Damage Assessment Using Natural Frequency on Concentric Braced Frame Steel Structures

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Abstract. At present, structural assessment using dynamic characteristics remains to be explored. In this study, a correlation between damage index and natural frequencies of Concentric Braced Frame steel structures has been observed. The study consists of two sections: the first section presents the calculation of the damage indices of structures by means of monotonic and semicyclic pushover analyses using OpenSEES software, while the second section evaluates the structures’ natural frequencies by means of modal analyses using SAP2000 software. Our results show a trend in which with increasing amounts of lateral load, natural frequencies of the structures decrease while the damage indices increase. There is also an apparent ‘jump’ in the damage index values after the lateral loads reach their critical limits. The study results help the understanding of the structural assessment process at the global scale.

1. Introduction

Indonesia is a country in which earthquakes often happen. To anticipate the damage, structural design codes in Indonesia require structures to be able to resist lateral loads. Seismic design requires evaluation of damage in structures, which is best represented by its loss of stiffness. This makes natural frequency, which is a function of stiffness, a good indicator of structural strength degradation. Along with that, damage index is also capable of representing strength loss in structures due to it being able to quantitatively assess structures’ strength.

Damage index is a function of structural deformation. A study by Park and Ang [9] in 1987 suggests that the damage index is a parameter that represents damage to a structure, where 0 indicates no damage while 1 indicates total failure. This is also true in other damage index theories, such as the one proposed by Ghobarah [1]. For this research, the damage index theory that will be used is the Park & Ang damage index which uses deformation and energy parameters, not the Ghobarah damage index which uses stiffness as a parameter. All parameters used in calculating damage index can be obtained through pushover analysis.

An earlier research by Bastian O. B. S. [3, 10] suggests that in RC frames, damage index values increase as cracks start to form. This is also accompanied by the decrease of natural frequency values, as shown in the research.

A numerous amount of research has been done to study the damage indices of structures, but only few them are done on steel structures. There are three types of lateral load resistant steel structures, namely moment-resisting frames (MRF), eccentrically braced frames (EBF) and concentric-braced frames (CBF). This research focuses on CBFs since its stiffness allows it to produce results with a high
amount of disparity, allowing for better analyses. The index will be examined in relation to natural
frequency, a parameter which is a function of stiffness and structural mass as stated by Chopra [2]. The
stiffness decreases with increasing damage, whereas in the steel structure, the mass of the structure does
not decrease with increasing damage. Therefore, natural frequencies can be a good parameter for
reviewing damage to structures. The results of this study can be used as a reference to predict the damage
index value of structure. The results of this study can also be used as a design reference by adjusting the
target damage index and natural frequency according to the damage index.

2. Model Validation
The study starts with model validation to ensure that model built by two structural software, OpenSEES
[6] and SAP2000 [8] can represent the real structure. The models were validated against experiment
conducted by Wakabayashi et al [5], also shown in the research by Faggiano B. et al [4]. The CBF
structure is shown in figure 1 which consist of one floor and one bay. The dimensions of the structure
are 2600 mm x 5000 mm. The structure is made of SS41 steel (f_y = 235 MPa, f_u = 400MPa, strain
hardening = 0.014) with different H profiles for columns, beams and braces. For columns, the profile
used is H-175x175x7.5x11. For beams, the profile used is H-250x125x6x9. For braces, the profile used
is H-100x50x4x6.

![Figure 1. Model for validation.](image1)

A NonlinearBeamColumn element in OpenSEES is assigned for beam and column. The element
define plastic deformation distributed along the member. The material used for the structure is Steel02,
which behaviour is a bilinear curve. According to the experiment, the load is applied horizontally on top
through pushover menu. In SAP2000, all members are modelled as frame element. Moment release is
applied to accommodate pin connection between bracing and column. Hinge is also defined to all
members, locating at the end of beam and column while braces are assigned at their ends and midpoints.
Result of validation is shown in figure 2.

As can be seen, the load-displacement curves made using OpenSEES and SAP2000 has closely
resemble the one shown in the research by Wakabayashi. Both curves show the same elastic behaviour,
while only showing little disparity in the plastic region. This allows the assumption that both the models
made in OpenSEES and SAP2000 are able to be the basis of other models made for this research.

![Figure 2. Validation of CBF Model.](image2)
3. Research Methodology

Since the models have been validated, then the study of damage index can be carried out on 3 different stories of CBF, one, three and four stories. The geometrics are shown in figure 1, figure 3 and figure 4. The 3 and 4-stories were based on research of CBF conducted by Ernesto G. and Alessandro R [3]. The 3 and 4-storey were made of S235 steel with yield stress and ultimate stress as 235MPa and 400MPa, respectively. The profiles used are HEA220 for the 1st and 2nd story beams and columns, HEA200 for the 3rd and 4th story beams and columns and 2L 60x6 for the braces on all floors.

