Moragaspitiya, Praveen, Thambiratnam, David, Perera, Nimal, & Chan, Tommy H.T. (2012) Health monitoring of buildings during construction and service stages using vibration characteristics. *Advances in Structural Engineering*, *15*(5), pp. 717-726.

http://dx.doi.org/10.1260/1369-4332.15.5.717

Health Monitoring of Buildings during Construction and Service Stages using Vibration Characteristics

H.N. Praveen Moragaspitiya, David P. Thambiratnam, Nimal J. Perera, Tommy, H.T Chan
School of Urban Development, Queensland University of Technology, Brisbane, Australia

Columns and walls in buildings are subjected to a number of load increments (or variations) during the construction and service stages. The combination of these load increments and poor quality construction can cause defects in these structural components. In addition, defects can also occur due to accidental or deliberate actions by users of the building during construction and service stages. Such defects should be detected early so that remedial measures can be taken to improve life time serviceability and performance of the building. This highlights the need for a simple and reliable procedure to detect and locate defects in columns and walls of buildings during construction and service stages. Vibration characteristics of a building can be used to assess its heath status and performance as well as to validate numerical models used at the design stage. Vibration characteristics of a building change continuously during its construction and service stages due to the stiffness and mass changes. This paper uses micro and macro model upgrading methods during construction and service stages of a building based on the mass and stiffness changes to develop a comprehensive procedure for locating and detecting defects in columns and walls of buildings. A novel vibration based parameter called Heath Index (HI) is proposed and incorporated into the procedure. The capability of the procedure is illustrated through examples. Results show that the procedure has the ability to successfully identify defects in columns and walls of buildings during construction and service stages.

Key Word:-Vibration Characteristics, Columns, Walls, Detecting defects and their locations, Construction stage, Service Stage, Model Upgrading Methods

1.Introduction

Considerable amount of research has been carried out in the area of Structural Heath Monitoring (SHM) of civil engineering structures using changes in modal parameters such as natural frequencies and mode shapes. These modal parameters depend on the mass and stiffness distributions in the structure and hence any subsequent changes in these distributions will result in a change of the modal parameters (Catbas, Brown & Aktan, 2006).

Sensor systems including accelerometers, GPS (Global Position System), FBG (Fiber Bragg Grating) sensors are normally used to extract the modal parameters of structures and hence to assess their health and performance (Xu & Chen, 2008). Bridges comprise a relatively smaller number of structural components compared with buildings. It is hence obvious that measuring vibration characteristics of buildings requires a comprehensive set-up. Presently, use of modal parameters to assess health and performance of structures and validate numerical models of the structure, is becoming increasingly popular. Ellis & Ji (1996) conducted a broad study to establish the dynamic characteristics of a building during and after its construction. The study was carried out using a reasonably large building model to simulate its behavior and provide information on the dynamic characteristics at different construction stages of the building model and to understand the behavior of structural components under dynamic excitations such as wind, traffic loads, and earthquakes. Using both a long-range laser interferometer and accelerometers, the dynamic characteristics of the laboratory model at several selected construction stages were studied under free and forced vibrations. Meanwhile, finite element analysis was carried out for each construction stage and the results when compared with the experimental results showed a satisfactory agreement. Damage assessment of structural members in a seven story building after an earthquake was performed using ambient vibration measurements by Ivanovic et al (2000) and the outcomes provide a guide for future implementations of SHM systems in buildings. This study also highlighted that ambient vibration measurements can be conveniently acquired using light equipment and few operations. Ambient Vibration Test (AVT) on the Republic Plaza, one of the tallest buildings in Singapore, was conducted over two years from the commencement of construction to the service stage. Sensors such as accelerometers, GPS (Global Position System) and strain gauges were deployed on the structure to examine its behaviour during and after construction. Meanwhile, Finite Element (FE) models were developed applying micro and macro model updating methods and were analyzed to simulate the construction and service stages. The comparison study between results from the FE analysis and the ambient measurements showed a satisfactory agreement (Brownjohn, Pan & Deng ,2000). Ventura et al (2003) conducted ambient vibration tests on a base-isolated building in Japan in order to investigate its dynamic response characteristics under low excitation. The natural frequencies and mode shapes of the building in the longitudinal and transverse (or length and width) directions and about a vertical axis (torsional mode) were determined in order to calibrate a finite element model of the building. Li et al (2004a, 2004b) reported that measured dynamic characteristics facilitate to understand the real structural behavior, especially of modern tall buildings under wind action as many important phenomena can only be investigated by full scale tests. Additionally, these measurements are very useful to calibrate the numerical model of the building. Kanwar et al (2008, 2010) identified damages in building models using a damage index (method) based on vibration characteristics. In this method, different limits for damage Index can be defined as required. This method was then applied to a real building to examine the accuracy of the defined limits. Results depicted that the Damage Index method with its limits can be used to identify damages of structures successfully. This research also emphasized that ambient vibration characteristics can be successfully employed to locate damages in structures after being subjected to natural hazards.

During the construction stage, structural components are added into the structural framing system according to the construction sequence. As a result, mass and stiffness matrixes of the structure change during the construction stage. During the service stage, stiffness of members and mass of the structure amend due to service /live loads. The modal parameters associated with mass and stiffness matrices therefore change during these two stages continuously and can therefore be used to examine the bahaviour of the structural components of the building structure. Further discussion on the change of the modal parameters during these two stages will follow in the next section.

Defects that occur in a building either during its construction or during its service stages should be detected early and remedial measures taken to enhance the life time serviceability and performance of the building. Figures 1 and 2 show defects of columns in a medium rise building. Heights (or thickness) of these defects were observed as 0.2-0.25m in a 4 m high column. As a consequence, the stiffness of the column reduces by around 5-10%.

