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A Review: Damage Assessment of Reinforced Concrete Buildings Using Ambient Vibration Testing

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Abstract: Ambient vibrations such as excitations from the environment, human activities and seismic events had cumulatively induce damages to RC building. Cost-consuming regular building maintenance was the reason for a building's integrity to be assessed first before decision making. Recently, vibration-based damage assessment approach had been widely practiced using data from ambient vibration testing (AVT). The purpose of this study was to identify the damage assessments on structure using vibration approach and to investigate the empirical and analytical based damage relationships with scope of stiffness or natural frequency as the main parameters in damage assessments. From literature studies, ten related articles that utilized stiffness or natural frequency in their damage relationships had been collected and reviewed. Vulnerability index, damage index and rapid screening indicator were the damage relationships employed in the reviewed studies and the results had been discussed in terms of damage detection validation, damage parameter and damage state. Stiffness was used as the main parameter in damage index and rapid screening indicator while natural frequencies was used in vulnerability index. Based on the review conducted, the application of stiffness or natural frequency in the damage relationships was reliable to detect damage with high accuracy. This study had suggested for future studies to investigate the method to convert the subsequent damage values into building's damage condition since there is still no appropriate development on this damage rating score.

Keywords: Damage Assessment, RC Building, Ambient Vibration

1. Introduction

Civil structures tend to be subjected toward various types of natural excitations such as wind, temperature, humidity as well as disruptions from human's activities like traffic movement and footfall [1, 2]. All of these external excitations might slightly contribute impacts to the initial building's stiffness

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as a whole which usually could be seen and detected through damage occurrences mainly cracks, fatigue, corrosion and bolted joints loosening [3]. Stiffness, mass and mechanisms of energy dissipation of a structural member are affected by the damage experienced on a building that eventually influenced the behaviour of the structural dynamic [4]. Vibration Based Damage Identification (VBDI) implements the monitoring of structural dynamic response toward ambient excitation, external shaker or embedded actuator to detect damage [5, 6]. The integrity and performance of civil structures must be given extra attention for their deficiency especially on its strength to resist external excitations throughout its design life. Any deterioration toward the building's health performance should be identified and assessed at an early stage to avoid any future catastrophic event. Maintenance or repairing works were concerned typically when there were defects reported in a structure was among the problems that must be improved. This practice would be cost and time consuming especially for old buildings with high deterioration. The maintenance activities should be optimized by at least understanding the damage condition experienced by the buildings before any decision making.

Numerous methods under VBDI had utilized vibration properties like natural frequencies and mode shapes to detect the presence, location and severity of a structural damage [7, 8]. Among of all the vibration-based testing types, Ambient Vibration Testing (AVT) was the most preferred in the field due to its features which are non-destructive, inexpensive, quick and simple to implement [9, 10]. Since natural frequencies, damping and mode shapes were directly correlated to the structural rigidity and integrity [1, 11], these modal parameters had been commonly measured in ambient vibration testing to monitor the building's performances. Reduction in the parameters (particularly natural frequency and stiffness) indicated that a structure experiencing deterioration. Recent researches had used the parameters as buildings preassessment by mean of empirical or analytical approaches. When a building's natural frequencies were equivalent with the ground natural frequencies, resonance effect would be produced that eventually created an excessive amplitude high. As a result, severe damages would be experienced by the building which usually irreparable. These parameters subsequently affect the structure's performances toward dynamic response [12]. According to [13], damages occurred due to the alterations that happened on the building's initial material and geometric properties.

Current practices in structural damage detection had shifted into a global, faster and simpler approach which was vibration-based methods. Most of these methods made use of modal parameters interpretation, advancement in sensing technologies and software modelling to assess the damage within structures without having to destruct it. Although past researches had proposed various methods of detection, there was still lack of study had highlighted the employment of empirical and analytical based damage relationships to assess damage in RC buildings using natural frequencies or stiffness as one of the main parameters. This study hence intended to fill the gap by identifying the damage assessments on structure using vibration approach and investigating the empirical and analytical based damage relationships with focus of stiffness or natural frequency as the main parameters in damage assessments. Therefore, ten related articles within the previous ten years that utilized the criteria mentioned in their damage relationship had been collected and reviewed. Based on the articles, the damage formula that was employed were vulnerability index of Nakamura method, damage index and rapid screening indicator. The results obtained by those studies were evaluated, discussed and summarized in terms of their damage validation, damage parameter and damage state at the end of this study.

