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Structural Vibration Assessment of an Old Building Using Experimental Vibration Data

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Abstract: Vibration may cause damage or reduce the serviceability of a building, especially for buildings that were constructed before vibration limits guideline was established. This study focuses on an old telecommunication building in Muar with the aim of assessing the vibration response of the building and whether the vibration is within the vibration limits as determined by the Department of Environment. A Finite Element Modelling is produced to simulate the building's displacement and deformation under natural frequency and a series of test consisting of walking test and heel-drop test was performed on site to obtain the vibration response of the building in terms of acceleration, velocity and frequency. The maximum value for acceleration, velocity and frequency are 0.012 m/s^2, 0.0003 m/s, and 6.641 Hz. According to the source guideline for the The Planning Guidelines for Vibration Limits and Control in the Environment which is DIN 4150-3, the peak vibration velocity is within the recommended limit for its frequency which is below 3 mm/s for the frequency range of 1 to 10 Hz.

Keywords: Building, In-Situ Test, Vibration

1. Introduction

Vibration is an oscillatory motion of dynamic systems that possesses mass and capable of relative motion [1]. The system may be in the forms of structures, machines and its components, or a group of machines. The parameters that are often related with vibration are frequency and amplitude. A typical representation of vibration is a graph of displacement against time.

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Building vibrations originating from within the building comes from two sources which are machineries such as elevators and fans, and human activities such as walking, jumping and running [2]. The resulting effect of vibrations on buildings may trigger annoyance among occupants, impaired function of instruments or structural damage. Humans are traditional participants in the dynamic behaviour of a structure by acting a source of dynamic loading mainly in the form of footfall-induced excitation. Internal vibrations are considered smaller in amplitude compared to external vibrations [3].

Internal vibrations from mechanical systems and human activities are encountered by buildings on a daily basis. The structural strength of buildings decreases over time which reduces the ability to support larger loads as in the past. For buildings that were constructed before current local building standards were established, the amount of vibration experienced may exceed the allowable limit which may cause safety concerns for occupants and structure.

The objectives of this research is to determine the vibration response of an old building due to human-induced sources and to assess whether the vibration experienced by the building in terms of frequency range and peak velocity is acceptable according to Malaysian vibration standards or not.

1.1 Floor vibration

Floor vibration is an up and down motion originating from applied forces onto the floor by people or machinery, or vibrations transmitted from its structures such as columns, upper floors and ground floors [4]. The vibration performance of a floor structure depends on its stiffness, mass and damping. Excessive floor vibrations occur more frequently in the present due to a decrease in floor mass as high strength materials and composite systems are more common, decrease in natural frequency of floors due to longer floor spans, increase in rhythmic human activities like dancing, and decrease in damping from less partitions and furniture [5]. Heavy floors are regarded as low-frequency floors in which a person in a motionless state may sense the resonance vibration due to the walking motion of another person [6]. Meanwhile, a person standing still may sense the impacts of another person’s footsteps in light floors which are considered to be high-frequency floors.

1.2 Resonance

Resonance exist when the frequency of floor disturbances are equal to the natural frequency of the floor system [7]. The amplitude of the vibration is mainly affected by the damping and weight characteristics of the floor structure when resonance occur which means that a decrease in weight and damping would result in higher vibration amplitude from certain level of disturbances. Most floor vibrations issues are caused by resonance and sudden deflections caused by footsteps for light-frame constructions [4]. Rhythmic activity that occurs in stadiums, auditoriums, and convention centers causes large resonance vibrations that are generally too large to be acceptable. Natural frequency of floors becomes lower as the span increases. The resonance frequency of floors is commonly within the range of 1 to 5 Hz [8]. The demand of rooms with open spaces with minimal columns in the present means larger span-width which causes more dynamic problems in floors.