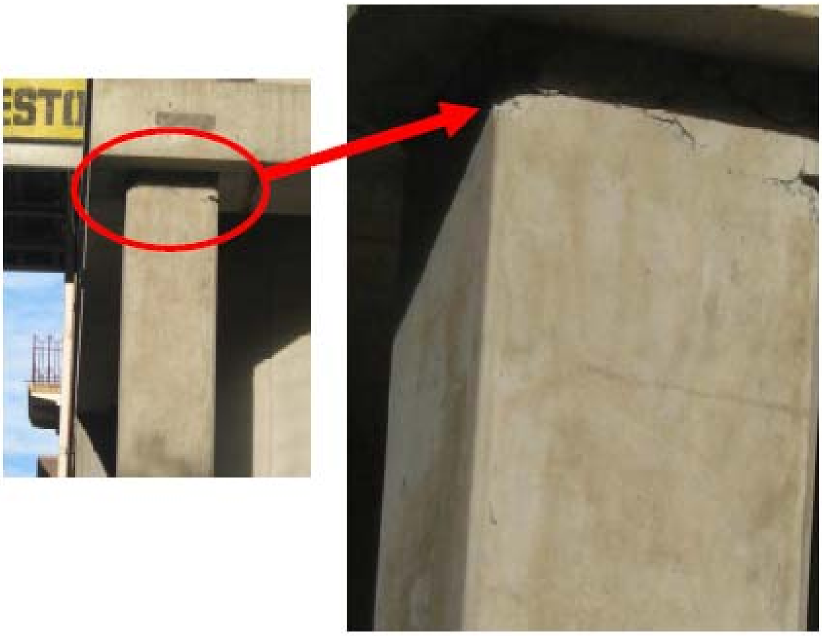


Figure 1: Defect in the column located at the second floor

Figure 2: Defect in the column located at the fifth floor

A building is normally constructed in a sequence such as (i) The structural frame comprising the shear core, columns, beams, floor plates, outrigger and belt systems (ii) The external envelope which is the façade, (iii) Mechanical, Electrical and Plumbing services and (iv) Internal floor-partitions, wall cladding etc. Items (ii), (iii) and (iv) are called the follow up services and trades. It is possible that construction defects (of the types shown in the figures) may get covered by these follow up processes. Consequently, a simple and reliable method to capture defects /damages and their locations accurately during and after the construction is very important as discussed earlier. A procedure using the vibration characteristics of the building will be developed for this purpose. Use of vibration characteristics to capture structural defects has been an effective and well established procedure during the past two decades (Zhao & Dewolf, 1999), (Ivanovic et al, 2000), Kanwar et al (2008, 2010), Lombaert et al (2009) and Koo et al (2010).

2 Methodology

2.1 Model Upgrading Methods

The main advantage of using Finite Element (FE) methods in structural analysis is the ability to generate accurate numerical models to simulate the action effects, stresses and strains under variable conditions of stiffness and loads. As mentioned earlier, parameters such as stiffness and mass and their variations can be represented by vibration characteristics through the modal flexibility, which will be discussed in section 2.2 below.

The research work presented in this paper defines and uses two model upgrading methods; Micro and Macro methods based on variation of the mass and stiffness of a structure during and after the construction. Micro-upgrading occurs when mass is added by the structural components without any significant contribution to the stiffness of the whole building, for example, when wet concrete and simply supported beams are included into the building. Macro-upgrading occurs when structural components added to the building contribute to the stiffness as well as the mass of the whole structure, and includes matured concrete and moment resisting frames. Young's Modulus is assumed as a constant during Micro upgrading stage. Figure 3 depicts Micro and Macro upgrading methods defined in a structure from construction to service stages. As shown in this figure, instantaneous loads from mass of materials used to fabricate the floor above (a certain level) are applied on the structure at stage 1, stage 2 , etc.. Axial forces of the structural components below these levels therefore increase and reduce the stiffness. This is called Micro Upgrading. When added materials such as wet concrete develop and contribute stiffness and mass to the structure, that process is called Macro Upgrading, which occurs across stages 1-2, 2-3, etc with greater changes in the vibration characteristics as well.