2. Methods of Articles Review

The methodology was divided into three main stages which were literature studies, analysis of data as well as results and discussion. The explanation on the stages is as the following:

2.1 Literature Studies

In this stage, two criteria had been previewed for article selection which was damage assessment on RC building as well as the equipment and the testing method employed in the ambient vibration testing. The studied RC buildings consisted of many operational uses, configurations, geometries, sizes and number of stories as could be found in [14–23]. The location of the building was also not restricted to any specific condition or area. For the reviews on damage assessment, it was mostly conducted using AVT. The modal parameters were used for damage detection in several techniques. The techniques may be in form of data driven or model based [5, 14]. The damages could be artificially or naturally introduced to create building's damage state such as wall demolishing or removing, retrofitting works or other modifications that modified the structural stiffness. The changes in natural frequencies or stiffness from the initial measurement would signify the damage presence in the building. The ambient vibration testing that was focused on this review study were Horizontal/Vertical Spectral Ratio (HVSR) microtremor measurement method by [9], system identification methods and pushover analysis method. From the literature studies, four papers had used HVSR microtremor equipment [3–6], four papers employed the system identification methods [7–10] while two studies used pushover analysis [11, 12].

2.2 Analysis

Based on the literature studies, ten articles that fulfil most of the criteria mentioned above had been selected for review. The stiffness and natural frequency parameters in the empirical or analytical based damage relationships were analysed in this phase. The changes on the parameters' values were investigated and discussed to get brief idea on the building's deterioration due to damage. It was also assumed that higher natural frequency and stiffness values indicated low or no damage and lower values as high damage [14, 15, 17]. After the analysis, several damage equations that used natural frequencies and stiffness as one of their variables had been obtained which were vulnerability index, damage index and rapid screening indicator.

2.3 Results and Discussion

A critical review approach was implemented in this part where the damage evaluation results by the researchers were investigated. The trends in similarities and comparison between the methods were also discussed in terms of damage detection validation, damage parameter and damage state. Table 1 shows the list of the selected studies for review.

Table 1: Case studies

Reference	Damage Relationship	Equation	Application	Damage State/Level
[14]	$K_g = \frac{{A_g}^2}{F_g}$	*Eq.1*	188 RC buildings with various structural properties.	$K_g \leq 3$ (Low) $3 < K_g \leq 5$ (Moderate) $5 < K_g \leq 10$ (High) $K_g \geq 10$ (Very high)
[15]	$\eta = \frac{k_b}{k_g}$	*Eq.2*	11 buildings with various construction age, floor number, construction style and building materials.	$\eta \leq 1$ (Poor) $1 < \eta < 2$ (Moderate) $2 < \eta < 3$ (High) $3 < \eta$ (Strong)
[16]	$K_{av} = \frac{A \times 10000}{H \times (2\pi F)^2}$	*Eq.3*	Rural buildings with mainly 1 story	$\frac{Kav_{damaged}}{Kav_{undamaged}} \geq 2.5$ (Critical)
[17]	$\overline{K}_{bi} = 10^4 \times \frac{A}{H(2\pi F_b)^2}$	*Eq.4*	6 in situ buildings with range of 1 to 3 story	Based on the observed building's strength: $\overline{K}_b$=11.623 (Strong)

Table 1: (Continued)

