Damage assessment of moment resisting frame structures using correlation between damage index and natural frequency

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Abstract. Damage index is a define scale to describe damage of the structure due to earthquake. Several studies of damage index have been carried out on reinforced structures, but not many studies performed on steel structures. Numerical research about damage index on moment resisting frame of steel structure has been conducted. Monotonic and semi-cyclic pushover analyses using OpenSEES software was carried out to obtain the index. Two parameters that affect the damage index value are the displacement ratio and energy absorption. Damage index value of MRF obtained in this research is governed by the displacement ratio. The main objective of this study is to correlate damage index and the natural frequency. SAP2000 is used to get the natural frequency through modal analysis. The results show that natural frequency can be used to assess structural damage. Hence, structural health monitoring can be simplified by assessing the natural frequency.

Keywords: Moment Resisting Frame, Damage Index, Natural Frequency, OpenSees.

1. Introduction

Lateral load-resistant structural design uses the performance-based seismic design method as this method results in a more realistic structure than that with conventional methods. This is because this method simulates several lateral loads on the structure, resulting in a certain damage level which is used as a reference design point. The damage levels are categorized as Immediate Occupancy, Life Safety and Collapse Prevention, as stated in FEMA 356 [1]. These damage levels are measured using structural drift, which is the maximum deformation of the top level of a structure due to a certain type of lateral loading. However, these categories are all qualitative and can’t represent the actual condition. Therefore, there needs to be a damage assessment method that can quantitatively evaluate structural damage, namely the damage index.

The damage index theory that will be used in this research is the Park-Ang damage index [9]. This theory was made based on experimental results and this damage index model have acquired numerous recognitions in the field of earthquake engineering. The Park-Ang damage index is calculated not only based on maximum displacement, but also on hysteretic energy, thus representing the actual state of a structure. Damage index valued 0 means an absence of structural damage while a value of 1 means the
total failure of a structure. The parameters for the calculation of damage index are obtainable through pushover analysis.

The Park Ang’s damage index has been widely used by researchers, one such being Bastian Okto B.S. [3] in his research on the damage index behaviour of reinforced concrete structures with relations to its natural frequency since in some cases visual inspection on concrete is quite complicated to do, so inspection of damage structures with vibration test will facilitate the damage assessment. A damaged structure tends to have a decrease of natural frequency, corresponding to the formula of natural frequency which is a function of stiffness and mass, thus allowing this parameter to be representative of loss of stiffness, and natural frequency assessments can be used as dynamic parameters to identify actual conditions of the structure.

Not many Park-Ang damage index studies have been done on steel structures, therefore this research will be done on steel moment-resisting frames. According to Mazzolani, [5] there are three lateral load-resistant steel structures, namely moment-resisting frame (MRF), concentric braced frame (CBF) and eccentrically braced frame (EBF). Among the three categories, MRF has the best ductile behaviour, which is a good behaviour to have against seismic loading, thus is why MRFs have been selected for this study.

2. Model Validation

Model validation is done to ensure that the models made in OpenSEES [7] and SAP2000 [4] can represent the actual behavior of the structures reviewed. The validation is done by conducting pushover analyses on both programs and comparing the base shear-displacement graph to the results shown in the corresponding research. The model used for validation is based on the studies from journal “A Selection of Calibration Frames in North America for Second Order Inelastic Analysis” [8]. The model is a 1 bay 1 floor MRF. The material properties of this model are $F_y = 26$ ksi and $E = 29000$ ksi with strain hardening = 0.0034. The profile for the beam and columns is W8x31. On both ends of the portal there is a point load applied with $P = 65.73$ kips.

In OpenSEES, modelling an element’s plasticity can be done using the Ibarra-Krawinkler rotational springs command, the beamwithHinges command, or the nonlinearBeamColumn command. The nonlinearBeamColumn command shows results most resembling the experimental results, therefore it will be the command used in this research. The material used in this model is Steel01. The columns are given P-Delta transformation behavior while the beam is given linear transformation behavior. In SAP2000, the plasticity of an element is modelled using the automated plastic hinge which is based on ASCE 41-13 [2]

As shown in the graph below, the models made in OpenSEES and SAP2000 show the same behavior as the experimental results of the model. Therefore, both the models in OpenSEES and SAP2000 can be used as the basis of modelling MRFs for this research.
3. Research Methodology

After model validation, the next step in this research is to model the 3 and 5 storey structures. The 3-storey structure is based on the model by Yamrici [8] while the 5-storey structure is based on the model by M.Reza et al [6]. The material properties of the structures can be seen in the table below while the geometry of the structures are shown in figures 3 and 4.

