Study the correlation of natural frequency and damage index of 2D steel EBF-vertical shear link

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Abstract: Study of damage index of Eccentrically Braced Frame-Vertical Shear Link (V-EBF) was performed. The study was part of the research of damage index of several types of seismic resistance of steel structure. Three different stories of the V-EBF were taken from the preceding experimental study conducted by other researchers. Monotonic and semi-cyclic pushover analysis was carried out by using OpenSees software to get the parameters needed to determine the damage index which was calculated according to Park Ang’s theory. The index is measured as a sum of deformation per-cycle and the energy absorption. The study found that the natural frequency of the structure decrease with the increasing of structural damage. The reduction of natural frequency from the initial condition to the third damage is 70.79%, 71.68%, and 62.13% of the one, two and three stories of The V-EBF structure, respectively. The study observed the critical limit where the damage index begins to increase drastically, followed by a decrease of the natural frequency. It occurred when the ratio of natural frequency to the initial frequency was in the range of 43% to 59%.

Keywords: Damage Index, Natural Frequency, Eccentrically Braced Frame-Vertical Shear Link, OpenSEES

1. Introduction

According to the United States Geological Survey (USGS), earthquakes are vibrations or shocks at the bottom of the earth due to sudden movements of the earth’s plates. The movement is continuous, and if the pressure caused by the meeting of the two moving plates exceeds the limit of the plate’s capacity, a fault occurs, which causes the release of energy and is known as an earthquake. The energy released during an earthquake will transmit in the form of waves that cross the earth’s crust. The waves will forward to building structures through the foundation system then to the building structure [1]

The earthquake force received by a building is in a lateral and vertical direction. However, in the vertical direction, it is often neglected, considering that the building’s weight can generally provide adequate resistance. Thus, the most significant influence of earthquake waves is the lateral force [1]. Each building has a different response to the same earthquake waves. It depends on the type of structure used. However, one of the most fundamental building characteristics is the period of waves in the structure. The structure’s period is influenced by the complexity of the stiffness, mass, and total building height. If the earthquake wave period is the same as the building period, the wave will experience resonance, and the building must be able to withstand the intensity of the earthquake force [2].

The quantification of damage of RC buildings due to earthquakes is very important [3]. Park and Ang [4] proposed a damage index as a parameter that represents the damage of a structure in scale numbers, where 0
indicates no damage while 1 indicates total failure. The index is used to assess vulnerability and post-disaster damage and to evaluate structural performance whether the strengthening is required. A recent study about damage index conducted by Sentosa [5]. The research found that the index increased dramatically on RC structure as cracks start to form and the index value was correlated with the natural frequency of the structure.

A numerous amount of research has been done to study the damage index of structures, but most of them were RC structures. This is because the steel material has several advantages, such as high strength, uniform, hardness, good elasticity, and ductility. In the past, moment-resisting frame and concentrically braced frame were the most commonly used for earthquake resistant steel structure systems. However, both types of structures are considered less effective in meeting seismic requirements, such as stiffness and ductility.

Eccentric braced frame combines the high elastic stiffness characteristic of a concentrically braced frame (CBF) and the energy dissipation stability of a moment-resisting frame (MRF). The EBF is a structural variation with braces, where the axial force components on the braces are moved through the shear forces on the beam. These beams refer to as links. The EBF structure has several configurations of braces and links. The braces must be connected to the link so that extreme deformation only occurs in the link. Vertical Eccentrically Braced Frames (V-EBF) is an EBF structure with vertical links. Bracing with an inverted V shape is connected to a beam with a sliding panel or a vertical shear link. Extreme inelastic deformation is localized in the sliding panels so that there is no damage to the main elements. Repairs after a large earthquake are easier to do [6].

