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Vibration Analysis of Beam and Block Precast Slab System due to Human Vibrations

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Abstract. Beam and block precast slabs system are very efficient which generally give maximum structural performance where their voids based on the design of the unit soffit block allow a significant reduction of the whole slab self-weight. Initially for some combinations of components or the joint connection of the structural slab, this structural system may be susceptible to excessive vibrations that could effects the performance and also serviceability. Dynamic forces are excited from people walking and jumping which produced vibrations to the slab system in the buildings. Few studies concluded that human induced vibration on precast slabs system may be harmful to structural performance and mitigate the human comfort level. This study will investigate the vibration analysis of beam and block precast slab by using finite element method at the school building. Human activities which are excited from jumping and walking will induce the vibrations signal to the building. Laser Doppler Vibrometer (LDV) was used to measure the dynamic responses of slab towards the vibration sources. Five different points were assigned specifically where each of location will determine the behaviour of the entire slabs. The finite element analyses were developed in ABAQUS software and the data was further processed in MATLAB ModalV to assess the vibration criteria. The results indicated that the beam and block precast systems adequate enough to the vibration serviceability and human comfort criteria. The overall vibration level obtained was fell under VC-E curve which it is generally under the maximum permissible level of vibrations. The vibration level on the slab is acceptable within the limit that have been used by Gordon.
1. Introduction
All structures are subjected to significant dynamic loads produced by occupants inside it. Coherent crowd harmonic movements can produce resonant or near-resonant structural vibrations that are uncomfortable and intolerable for some structural components. Various levels of amplitude produced by the vibrations sources that acted on the particular structure may affect the existing and workability of the whole building. Generally, slab structure component facing the most vibrations indication due to most dynamic actions acted on slab. Low-frequency slab vibration serviceability problems typically arise when a slab is excited in resonance due to a walking excitation and the resulting accelerations exceed human comfort levels for vibration according to the use of the slab [1].

Beam and block precast slab systems are such a structural slab component that specifically for building which mainly designed with load bearing masonry system [2]. The precast slab systems were found structurally effective with thin layer of precast member taking into account of the benefits which include with shorter construction time, less dependent on heavier equipment on job site, less wastage of material, high quality smooth surface finish, in situ structural concrete topping and in-fill forming monolithic structures, eliminate convention formworks [3]. Most of presents structural systems designed in Malaysia ignore the possibility of any occurrence regarding to unwanted vibrations that may acted on the structure. Slab vibration acceptability is an essential issue that should be incorporated in the design phase in addition to the strength and more important is to the safety criteria. This is essential because it seeks to ensure that Malaysia’s building are compliance with the international requirement and achieve the highest standard together with the quality. The most frequent vibration sources in the building induced by human daily activities such as walking and jumping. Therefore, the excitation from walking and jumping will be the vibration signal input for vibration analyses in this study.

2. Literature review

2.1 Human induced vibrations

A review of vibration sources has revealed that humans are the most important source of excitation on building floors. Generally, human activities can generate dynamic forces of periodic or transient nature. These actions can cause undesirable effects such as excessive internal forces in structural elements, damage to non-structural elements, intolerable vibration and noise for occupants. The amplitude of these vibrations depends basically on the relationship between the dominant excitation frequency and the natural frequency of the structure [4]. The dominant frequency in the case of persons in normal walking is between 1.5 and 2.5 Hz, and this frequency range and force pattern grows with the walking speed as shown in figure 1. Meanwhile, jumping activity involved with the physical substantial vertical load which this action is due to a sudden impact of human feet onto the contact surface, which this action produced the load with magnitudes higher than human static mass corresponding to spiking impulsive force once the jump ends with a landing on the ground. The schematic illustration of jumping activity is shown as in figure 2.
2.2 *Generic vibration criteria*

