Structural Health Monitoring of Staircase using Vibration Measurements and Analysis Amit R Bhende1, Jayant Giri2,3,6, Neeraj Sunheriya2, xxxxxxxxxxx4,5 Rajkumar Chadge2 1Department of Mechanical Engg., St Vincent Pallotti College of Engineering & Technology, Nagpur, India; abhende@stvincentngp.edu 2 Department of Mechanical Engineering, Yeshwantrao Chavan College of Engineering, Nagpur, India; jayantpgiri@gmail.com; neeraj.sunheriya@gmail.com; rbchadge@rediffmail.com 3 Department of VLSI Microelectronics, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai 602105, TN, India 4 xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx. 5 University of Business and Technology, Jeddah, 21448, Saudi Arabia. 6 Division of Research and Development, Lovely Professional University, Phagwara, India *Corresponding Author: jayantpgiri@gmail.com ABSTRACT: Though any civil structure is constructed by following the design guidelines, but over the period of its use, it shows different behaviour. So it becomes empirical to conduct the structural health monitoring of some critical assets such as dams, bridges, high rise buildings, shopping malls, educational institutions etc. In buildings, the most vulnerable components is staircase. Vibration based periodic structural health monitoring (SHM) of staircase leads to access the condition of staircase by analysing its response to various excitation conditions. The vibration signal is analysed in time domain and frequency domain plots to access the condition of staircase under study. Natural frequency, RMS accelerations and damping ratios are used as health indicators to access the condition. The methodology adopted in the study is to compare vibration response and health indicators of healthy staircase with that of staircase under study because many researchers found the health indicator values to be higher than the one in guidance documents. 1 INTRODUCTION 1.1 Vibration of stairs Fabricated staircases are more prone to high vibration due to very low mass to dynamic weight ratio. The other problem associated with the fabricated staircase is that of low damping ratio which results in high vibration amplitude (Smith (2009)). Low natural frequency (less than 10 Hz) of any staircase may have possibility to show resonance effect which results in extremely high level of structural vibration (Kerrand Bishop (2001)). Vibration is phenomenon whose response can be measured in terms of displacement and/or velocity and/or acceleration. But acceleration is generally used to measure the response of high frequency dynamic forces. To strike out the possibility of high level of vibrations due to any non periodic shocks, root-mean- square acceleration arms is used instead of absolute acceleration value. As per the structural vibration measurement procedure laid down by International standards ISO 10137:2007 and BS 6472-1:2008, arms to baseline RMS ratio is value is used to check the severity of structural vibrations at a given frequency. The ratio is further multiplied by 24 or 32 for heavy use or light use staircase respectively to check the levels of vibrations (Bishop et al. (1995)). Staircases is subjected to much higher loads as compare to the floors because of a fast stair decent with a footfall rate of between 3 to 4.5 footfalls per second (Bishop et al. (1995)). The study shows that only first two harmonics of walking frequency to be considered while analyzing staircase vibrations (Kerr and Bishop (2001)). the study also proposed the corresponding Fourier coefficients. Staircase design guidelines subjected to footfall vibrations are given in SCI P354 (Smith et al. (2009)) and Concrete Centre document (Willford and Young (2006)). The two popular methods of staircase vibration analysis are heel drop and walking tests (Willford and Young (2006)). 