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Seismic fragility curves of steel structure industrial building using IDA method

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Abstract. Recent natural disaster events have caused damage to structures and led to loss of lives. Steel structure industrial building is one of the important structures that needs to be examined as these structures can have huge impact on the surrounding areas. Therefore, this study presents the fragility curves and performance curves of steel structure industrial building under earthquake loading. The structure consisted of beam, column, and bracing were modelled using three dimensional finite element modelling. The fragility curves were obtained for the structure, and the performance curves were developed based on lateral load, which was affected by the geometry of the building. Three records of far-field ground motion and three records of local ground motion were used for incremental dynamic analysis (IDA). The five levels of performance stated by FEMA-273, namely, operational phase (OP), immediate occupancy (IO), damage control (DC), life safety (LS), and collapse prevention (CP) were used as main guidelines to evaluate the structural performance. Results showed that, probability damage for operational phase, OP started at 0.19g and 5% of the structure analysed are expected to have immediate occupancy IO, indicating minor cracks to the structure at 0.4g PGA. Moreover, the performance response of the structure to the earthquake was obtained from the study.

1. Introduction

Earthquake is one of the most destructive natural hazards. An earthquake with a moment magnitude of 7.4 on the Richter scale occurred on August 17, 1999 at 03:02 a.m. and affected the northwest of Turkey. After the Marmara Earthquake, the Turkish Power System collapsed. This was the largest power blackout in Turkey in the last twenty years, with the impact of the earthquake the cause of the large blackout [1]. Earthquakes effects must be considered in the siting of industrial structure for two main reasons which are: 1) Potential damage during earthquakes, with potential for subsequent capital loss, environmental damage, and public health risk, 2) Electricity generation reliability; in times of disaster, reliable sources of power are vital [2]. Moreover, the industrial steel frame buildings have demonstrated high levels of reliability in earthquake event; although not designed to stand earthquake, they remained either unharmed of suffered slight damage [3].

In recent years, Malaysia has been exposed to the seismic effects on structures as the tremors were repeatedly felt from the earthquake events in countries around Malaysia. The tremors occurred several times from some of the large earthquakes coming from the intersection areas of Eurasian plate and Indo-Australian plate near Sumatra, and some of the moderate to large earthquakes originated from the Great Sumatran fault. The earthquake on 2 November 2002 caused cracks on some buildings in Penang, which is more than 500km from the epicentre. Moreover, earthquake in South Sumatra with magnitude Mw

7.3 caused cracks on one apartment building in Gelang Patah, Johor Bahru. Although it is unenviable for earthquakes to occur, there is an approach to mitigate the effects of strong earthquake shaking and to reduce death injury and destruction.

Non-linear analysis is required specifically for complex structures such as buildings with various different configuration in terms of heights and widths of bay. There are two types of non-linear analysis which are pushover analysis and time history analysis. The pushover analysis will be used to identify the damage level of the building (e.g. OP, IO, DC, LS, and CP). The damage level is used in the fragility curve construction after non-linear time history analysis is conducted to the structure. To study the behaviour of structure and to predict failure, fragility can be utilized for estimating structural and non-structural damage [4]. The fragility indicates the condition of a structure and whether it can be easily damaged or collapsed [5-11]. Also, fragility curve is included as one of the major tasks in seismic vulnerability assessment as the result influence the whole assessment [12]. Table 1 shows the typical earthquake damage that involve the industrial facilities in Japan. Most of the damage involved massive machineries, power stations, and thermal power plants.

Table 1. Typical earthquake damage to industrial facilities in Japan [13]

Year	Earthquakes	Typical Damages
1960	Niigata EQ 1964	Destructive damage to Industrial Area
		Long term fire in petroleum refinery
	Tokachi-oki EQ 1968	Damage to large scale machinery
		Damage to power stations and sub stations
		Breakage and pulling out of anchored structures
1970		Damage to lifeline systems
	Miyagi ken-oki 1978	Damage to underground equipment and piping
		Fire of thermal power station and petroleum tanks
1980		Fire induced damage of large tank due to sloshing
	Nihonkai-Chubu EQ 1983	Long term stoppage of power and gas supply
1990	Hyogoken-nanbu Kobe EQ 1995	Destructive damage to heavy industries
		Stoppage of product transport
		Serious damage to medical/radioactive equipment
2000		Long term damage to thermal plant structures
	Niigata-Chuetsu EQ 2004	Destruction of port facilities