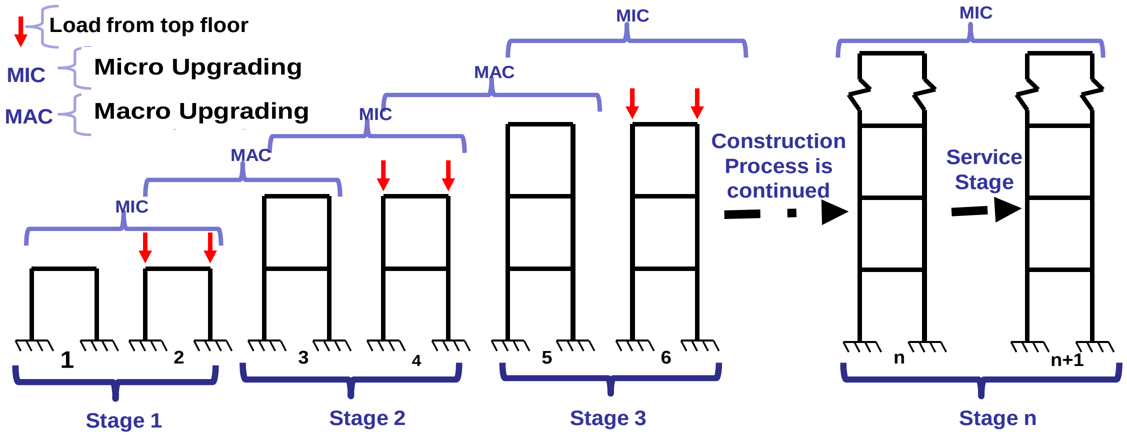
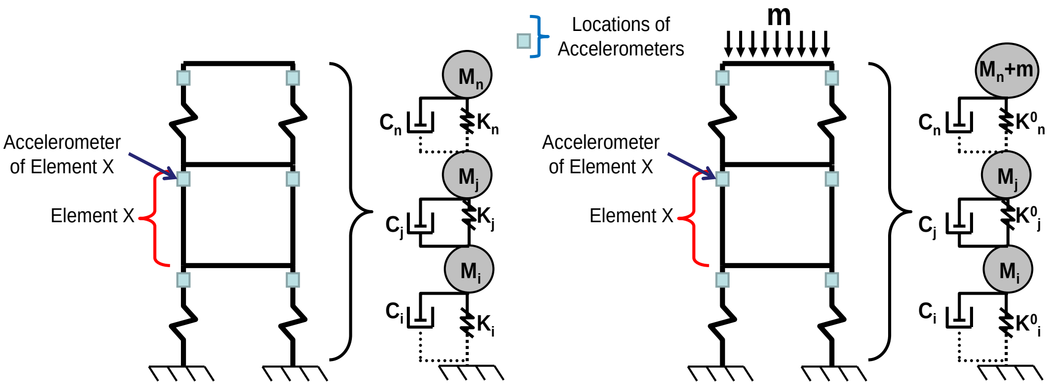


Figure 3: Model upgrading methods defined from the construction to service stage

Figure 4 shows one of the construction stages. In this figure, “m” refers to mass of materials of the floor above (under construction) while Mx, Kx and Cx (where number of floor, x= i, j and n) denote lumped masses, stiffness and damping of each floor of the lumped mass system. The superscript “o” indicates the new value of stiffness of the floors due to the mass “m” acting on the top of the structure. Locations of Accelerometers are shown in this figure and these gauges can be used to capture the vibration characteristics at any stage.



(a) (b)

Figure 4: Lumped mass systems for a structure (a) - before upper floor construction and (b)- during upper floor construction

When a structure is subjected to free vibration during the construction stage, the mass of materials used to fabricate the upper floor contributes to the lump mass system as illustrated in Figure 4(b). The axial forces and deformations in vertical structural components, such as columns and cores, increase due to additional mass. Based on the literature review (Swaddiwudhipong et al 2001,2002), it can be stated that the stiffness of the structural components and hence stiffness of the whole structure decrease due to the increased axial forces which impact significantly on the dynamic stiffness matrix associated with the vibration characteristics. Vibration characteristics such as natural frequencies and the corresponding modal vectors thus change with load increments. Additionally, as the Young’s modulus of concrete changes with time, the stiffness of the structure and its vibration characteristics also change. Increasing mass reduces the natural frequency of the structure and increasing stiffness increases the frequency of the structure. The impact of additional mass from new construction is instantaneous while the increment of stiffness of the newly built components is time dependent. These changes result in a continuous change of the Modal Flexibility (MF – discussed below) with time.

2.2 Model Flexibility Method (MFM)

Modal Flexibility Method (MFM) which incorporates the modal vectors and natural frequencies is widely used to examine the heath/performance of structural components of structures because of convenient computation, accuracy and the ease of application (Shibukumar, Leslie & Girija,2008 ; Zhao & Dewolf,1999).

2.2.1 Definition

Modal Flexibility (MF) is associated with the modal parameters of a structure - modal vectors and natural frequencies and is a measure of the structural state (Adewuyi & Wu, 2010; Shih et al, 2009; Zhao and Dewolf, 1999). This phenomenon will be used to develop an innovative procedure with a vibration based parameter to capture defects/damages of structural components such as columns and walls in a building.

Modal Flexibility, F_x of structural component x of a structure can be written as (Adewuyi & Wu, 2010 ; Zhao & Dewolf, 1999)

$$\mathbf{F_x} = \sum_{\mathbf{r=1}}^{\mathbf{n}} \frac{\mathbf{1}}{\omega_{\mathbf{r}}^{2}} \phi_{\mathbf{xr}} \phi_{\mathbf{xr}}^{\mathbf{T}} \tag{1}$$

Where

x**-** structural component considered

r and n**-** the mode and total number of modes considered respectively

ϕ_{xr} -magnitude of modal vector of mode **r** at structural component x

Modal Flexibility (MF) for structural component x (column or wall) without any damage or defect can be written as

$$\mathbf{F}_{\mathbf{XH}} = \left[\sum_{r=1}^{n} \frac{1}{\omega_r^{\;2}} \phi_{xr} \phi_{xr}^{T} \right]_{H} \tag{2}$$

Where subscript H denotes the undamaged (healthy) case

The stiffness and mass matrices of a structural component and hence the whole structural framing system change due to the defects/damages so that the modal parameters and hence MF of such a component will also change.