				$\overline{K}_b$=8.7285 (Strong) $\overline{K}_b$=23.739 (Medium) $\overline{K}_b$=32.75 (Medium) $\overline{K}_b$=41.802 (Weak) $\overline{K}_b$=36.645 (Weak)
[18]	$SDITC_{x_l} = 1 - \frac{k^*_{x_l}}{k_{x_l}}$ $= 1 - \frac{{\omega^*_j}^2}{\omega^2_j} \frac{\sum_{i=l}^{N} \frac{m_i \emptyset^*_{x_i j}}{m_l \Delta\emptyset^{CR*}_{x_i j}}}{\sum_{i=l}^{N} \frac{m_i \emptyset_{x_i j}}{m_l \Delta\emptyset^{CR}_{x_i j}}}$	$Eq.5$	4 story irregular RC building with partial basement	DI=0 (No damage) DI=1 (Collapse)
[19]	$pSDI_s = 1 - \frac{k^*_s}{k_s}$ $pSDI_s = 1 - \frac{{\omega^*_i}^2}{\omega^2_i}$ $= \left\lvert \frac{\emptyset^*_{ni} \Delta\emptyset_{si}}{\emptyset_{ni} \Delta\emptyset^*_{si}} \right\rvert \sqrt{\frac{\bar{k}^*_{si} \bar{k}_{ni}}{\bar{k}_{si} \bar{k}^*_{ni}}}$	$Eq.6$	8 storey RC building encased by steel	pSDI=0 (No damage) pSDI=1 (Total stiffness deterioration and collapse)
[20]	$SDI_l = 1 - \frac{k^*_l}{k_l}$ $= 1 - \frac{\frac{\omega^{*2}_j}{\Delta\emptyset^*_{lj}}}{\frac{\omega^2_j}{\Delta\emptyset_{lj}}} \frac{\sum_{i=l}^{N} m_i \emptyset^*_{ij}}{\sum_{i=l}^{N} m_i \emptyset_{ij}}$ $ASDI_l$ $= 1 - \frac{\frac{\omega^{*2}_j}{\Delta\emptyset^*_{lj}}}{\frac{\omega^2_j}{\Delta\emptyset_{lj}}} \frac{\sum_{i=l}^{N} \emptyset^*_{ij}}{\sum_{i=l}^{N} \emptyset_{ij}}$	$Eq.7$	38-storey RC prototype building with 31 stories typical floors supported by a transfer plate and a two-level podium	Based on modal analysis result (in Hz): No damage=4.61 Trifling damage=4.55 Moderate damage=4.32 Serious damage=3.70 Complete damage=2.58 Based on [24]: DI=0 (No damage) DI=1 (Collapse)
[21]	$DI_c = 1 - \frac{K_c}{K_o}$	$Eq.8$	4, 6, 8, 10 and 12 stories of RC moment resisting frames with different number of bays	DI=0 (No damage) 0.55≤DI≤0.65 (Light damage) 0.70≤DI≤0.80 (Moderate damage) 0.80≤DI≤0.90 (Severe damage) DI=1 (Extreme damage)

Table 1: (Continued)

[22]	$DI_c = 1 - \frac{K_c}{K_o}$	$Eq.9$	4 storeys RC frames	As prescribed in [25]: DI=0 (No damage) DI=0.462 (Light damage) DI=0.548 (Moderate damage) DI=0.692 (Severe damage) DI=0.325 (Extreme damage)
[23]	$RSI \times 100(\%) = 1 - \frac{k_s^*}{k_s}$	$Eq.10$	8-story residential & 7-story school RC building	RSI=0% (No damage) RSI=100% (Collapse)

3. Results and Discussion

Based on selected studies, the results of the damage assessment were reviewed. The trends in the validation of damage detection, parameters involved and damage state determination were also discussed in the discussion part.

3.1 Results

Referring to [14], the seismic vulnerability index was computed using Equation 1 and compared with the buildings' damage ratio map. The map was generated based on the buildings' damage rate from previous earthquake event and it was found that the rate had a good correlation reaching until 80% with the computed seismic vulnerability index, K_g values [14]. From the comparison, the degree of building's damage in the map was found to be increased when both vulnerability indices in buildings and soil also increased. Besides, the building irregularities and soil condition factors toward damage in the studied buildings were also observed and it was found that aside than local soil condition, building properties also played an important role to affect the level of damage in the structures [14]. Based on assessment, among the 188 studied buildings, 94 of them experienced minor damage, 26 with moderate damage, 58 having heavy damage and the rest were collapsed [14]. Besides, [15] had computed the disaster factor or vulnerability ratio, η for the 11 studied buildings using Equation 2. The damage rate of this study was determined based on the computed disaster factor that clustered according to the building's properties and age that graded from A until D. The range of disaster factor for each building's damage rate was as included in Table 2.