Vibration criteria (VC) curve guideline which was developed by Gordon [7] is commonly used in the design of structural building which concerning to vibration. The criteria curves were developed in response for a need of design standards to accommodate a wide range of tools and instruments used by the microelectronics, medical and biopharmaceutical industries. Nine levels of vibration criterion were categorized which are within workshop (ISO) until VC-E [7]. Consequently, the standards range for school building is between offices (ISO) to residential (ISO). Each of the criterion consists with different range of frequency and other parameters. The values given take into account the observation that the vibration requirements of many items depending on the detail size of the process. Hence, the VC curves is appear to provide a valid and useful generic basis as the guideline for evaluating sites and designing structures that generally support vibration-sensitive equipment and processes as shown in figure 3. The detail description of each curve is explained in table 1.
Figure 3. Generic vibration criterion curves [7].

Table 1. Application and interpretation of the generic VC curves [7].

| Criterion Curve | Max Level | Detail | Description of use |
|-----------------|-----------|--------|--------------------|
| Workshop (ISO)  | 800       | N/A    | Distinctly feelable vibration. Appropriate to workshops and nonsensitive areas |
| Office (ISO)    | 400       | N/A    | Feelable vibration. Appropriate to offices and nonsensitive areas |
| Residential Day (ISO) | 200 | 75 | Barely feelable vibration. Appropriate to sleep areas in most instances. Probably adequate for computer equipment, probe test equipment and low – power (to 20X) microscopes. |
| Op. Theatre (ISO) | 100 | 25 | Vibration not feelable. Suitable for sensitive sleep areas. Suitable in most instances for |
microscopes to 100X and for other equipment of low sensitivity.

VC-A 50 8 Adequate in most instances for optical microscopes to 400X, microbalances, optical balances, proximity and projection aligners, etc.

VC-B 25 3 An appropriate standard for optical microscopes to 1000X, inspection and lithography equipment (including steppers) to 3 micron line widths

VC-C 12.5 1 A good standard for most lithography and inspection equipment to 1 micron detail size

VC-D 6 0.3 Suitable in most instances for the most demanding equipment including electron microscopes (TEMs and SEMs) and E-Beam systems, operating to the limits of their capability

VC-E 3 0.1 A difficult criterion to achieve in most instances. Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems and other systems requiring extraordinary dynamic stability

2.3 Beam and block precast slab

Beam and block precast slab system typically designed as a series of T-section beams (joist) with the assembly of soffit blocks which generally it is a common one-way slab system. In general the beam and block floors are consisting of three major elements which are soffit unit block, joist, and topping [4]. Soffit block is an elements of brick with cavities or hollow blocks as shown in figure 4. The floor is usually completed with a concrete screen which typically known as topping cast on the top surface of the components, with the aim to connect the different elements involved and to distribute the load acted onto the slab. Other than that, the addition of the concrete screen is the only way to achieve a level and smooth floor surface since the flooring system is made up of different elements with different level. Despite of concrete screed, additional reinforcing also required to distribute the loads effectively. This reinforcing together with concrete screen enhancing the structural design of the precast slab system respectively. Among the plans bearing surface, this structure represents the best compromise between the weight and load capacity in the same walking surface which also good in acoustic performance at low frequencies.
3. Materials and methods

A parametric study was developed to evaluate the influence of parameters such as slab thickness, span and elastic modulus of concrete on natural frequencies and vibration generated by walking and jumping in beam and block slabs. The study was carried out through numerical simulation with finite element software ABAQUS. The cross section geometries and spans were created according to the selected investigated slabs.

3.1 Finite element modelling

The slabs are supported by two wall panels which is known as concrete masonry load bearing wall, meanwhile there are two supported beams at the middle of slab with distance 2.8m away from both end of slab, where each one with rectangular section (0.60x0.40 cm) and simply supported at the ends. The main other purpose of the beams are to locate joist structural components together with the combination of soffit blocks. The span in the direction of the beams is 7.48m, equivalent to 13 combination of joist and soffit block elements. Solid elements were used to model both the slabs and beams which is known as eight-node continuum elements (C3D8R). Next, beam steel reinforcement was modelled with 2 nodes of wire base feature where the coordinates of the whole model was set up earlier to ensure the smooth progress for assembly section. Consequently, $113.1 \times 10^{-6} \text{ m}^2$ is the cross sectional area of reinforcement bar and $50.3 \times 10^{-6} \text{ m}^2$ is the cross sectional area of link. In addition, mesh rebar reinforcement were developed with the same approached. Aiming to reduce computational effort, micro-macro modelling technique was applied [9]. A schematic view is shown in figure 5 and figure 6 [10].
3.2 Elements interaction