Modal Flexibility (MF) for structural component x with defects/damages can be written as

$$\mathbf{F}_{\mathbf{XD}} = \left[\sum_{r=1}^{n} \frac{1}{\omega_r^{\;2}} \phi_{xr} \phi_{xr}^{T} \right]_{D} \tag{3}$$

Where subscript D denotes the damaged case

Magnitudes of modal vectors, especially during the construction stages of the first few floors of the structure, are small and so are the modal flexibilities of the damaged and undamaged cases. In order to amplify the effects of these modal flexibilities, reciprocals of the two MFs are considered as below:

$$\frac{1}{\mathbf{F}_{\mathbf{XH}}} = \frac{1}{\left[\sum_{r=1}^{n} \frac{1}{\omega_r^{\;2}} \phi_{xr} \phi_{xr}^{T} \right]_{H}} \tag{4}$$

$$\frac{1}{\mathbf{F}_{\mathbf{XD}}} = \frac{1}{\left[\sum_{r=1}^{n} \frac{1}{\omega_r^{\;2}} \phi_{xr} \phi_{xr}^{T} \right]_{D}} \tag{5}$$

The vibration based parameter called Heath Index (HI) is defined through the following equation in order to detect damage/defect in a structural component x.

$$\mathbf{HI} = \left| \mathbf{ln}\left[\frac{\mathbf{1}}{\mathbf{F_{XH}}} - \frac{\mathbf{1}}{\mathbf{F_{XD}}} \right] \right| \tag{6}$$

It can be seen that HI is proportional to stiffness reduction of the structural component due to its damage/defect. The Heath Index (HI) can be applied to a structure using the procedure described below.

Finite Element Models (FEM) at the different construction and service stages of a building are developed. These FEMs are used to calculate the modal flexibilities (F_{xH}) of columns and walls. During construction and service stages of the building, modal parameters can be determined using the deployed accelerometers. These modal parameters can then be used to calculate, F_{xD} and hence HI of the structural components. The HI parameter can then be used to identify both the damaged structural component and the level at which the damage/defect occurs. This is done as follows: (i) HI values of all the (vertical) structural components at all the levels are obtained and used to calculate the average value for each structural component across the building height. Those structural components showing an enhanced average value are identified as having a damage/defect (ii) the variation of HI with height of the identified structural components are then plotted. The peaks in these plots will indicate the floor (or level) at which there is a damage/defect.

3.0 Illustrative examples.

Two numerical examples are presented in this section. The first example is used to examine the validity of the vibration based parameter, Heath Index (HI) while the next example will present the application of this parameter for damage detection in a 10 storey building during its construction and service life.

3.1 Example 01

A bench mark structure developed by Johnson et al (2004) is selected to examine the validity of the vibration based parameter, HI proposed earlier. Figure 5 shows an isometric view of the bench mark structure while details of the column, beam and bracing sections of this structure are presented in Table 1 . More information of the structure can be found from the publication (Johnson et al 2004). In the previous research conducted by Johnson et al (2004), damages in the bench mark structure were simulated by removing the braces. Two damage simulation cases are considered: (i) removing the first floor bracings and (ii) removing first and third floors bracings. The validity of the HI of column X (Figure 5) for these two cases is examined.

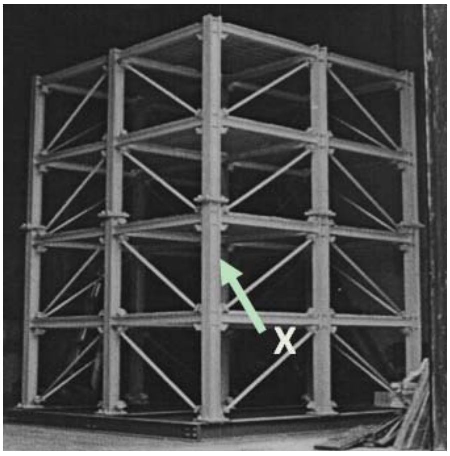


Figure 5: Bench mark structure

Table 1: Section properties

Property	Columns	Floor beams	Braces
Section type	B100x9	S75x11	L25x25x3
Cross-sectional area *A* (m^2)	1.133 x 10^{-3}	1.43 x 10^{-3}	0.141 x 10^{-3}
Moment of inertia ~strong direction *I* (m^4)	1.97x10^{-6}	1.22 x10^{-6}	0
Moment of inertia ~weak direction *I* (m^4)	0.664 x10^{-6}	0.249 x10^{-6}	0
Young's modulus E (GPa)	200	200	200
Shear modulus G (Pa)	E/2.6	E/2.6	E/2.6
Mass per unit volume (kg/m^3)	7800	7800	7800

A finite element model (FEM) was developed for the bench mark structure shown in Figure 5 and model updating technique was implemented to improve the model. Free vibration analysis was conducted for the FEM and the results compared with those in the previous publication. The comparison of natural frequencies is presented in Table 2. The difference between the natural frequencies is less than 5%. This difference occurred because the joint connections of bracings in the bench mark structure could not be incorporated into the finite element model due to lack of adequate information in the publication. Results from the present free vibration analysis indicated that the first and second modes are bending while the third mode is torsional. These mode shapes are similar to those obtained in the previous study of the bench mark structure. These results confirm the accuracy of the finite element model developed in this research.

Table 2: Natural frequencies for the undamaged case

Mode Number	Previous Publication	This research	Difference (%)
1	8.59	8.19	4.71
2	9.18	9.27	-1.02
3	14.58	13.88	4.80

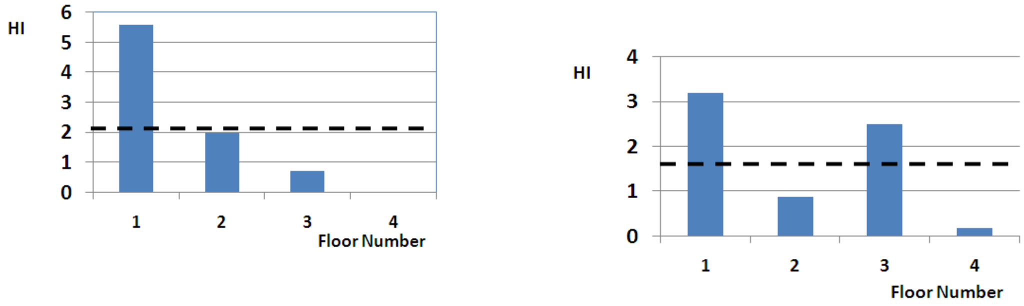
Table 3: Natural frequencies for damaged case 1