1.3 Effect of vibration on occupants

Excessive vibrations in building floors are generally not a cause of concern for safety but a cause of annoyance and discomfort. Human responses to vibrations generated in buildings depend on various factors such as audible raise, visual cues, population type, familiarity with vibration, structural appearance, confidence in a building structure, and knowledge of the source of vibration [9]. The perception of occupants towards vibration is also influenced by the characteristic of the vibration, amplitude and duration [5].

2. Methodology

For this research, modal analysis of the building was performed as an application of literature review through ANSYS Mechanical APDL to determine the shapes and frequencies of the structure that would amplify the effect of a load. Walking test and heel-drop test were performed on site to obtain actual vibration response of floors of the building from human excitation which is recorded through the iDynamic mobile application on smartphones and the data is used for direct comparison with Malaysian vibration standards.

2.1 Smartphone calibration

Before any data collecting can be made, the smartphones needed to be tested first so that the output produced from the iDynamics application is accurate and consistent. Seven smartphones are placed on a flat surface on the ground and records vibration reading within a 10 second span. This process is repeated three times. The three smartphones that shows the best consistency are selected to be used during testing. The three smartphones selected are labeled as Phone 1, Phone 2 and Phone 3. Each smartphones have different properties, most notably in terms of resolution which is a large factor on the differing recorded vibrations reading on each phone. Table 1 shows the properties of the three smartphones used for testing.

Table 1: Properties of smartphones

Smartphone	1	2	3
Smartphone model	YES 4G M631Y	VIVO Y20	SAMSUNG Galaxy Mega (GT-I9205)
Name	BMA 2X2 – Accelerometer	Accelerometer	MPU-6K Accelerometer
Vendor	BOSCH	MTK	INVENSENSE
Version	1	1	1
Type	1	1	1
Power	0.13 mA	0.001 mA	0.2 mA
Resolution	0.00957031 m/s^2	0.0012 m/s^2	0.15328126 m/s^2
Maximum range	±156.8 m/s^2	±78.4532 m/s^2	±39.24 m/s^2
Maximum delay	4000000 μs	20000 μs	-
Minimum delay	10000 μs	5000 μs	10000 μs

2.2 Heel-drop test

Mohd Azaman, et al [10] investigated the concrete floor vibration of a newly constructed two-storey building in Yong Peng, Johor through a series of heel-drop test. The purpose of the heel-drop test was to obtain the vibration response or behaviour of floors such as the natural frequency and damping ratio. The test was performed on 3 selected floor panels in which gridlines with a distance of 1200mm from each point were established to determine the position of accelerometers. The position of the input is located 100mm away from the centre grid. Figure 1 displays the layout for the location of the heel-drop test along with the gridlines for each panel.

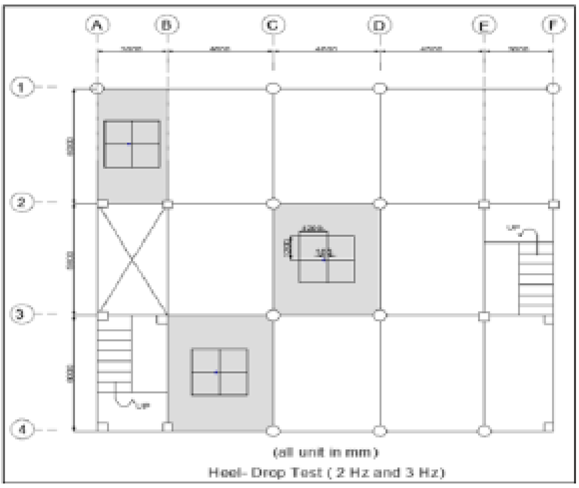

Figure 1: Layout for location of heel-drop test [10]

The purpose of the heel-drop test is to obtain the vibration response of the floor from sudden human actions. It can also be used to determine the effect human has on floor damping as it will be compared to the walking test that requires 3 test subjects whereas this test only requires a single test subject. The vibration behaviour of the floor will also determine if the floor is a low-frequency floor or a high-frequency floor.