The study of damage index on several types of steel structure such as moment-resisting frame, concentric braced framed and eccentric brace frame have been conducted [7-9]. As a part of the research of damage index on several types of steel structure system, the study was continued to V-EBF. The study of DI on EBF previously conducted by Victor [4] was the inverted V shear link which was different from this research. The study aimed to investigate the damage index of (V-EBF) system and its correlation to the natural frequency of the structure.

2. Research Method

A structure has a risk of failure due to a combination of high and repetitive stresses. The failure criteria need to be calculated not only at maximum conditions but also due to cyclic loading. According to Park and Ang (1985) [4], the failure of an earthquake-resistant structure is a linear combination of failures caused by an excessive deformation and the effects of repeated cyclic loading. Hence, Park and Ang formulate the damage index as the equation below.

\[ D_{PA} = \frac{\delta_M}{\delta_u} + \beta \frac{Q_y}{Q_y \delta_u} \int dE \]

\( \delta_M \) and \( \delta_u \): the maximum deformation due to earthquake monotonic loading,
\( d_y \) and \( Q_y \): yield displacement and yield strength
\( \int dE \): absorbed hysteric energy
\( \beta \): non-negative coefficient, for RC = 0.05, steel = 0.025

The natural frequency is the main dynamic parameter of a structure which depends on its mass and stiffness. Damaged structures tend to experience reduced stiffness which causes changes in the natural frequencies [12]. Hence, the damage index and the damage status of structural elements (i.e., beams and columns) of RC structures can be evaluated through its natural frequencies [12].

The research was conducted using OpenSEES (Open System for Earthquake Engineering Simulation) software to analyze the damage index of the Vertical Shear Link EBF using monotonic and semi cyclic pushover analysis. In the early stages of research, model validation was carried out using experimental results from other published research. Then, the parametric test was performed on one, two and three of VSL EBF steel structures to obtain the correlation of the damage index and the natural frequency. The damage index was analyzed using Park and Ang equation.

The validation was conducted by comparing the pushover analysis results obtained by using OpenSees with the experimental results conducted by Ming L [9]. He conducted a test on a vertical shear link EBF (EBF-VSL) constructed by high strength steel material (HSS). The dimension of one-story VSL EBF is shown in Figure 1. All the members, beams, columns, and braces, were made of Q460 steel with a yield strength as 460MPa, except the shear link which was made of Q345 steel with yield strength of 345MPa. A H225x125x6x10 was selected for beam and shear links, whereas the column was used H225x125x6x10 and bracing was H125x120x6x10.
Steel02 was selected for steel material which is a uniaxial Giuffre-Menegotto-Pinto model with isotropic strain hardening. Truss element was assigned for bracing. Beam and column used the NonlinearBeamColumn element that assumes plastic deformation to be distributed along with the element. The link was defined with BeamWithHinges command, where the plasticity is concentrated at the end of the link. Three rotational and translational multilinear springs were assigned to represent the flexural and shear inelastic behavior of the plastic hinge at the link ends by the multilinear function [10]. The validation results are presented on the load-displacement curve and compared to test results conducted by Ming [10] as shown in Figure 2. As can be seen both graphs is very close with no significant difference, hence the FE model from OpenSees is considered valid and the model could be used for parametric study.

A parametric study was conducted on three V-EBF shown in Figure 3 which were one-story, two-story, and three-story structures. The frames were taken from previous research conducted by another researcher. The one-story structure was similar to that used for the validation model with slight modification by removing the extended column. The entire material property and structure section referred to the journal. The two-story V-EBF is based on research conducted by Musmar [11] whereas the three-storey was taken from experimental conducted by Muhammad G [10]. The structure has a span length of 5 m with a total height of 9.85 m. The dimension of three VSL EBF is shown in Figure 3.
3. Results and Discussions

3.1. Damage Index

Pushover analysis was performed using monotonic and semi-cyclic loading. Technically, the load was applied on the roof story until the structure collapses or reaches the control deformation. The monotonic pushover is meant to get the curves of base-shear versus lateral. Based on this curve a semi-cyclic pushover curve is obtained to find each cycle’s deformation and the amount of hysterical energy. The amount of energy is determined based on the area of each cycle at particular deformation. Technically, the force was applied until it reaches the roof displacement target on the first cycle, then the force was released so that the structure deforms when the base shear returns to zero. Furthermore, the deformed structure was pushed until it reaches the second displacement target and again, the force was released. This process produced a semi-cyclic graph with three cycles. The analysis was carried out using OpenSEES software. The results are shown in Figure 4.