Mode Number	Previous Publication	This research	Difference (%)
1	5.47	5.50	-0.49
2	7.37	7.70	-4.48
3	9.69	9.97	-2.85

Table 4: Natural frequencies of damaged case 2

Mode Number	Previous Publication	This research	Difference (%)
1	4.96	5.02	-1.24
2	6.68	7.03	-5.24
3	8.70	9.03	-3.81

Magnitudes of the modal vectors at the top of column X as shown in Figure 4, considering three degrees of freedom were extracted from the analysis and used to calculate the HIs of column X for both damage cases, based on the modal parameters of the first three modes. This is because change of these modal parameters under damage were more pronounced compared to the others. Figure 6 illustrates the variation of HI of the column X with the floor number. In this these figures, the average HI lines are plotted as dotted lines.



(a)

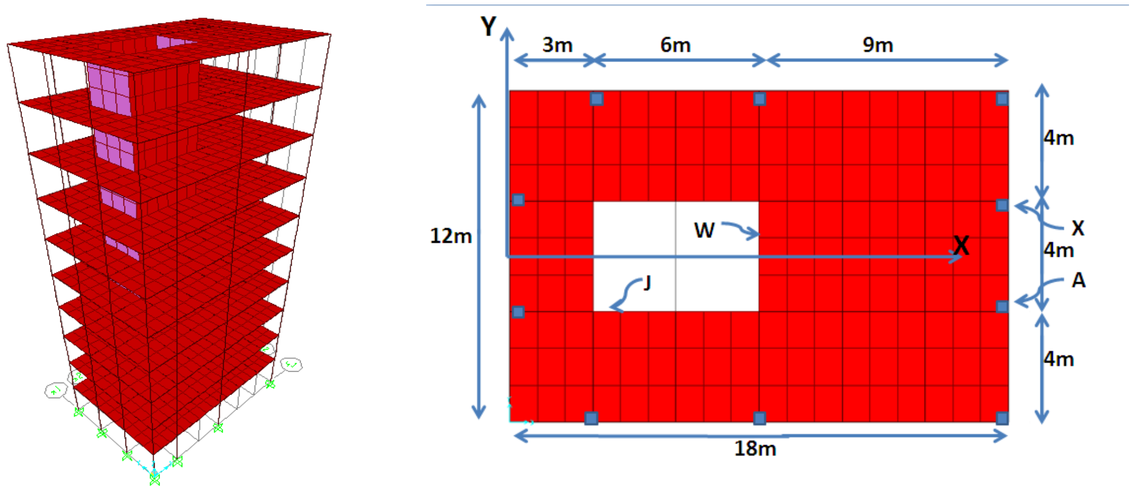
Figure 6: Variation of HI of column X (a) damage case 1 and (b) damage case 2

Figure 6 (a) shows that the HI of the column X in the first floor level is higher (above the average line) than that at the other levels as the stiffness of the column has changed significantly due to removal of bracings in the first floor. Similarly, Figure 6(b) shows that the HIs of the column X in the first and third floor levels are more pronounced (above the average line) in comparison with the HI of other floors. This is because stiffness of the column has changed (reduced) due to the removal of bracings at these two levels. Outcomes of Figure 6 clearly indicate that the HI parameter has the ability to capture the stiffness change of columns and hence the defect/damage in a structural framing system.

The next example will evaluate the capability of the HI parameter to detect damage/defect in a 10 storey structural framing system during its construction and service life. According to the best of the authors' knowledge, none of the previous research on damage/defect detection had treated a complex building structural framing system using the Modal Flexibility (MF) phenomenon and that this is the first time a comprehensive method based on MF has been developed and presented (in this paper).

3.2 Example 02

As discussed in section 1 (along with Figures 1 and 2), defects can take place in reinforced concrete buildings during and after its construction due to the poor quality construction and application of higher loads. Additionally, stiffness change of a reinforced concrete structure is more pronounced in comparison with a steel structure because of the time varying value of Young's Modulus of concrete. As a consequence, the need to study the capability of the proposed HI of structural components of a reinforced concrete building was identified for this research. The example presented herein treats a 10 storey reinforced concrete structural framing system shown in Figure 7. Stiffness of column A and core shear wall W were reduced by 5% in order to simulate their damages/defects. These two structural components were selected as they are subjected to higher axial loads compared to the other vertical load bearing structural components and hence their defects/damages can impact significantly on life time serviceability and performance of the structural framing system. The time dependent Young's Modulus of reinforced concrete was calculated based on equations presented by (Moragaspitiya et al 2010). Figure 8 depicts the variation of the time dependent Young's Modulus of the reinforced concrete. This modulus was implemented in the finite element models used to simulate the construction and service stages.