1.2 Dynamic testing of staircases Many researchers have used heel drop test and walk-by tests to determine natural frequency of a steel as well as reinforced concrete stairs (Kimet al. (2008)). this information is useful for the designer to avoid resonance during its use. Another way of finding the natural frequencies of staircase is by using an impact hammer. In this method, the staircase structure is excited by applying impact hammer and then determine the modal properties (Davis and Avci (2015)). In this work, dynamic testing is carried out on the staircases of two buildings namely Block-A and Block-B using heel drop test as described in Wilford and Young (2006). A data acquisition (DAQ) system consists of a National Instrument (NI) make DAQ card 9134 fitted in NI cDAQ-9171 small DAQ chassis. The entire assembly is USB connected to LabVIEW 15.0 software. NI DAQ card is C-series sound and vibration input module, including four channels and a maximum sampling frequency of 51.2 kilo samples/s, was used to record the vibration readings. For the experiment, an industrial two-pin accelerometer with a frequency response of 15 KHz and a sensitivity of 100 mV/g was utilized. Software called Lab VIEW 2015, which is based on virtual instrumentation, was used to analyse the vibration data. Fig. 1 shows the entire vibration measurement setup. (a) (b) (c) Figure1.Vibration measurement setup a) accelerometer b) DAQ system c) LabVIEW 15.0 software 2 DYNAMIC TESTING 2.1 Description of the staircase Figure2.Staircase of Block-A and Block-B under study The concrete staircase of Block-A and Block-B are flight type consisting of top flight then middle flat the bottom flight. Block-A stairs are supported by beam whereas Block-B stairs are not supported by beam underneath. Block-A have two floors that is ground plus two floors whereas Block-B have three floors. Block-A stairs are provided in East-West direction and Block-B stairs are provided in North-South directions. The nomenclature for the experimentation is used as E_2-1_S1 which indicates that the stairs are starting from East direction, from second floor to first floor at station 1. Similarly, N_3-2_S2 indicates that the stairs are starting from North direction, from third floor to second floor at station 2. Fig.1 shows Staircase of Block-A and Block-B under study. 2.2 Heel drop tests A heel drop test is conducted to excite the staircase and study its vibration response. In heel drop test, person (70kg) raising up on their toes and then dropping down to their heels. Vibration data (accelerations in m/s2) is recorded in time domain plot. The same signal is further processed using Fast Fourier Transform (FFT) to record in frequency domain plot. Time domain study is useful to find the RMS acceleration of the vibrations whereas frequency domain analysis is useful for the study of modal frequencies of the structure. (a) (b) Figure3. Time domain plot for 1 sec a) Normal view b) zoom view For every flight section, vibrations are measured at three stations. First station is mid of the top flight, second station is middle of the flight and third being the middle of bottom flight.For each test, the accelerometer was positioned at the middle of the midway between cantilever supports where the biggest vibration response was likely to occur. A vibration data for 1 second is recorded, sampling frequency of 25 KHz is set for the measurement. The entire data acquisition system is connected to LabVIEW software. Figure4. Heel drop frequency domain plot The time domain plot from the middle landing is in shown in Fig. 3. The same signal is processed using FFT to see it in frequency domain. The frequency domain plot is shown in fig.4. From the frequency domain, it is possible to estimate the fundamental frequency of the staircase. Fig. 4 show two prominent peaks in frequency domain plot. The first peak at 14 Hz indicates the first principal mode of vibrations whereas second peak at 24 Hz indicates second mode of vibrations. These two prominent peaks of 14 Hz and 24 Hz indicate that the external excitation frequencies should stay away from these frequencies to avoid resonance condition. Fig 3(b) is zoomed signal in time domain plot. The fig 3(b) shows the amplitude decay of the structure in case of free vibrations. From the amplitude decay, damping ratio could be estimated approximately from the logarithmic decrement of damping. 