![Figure 4. The comparison of load-displacement curve of three-story monotonic & semi-cyclic POA](image)

The damage index ranges are from 0 to 1, where 0 represents the structure is at the initial condition when the structure is intact, while 1 represents the structure that has suffered the most damage. The index was determined on six conditions. Apart from the damage 1, 2, and 3 conditions, the damage index was calculated at the elastic and yield points. This is to increase the variety of structural conditions so that the analysis can be carried out in more detail. The first condition is the initial condition when the structure is intact. The second and the third are the elastic condition until reaching the yield point. The fourth condition is when the structure is damage with the damage index reach 1. This is the maximum deformation of the first cycle of the semi-cyclic graph. The fifth condition is damage #2 when the structure reaches the maximum deformation from the second cycle of the semi-cyclic graph. The sixth condition is damage #3, which is when the structure reaches its maximum deformation from the third cycle on the semi-cyclic graph. The damage index present in Table 1. The greater the level of damage, the higher the damage index value.
Table 1. Damage index of each cycle

| Damage Index One-Story | DI Initial | DI Elastic | DI Yield | DI Damage #1 | DI Damage #2 | DI Damage #3 |
|------------------------|------------|------------|----------|--------------|--------------|--------------|
| dM (mm)                | 0.00       | 5.20       | 26.60    | 43.00        | 79.20        | 120.00       |
| dU (mm)                | 120.00     | 120.00     | 120.00   | 120.00       | 120.00       | 120.00       |
| β                      | 0.025      | 0.025      | 0.025    | 0.025        | 0.025        | 0.025        |
| Qy (kN)                | 534.70     | 534.70     | 534.70   | 534.70       | 534.70       | 534.70       |
| GraphArea1 (kNmm)     | 0.00       | 0.00       | 0.00     | 2655.87      | 3593.00      | 0.00         |
| GraphArea2 (kNmm)     | 0.00       | 0.00       | 0.00     | 4043.37      | 5703.57      | 0.00         |
| dE (kNmm)              | 0.00       | 0.00       | 0.00     | 1387.50      | 2110.57      | 0.00         |
| DI.PA                  | 0.00       | 0.04       | 0.22     | 0.36         | 0.66         | 1.00         |

| Damage Index Two-Story | DI Initial | DI Elastic | DI Yield | DI Damage #1 | DI Damage #2 | DI Damage #3 |
|------------------------|------------|------------|----------|--------------|--------------|--------------|
| dM (mm)                | 0.00       | 3.40       | 36.40    | 43.00        | 75.50        | 110.00       |
| dU (mm)                | 110.00     | 110.00     | 110.00   | 110.00       | 110.00       | 110.00       |
| β                      | 0.03       | 0.03       | 0.03     | 0.03         | 0.03         | 0.03         |
| Qy (kN)                | 442.00     | 442.00     | 442.00   | 442.00       | 442.00       | 442.00       |
| GraphArea1 (kNmm)     | 0.00       | 0.00       | 0.00     | 1960.89      | 2043.84      | 0.00         |
| GraphArea2 (kNmm)     | 0.00       | 0.00       | 0.00     | 3841.39      | 9779.38      | 0.00         |
| dE (kNmm)              | 0.00       | 0.00       | 0.00     | 1880.50      | 7735.54      | 0.00         |
| DI.PA                  | 0.00       | 0.03       | 0.33     | 0.39         | 0.69         | 1.00         |