(a) (b)

Figure 7: (a)-Isometric and (b) –Plan views of the building

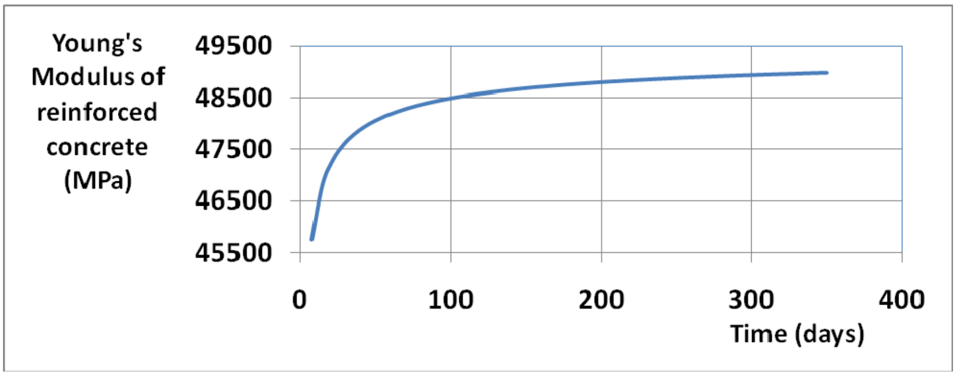


Figure 8: Time variation of Young's modulus of reinforced concrete

Five and two finite element models of the structural framing system shown in Figure 7 were developed to represent the construction and service stages respectively. Free vibration analysis was conducted for these models and the natural frequencies and the corresponding mode shapes were studied. Figure 9 presents the frequency variation of the first three modes (modes 1 and 2- bending and mode 3-torsional) during and after the construction stages. In this figure, the horizontal axis represents the construction and service stages while the vertical axis represents the frequency (Hz).

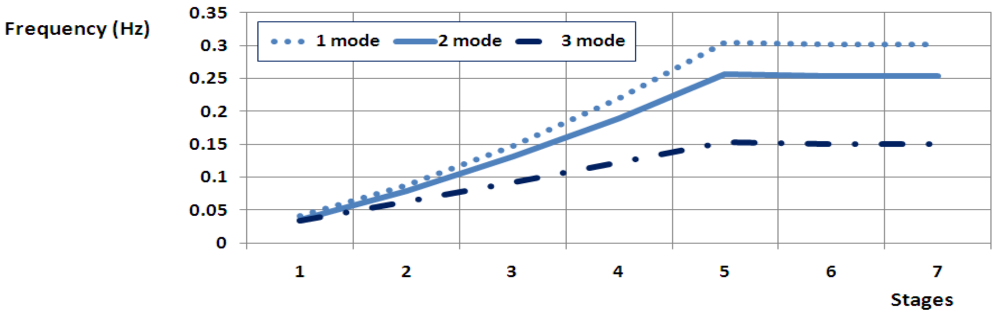


Figure 9: Frequency variation during and after the construction

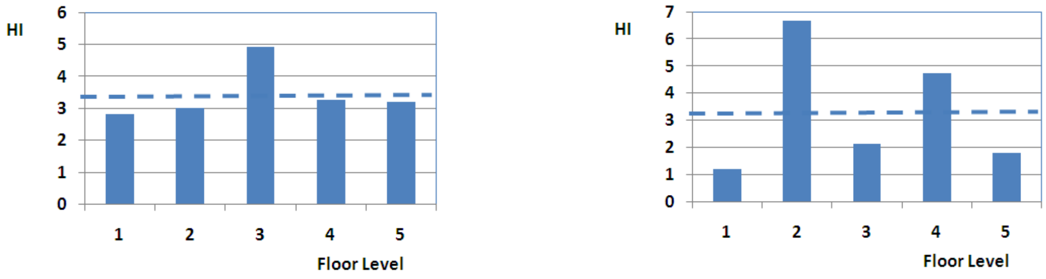
Figure 9 shows that the frequencies increase significantly during the construction stage and decrease slightly during the service stage due to Micro and Macro updating methods described using Figures 3 and 4. Figure 9 also indicates that the frequency increments reduce with the model number.

In this paper, only the results of the two finite element models used to simulate the construction and service stages are discussed. Damages/defects of structural components are implemented by reducing 5% of their stiffness in order to examine the capability of the HI parameter. The damage cases studied after 5th floor construction (during the construction stage) are presented in Table 5

Table 5: Defect/damage cases during the construction stage

Cases	Damage cases A	Damage case B	Damage case C	Damage case D
	Column X at floor level 3	Column X at floor levels 2 and 4	Core shear wall W at floor level 3	Core shear wall W at floor levels 2 and 4

Natural frequencies and modal vectors of the first three modes were used to calculate HI for each damage case highlighted in Table 5. Magnitudes of modal vectors at the top of the columns and walls, considering three degrees of freedom, were extracted from the analysis and used to calculate HI, as also done in Example 1. Figure 10 shows the variation of HIs of column A across the height of the building (up to level 5). In this Figure, the average lines (shown dotted) are plotted to enable the identification of the floor levels at which the column has suffered damage/defect.



(a) (b)

Figure 10: Variation of HI of column A after the 5th floor construction (a)-damage case A and (b)-damage case B

Figure 10 (a) depicts that only HI of column A at 3rd floor is above the average line (the dotted line) while Figure 10 (b) shows that HIs of column A at 2nd and 4th floor levels are above the average line. This is because stiffness of column A at these levels was reduced due to the damage implementation causing the HI at these levels to increase. Outcomes of Figure 10 conclude that the proposed HI has the ability to capture single and multi damages of columns during the construction stage of the building,

Figure 11 shows the variation of HI of the core shear wall W for damage cases C and D defined in Table 5. The average value lines are also shown (dotted) in these figures in order to identify the structural components with damage/defects. The stiffness of the core shear wall decreases at the floor levels where the damage is implemented and hence Figure 11 shows that the HIs of the core shear wall W at those levels are above the average line (similar to what was shown in Figure 10). This highlights that single and multi damage cases of core shear walls of buildings during the construction stage can be successfully captured by using the HI.