3 Dynamic Test Results Heel drop test is conducted at three stations on the each flight of staircases of Block-A and Block-B building. Each test measures vibrations in terms of peak acceleration, frequency of vibration and statistical parameters such as crest factor, kurtosis, RMS etc. Logarithmic decrement and damping ratio are very important health indicators to access the condition of vibrating structure. Logarithmic decrement can be determined from the amplitude decay deom the time domain plot. These parameters (peak acceleration, frequency of vibration, RMS acceleration, Logarithmic decrement, damping ratio) are termed as health indicators because they indicates the present status of the structure under study. Vibrations readings of Block-A and Block-B are tabulated in table 1 and table 2 respectively. Over the period of time, it has been observed that the Block-A staircase vibrates less as compared to the staircase of Block-B hence vibration readings of Block-A staircase is taken as bench marks readings or acceptable level of vibrations in staircase. Block-B vibrates very heavily when mob of students use staircase. Another reason of adopting this methodology because many researchers found the health indicator values to be higher than the one in ISO guidance documents. Health indicators of Block-A and Block-B are compared together and tabulated in table 3. Floor wise comparison of health indicators of Block-A and Block-B are tabulated in table 4. E_2-1_S1 E_2-1_S2 E_2-1_S3 W_2-1_S1 W_2-1_S2 W_2-1_S3 W_1-0_S1 W_1-0_S2 W_1-0_S3 E_1-0_S1 E_1-0_S2 E_1-0_S3 N_3-2_S1 N_3-2_S2 N_3-2_S3 S_3-2_S1 S_3-2_S2 S_3-2_S3 N_2-1_S1 N_2-1_S2 N_2-1_S3 S_2-1_S1 S_2-1_S2 S_2-1_S3 N_1-0_S1 N_1-0_S2 N_1-0_S3 S_1-0_S1 S_1-0_S2 S_1-0_S3 Figure 5. Time domain and frequency domain plots of Heel drop test Table 1:Vibration readings of Block-A building Location Peak Acceleration RMS Acceleration % Damping ratio Time Period Freq Mode1 Freq Mode2 E_2-1_S1 0.24 0.0139 7.318140464 0.045 8 25 E_2-1_S2 0.87 0.0406 0.025 8 E_2-1_S3 0.6 0.0279 10.2783203 0.03 8 24 E_1-0_S1 0.875 0.0374 5.256215029 0.06 E_1-0_S2 0.75 0.036 10.2783203 0.025 12 E_1-0_S3 1.25 0.0544 6.505615673 0.028 W_2-1_S1 1.75 0.1082 8.206485615 0.022 16 W_2-1_S2 0.625 0.0397 10.65598001 0.03 16 W_2-1_S3 0.035 0.0035 7.94411094 0.0275 W_1-0_S1 0.1161 0.0225 W_1-0_S2 0.87 0.0335 18.31715458 0.03 21 W_1-0_S3 1 0.0446 12.92940848 0.035 Average 0.8059 0.0463 9.7689 0.0316 12.714 24.5 Table 2:Vibration readings of Block-B building Location Peak Acceleration RMS Acceleration % Damping ratio Time Period Freq Mode1 Freq Mode2 N_3-2_S1 1.75 0.0575 18.00329414 0.025 14 25 N_3-2_S2 0.25 0.0102 14.96712616 0.0325 14 N_3-2_S3 0.48 0.0207 10.2783203 0.028 21 28 N_2-1_S1 0.25 0.0167 6.886988435 0.0185 28 N_2-1_S2 0.64 0.0285 8.586384825 0.0275 N_2-1_S3 2.5 0.09151 6.886988435 0.024 N_1-0_S1 0.5 0.0318 8.586384825 0.04 22 N_1-0_S2 0.9 0.0417 12.92940848 0.05 6 N_1-0_S3 1.8 0.067 8.848332494 0.02 33 S_3-2_S1 25 0.6858 10.65598001 0.015 12 24 S_3-2_S2 0.3 0.0213 10.2783203 0.045 12 25 S_3-2_S3 3 0.099 16.61814242 0.02 11 18 S_2-1_S1 0.2 0.02146 2.704816459 0.0225 14 22 S_2-1_S2 1.2 0.048 8.206485615 0.025 S_2-1_S3 0.87 0.0432 7.288937346 0.035 14 22 S_1-0_S1 1 0.0378 12.92940848

0.035 S_1-0_S2 0.87 0.0418 9.964345305 0.06 S_1-0_S3 6 0.175 35.93692584 0.02 50 Average 2.6394 0.0854 11.6975 0.03016 19.3076 23.428 4 Result and discussion Table 3 shows the average values of health indicators of Block-A & B vibration readings. Peak acceleration is increased by 227.51% in Block-B as compare it with that of Block-A. RMS acceleration is increased by 84.59% in Block-B as compare it with that of Block-A. % Damping ratio is increased by 19% in Block-B as compare it with that of Block-A which means amplitude decay is faster in Block-B as compared to Block-A hence time period is reduced by 4.736% in Block-B. So a reduction of 4.736% in time period results in 19.74% increase in the damping ratio of Block-B. There is substantial deviation (of 51.85%) in the first mode of frequency of Block-B. As far as second mode of vibration, there is little deviation in Block-A and Block-B readings. Table 4 compares floor wise Average RMS acceleration of Block-A and Block-B. It shows that RMS acceleration of Block-B North flight from second floor to first floor is increased by 65.91% from the bench mark reading of Block-A. Similarly RMS acceleration of Block-B South flight from first floor to ground floor is increased by 99.21% from the bench mark reading of Block-A. Table 5 shows floor wise comparison of average Peak