Numerical study of damage index of 2d steel building with eccentrically braced frame using OPENSEES

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Abstract. Measuring degree of damage of structure under an earthquake has been researched by numerous researchers since it is difficult to ensure whether the designed building structure could withstand. In earlier research, structural damage detection method used natural frequency to indicate damage. However, this method is not spatially specific, nor are they sensitive to damage. Thus, damage index is introduced as a tool to measure the damage in specific scale of zero to one. Among different types of damage index, Park-Ang damage index is used. Model of building structure that will be analysed is steel building with Eccentrically braced frame system. EBF system has extraordinary characteristics which has high ductility of dissipating energy and also sufficient stiffness to prevent from buckling. 2D model of EBF building with variation of number of story (one, three and five story) is identified regarding to behaviour, damage index and natural frequency. The behaviour of EBF building is identified by observing the monotonic and semi- cyclic pushover analysis. Damage index of EBF building structure is identified using OpenSees program. Furthermore, natural frequency that also measure degree of damage is identified using SAP2000. By determining damage index and natural frequency, the correlation between two can be observed.

1. Introduction
Effect of Earthquake towards building structure has always been the interest of researchers and engineers, because destructions due to earthquake are critical and vulnerable to building structures. Use of steel as material of the structure is well-performed under earthquake compared with other types of material buildings and structures. Henceforth, use of steel in the building structures considerably increases. However, steel structure itself cannot withstand the major earthquake when the steel reach beyond the elastic limit and permanent deformation occurs. Consequently, design of frame is considered to enhance the stability of the structure such as moment resisting frame and braced frame. Among the framing systems, eccentrically braced frame has extraordinary characteristics of having the advantages of both moment resisting frame and concentrically braced frame. It has high ductility of dissipating energy and also sufficient stiffness to preventing from buckling [1].

However, engineers have difficulties on ensuring whether the designed structure subjected into major earthquake will withstand or collapse. One of the method to analyse the degree of damage receive by structure is known as damage index. Therefore, damage index is studied and introduced as a tool to measure the damage on the building structure that afflicted by earthquake and expressed in specific scale. By identifying the damage index of existing building structure, engineers could estimate and diagnose the condition of the existing or designed structure based on the result of damage index to prevent from collapse due to earthquake. Former study related to damage index are numerous. However, compared with other damage indexes [2] stated Park-Ang damage index is considered to be one of the most realistic measures of structural damage. Thereby, Park and Ang damage index applied in this research. Furthermore, damage index has close relation with natural frequency. Any damage in structure changes the local stiffness and energy dissipation characteristics which result in changes in
the natural frequency of the structure. Study of natural frequency respect to structural damages such as cracks and holes have been conducted by numerous researchers. Thus, the correlation of damage index with natural frequency can be identified.

2. Method

Research is conducted using OpenSees (Open System for Earthquake Engineering Simulation) software to analyze the damage index of chevron EBF using monotonic pushover analysis and semi-cyclic pushover analysis. Before further research structure modelling using OpenSees software must be validated. After validation, one, three and five story EBF steel structures are consequently analyzed to identify the damage index using Park and Ang damage index. Furthermore, natural frequency of the structure under lateral load will be identified using SAP2000 program since it could also measure the degree of damage. In conclusion, it will be compared and analyzed with damage index to understand the relation.

2.1. Validation model

Prior to analysing the damage index of several different steel structure building, validation of structure using OpenSees (The Open System for Earthquake Engineering Simulation) software has been done. Dimension of one story EBF with shear link regarding to Wang Shujun [3] and commands used on coding the structure in Open Sees are as following:

![Figure 1. Dimension & OpenSees model of one story EBF with shear link.](image)

The dimensions of the structure are 3000 mm x 5600 mm with link length of 640 mm. The structure is made of the steel with property of 206 KN/mm² modulus of elasticity, 235 N/mm² yield strength and 0.1 strain hardening. For beam and link, the profile used is H300x150x6.5x9. For bracing, the profile used is RHS150x8. For column, the profile used is H350x350x10x16.