Modelling of beam and block precast slab structure consist of various combination of elements which are soffit unit block, joists, beams and topping. Every individual elements was modelled separately specifically known as ‘part’ to ensure the originality of the component according to the exact investigated slab structure. The individual modelled elements have to be connected properly to each other after assembling the structural and non-structural elements. Tie contact technique was utilized to create proper interaction between undeformable discrete rigid element (reinforcement bar) and solid element (concrete element. This technique can avoid the shear interaction between these two elements.

Next, the embedded region technique was used to constraint the wire element (steel reinforcement) into solid element (concrete beam) in order to create a proper bond action. Both of this constraint are much important in micro-macro modelling technique [10] in order to obtain proper bonding between those elements. Furthermore, it is possible to eliminate and mitigate the possible errors with the present of variety layers and numbers of element properties.

3.3 Materials properties

The modulus of elasticity of concrete directly affects the stiffness of the structure which it vary with the concrete strength. The concrete elements was allowed to be modelled as linear elastic materials due to the structure was only exposed to small loads and displacement where isotropic platform was chosen. Bachmann et al. [11] suggested that for bare structure of uncracked prestressed concrete $\beta$ varies from 0.004 to 0.007. Based on these considerations a value of 0.009 was adopted. Meanwhile, the reinforcement components such as rebar and link were modelled as an elastic-plastic material in both tension and compression. It is possible to obtain a close approximation of the actual material behaviour. Table 2 represent all the materials properties for the finite element model.

| Materials             | Weight density (kg/m$^3$) | Elastic modulus | Poisson ratio | Yield stress | Plastic strain |
|-----------------------|---------------------------|-----------------|---------------|--------------|----------------|
| Reinforced Concrete   | 2400                      | $3.0 \times 10^{10}$ | 0.2           | $27 \times 10^6$ | 0              |
| Soffit block and joist| 4100                      | $63 \times 10^8$  | 0.2           | $30 \times 10^5$ | 0              |
| Reinforcement bar     | 7800                      | $21 \times 10^{10}$ | 0.3           | $21 \times 10^7$ | 0              |

3.4 Mesh generation

For the three-dimensional model, there are 77,456 linear hexahedral elements of type C3D8R and 121,063 total number of nodes are used to represent the solid elements which generally was assigned as concrete. Meanwhile, 1950 linear line beam elements of type T3D2 represent the reinforcement bars.
where in the form of where linear quadrilateral. Several partitions have been made for topping component regarding to the present of complex meshing procedure due to the present of hollow section of soffit blocks. Distortion warning will occur if this indication never been done which it might affect the final result. In order to obtain approximately accurate results from the finite element model, all the elements were purposely assigned with ABAQUS default mesh size except for topping part where 0.05 meshing size was used. The purpose of this indication was to ensure that the reaction on that particular topping is closely elaborated.

3.5 In situ field measurement

Field test was conducted to obtain the vibration input data of this study where Laser Doppler Vibrometer (LDV 100) was used as the data measurement. Consequently, series of tests were performed with the controlled number of walker and jumper on five different points [10]. The purpose of multipoint were selected in order to investigate the behaviours of the entire location of slab with response to vibration. Practically, the equipment is assigned exactly at the set up point and test persons supposed to walk in circular form 1m away from the LDV.

Next, jumping test is done with similar distance which is 1m from the LDV. Visual sound will be used as the reference for the persons to obtain the similar pace of walking and jumping, as required to obtained similar step frequencies. It is very important for both experimental test to ensure that the pacing of walking and jumping pattern have to be the same and trajectories for every repetition of test at every single point The amplitude of the vibration produced by walking and jumping are measured a five different selected location of the slab. Figure 7 shows location of the measurement for five different points and figure 8 shows the in situ measurement test.