2. Finite element

The steel structure industrial building has 5 storey. Three dimensional modelling consisted of 11 frames in X-direction and 6 frames in Y-direction are shown in Figure 1. The frame element represents beam and column and area element represents slab [14,15]. Both elements use the same material properties as steel with density $77kN/m^3$. Meanwhile, the foundation is not modelled in this analysis and the point at the lower level of ground floor column is defined as fixed. The structure modelling is referred to the drawing as shown in Figure 2a. In addition, to ensure the three modelling is accurate, the frame is modelled by X, Y and Z direction. Figure 2b is one of the examples of frame in X-direction.

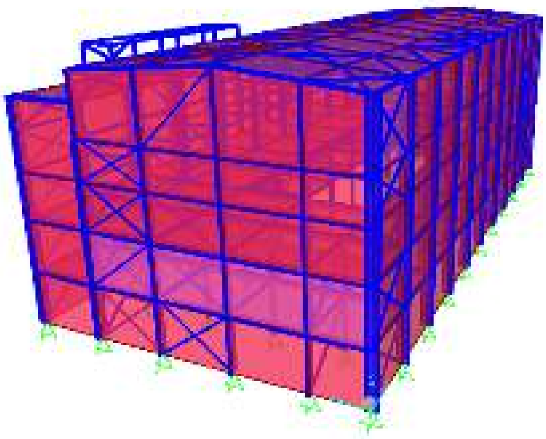
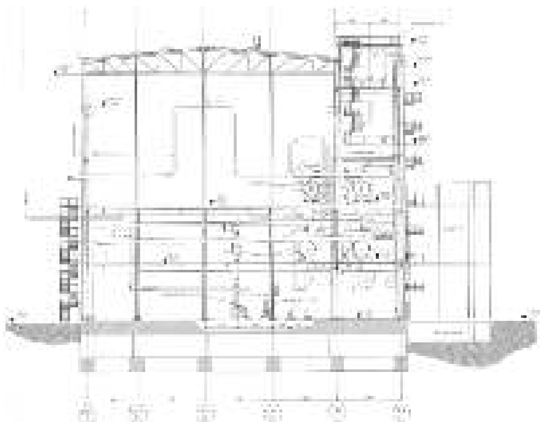
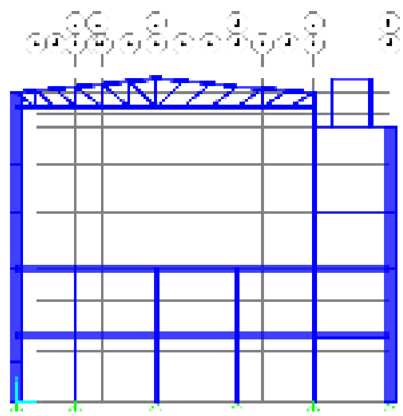


Figure 1. 3D model of steel structure industrial building



(a)



(b)

Figure 2. Geometry of the steel structure industrial building: (a) Schematic of the steel industrial building elevation (b) Structure model in X-direction

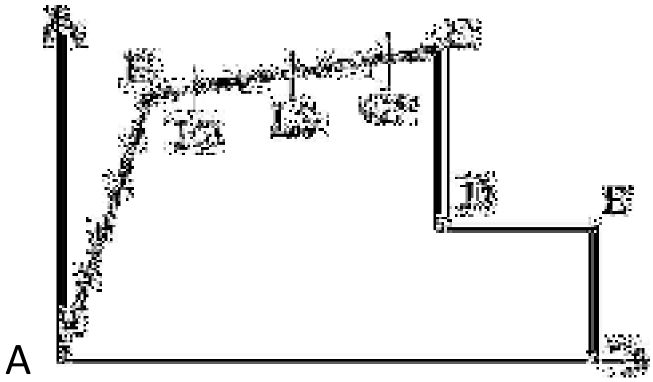


Figure 3. Typical load – deformation and target performance levels [16]

The five points (A, B, C, D and E) in Figure 3 are used to define the hinge rotation behaviour of members according to FEMA. Three more points Immediate Occupancy (IO), Life Safety (LS) and (Collapse Prevention) CP are used to define the acceptance criteria for the hinge [16]. Incremental Dynamic Analysis (IDA) is one of the methods used to evaluate seismic performance. A series of nonlinear time history is applied to a structure for many ground motion records by scaling every second to a few levels of intensity. That is how the IDA established the full set of the structure performance from elastic to yielding, nonlinear inelastic and ultimately leading to global instability [17].