In detail, multiple sub-springs, 3 translational springs and 3 rotational springs, for the link of EBF system designed using material command. Design of both translational springs and rotational springs are designed based on [4]. As a result, the load displacement curve obtained from OpenSees and the load displacement curve of [4] shows no significant difference which is valid to be use for further research in determining the damage index and natural frequency.
2.2. Problem formulation

Park and Ang proposed a ratio of maximum to ultimate deformation and hysteretic energy based damage index. It is the best-known and most widely explored damage index. Generally, the damage due to earthquake loading caused by the combination of repeated stress reversals and high stress excursion.

\[
D_{pa} = \frac{\delta_m}{\delta_u} + \frac{\beta}{\delta_u Q_y} \int dE_h
\]

where \(\delta_m\) is maximum deformation, \(\delta_u\) is ultimate deformation under monotonic loading, \(\beta\) is non negative strength deteriorating constant, \(Q_y\) is yield strength and \(\int dE_h\) is hysteretic energy absorbed by the element during the earthquake. Theoretically value of \(D_{pa}\) is zero under elastic response and \(D_{pa}\) equal or greater than 1 is complete collapse or total damage. Hence, function of the responses \(\delta_m\) and \(dE\) represent the structural damage. It dependent on the loading history. Meanwhile, \(\delta_u\) and \(Q_y\) are independent of the loading history.

Natural frequency is a frequency of the structure itself tend to vibrate when subjected to certain external forces. It can be determined using Rayleigh’s analysis which is regard of the conservation of energy. This method offers a good approximation to determine the initial natural frequency. Total energy of structure in absence of damping in a free vibration system is considered in the principle of conservation of energy.

\[
\omega = \sqrt{\frac{k}{m}}
\]

where \(\omega\) is natural frequency, \(k\) is stiffness and \(m\) is mass.

2.3. Parametric test

Several parameters are analysed in this research. Three different stories of EBF with shear link steel building are additionally built using OpenSees and SAP2000: one story, three story and five story. As validation model using OpenSees being compared with experimental result is verified, the system on modelling detail structure such as link and connection built regarding to the validation model. Model of three story chevron EBF with shear links is based on the model from Wang Shujun [3]. The total dimensions of the structure are 11000 mm x 8000 mm with link length of 600 mm. The structure is made of the steel with property of 205 KN/mm² modulus of elasticity, 235 N/mm² yield strength and 0.1 strain hardening. Meanwhile, model of five story chevron EBF with shear links is based on the model from Sullivan Timothy [5]. The total dimensions of the structure are 17500 mm x 7000 mm. The link length of one and second stories are 800 mm whereas the link length of third, fourth and fifth stories are 700 mm. The structure is made of the steel with property of 210 KN/mm² modulus of elasticity, 450 N/mm² yield strength and 0.1 strain hardening. For further information of three and five story EBF building such as profile and command used in OpenSees are shown in following figures:
Figure 3. Dimension & OpenSees model of three story EBF with shear links (left) and five story EBF with shear links (right).

Table 1. Profile of three story chevron EBFs with shear links.

| Element | 1st Story Size(mm) | 2nd Story Size(mm) | 3rd Story Size(mm) |
|---------|-------------------|--------------------|--------------------|
| Beam    | W250x45           | W200X31            | W130X28            |
| Link    | W250x45           | W200X31            | W130X28            |
| Bracing | HSS203X203X8      | HSS178X178X8      | HSS152X152X8       |
| Column  | W310X79           | W310X79            | W250X33            |

Table 2. Profile of five story EBFs with shear links.

| Element | 1st Story Size(mm) | 2nd Story Size(mm) | 3rd Story Size(mm) | 4th Story Size(mm) | 5th Story Size(mm) |
|---------|-------------------|--------------------|--------------------|--------------------|--------------------|
| Beam    | HE 220 B          | HE 220 B           | HE 200 B           | HE 200 B           | HE 200 B           |
| Link    | HE 220 B          | HE 220 B           | HE 200 B           | HE 200 B           | HE 200 B           |
| Bracing | HE 220 B          | HE 220 B           | HE 200 B           | HE 200 B           | HE 200 B           |
| Column  | HE260 B           | HE260 B            | HE260 B            | HE 200 B           | HE 200 B           |