**Table 1. Section Properties of 3 Storey and 5 Storey Model.**

| Section Properties | Modulus Elasticity (E) | Yield Stress (Fy) |
|--------------------|------------------------|-------------------|
| **3 Storey**       |                        |                   |
| 8WF21              | 31.5 Ksi               | 26826 Ksi         |
| 6WF25              | 32 Ksi                 | 35018.73 Ksi      |
| **5 Storey**       |                        |                   |
| All Section Properties | 51.5 Ksi             | 30457.91 Ksi      |

**Figure 2.** Validation Result of MRF Model.

**Figure 3.** 3 Storey Structure

**Figure 4.** 5 Storey Structure
Monotonic and semicyclic pushover analyses are then conducted on the three structures (1-storey, 3-storey & 5-storey structures) using OpenSEES. Ultimate deformation and yield strength will be obtained from the monotonic pushover analysis while maximum deformation of the cycle and the dissipated hysteretic energy will be obtained from semicyclic pushover analysis. These parameters will be used in the calculation of the Park-Ang damage index, which is defined as

\[ D = \frac{\delta m}{\delta u} + \frac{\beta}{Q_y} \int dE \]  

where \( \delta m \) is maximum deformation, \( \delta u \) is ultimate deformation, \( Q_y \) is yield strength, \( dE \) is hysteretic energy, \( \beta \) is a nonnegative constant acquired from empirical data, where for steel structures its value is 0.025. Damage index will be calculated for the condition of the structures at the end of the three cycles. The first cycle is when the structures experience yielding, the second is exactly between the first and third cycle, the third is when the structures experience its ultimate deformation.

From the graph above, we can obtain the value needed for the damage index calculation, for 1 storey structure the ultimate deformation (\( \delta u \)) is 8 inch, the maximum deformation (\( \delta m \)) is 3 inch, and yield strength (\( Q_y \)) of 1 storey structure is 10.25 Kips. For the hysteretic energy (\( dE \)), there is no significant looping area, so we can assume that the hysteretic is equal to zero. By using the equation (1), we can calculate the damage index for the 1st cycle of 1 storey structure is 0.38, and for other damage index calculation, can be seen in table 2.

After the damage index values have been obtained, the next step is to obtain the natural frequency values of each cycle of the loading for all of the structures. This is done by conducting modal analysis on each of the structures in SAP2000. Loss of stiffness is also modelled in SAP2000 for each of the conditions by defining the partial fixity of each element. This will result in a natural frequency value that degrades with structural stiffness loss.

4. Results and Analysis
From the results below, it can be seen that as the structures suffer increasing displacement, the damage index values will increase as well. This is in correspondence to the fact that increasing structure displacement means that the structure is suffering an increasing amount of damage, thus increasing its damage index value.
Table 2. Damage Index Value of The Structures.

| Parameter | 1 Storey | 3 Storey | 5 Storey |
|-----------|----------|----------|----------|
| δM (inch) | 3.00     | 5.50     | 8.00     | 3.33     | 6.67     | 10.09    | 9.45     | 14.73    | 20.01    |
| δu (inch) | 8.00     | 8.00     | 8.00     | 10.09    | 10.09    | 10.09    | 20.01    | 20.01    | 20.01    |
| β         | 0.025    | 0.025    | 0.025    | 0.025    | 0.025    | 0.025    | 0.025    | 0.025    | 0.025    |
| Qy (kips) | 10.25    | 2.27     |          | 121.95   |          |          |          |          |          |
| ∫ dE      | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     |
| DIA       | 0.38     | 0.69     | 1.00     | 0.33     | 0.66     | 1.00     | 0.47     | 0.74     | 1.00     |

It can also be concluded that the most contributing factor towards the values of damage index is the $\frac{\delta M}{\delta u}$ ratio, where $\delta M$ is the maximum deformation due to seismic loading and $\delta u$ is the ultimate deformation under monotonic loading. The value of hysteretic energy could be obtained by measuring the area under each cycle. However, all three structures show no significant looping under the semicyclic pushover curves. This is in accordance to the fact that MRFs do not absorb hysteretic energy well and also due to the semicyclic analysis, no lateral negative force is given, therefore, in this study, the effects of hysteretic energy can be neglected.