acceleration of Block-A & B. It shows that Peak acceleration of Block-B North flight from second floor to first floor is increased by 98.24% from the bench mark reading of Block-A. Similarly Peak acceleration of Block-B South flight from first floor to ground floor is increased by staggering 173..73% from the bench mark reading of Block-A. Table 3: Percentage deviation of health indicators of Block-A & B Averages of indicators Block-A Block-B % Deviation Peak Acceleration 0.8059 2.6394 227.5114 RMS Acceleration 0.0463 0.0854 84.59517 % Damping ratio 9.7689 11.69759 19.74223 Time Period 0.0316 0.03016 -4.73684 Freq Mode1 12.714 19.3076 51.85825 Freq Mode2 24.5 23.4285 -4.37318 Table 4: Floor wise comparison of average RMS acceleration of Block-A & B Block-A Avg RMS Acceleration Block-A Avg RMS Acceleration % Deviation E_2-1 0.027467 N_2-1 0.04557 65.91019 W_2-1 0.050467 S_2-1 0.037553 -25.5878 W_1-0 0.064733 N_1-0 0.046833 -27.6519 E_1-0 0.0426 S_1-0 0.084867 99.21753 Table 5: Floor wise comparison of average Peak acceleration of Block-A & B Block-A Avg Peak Acceleration Block-A Avg Peak Acceleration % Deviation E_2-1 0.57 N_2-1 1.13 98.2456 W_2-1 0.8033 S_2-1 0.7567 -5.80912 W_1-0 0.935 N_1-0 1.0667 14.0819 E_1-0 0.95833 S_1-0 2.6233 173.7391 5 CONCLUSIONS The paper presented a method of structural health monitoring of the staircase subjected to footfall oscillations. The results show that the staircase with higher fundamental frequency of 19.30 Hz is more prone to vibrations as compared to the staircase with low fundamental frequency of 12.71 Hz. Similarly, damping ratio plays crucial role in the prediction of floor vibration during service. Although this study focused on a building staircases but same can be implemented to other human excited structures. Following modifications are suggested to reduce the vibration levels of Block-A and Block-B staircases: 1. For Block-B staircases, it is recommended to increase the mass of the structure by providing a layer of concrete fill to the threads so as to reduce the staircase frequency and improve the resistance against human induced vibrations. 2. If the above structural modifications are not allowed due to certain architectural limitations then fabricated stiffners can be used from the bottom of the threads to improve the resistance against human induced vibrations.
REFERENCES 1. Bishop N.W.M, Willford M. & Pumphrey R. 1995. Human induced loading of flexible staircases. Safety Science: 261- 276. 2. BS 6472-1:2008 Guide to evaluation of human exposure to

vibration in buildings – Part 1: Vibration sources other than blasting. London: British Standards Institute. 3. Davis, B. & Avci, O. 2015. Simplified vibration serviceability evaluation of slender monumental stairs. Journal of Structural Engineering 141(11). 4. Fang, K., Tian, J.D., Zhang, D.Y. & Li, H., 2016. Smartphones equipped with android application software for structural health monitoring. Proceedings of the International Conference on Smart Infrastructure and Construction: 271– 275. 5. Feldbusch, A., Sadegh-Azar, H. & Agne, P., 2017. Vibration analysis using mobile phone devices (smartphones or tablets). Procedia Engineering 199: 2790–2795. 6. ISO 10137:2007 Bases for design of structures – Serviceability of buildings and walkways against vibration. 2 ed. Geneva: International Standards Organisation. 7. Kerr, S.C. & Bishop, N.W.M.2001. Human induced loading on flexible staircases. Engineering Structures 23(1): 37–45. 8. Kim,S.B.,YoungH.L.,Scanlon,A.,KimH.&HongK.,2008. Experimental assessment of vibration serviceability of stair systems. Journal of Constructional Steel Research 64: 253– 259. 9. Lacy, A.D., Parker, J. & Winslow, P., 2015. Do-it-yourself dynamics: testing of the staircase at Institution HQ. The Structural Engineer (July): 48–51. 10. Smith, A. 2009. AD 330 Vibration of steel staircases. Acot: Steel Construction Institute. 11. Smith, A.L., Hicks, S.J. & Devine, P.J., 2009. SCI P354Design of Floors for Vibration: A New Approach. Revised ed. Ascot: The Steel Construction Institute. 12. VibSensor smartphone application user guide. 2017. Now Instruments + Software. 13. Willford, M.R. & Young, P., 2006. A Design Guide forFootfall Induced Vibration of Structures. Surrey: The Concrete Society.