Table 2: Disaster factor related to building styles [15]

Disaster factor	A	B	C	D
η	$\eta \le 1$	$1 < \eta < 2$	$2 < \eta < 3$	$3 < \eta$
Damage rate	Poor	Moderate	High	Strong

As stated in Equation 3, [16] calculated the average vulnerability index of rural buildings with mostly having same storey number (1 story). The damage and undamaged buildings in the studied area were compared and it was found that the damaged structures' vulnerability index was 2.5 times greater than that of undamaged buildings, implying the critical situation of such structures for future earthquakes [16]. The frequency in HVSR result in the damaged buildings were much lower as it located near the fault area that facing ground instability [16]. As for Equation 4, [17] had assessed the vulnerability indices of the ground and six in-situ buildings (K_g, K_b and K_{bg}) in their study. This study used the maximum allowable acceleration, α_a that could be sustained by the building as initial indicator of building's strength where its formula could be found in [17]. Buildings with maximum allowable acceleration values larger than the earthquake's corresponding value was indicated as strong and the lowest as weak building. It was also analysed that lower building's vulnerability index had higher maximum allowable acceleration.

Based on [18] study, Equation 5 was used to compute the damage index in a 4 storey irregular building experiencing torsional coupling. The first three modes of modal parameters in the first story from prior and post-earthquake were acquired from System Realization using Information Matrix (SRIM) technique. In comparison, the deterioration of the fundamental modal frequency between those two readings had reached until 55% for the first mode while 42% in the second mode [18]. The degradation that almost half of the actual readings thus indicated serious damage had been experienced by the buildings. The eccentricities changes in both x and y directions were calculated along with SDITC by using the first modal data mode. From the eccentricities values, the building's centre of rigidity (CR) was observed to have shifted to the southwest direction thus indicated the damage was in the northeast area. For validation purpose, the SDITC was also compared with other symmetrical building index known as approximate story damage index (ASDI) which proposed in [24]. This was to investigate the effect of eccentricity in building's damage assessment. The outcome showed by ignoring the torsional coupling element in building, the damage indicated through ASDI would be overestimated until 81% compared to only 66% in SDITC due to its significant effect [18]. The SDITC values in the building's x direction indicated greater value than in y direction which meant that damage was more severe in the y or NS direction.

A damage assessment method was proposed in [19], which named as first order story pseudo-stiffness-based damage index (pSDI). It was applied for an 8-story steel-encased real RC building. The first eigenpair values of undamaged and damaged building were used as the input parameter of pSDI which shown in Equation 6. For validation, the pSDI values were compared with other previous method named as storey damage index (SDI) that had been applied in [24]. A precise damage recognition despite slightly minor discrepancy was indicated from the comparison of both methods hence indicating the proposed pSDI method was pertinent [19]. Story Damage Index (SDI) and Approximate Story Damage Index (ASDI) were computed by [20] using equations stated in Table 1. Building's mass was assumed to be uniformly distributed along the height of building in ASDI. The natural frequencies and mode shape in x direction were obtained using Complex Mode Indicator Function (CMIF) and the result as shown in Table 3. Only first translational mode of the modal parameters had been used in the SDI and ASDI computations considering the critical state of the structure.

Table 3: Identified natural frequencies for the first mode in x-direction [20]

Case	CMIF method (Hz)
No damage (N)	4.61
Trifling damage (T)	4.55
Moderate damage (M)	4.32
Serious damage (S)	3.70
Complete damage (C)	2.58

The result of the computations was plotted for both SDI and ASDI. When compared with the four actual damages in Table 3 and first translational mode was opted, the damage location could be accurately detected using SDI where an increasing trend of damage along the building's height was also discovered [20]. Although the tested buildings did not have uniform mass distribution as assumed in the ASDI formula, the result for ASDI linked well with the outcome from SDI except the data for the trifling damage [20]. This proved that ASDI could still gave accurate result even in structure with nonuniform distribution of mass. The study at the end had summarized by using first mode data, both SDI and ASDI had better performance compared to another damage index types [20].