![Figure 3. 3-Storey Structure.](image3)

3.1. Equation for Damage Index

As mention earlier, the study was conducted in two steps. First OpenSEES was used to determine the damage index. Refer to equation proposed by Park and Ang., the index can be calculated by integrate the energy below the curve obtained through semi-cyclic loading. The equation is expressed on equation 1, where $D$ is damage index, $\delta_m$ is maximum deformation, $\delta_u$ is ultimate deformation, $Q_y$ is yield strength, $dE$ is dissipated hysteretic energy and $\beta$ is a non-negative constant obtained through empirical data. For steel structures, $\beta = 0,025$.

$$D = \frac{\delta_m}{\delta_u} + \frac{\beta}{Q_y \delta_u} \int dE$$  \hspace{1cm} (1)

The objective of the research is to investigate the correlation between damage index and natural frequency. The second part of this research revolves using SAP2000 to obtain the change of natural frequency after step-by-step loading. The geometric changes of the CBF obtained through OpenSEES was remodelled in SAP2000 to obtain its natural frequency through modal analysis. Each structure was modelled in 4 different geometric conditions to illustrate the condition of the structure after every cycle of the semi-cyclic loading, with Model 1 being its initial condition, Model 2 after the 1st cycle, Model 3 after the 2nd and Model 4 after the 3rd.

4. Results and Discussions

Monotonic and semi-cyclic pushover analysis is performed on all three structures. From the analysis, data was obtained for calculation of damage index values. Damage index is calculated at the end every
cycle to represent the damage that occurs after the cyclic loading is experienced by the structure. The data for the calculation of damage index values is as follows

**Table 1. Damage Index Values of Structures.**

| Parameter | 1-Story Structure | 3-Storey Structure | 4-Storey Structure |
|-----------|-------------------|-------------------|-------------------|
| $Q_y$ (kN) | 270.78            | 398.21            | 413.48            |
| $\delta_u$ (mm) | 80.00            | 100.00            | 130.00            |
| $\delta_m$ (mm) | 26.70            | 53.40            | 50.00            |
| $\int dE$ (kNmm) | 0.00            | 0.00            | 0.00            |
| $DI_{PA}$ | 0.33              | 0.67              | 1.00              |

Model 1 has a damage index value of 0 while Model 4 has a damage index value of 1. The damage index values show a trend which increases with increasing lateral load. In accordance to the research by Bastian O. B. S., the biggest factor of structural damage is structural deformation. This parameter is in the first aspect of the damage index formula, which contributes 99% of the overall damage index value by generating values between 0.10 to 1.00. The second aspect of the formula, which is an aspect involving dissipation energy, only contributes 1% by generating values between 0.001 to 0.01.

**Table 2. Natural Frequencies of the Structures.**

| Model | 1-Story Structure | 3-Storey Structure | 4-Storey Structure |
|-------|-------------------|-------------------|-------------------|
| Model 1 | 77,717            | 20,588            | 14,803            |
| Model 2 | 41,025            | 16,135            | 8,476             |
| Model 3 | 27,021            | 13,568            | 7,999             |
| Model 4 | 22,463            | 12,646            | 7,381             |

The natural frequencies of the three structures decrease with increasing lateral load. This is consistent to the theory that said that structural stiffness decreases with increasing amount of structural damage, thus resulting in lower natural frequencies. Since the structures are steel, mass loss does not factor into the changes of the natural frequencies. That is why in this research, the loss of natural frequency corresponds directly to loss of structural stiffness.

What differentiates the three structures are their initial natural frequencies, as shown in table 2. This is in accordance to the theory by Peifu Xu et al [7] which stated that the natural period of a structure increases with the increase of structural height. Natural frequency is inversely proportional to natural period, thus making it decrease as structural height increases.

As shown in figure 5, there can be seen a certain limit where excessive lateral loading causes damage index values to increase more significantly than the decrease of natural frequencies. This limit is called a critical limit in the research by Bastian O. B. S. This limit is different for the three structures. These limits are at $V = 88\%$ $Vu$ for the 1-story structure, $V = 93\%$ $Vu$ for the 3-storey structure and $V = 97\%$ $Vu$ for the 4-storey structure. It can be concluded that the critical limit value of a structure increases with structural height.
Figure 5. Damage Index and Natural Frequency of (a) 1-Story Structure (b) 3-Storey Structure (c) 4-Storey Structure.

5. Summary
As the amount of lateral load applied to a structure increases, the corresponding structure’s damage index value increases while its natural frequency decrease. This trend can be seen in all three structures. As observed, there exists a critical limit where any amount of load exceeding the limit will cause damage index values to increase much more significantly than the decrease of the structure’s natural frequency. These limits are at $V = 88\%$ $V_u$ for the 1-story structure, $V = 93\%$ $V_u$ for the 3-storey structure and $V = 97\%$ $V_u$ for the 4-storey structure.

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