| Damage Index Three-Story | DI Initial | DI Elastic | DI Yield | DI Damage #1 | DI Damage #2 | DI Damage #3 |
|--------------------------|------------|------------|----------|--------------|--------------|--------------|
| dM (mm)                  | 0.00       | 3.80       | 9.00     | 32.00        | 54.50        | 75.00        |
| dU (mm)                  | 75.00      | 75.00      | 75.00    | 75.00        | 75.00        | 75.00        |
| β                        | 0.03       | 0.03       | 0.03     | 0.03         | 0.03         | 0.03         |
| Qy (kN)                  | 240.00     | 240.00     | 240.00   | 240.00       | 240.00       | 240.00       |
| GraphArea1 (kNmm)       | 0.00       | 0.00       | 0.00     | 1960.89      | 2043.84      | 0.00         |
| GraphArea2 (kNmm)       | 0.00       | 0.00       | 0.00     | 3841.39      | 9779.38      | 0.00         |
| dE (kNmm)                | 0.00       | 0.00       | 0.00     | 1880.50      | 7735.54      | 0.00         |
| DI.PA                    | 0.00       | 0.05       | 0.12     | 0.43         | 0.74         | 1.00         |

3.2. The Natural Frequency

SAP2000 software was used to obtain the natural frequency by performing modal analysis which was examined in six structural conditions. As shown in Figure 5, a one-story structure has the most considerable natural frequency. One-story structures tend to have a greater stiffness than other structural variations so that the period will be smaller. The relationship between period and natural frequency is inversely proportional. This explains when the period is small, the natural frequency is large.

Figure 5. The natural frequency of one, two, and three-story EBF building

Another parameter investigated was the number of floors or the height of the structure. As the height increases, the natural frequency decrease because taller structures are more flexible. Based on three V-EBV structures studied, the natural frequency obtained were not totally confirmed with this theory. For example, the natural frequency a two-story structure when experiencing yield conditions is 21.22 Hz, which is less than a
three-story structure at similar condition, which is 23.09 Hz. This fact might be due to the different height for each floor, the material, and the cross-section.

3.3. Correlation between damage index and natural frequency

Figure 6 to 8 present the damage index and the natural frequency plotted in the same graph to find the correlation. The natural frequency is presented as the ratio to the initial condition, hence the value is between 0 and 100% which is similar to the damage index scale, 0 to 1. A value of 1 or 100% is the natural frequency in the initial stage. The horizontal axis shows the maximum lateral force at each cycle. As can be seen from the three figures, there is a point where the damage index increase drastically, and the natural frequency decreased gradually. This point is called a critical limit \([12]\). When the lateral loading passed the critical limit, the damage index increase drastically. The critical limit of the one-story structure occurs when the structure reaches 43.47% of its initial frequency. Meanwhile, the two and three storeys have the value of 43.26% and 59%, respectively.

Figure 6. Damage assessment of one-story EBF building on each cycle

Figure 7. Damage assessment of two-story EBF building on each cycle

Figure 8. Damage assessment of three-story EBF building on each cycle
4. Conclusions

The damage index was calculated at six points, namely the initial condition, elasticity, yield, damage #1, damage #2, and damage #3. The natural frequency of the structure decrease along with the increasing of structural damage. The reduction of natural frequency from the initial condition to the 3rd damage is 70.79%, 71.68%, and 62.13% of the one, two, and three stories structure, respectively. The most significant reduction of the natural frequency occurs in a two-story structure. In general, the natural frequency decrease as the height of the building increases. However, due to different material properties, cross-section, and height of V-EBF, the theory was not fully applied in this study.

The correlation of damage index and natural frequency is inversely proportional. The higher the index, the smaller the natural frequency. The critical limit occurs when the damage index begins to increase drastically, followed by a decrease in the natural frequency. In a one-story structure, it happens when the natural frequency is 43.47% of the initial condition, the two-story structure is 43.26%, and the three-story structure is 59%.

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