A different methodology had been applied by [21] that named as stiffness-based damage index, DIc as in Equation 8. The equation was developed based on structural stiffness degradation from pushover analysis on several frames. From the pushover analysis's result, the stiffness value at an intended performance level such Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) were compared to the intact stiffness or operational level (OP) where the first crack/plastic hinges were appeared to obtain the damage index. From the damage indices obtained, the damage state of the RC frames was determined based on the scaling in Performance Based Seismic Design (PBSD) guideline at various performance levels. Similar pushover analysis approach had been applied by [22] but the difference was the damage index obtained had been correlated with drift-based damage index according to various performance levels in Federal Emergency Management Agency (FEMA) 356. The damage values in various performance levels obtained in the study was shown in Figure 1. An increasing trend in the storey number had shown lower damage index values and with comparison to other performance levels, IO had a higher damage value and was more impacted by storey height than the others [22].

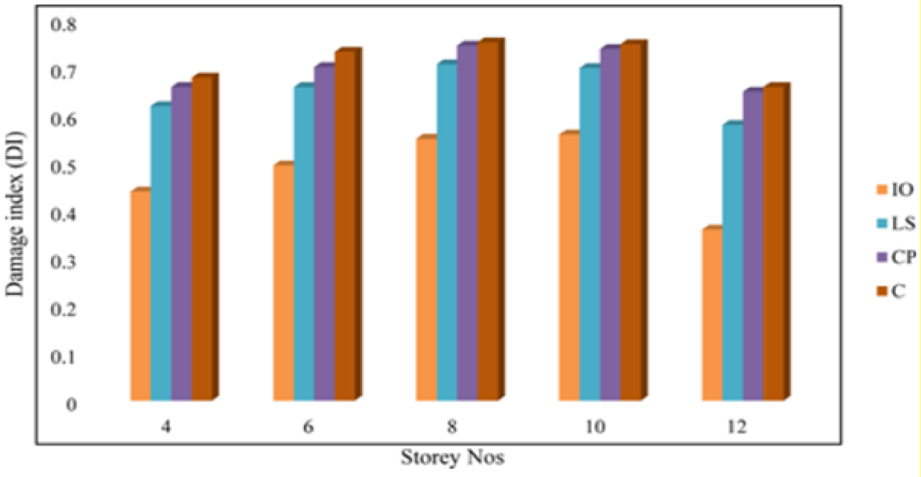

Figure 1: Damage values at different performance levels of study frames [22]

A rapid damage screening in an eight residential RC building also had been performed by [23] using Rapid Screening Indicator (RSI) as in Equation 10. Only the absolute accelerations of the ground and the seventh storey were utilised for rapid screening to determine the pseudo stiffness, k_s followed by the RSI value of the structure. The results acquired from previous earthquake recordings had demonstrated the pseudo stiffness values in x and y directions were relatively persistent, even with noise contamination [23]. Using the obtained pseudo stiffness (k_s) values, RSI was computed and found to be less than 4%, indicating the damage was minor and the building was in good condition [23]. The RSI values were seen increasing across the years of several earthquake events, that revealed the stiffness in the building was also decreasing. The research also discovered that pseudo stiffness parameter had higher sensitivity towards story damage, double than using the fundamental frequency itself [23]. This approach also had better work performance for minor (stiffness reduction ratio below 20%) and moderate to major damages compared to frequency changes concept [23].

3.2 Discussions

The trends of the results obtained from the studies were discussed in terms of validation of the damage detection, damage parameter as well as damage state. Further explanations are included in following sections.

3.2.1 Damage Detection Validation

The vulnerability index of HVSR microtremor method could be seen as one of the simplest approaches with low cost, fast, precise in results with less parameter involvement [4, 6, 17–19].

Basically, the instalment of several sensors followed by few signal processing methods using software were sufficient for the parameters acquisition (amplification factor and predominant frequencies). Most of current studies had applied HVSR method and focused to determine the amplification factor and predominant frequency of ground or seismic vulnerability index [3, 20–22], while several had computed the building's amplification factor and predominant frequency or building's vulnerability index [5, 23], also few of them determined and compared both ground and building's vulnerability indices for damage detection [4, 6].