The real ground motion is scaled with the design response spectrum as stated by Eurocode 8 (2004). However, many codes [18-20] suggest a minimum of three or seven sets of ground motion records to perform the IDA.

2.1. Earthquake Data

Table 2 shows the ground motion records used in this study. The table consists of the six different earthquakes with the earthquake location and Peak Ground Acceleration (PGA). Three earthquake time history data are from PEER Database and three are from Malaysian Meteorological Department. The local earthquake time histories are obtained from seismic stations in Kota Kinabalu from Ranau earthquake events in June 2015. The local earthquake has low acceleration as compared to the North America acceleration.

Table 2. Selected ground motion records

No.	Name of earthquake	Earthquake Location	PGA (g)
1.	Opaco	North America	1.17g
2.	El-Centro		0.31g
3.	Pomona		0.16g
4.	KKMRanau	Ranau, Sabah	0.13g
5.	KDMRanau		0.003g
6.	SPMRanau		0.005g

3. Result and Discussion

3.1. Pushover analysis

Pushover analysis is a method used to detect the sequential damages state of a building in the existing condition and under a proposed retrofit scheme [21]. The static pushover analysis is a partial and relatively simple intermediate solution to the complex problem of predicting force and deformation demands imposed on structures and their elements by severe ground [22]. The slope of the pushover curves is gradually reduced with increase of the lateral displacement of the building. This is due to the progressive formation of plastic hinges in beams and columns throughout the structure. The pushover curves reach a maximum point and afterwards there is a sudden drop of the curve. This maximum point corresponds to failure of the structure, i.e. there are many plastic hinges formed with big plastic rotations and the structure can no longer sustain them.

In this study, a static nonlinear (pushover) analysis of the steel structure industrial building was carried out using finite element software. A controlled displacement force was chosen to be applied. Pushover analysis was carried out separately in the X and Y directions for 3-dimensional model.

The formation of plastic hinges based on FEMA 356 rules are introduced as the input into the finite element software program. At every deformation step of the pushover analysis, the program can do the following. (a) Determine the position and plastic rotation of hinges in beams and columns (b) Determine which hinges have reached one of the three FEMA limit states: IO, LS and CP using suitable colors for their identification [23]. The steps at which the three limit states of plastic hinges are reached and the corresponding values on the pushover curve are given. Figure 4 shows the hinge deformation of the structure. Blue indicates the IO limit state at structure, while turquoise and green represent LS and CP respectively. The structure may collapse when too many failures occurred at the beam, column and bracing.