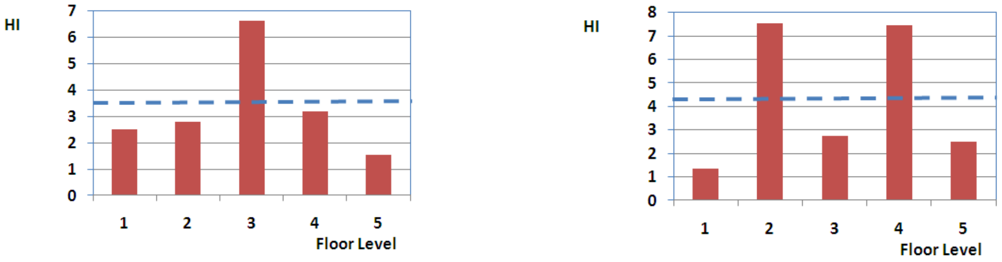


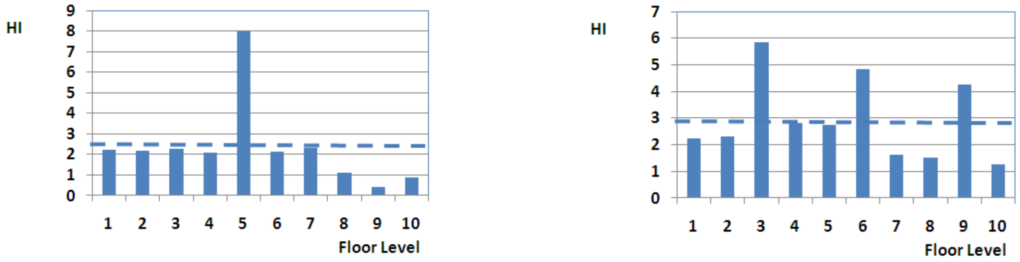
Figure 11: Variation of HI of the core shear walls after 5th floor construction (a) damage case E and (b) damage case F

The example presented herein is also used to examine the capabilities of HI during the service life of the structure for several damage cases presented in Table 6. Only the first three modes are used to quantify HI due to the reason stated earlier. Figures 12 and 13 depict the variation of the HI of column A and core shear wall W respectively. The average HI value lines (shown dotted) are also shown in these figures for identifying levels which have damage/defects.

Table 6: Defect/damage cases –during the service life

cases	Damage cases E	Damage case F	Damage case G	Damage case H
	Column X at floor level 5	Column X at floor levels 3,6 and 9	Core shear wall W at floor level 5	Core shear wall W at floor levels 3,6 and 9

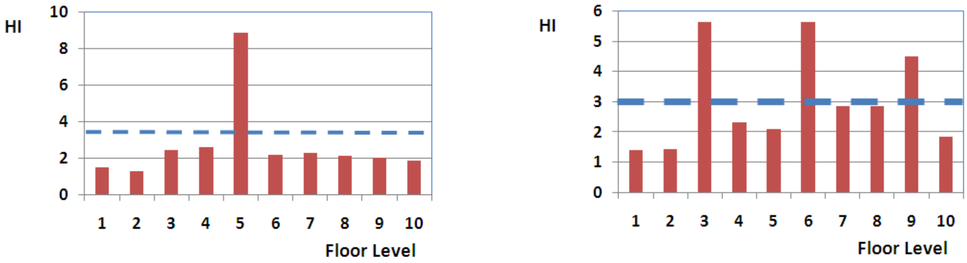
The variations of HI of column subjected to the damage cases E and F are shown in Figure 12. Figure 12 (a) shows that the value of HI of column A in the 5th floor level is more pronounced (above the average line) in comparison with that at the other floor levels. Additionally, Figure 12(b) shows that the values of HIs of column A at the 3rd, 6th and 9th floor levels are all above the average line (shown dotted). This is because the stiffness of column A decreases at these floor levels under the damage scenarios in Table 6 and hence the HIs of the structural component at these levels are more pronounced. This clearly indicates that HI has the ability to successfully capture the damages/defects of columns of buildings during their service life.



(a) (b)

Figure 12: Variation of HI of column A after the construction

Figures 13(a) and (b) illustrate the variation of HI of core shear wall W with single and multi damage cases defined in Table 6. Figure 13 (a) shows that the HI of the core shear wall at the 5th floor level is well above the average value (line) while Figure 13(b) shows that the HIs of the core shear wall at the 3rd, 6th and 9th floor levels are also much higher compared to the other levels. As explained earlier, the stiffness of the core shear wall W at these floor levels reduces due to the damages. These examples clearly show that stiffness reduction of the core shear walls due to damage can be captured successfully using the HI parameter.



(a) (b)

Figure 13: Variation of HI of the core shear wall W after construction

According to the outcomes of Figures 10 to 13, it can be concluded that HI can be applied to capture 5% of the stiffness reduction due to damages/defects and their locations in columns and walls of a building during its construction or service life. It can be also concluded that HIs will show higher peaks when the stiffness reduction is more than 5% as HI is proportional to the stiffness change. Variations of HIs of other structural components (which did not have a defect/damage) were also studied and it was observed that they were very much lower than those of column A and core shear wall W (the damaged structural components).

Conclusion

A combination of higher loads and poor quality construction can cause defects/damages in the structural components in buildings. Defects/damages can also occur due to accidental or deliberate actions by users of the building during its construction and/or service stages. Such defects need to be detected early and remedied in order to enhance life time serviceability and performance of the building. This motivates the need for a procedure to detect and locate defects/damages in columns and walls of buildings during construction and service life. An innovative method incorporating a vibration based parameter called the Heath Index (HI) has been developed and presented in this paper to (i) identify structural components with damage/defect and (ii) determine the locations of such damage/defect. The method is applicable both during the construction of the building as well as during its service life. The capability of the procedure is illustrated through a number of examples. Results confirm that the proposed procedure incorporating the Health Index (HI) parameter has the ability to successfully identify defects in columns and walls of buildings during construction and service stages.