For studies that computed only the ground vulnerability index, the value would be related with building's damage ratio from previous earthquake events to establish the damage state of the structure either having low, moderate, high or very high as in [14]. There was also studies that compared the damaged building's vulnerability index with the undamaged state for damage detection and verified the result with the soil status by using geoelectric method such in [16]. A study by [15] related the building and ground vulnerability index with type of building properties and ages to determine the building's damage rate. Therefore, for vulnerability index, it could be observed that HVSR or Nakamura method had various possible approaches and validation methods which either comparison between the building's damage and undamaged state, correlation with building properties and age or comparison with local ground condition/status.

As for damage index in the selected papers, this method mostly relied on the stiffness degradation in building as its basic formula. Since the stiffness value could not be obtained directly from the modal analysis, derivations were performed which usually multiple parameters such as mode shape and frequency were employed as could be seen in [7], [9] and [10]. Different kind of techniques to obtain the modal data had been used by those papers which included sensors application with System Realization using Information Matrix (SRIM) and ARMAX system identification, as well as Complex Mode Indicator Function (CMIF) output only method, respectively. Only the first translational mode of modal data was used as damage index's input parameter in the three papers considering its significant impact toward structures.

Few authors had compared their damage index result with another method for validation for example, [18] compared SDITC with ASDI, [19] that used pSDI with SDI and [20] evaluated damage using multiple damage indices types including SDI and ASDI. Majority of the results from those papers indicated good correlations through the comparison that had been made. In another words, it could be simplified that by using multiple damage indices approaches could result into better damage detection and validation in buildings. In addition, [18] and [23] also claimed that their proposed damage index's result agreed fairly well with the visual damage inspection which this had demonstrated the involvement of physical damage inspection to verify the output from damage index.

For the last technique in this study, [23] had proposed RSI technique that could be classified as one of the simplest damage detection method in terms of its parameter. The building's acceleration measurement was obtained using sensors. Linear regression of the produced absolute acceleration-displacement diagram was applied to calculate the global pseudo stiffness. The damage level of the buildings was defined as the percentage drop in global stiffness during prior and post damage. The building mass, m was assumed to remain constant and the time variation of the normalised pseudo stiffness was estimated based on the data of one fundamental period cycle to examine the building's nonlinear behavior and degree of damage during a seismic event.

3.2.2 Damage Parameter

In terms of the methods' applicability, the ability to serve for an economical, simple installation, time saving with good accuracy or performance could be the best choice if a rapid damage detection was needed. However, if an intensive damage detection may be performed in concern of its accuracy, a more sensitive damage index's parameters must be used. Vulnerability index of Nakamura HVSR method was an example of a simple on-site damage detection technique because of its straightforward operating procedure and accurate prediction on weak spots in ground and buildings [4, 6, 18]. Besides, the parameters in the vulnerability index itself was also simple in computation which involved only the amplification factor and predominant frequency values.

Another method with less than two input parameters was Rapid Screening Indicator that consisted of one pseudo stiffness in damaged and undamaged state. The pseudo stiffness value could be simply obtained from the slope of absolute acceleration-displacement diagram. As mentioned in the previous section, this technique served a good association with visual damage assessment and higher sensitivity toward damage compared to frequency as the parameter. The author also stated that RSI could detect damage well in short time even with limited number of sensors that located in the ground and the highest building's floors. While in damage index, its input parameters generally used first modal data which could be obtained using sensors with any suitable system identification techniques except in [12] and [15] that employed nonlinear static pushover in the SAP 2000 software.

The first modal data was preferred in the studies considering its larger impact toward building. First eigenpair could accurately detect and quantify storey damage since it was more sensitive to variations in floor mass distribution and when the mass distribution along the floors was not uniform, damage could be overestimated [19]. Basically, with inclusion of high sensitivity parameters, a better damage accuracy could be detected by a damage index formula aside than it also affected the complexity of detection work. For example, ASDI resulted in sufficiently precise damage measurement when using fundamental mode [23]. Any modal data mode could be used in SDI method if the floor mass distribution parameter was known [23]. It was difficult to detect multiple structural damage with single damage sensitive parameter [27]. Determining the damage region by relying only on modal frequencies was difficult [28]. The combination between modal frequencies and mode shape for damage detection and localization required tedious process especially during evaluating the stiffness matrices [28]. Comparison between damaged and undamaged stiffness provided easier step for damage quantification [28].