This test will be conducted on the interior ground floor within the front portion of the building. For each point, a gridline is established with a distance of 1200mm between each points. The smartphones are placed at the top and bottom of the grid while the input is located 100mm away from the centre grid. To perform the heel-drop test the heels are temporarily raised off the floor before allowing it to drop naturally. The response is recorded by the smartphones using the iDynamics mobile application. The test is repeated 10 times to reduce uncertainty. Figure 2 shows the gridline at the center of each floor for the heel-drop test and Figure 3 shows the layout for the heel drop test on the ground floor of the building. While on site image for heel drop test is shown in Figure 4.

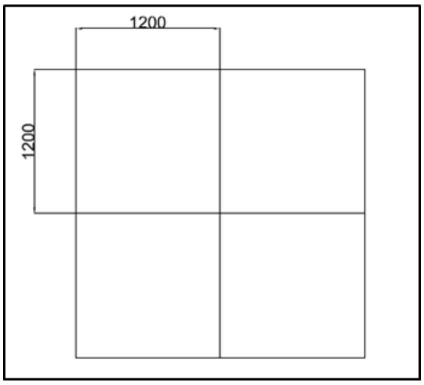

Figure 2: Gridline for the heel-drop test

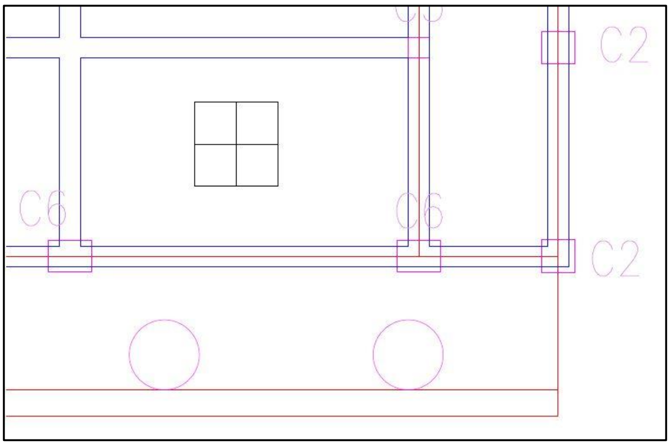

Figure 3: Layout for the heel-drop test

Figure 4: On-site image of heel drop test

2.3 Walking test

Internal vibrations are mostly generated by humans. Several researchers mentioned that most occupants cause excitation on building floors from their activities such as walking, dancing and running which are problematic because they frequently occurs and difficult to isolate from the structure [5]. Dynamic forces induced by humans are subjected to floor offices and apartments. Occupancy or usage of a structure produces live loads. Live loads resulting from human presence are categorized into two categories which are in situ and moving. In situ live loads consist of activities such as random in-place movements, periodic jumping and sudden standing of crowds. Moving loads include activities such as walking, marching and running. The interaction between human and structure which is known as human structure interaction is an important aspect of human-induced vibration. Humans that occupy civil engineering structures do not only cause excitation of the structure but also alters its modal properties. Although humans are the source of excitations in building floors, they can also act as a damper by absorbing energies transmitted from vibration sources through their postures [11].

An experimental study on measuring walking-induced vibration on a slender prefabricated prestressed concrete slab using smartphone recordings was done by Martinelli, et al [12]. Three smartphones along with four reference accelerometers were placed in two different arrangements where one has all the instruments on the same girder while the other has the instruments placed on separate girders. Two types of test were conducted which was the heel-drop test and walking test as shown in Figure 5. The series of test reveals that the accuracy of smartphones depends on the specific smartphone model and considered to be satisfactory for preliminary modal testing.