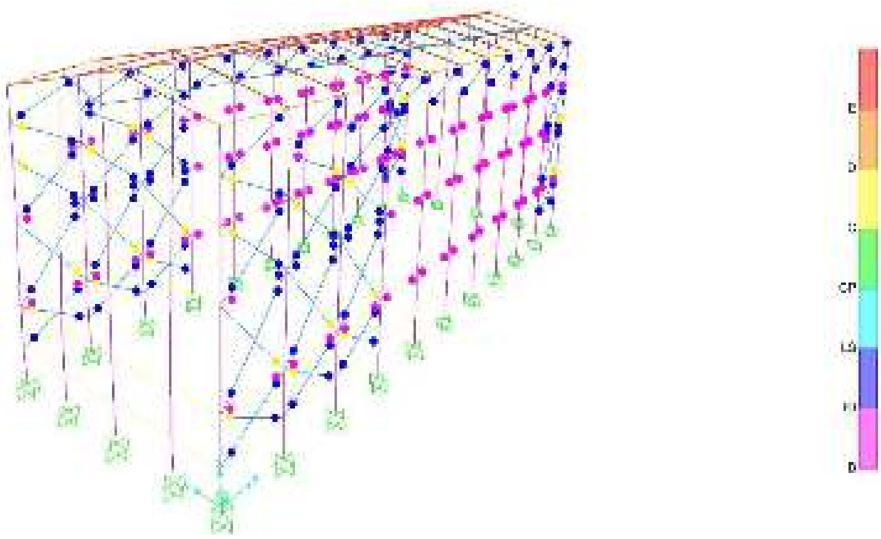


Figure 4. Hinge deformations on structure

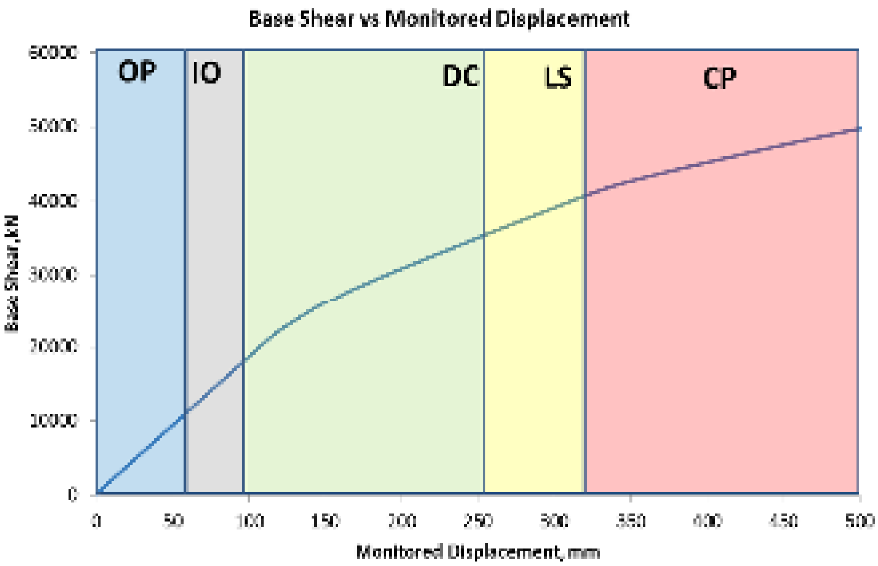


Figure 5. Pushover curve result with performance level

From Figure 5, it can be seen that the indication minor cracks of the structure, (IO) will occur at 100mm displacement while collapse level (CP) of structure begins at 320mm. Table 3 summarizes the performance level, displacement and drift ratio from the fragility curve. The drift ratio is the difference in the displacements of two immediate floor levels divided by the height of that floor [24].

Table 3. Performance level, displacement and drift ratio

Performance level	Displacement (mm)	Drift (%)
OP	80.00	0.21
IO	100.00	0.26
DC	210.00	0.55
LS	300.00	0.79
CP	400.00	1.05

3.2. Fragility curves

Fragility curves represent the probability of the structural response exceeding a specific limit state at a particular seismic intensity level with some method namely empirical, experimental, computational (analytical), and hybrid [25]. The incremental dynamic analysis (IDA) yields a division of results at varying intensities that can be used to generate a collapse fragility. In this study, six types of recorded ground motion as listed in Table 2 were used in the establishment of fragility curve. This relationship also shows a range of behaviour with large variation from each record. IDA must be considered as the first step before developing fragility curves. Then, the ground motions were scaled and scaled incrementally developed from 0.05g to 0.6 g every 0.05 g. Nonlinear time history analysis was carried out under each ground motion. Figure 6 shows the result in graph form of IDA. The ground motion records affects the behaviour of structure. Therefore, the IDA curve is different. The mean drift was calculated for every PGA to determine the average of the IDA curve.