3. Results and discussions

Pushover analysis using monotonic and semi-cyclic loading are conducted in OpenSees software. This bring a result of load displacement curve in order to calculate the Park and Ang Damage Index. Moreover, monotonic pushover analysis is consequently conducted in SAP2000 in order to obtain the natural frequency of the building on each cycle. Therefore, the results of pushover analysis in OpenSees and SAP2000 of one, three and five story EBF building are following:
Figure 4. Comparison load displacement curve of one story monotonic & semi-cyclic POA (Left) and three story monotonic & semi-cyclic POA (Right) in each OpenSees and SAP2000.

Figure 5. Comparison load displacement curve of five story monotonic & semi-cyclic POA in each OpenSees and SAP2000.

Table 3. One story (left) and three story (right) Park-Ang damage index of each cycle.

| Variable | First Cycle | Second Cycle | Third Cycle | Fourth Cycle | Fifth Cycle |
|----------|-------------|--------------|-------------|--------------|-------------|
| δm       | 5.5192      | 11.03985     | 16.55976    | 22.07966     | 27.5996     |
| δu       | 27.5996     | 27.5996      | 27.5996     | 27.5996      | 27.5996     |
| β        | 0.025       | 0.025        | 0.025       | 0.025        | 0.025       |
| Qy       | 586489      | 586489       | 586489      | 586489       | 586489      |
| δEd     | 5109.485   | 118940       | 372399.3    | 755234.4     | 0           |
| DI       | 0.199982   | 0.400184     | 0.600575    | 0.801166     | 1           |

Table 4. Five story Park-Ang damage index of each cycle.

| Variable | First Cycle | Second Cycle | Third Cycle | Fourth Cycle | Fifth Cycle |
|----------|-------------|--------------|-------------|--------------|-------------|
| δm       | 21.3506     | 42.7012      | 64.0518     | 85.4024      | 106.753     |
| δu       | 106.753     | 106.753      | 106.753     | 106.753      | 106.753     |
| β        | 0.025       | 0.025        | 0.025       | 0.025        | 0.025       |
| Qy       | 861748      | 861748       | 861748      | 861748       | 861748      |
| δEd     | 350.94      | 107.945.98   | 647.445.13  | 652.450.29   | -           |
| DI       | 0.2         | 0.40003      | 0.60018     | 0.80018      | 1           |
The value of Park-Ang damage index increased constantly until it reaches one where the structure is collapsed. As the value of maximum displacement increased as number of cycle increased, value of damage index will be increased. This trend can be seen from the value of damage index of each cycle which is steadily increased with around 0.2 for all structures. Moreover, the value of damage index will increase as the hysteretic energy absorbed by the structure is greater since non-negative constant, ultimate displacement and yield strength are constant. According to the damage index tables of all 3 different story of structures, the most ductile condition where has the greatest value of hysteretic energy absorbed by the structure is on fourth cycle.

3.1. Natural frequency

![Figure 6. Number of cycle - natural frequency relation graph of five story EBF building.](image)

In SAP2000, the mass of steel is defined as constant, because it doesn’t crack such as concrete which lose the mass from it. According to equation of obtaining natural frequency, natural frequency is determined by the square root ratio of stiffness and mass.