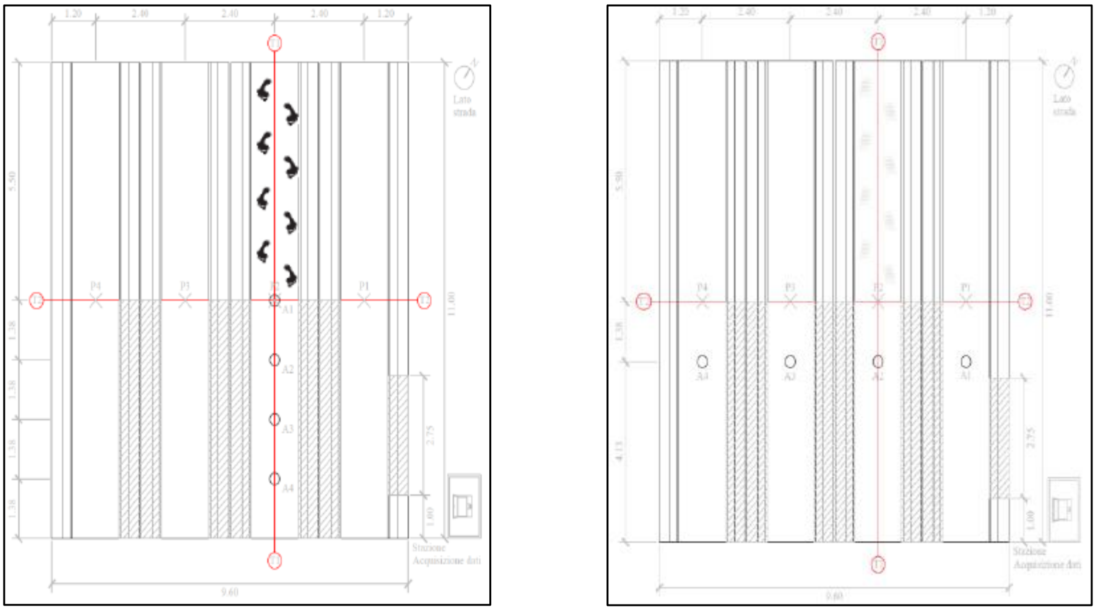

Figure 5: The arrangement of accelerometers in two different configurations [12]

In this study, the structural response of the floor from continuous human-induced vibration is measured by performing a test that requires test subjects to imitate the motion of walking. The response of the floor is recorded and processed in the iDynamics mobile application to be compared with recommended vibration limits as stated by the Department of Environment Malaysia. Similar to the heel-drop test, this test is also performed on the ground floor at the front portion of the building as it is the most likely location to support a large number of occupants. In this test, three test subjects are required to walk simultaneously on the spot for a period of around 10 seconds while the smartphones records the response of the floor from each actions through the iDynamics mobile application. The smartphones are placed approximately 1 meter away from the test subjects. The test is conducted on the exterior and interior of the front portion of the building. Figure 6 shows the layout of the test.

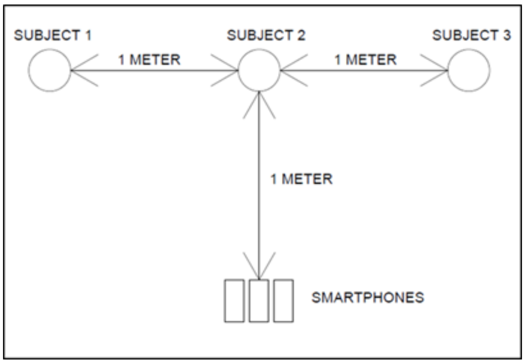

Figure 6: Layout of walking test

2.4 Modal analysis

Vibration characteristic of a structure can be identified through modal analysis. Characteristics such as natural frequencies (the frequency at which the structure tends to naturally vibrate), mode shapes (the shape in which the structure vibrates into at each frequency) and mode participation factors (the proportion of mass that shift towards a given direction in each mode) are determined as the structure is being designed. Modal Analysis is considered to be fundamental as it assist engineers to predict or visualise the response of a structure towards a variation of dynamic loads. It consists of several steps which are shown in Figure 7.