Table 3. Natural Frequencies of The Structures.

| Model       | Natural Frequency (Hz) |
|-------------|------------------------|
|             | 1 Storey | 3 Storey | 5 Storey |
| Initial Condition | 7.890 | 5.247 | 5.026 |
| Cycle 1      | 7.505    | 4.137    | 4.976    |
| Cycle 2      | 6.301    | 3.813    | 4.559    |
| Cycle 3      | 5.146    | 3.162    | 4.337    |

The differences between the natural frequencies of the three structures can be seen in the table above. The 1-storey structure shows the largest value among the three structures, due to it being the stiffest. Natural period values increase as structural height increases, thus is why natural frequency values decrease.

The aforementioned trend applies well to the three structures reviewed. However, the 3-storey structure modelled after the structure has yielded has a natural frequency lower than that of the 5-storey structure. This is due to the 5-storey structure having more than 1 bay, as opposed to the 3-storey structure. This causes the 5-storey structure to have a larger lateral stiffness than the 3-storey structure even with larger structural height.

Nevertheless, the overall trend stands in the case of the three structures. Natural frequency values decrease as the amount of lateral load applied increases. In this study, natural frequency corresponds directly to stiffness loss due to it being a function of stiffness and mass and in steel structures, structural damage does not cause mass loss, therefore allowing mass to be neglected in the analysis.
Figure 6. Damage Index and Natural Frequency of (a) 1 Storey Structure (b) 3 Storey Structure (c) 5 Storey Structure

From the graphic above, we can see the value of damage index of each storey compared to the actual state (actual state means the percentage between the decreased natural frequency and the natural frequency of the initial condition). For example, in the 1 storey structure when the structure imposed by the lateral force of 50 kips, the damage index is 0.2 and the actual state is 98% (The natural frequency has changed by 2% from its initial condition).

As can be seen in Figure 6, the 5-storey structure graph is different than that of the 1-storey structure and the 3-storey structure. In the 1 and 3-storey structure, failure occurs when the structures
experience strength loss after exceeding loading past their ultimate strength because the structure has experienced decreased ability to withstand the lateral forces before finally collapse, while in the 5-storey structure, failure occurs when the structure reaches its ultimate strength at 157.64 kips. This, however, does not affect the trend of the damage index and natural frequency, the trend of damage index and natural frequency remains the same, the damage index increases while the natural frequency or the percentage of the actual states of the structure decreases.

A result of an observation of the graphs above show a critical limit, a phenomenon where damage index values increase much more significantly than the decrease of natural frequency. In the 1-storey, 3-storey and 5-storey structures, this phenomenon occurs when the structures’ base shear reaches 94.7%, 93.4% and 80% of its ultimate base shear respectively. This leads to the conclusion that, in this research the phenomenon only occurs when the lateral load applied exceeds 80% of the structure’s ultimate base shear.

5. Conclusion
As the amount of lateral load applied increases, the structure’s deformation will increase. This represents an increase in structural damage, thus making damage index values increase as well. This is because in the Park-Ang damage index, the most contributing factor is the maximum deformation due to seismic loading. Another reason for this is that in MRFs, no significant looping area can be found under the semicyclic pushover curves, thus resulting in no dissipated hysteretic energy.

Moreover, with increasing structural deformation, there will be a decrease of stiffness, which is represented in a decrease of natural frequency. The graphs shown show a critical limit, a limit where damage index increases much more than the decrease of natural frequency. The critical limit of the three structures occur when the lateral load applied exceeds 80% of the structures’ ultimate strength. The critical limit values of the three structures occur at 94.7%, 93.4% and 83.62% of the structures’ ultimate strength for the 1-storey, 3-storey and 5-storey structure respectively.

Later, this research is expected to be applied for damage calculations by assessing the natural frequencies (which are the dynamic characteristic of the structure) of the damaged structure using vibration test (accelerometer) and then modelling the original condition of the structure to determine the damage index of the damaged structure (by comparing the damaged index value to the degradation of the natural frequency), which can be correlated with the damage states and determine what retrofitting or repairs must be done for the damaged structure.

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Acknowledgments
This works is supported by Hibah PITTA 2019 funded by DRPM Universitas Indonesia No. 5000/UN2.R3.1/ HKP.05.00/2019.