References

Adewuyi,A.P & Wu,Z.S 2010, *Modal macro-strain flexibility methods for damage localization in flexural structures using long-gage FBG sensors*, Journal of Structural Control and Health Monitoring, www.interscience.wiley.com. DOI: 10.1002/stc.377

Brownjohn, J.M.W, Pan, T.C, & Deng, X.Y. 2000. *Macro-updating of finite element modelling for core systems of tall buildings,* Proceedings of the 14th Engineering Mechanics Conference. Austin, TX: ASCE.

Catbas, F.N., Brown , D.L, & Aktan, E. 2006, *Use of modal flexibility for damage detection and condition assessment: case studies and demonstrations on large structures*, Journal of structural engineering, ASCE, Vol 132,No 11, pp. 1699-1711

Ellis, B.R., & Ji, T. 1996. *Dynamic testing and numerical modelling of the Cardington steel framed building from construction to completion.* The Structural Engineer, 74(11/4), pp. 86-192

Moragaspitiya, H.N.P., Thambiratnam, D.P., Perera, N.J., Chan, T.H.T. *A numerical method to quantify differential axial shortening in concrete buildings*, Journal of Engineering Structures, 32 (8) (2010) 2310-2317

Ivanovic, S.S, Trifunac, M.D, Novikova, E.I, Gadkov, A.A. and Todorovsk, M.I 2000, *Ambient vibration tests of a seven story concrete building in Van Nuys, California, damaged by the 1994 Northbridge earthquake*, Journal of Soil dynamics and Earthquake Engineering, pp. 391-411

Johnson, E.A. , Lam, H.F., Katafygiotis, L.S., Beck, J.L., *Phase I IASC-ASCE Structural Health Monitoring Benchmark Problem Using Simulated Data*, Journal of Engineering Mechanics, ASCE, January 2004,1-15

Kanwar, V. S., Kwatra, N., Aggarwal, P., & Gambir, M. L. 2008, *Health monitoring of RCC building model experimentally and its analytical validation, Engineering Computations,* Vol. *25,* No 7, pp. 677-693..

Kanwar, V.S, Kwatra, N, Aggarwal, P. and Sing, R,P 2010, *Use of vibration measurements in health monitoring of reinforced concrete buildings*, International Journal of Structural Integrity, Vol 1, No 3,pp. 209-232

Kapania, R.K. and Yang, T.Y.1986, *Buckling, post buckling and non linear vibrations of imperfect laminated plates*, Proceedings of the ASME Pressure Vessels and Piping Conference, Chicago,pp. 100-109.

Koo, K. Y., Sung, S. H., Park, J. W., and Jung, H. J. 2010. *Damage detection of shear buildings using deflections obtained by modal flexibility,* Smart Materials and Structures, Vol. *19*, No. 11, 115026.

Lombaert, G., Moaveni, B., He, X., & Conte, J. P. 2009. *Damage Identification of a Seven-Story Reinforced Concrete Shear Wall Building Using Bayesian Model Updating*. Proceedings of International Modal Analysis Conference *(IMAC-XVII)*. Orlando, FL, USA.

Li, Q.S., Wu, J.R., Liang, S.G. Xiao, Y.Q. and Wong, C.K 2004 b, *Full scale measurements and numerical evaluation of wind-induced vibration of a 63 story reinforced concrete tall building,* Journal of Engineering Structures, vol:26, pp. 1779-1794

Li, Q.S., Xiao, Y.Q. Wong, C.K and Jeary, 2004 a, *Field measurements of typhoon effects on a super tall building*, Journal of Engineering Structures, vol:26, pp. 233-244

Liu, Y. | 2007, S*trength, modulus of elasticity, shrinkage and creep of concrete*, PhD thesis, University of Florida, USA

Shibukumar,K.S, Leslie,R & Girija,K 2008, *Locating damages in cable stayed bridges using flexibility*, IE(I) Journal-CV,Vol:88, pp. 37-40

Shih , H.W., Thambiratnam, D.P. & Chan,T.H.T. 2009, *Vibration based structural damage detection in flexural members using multi-criteria approach*, Journal of Sound and Vibration, vol: 323,pp. 645 – 661

Swaddiwudhipong, S, Lee,S.L and Zhous,Q. 2001, *The effects of axial deformation on vibration characteristics of tall buildings*, The Structural Design of Tall Buildings, vol: 10,pp. 79-91

Swaddiwudhipong, S., Sidji, S.S. and Lee, S. L 2002 , *The effects of axial deformation and axial force on vibration characteristics of tall buildings*, The Structural Design of Tall Buildings, vol: 11, pp. 309-328

Ventura, C.E. , Finn, W.D.L, Lord, J.F. and Fujita, N. 2003, *Dynamic characteristics of a base isolated building from ambient vibration measurements and low level earthquake shaking*, Journal of Soil Dynamics and Earthquake Engineering, Vol:23, pp. 313-323

Xu, Y.L. & Chen,B.2008, *Integrated vibration control and health monitoring of building structures using semi-active friction dampers: part 1-methodology*, Journal of Engineering Structures, Vol: 30(3), pp. 573-587

Zhao, J. & Dewolf, J.T. 1999, *Sensitivity study for vibration parameters used in damage detection*, Journal of structural Engineering, Vol 125, No 4,pp. 410-416