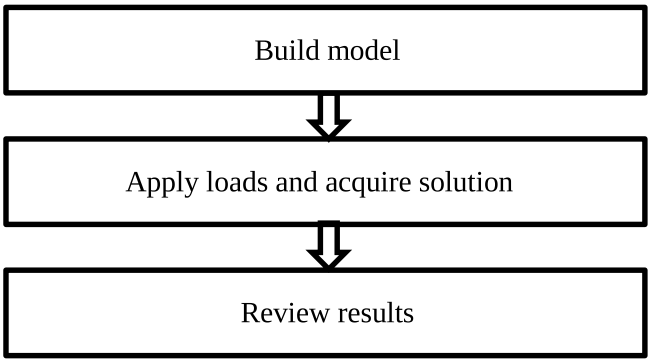

Figure 7: Procedure of modal analysis

For modal analysis, there are several properties that need to be defined to build a model. The first is building parameters which included exact measurement of structural members such as beams, slabs and columns, along with constituent elements such as dynamic modulus of elasticity, density and grade, and poisson ratio of concrete and timber are determined or assumed by referring to relevant standards. The second property is meshing which divides complex geometries into simple elements that are used to provide approximations in whole. The mesh size used for the whole structure is 5. The third property is degree of freedom or constraint in which the ground beams and columns are fully fixed to constraints translational and rotational movements. Table 2 shows the material properties used in modal analysis while Table 3 shows the cross-section of reinforced beams used in ANSYS.

Table 2: Overview of material properties used in ANSYS

Materials	Density (kg/m^3)	Elasticity	
		Elastic Modulus (GPa)	Poisson Ratio
Concrete	2500	38	0.2
Timber	500	8.5	0.4

Table 3: Cross-sections of reinforced beams

Floor		Cross-section of beam (mm)
Ground floor	RC primary beam	300x600
	RC secondary beam	300x500
First floor	RC primary beam	300x600
	RC secondary beam	300x500

3. Results and Discussion

The results and discussion section presents data and analysis of the study. This section is organised based on the chronological timeline of the research which starts with the simulation using modal analysis, in-situ testing for actual vibration response and ends with comparison between test results and vibration standards.

3.1 Modal analysis

The output from the modal analysis of the building is the first 100 mode shape of the building. For the first 18 modes, the building appears to undergo structural displacements without deformation with zero frequency. This implies that those modes are rigid body modes in which the structure translates and rotates without stress formation. The frequency value of zero does not indicate that there is no frequency, but rather that the frequency is very low, usually under 0.001 Hz. Visible deformation in shape can be seen on the 55th mode which has a frequency of 1.53 Hz that is assumed to be the fundamental frequency. Figure 8 shows the mode shape of the building at a frequency of 1.53 Hz.

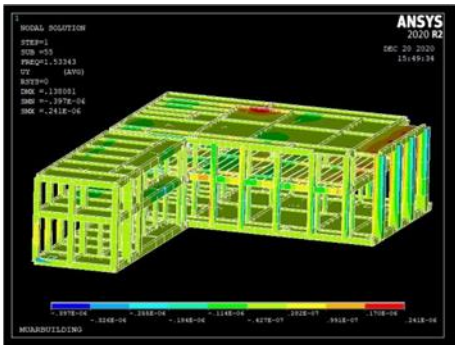

Figure 8: The 55th mode shape at a frequency of 1.53 Hz

3.2 Heel-drop test and walking test

Both the heel-drop test and walking test produced results in terms of acceleration, velocity and frequency. For each sequence of the test, the raw data is averaged by using Microsoft Excel before being processed in the iDynamics mobile application. The maximum value of velocity and frequency from the tests is used for comparison with selected vibration guidelines. Table 4 summarises the result of the heel-drop test and walking test.