Relying only on the frequency shift value as the initial damage indicator was not sufficient as it came with several practical constraint [19]. Due to the low sensitivity of frequency changes to damage, either highly accurate measurements or high degrees of damage were needed. Nonetheless, when the SHM procedure was just based on modal frequency shifts, it could seldom surpass any higher SHM level than Level 1, implying that it was difficult to pinpoint even the location of the damage simply by observing changes in modal frequencies [19]. As a damage-sensitive feature, using damping changes also offered advantages where undetectable cracks might create significant changes in form of damping factor, allowing damage to be detected compared to the variations that were produced when using modal frequencies (due to uncertainty or small decreases in frequencies). This was because, the increase in severity of the crack would also cause an increase in the damping factor [29].

Therefore, it could be decided that the parameters used in a damage relationship indirectly affect the damage detection results in term of accuracy and its applicability. SHM could become more effective by selecting the parameter that sensitive to structural deterioration but not to operational or environmental degradation [12]. Using the modes that were most responsive to the damage occurrence helped to the definition of better damage assessment technique [30]. Hence, it was concluded the accuracy between the proposed damage assessment methods was very subjective as it may vary for different kind of structures, site's location or even the parameters employed.

3.2.3 Damage State

Generally, zero damage index was classified as no damage while one was categorized as structural collapse. Within the limit were classified as building having an intermediate damage state [7, 9, 10, 12, 14, 15] as well as in RSI [23]. These studies did not highlight well in detail regarding the approach that had been used to establish the range for each damage state therefore the general damage state mentioned in [24] were automatically applied except in [12] and [15]. The damage state in these two studies were determined based on the correlation of the obtained damage value with the drift ratio of various performance levels established in FEMA 365 and pushover analysis result, respectively. As for vulnerability index, [14] had correlated the soil status with the HVSR data, and it was found that weak soils had lower frequencies compared to the area with solid/rock layers. Based on the observation made, the study mentioned that sites with more than 10 Kg value had high potential in causing damage to structures as the weaker the soil, the higher impact would be brought to the structures above. This value hence could be used as future reference as presumption of building damage when the same approach to be used.

For [15], the damage states were determined based on the buildings' properties and ages which was a quite promising attempt. This was because, older buildings tend to have lower frequencies due to higher stiffness deterioration compared to new buildings aside than the contribution from the local soil condition itself. Concern in terms of building's structural strength including its age along with the local soil condition would be a good indicator of building's damage state as both ground and buildings factors toward structural damage were considered. A study by [17] also related the ground factors along with the buildings ages to determine building's strength where it was found that the factors such buildings' age, strength, design and foundation had huge contribution towards the structural vulnerability index. It was analyzed that buildings with older age tend to experience more damage compared to new buildings yet, if mitigation of earthquake disaster was not planned well, the effect would be alike [17].

While in [16] there was no detail explanation on the method of the building damage state were determined however, the author had stated that the building was classified in critical damage when the damaged building's vulnerability index was greater than the undamaged buildings of the same area along with the soil status under the buildings. From the discussion, the building properties and local soil condition were the aspects that must be considered to determine the damage state of RC buildings. There would be many more contributing factors toward damage that needed to be investigated in future damage assessment so that more accurate damage detection could be produced. After all, there was no specific range for a particular damage state had been established except the one that was widely used which named as Park Ang damage index [31]. However, this method was on different approach that used plastic displacement and dissipated energy as input parameters. When nonlinear response or pushover analysis was opted, guidelines such as PBSD as applied in [12] and [26] could also be considered as a guidance.

4. Conclusion

The first objective of this study was successfully achieved where three damage assessments based on vibration approach had been identified throughout this study. The methods were vulnerability index, damage index and rapid screening indicator damage relationships. Modal parameters in these three methods were acquired from various form of ambient vibration testing before damage evaluations were performed. The second objective was also accomplished where stiffness was used as the main parameter in damage index and rapid screening indicator while natural frequencies was used in vulnerability index to detect damages in RC buildings. Based on the output from the reviewed researches, the damage relationships with inclusion of both parameters were capable of detecting damage with high accuracy. This study also suggests the future studies to focus on the method to convert the subsequent damage values into building's damage condition since there is still no proper development on this damage rating score.

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