At glimpse observation, one, three and five story EBF buildings shows similar trend on the number of cycle against natural frequency relation graph. Natural frequency decreased from initial condition of structure until it collapsed on fifth cycle which indicates the stiffness of structure weakened. For one and three story EBF building, on natural frequency of initial condition to first cycle condition, it reduced on a small scale which represent the structure slightly weakened. Afterward, the natural frequency drastically decreased until the third cycle and consequently the natural frequency moderately decreased. However, five story EBF building has prominently different trend compare to one and three story EBF buildings which the trend of the cycles produced natural frequency tends to fluctuate between initial and third cycle after which will decreased until the final cycle. This trend might have occurred on account of the length of shear links on the story. Contradictory to the one story and the three story EBF building, the five story EBF building has different length of shear link between first, second and third, fourth and fifth story which is displayed in Table 2. Difference of length of shear link generates different behaviour and capacity under lateral loads. Furthermore, since the plastic hinge only occur on the shear link in EBF steel building, the behaviour of different length of shear link could bring a result of fluctuated natural frequency. The first and second story restrained value of first to third cycle fluctuated which indicates the capacity of plastic hinge occurred fluctuated and leads to fluctuation of structure stiffness.
3.2. Correlation between damage index and natural frequency

![Graph](image)

**Figure 7.** Damage assessment of one story EBF building (left) and three story EBF building (right) on each cycle.

![Graph](image)

**Figure 8.** Damage assessment of five story EBF building on each cycle.

From these graphs, critical limit of the structure can be identified. Critical limit is a limit where the rate of damage index increase much more significantly than the rate of natural frequency. The critical limit of structure is determined at the plastic condition beyond the elastic region. Therefore, when the condition of structure exceeds the critical limit, the damage index increase much more significantly than decrease of natural frequency.

At glimpse of observation, damage index is inversely proportional to natural frequency as the value of force increased. The rate of damage index curve is steadily changed on each cycle until it collapses. For one story chevron EBF with shear link, critical limit is occurred on fifth cycle. The critical limit can be determined to be on fifth cycle where from fourth to fifth cycle is the greatest ratio of damage index to natural frequency after elastic region. It is occurred at 100% of ultimate base shear, $V_u$. Critical limit of three story chevron EBFs with shear links is occurred on fourth cycle. On the fourth cycle where the cycle is exceeded elastic region, the ratio of damage index to natural frequency is the greatest with 0.12637269. Regarding to ultimate base shear, $V_u$, the critical limit is located at 93.45% of it.

Unlike the one and the three story EBF building, five story EBF building doesn’t demonstrate same relation of damage index is inversely proportional to natural frequency as the value of force increased. The natural frequency from initial state to third cycle has slightly fluctuated with no significant difference and significantly changed until it collapses. Critical limit of five story chevron EBFs with shear links is occurred on fifth cycle. On the fifth cycle where the cycle is exceeded elastic region, the ratio of damage index to natural frequency is the greatest with 0.05434. Regarding to ultimate base shear, $V_u$, the critical limit is located at 100% of it.
4. Conclusions

Damage index of three different story of steel buildings with eccentrically braced frame system model have analysed using OpenSees. In order to determine the damage index, monotonic pushover analysis and semi-cyclic pushover analysis were conducted. With obtained data using OpenSees, Park-Ang damage index was calculated. From the load displacement curve of semi-cyclic pushover analysis, the behaviour of EBF building with shear links can be analysed. Without consider the number of story, the EBF building with shear links used in this research tend to be stiff at the beginning and steadily become ductile which absorbs the most hysteretic energy on the cycle before it collapses.

Entire damage index of one, three and five story EBF building steadily increased from cycle to cycle around 20%. However, the natural frequency of the one and the three story EBF building is slightly changed with under 1% from initial to first cycle and the highest decreased percentage from first to second cycle. Moreover, it is moderately decreased until fifth cycle. In the case of the five story, the natural frequency is fluctuated with no significant change from initial to third cycle and has the greatest change from third to fourth cycle with 21.01%. Afterward, it is moderately decreased until fifth cycle. In general, the natural frequencies are slightly decreased with no significant difference at the beginning until first cycle with under 1% whereas the damage indexes are steadily changed with around 20%. From first to fifth cycle, the natural frequencies are started to decrease significantly. Meanwhile, the damage indexes are constantly increased around 20%. In overall, damage index is inversely proportional to natural frequency as the force increased. The critical limit of all three different story EBF building occurred at the end of the cycles of semi-cyclic push over analysis. For the one and the five story EBF building, the critical limit is on the fifth cycle whereas the three story EBF building is on fourth cycle.

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