Equation (1), as suggested by [26] was used in this study to develop the fragility curve.

$$P[D/PGA] = \Phi\left((\ln(PGA) - \mu)/\sigma\right) \qquad (1)$$

where;
D = damage
PGA = Peak Ground Acceleration
Φ = standard normal cumulative distribution
μ = mean
σ = standard deviation of the natural logarithm of PGA

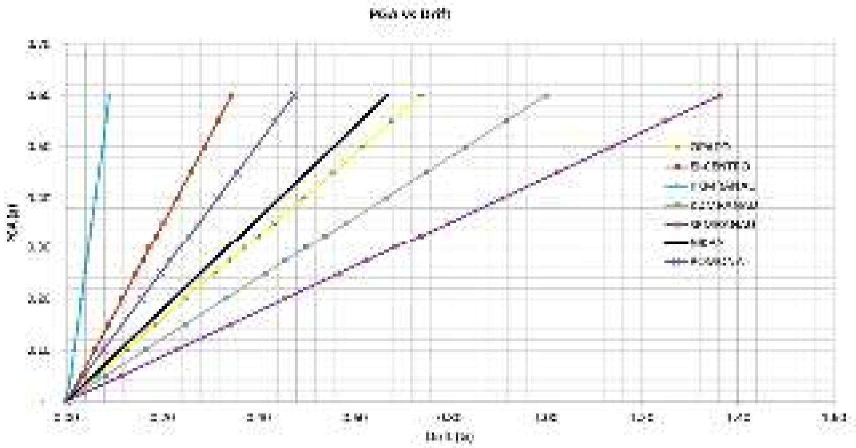


Figure 6. Incremental dynamic analysis (IDA) curve

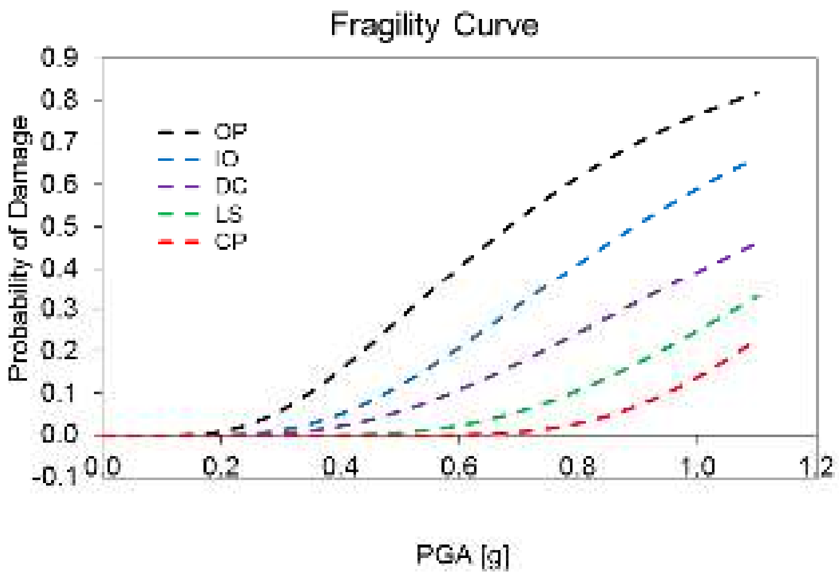


Figure 7. Fragility curve

Fragility curve was produced from Equation (1). As shown in Figure 7, at ground motion of 0.4g, the probabilities of exceeding the OP and IO levels are 20% and 5% respectively. Also, there is a 10% chance of occurrence of CP level when the PGA is 1.0g.

4. Conclusion and Recommendation

This study develops the fragility curve of steel structure industrial building based on the practice-oriented methods, namely, pushover analysis and Incremental Dynamic Analysis (IDA). Fragility curve offers great flexibility of hazard assessment for a typical building subjected to various performance levels. It can be utilised as a powerful tool to provide early estimate over vast area of affected region with ease within short period of time. For the analysis, finite element software was used as the main tool to analyse the structure under static nonlinear (pushover) analysis. Six sets of ground motion records were chosen for the analysis. The following conclusions can be obtained from this study.

1) Probability damage for steel industrial structure, OP started at 0.19g. At PGA below the steel structure industrial building is safe under OP level.

2) 5% of the structure analysed are expected to have high probability damage of IO, indicating minor cracks to the structure at PGA equal to 0.4g.

3) The performance of the structure is influenced by the peak ground acceleration value.

Therefore, to enhance the performance of the industrial steel building structure under earthquake loading, a laboratory test should be done of this structure model to study the performance. Also, more data is needed to compare the behaviour of the structure for further research.

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