Table 4: Summary of results from heel-drop test and walking test

	Maximum acceleration (m/s^2)	Maximum velocity (m/s)	Maximum frequency (Hz)
Heel-drop test	0.012	0.0003	6.055
Walking test (outside)	0.061	0.0006	5.958
Walking test (inside)	0.004	0.0001	6.641

3.3 Comparison with vibration guidelines

The data produced from the in-situ test is compared with the values in Vibration Limits and Control in the Environment by the Department of Environment. Since the frequency of the data is below 10 Hz, the data cannot be compared with recommended vibration limits for steady state for damage risk in buildings in the Vibration Limits and Control in the Environment. The data is compared with DIN 4150-3, the standard that the Vibration Limits and Control in the Environment is adapted from. The vibration from the test is considered to be short term because the building has been unoccupied for a long period of time. Table 5 shows the guideline values for vibration velocity to evaluate structural damage of buildings from short term vibrations. While Figure 9 shows the guideline curves for velocities measured.

Table 5: Guideline values for vibration velocity to be used when evaluating the effects of short-term vibration on structures [13]

Line	Type of structure	Guideline values for velocity, v_i, in mm/s			
		Vibration at the foundation at a frequency of			Vibration at horizontal plane of highest floor at all frequencies
		1 Hz to 10 Hz	10 Hz to 50 Hz	50 Hz to 100 Hz	
1	Buildings used for commercial purposes,industrial buildings, and buildings of similar design	20	20 to 40	40 to 50	40
2	Dwellings or buildings of similar design and /or occupancy	5	5 to 15	15 to 20	15
3	Structures that, because of their particular sensitivity to vibration cannot be classified under lines 1 and 2 and are of great intristic value (eg.listed buildings under preservation order)	3	3 to 8	8 to 10	8

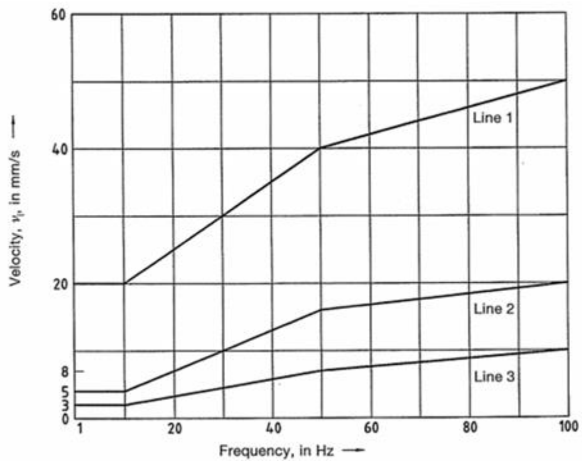

Figure 9: Curves for guideline values for velocities measured at the foundation [13]

The main findings from this research reveals that the vibration caused by human motions does not reduce the serviceability of the building at ground level because for the frequency range between 1 to 10 Hz, the velocity should not exceed 3 mm/s which is equivalent to 0.003 m/s. The maximum frequency and maximum velocity of the floor response from human excitation is 6.641 Hz and 0.0003 m/s.

4. Conclusion

The fundamental frequency of the building was found to be 1.53 Hz through modal analysis. The walking test and heel-drop test reveal that the maximum acceleration, maximum velocity and maximum frequency of the ground floor of the building were 0.012 m/s^2, 0.0003 m/s, and 6.641 Hz. Based on comparison with DIN 4150-3 standard, it is revealed that vibration produced from human motion does not damage or reduce the serviceability of the heritage building at foundation and ground level.

Although human-induced vibration may not be significant enough to cause damage to buildings, it is able to cause discomfort to occupants and disrupt sensitive equipment within the buildings. Further research on human-induced vibration on heritage or historic buildings, particularly in Malaysia, should be conducted as there are plenty of buildings with historical value that has been abandoned which could be refurnished or repurposed.

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