0.6	10503.12	2.23
D1 +x	7356.09	0.216	9801.583	0.516	10471.05	0.75	11121.87	0.984	8816.82	2.90
D2 +x	4172.62	0.087	6697.832	0.235	8702.14	0.4	9389.83	0.6	7160.93	2.41
D3 +x	5955.26	0.12	10299.59	0.303	11689.08	0.47	12385.43	0.69	10220.32	2.36
D1 –x	3541.82	0.1	4671.149	0.252	5728.76	0.4	6758.47	0.55	7667.46	1.07
D2 –x	6529.90	0.136	10215.95	0.296	10954.62	0.47	11532.41	0.65	9618.76	2.33
D3 -x	5458.92	0.1	7736.397	0.2	10662.17	0.32	11289.0	0.57	Unstable	

Table. 3. Calculation of Reserve Strength Ratio (RSR).

	Safety Factor
Condition	RSR
Undamaged	3.04
D1 +x	2.71
D1 –x	1.81
D2 +x	2.25
D2 –x	2.81
D3 +x	2.96
D3 –x	2.71

Table. 4. Calculation of Damage Strength Ratio (DSR).

Damaged Condition	DSR
D1 +x	0.89144737
D1 -x	0.59539474
D2 +x	0.74013158
D2 -x	0.92434211
D3 +x	0.97368421
D3 -x	0.89144737

RSR of different models can be observed in Table 3. It can be noted that the lowest value of RSR is for the D1-x case. The second lowest is for D2+x. For the other models, the values of RSR are more than 2.5. Table 4 describes the values of DSR. It can be noted that the value of DSR is lowest for D1-x. It means that the ultimate capacity reduces more than 40 percent due to removal of a single member in the top level. For D2+x, the DSR is 0.74 which is still acceptable, but for other models, the value is more than 0.85, which means that the capacity reduced due to member damage at lower stories is less than 15%. It can be concluded that the bracing members at top levels are significant enough for lateral load capacity of the jacket, and the behaviors of RSR and DSR are matched with the pushover curves and formation of first nonlinear hinges.

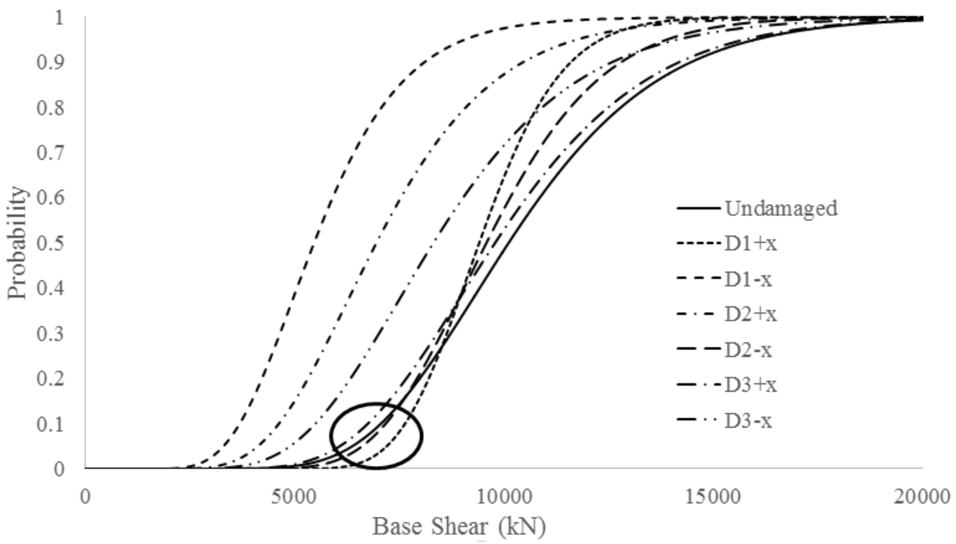


Fig. 7. Fragility curves of different damage models.

Figure 7 illustrates the fragility curves of all specimens. The fragility curves are fitted considering the force values which are required to initiate different states of damages. In this study, different nonlinear

DOI:10.4186/ej.2019.23.1.123

states are considered as B>IO>LS>CP>E. Five different data points (illustrated in Table 2) are used to fit the curve. It can be perceived that the D1-x is the most severe condition. D2+x and D3-x are the following severe models as described before. The behavior of D1+x, D2-x and D3+x are immediate to the undamaged model. In the red marked portion, it can be noticed that the force capacity of initial damage is higher for damaged models (D1+x, D2-x and D3+x). Moreover, after certain load levels, these become much lower than the intact model. The higher initiation force is due to the shifting of hinge formation of other story levels which already have been shown in Fig. 6. The range of damage initiation and ultimate capacity can also be noted in this figure. The ranges of different states of damage are comparatively much lower in the case of D1-x, D2+x and D1+x, but the range is higher for the rest which have closer values of intact models. Some more illustrations can be observed if we consider the RSR and DSR values. It can be noted that D1-x model has the worst performance from the fragility curve and RSR and DSR values. The RSR and DSR values of the model D1-x are 1.81 and 0.59. In the case of other models, the same approach is followed by the analysis results. The overall outcomes from the fragility curves indicate that bracings at higher levels are more significant for capacity of lateral loads. The fragility curves can state what is the probability of failure and at what base shear level. The pattern of RSR is followed by the fragility curve so that the designer can easily estimate the structural performance owing to redundant effects from nonlinear pushover analysis which takes lower computational time comparing with nonlinear dynamic time history analysis.

4. Conclusions

Significant outcomes are observed from pushover curves. The force-displacement curves illustrated variable behaviors for different damaged conditions. The linear and nonlinear behaviors are substantially visible in the pushover curves. The ultimate capacity of the full structure decreases while the damage gradually increases to the upper levels. Different damage conditions clarify that the position of damage governs the nonlinear behavior and ultimate capacity of structures. Damage position affects the RSR and DSR values. The importance of different members can be identified from the RSR and DSR values. It is found that bracing members at upper levels have greater importance which follows the pushover curves. The fragility curves illustrate the identical consequences as pushover curve and strength parameters (RSR and DSR). The use of fragility curves has a notable relation with the pushover curves and strength parameters. A designer can consider the RSR and DSR in advance so that the structure can be robust, even though a single bracing member is damaged. RSR and DSR values can be used as reliable sources to understand the behavior in the case of redundant condition. Inspection must be planned in advance for other types of phenomena such as corrosion.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation under the Marie Skłodowska-Curie grant agreement No. 730888. The authors would like thank Dr. Pramin Norachan for contributing knowledge on pushover analysis. The authors are also grateful to Dr. Naveed Anwar for arranging a software license for the research.

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