![Figure 7. Location of five different points.](image1)

![Figure 8. In situ measurement.](image2)

4. Results and discussions

4.1 Mode shapes and natural frequency

Natural frequency is determined with the aid of numerical simulations that computed in ABAQUS program where the direct method of Lanczos eigen solver was used as the simulation platform where 10 numbers of modes are requested. Mode shape analysis was carried out to determine the condition of the
floor structure of the building when subjected to different natural frequency modes. Three mode shapes are shown in figures 9 to 11 which consists of the first mode, fifth and tenth mode shape. The first mode was the fundamental mode of the slab as the reference for further subsequence analysis procedure. The fifth mode can be described as torsion of the floor. The tenth mode was a higher order bending mode of the slab.

**Figure 9.** Mode shape 1.  
**Figure 10.** Mode shape 5.  
**Figure 11.** Mode shape 10.

The natural frequency values varied significantly in the models within the parametric study where all the number of mode shapes and its values are listed in table 3.

| Mode number | Natural frequency (Hz) | Mode number | Natural frequency (Hz) |
|-------------|------------------------|-------------|------------------------|
| 1           | 20.148                 | 6           | 45.960                 |
| 2           | 26.969                 | 7           | 46.060                 |
| 3           | 32.846                 | 8           | 47.437                 |
| 4           | 35.976                 | 9           | 51.728                 |
| 5           | 43.705                 | 10          | 52.923                 |

**4.2 Transient analysis**

Transient analysis was performed to determine the dynamic response of structure towards the vibrations sources with arbitrary behaviour in time. Acceleration value is obtained from this analysis where in the form of time history graph. Peak accelerations for each of every point is selected to determine the behaviour of slab. Responses at point 1 shows that the peak acceleration value for jumping and walking test are 0.000563m/s² and 0.000281m/s². Figure 12 represent the transient result of point 1 based on jumping test. The peak amplitude are different for every selected location because the centre of slab is located a distance away from any column which mainly as the support system of the structural component.
Meanwhile, the other four points are generally located near to series of columns which mitigate the vibration. The behaviour of floor can be observed based on the mode shape obtained. For example, the centre of slab is the most sensitive where in first mode shape as the fundamental response is at middle of slab as shown in figure 12. Consequently, point 5 shows the least value of peak acceleration with the value of 0.000150 m/s\(^2\) for jumping test and 0.000113 m/s\(^2\) for walking test. This condition is similar with the other 4 points of analysis where it located nears to support system where it is more rigid to the vibration transmission. Table 3 represents the maximum value of acceleration for five different points for both excitations. The differences acceleration values between jumping and walking also listed in table 4.

![Figure 12. Transient analysis for Point 1 (Jumping).](image)

|                | Jumping | Walking | Differences |
|----------------|---------|---------|-------------|
| 1              | 0.000563| 0.000281| 0.000282    |
| 2              | 0.000360| 0.0000923| 0.000277   |
| 3              | 0.000365| 0.000104| 0.000261    |
| 4              | 0.000258| 0.000115| 0.000143    |
| 5              | 0.000150| 0.000113| 0.000037    |

### Table 4. Maximum value of acceleration (m/s\(^2\)).

#### 4.3 One third octave spectra

One third octave velocity spectra graph is obtained by using ModalV, developed program in MATLAB software. The graph is compared with generic vibration criterion (VC) curve from Gordon guidelines. From the overall analyses, one third octave velocity spectra showed that the curves are under the VC-E region for jumping and walking. Point 1 clearly shows the highest peak value regarding to the transient analysis part, yet the generated one third octave velocity spectra situated at lowest range of the guidelines. Besides, the vibration criteria analysis for other points which located nearest to support shows the similar criteria as Point 1 as shown in figure 13.
Figure 13 represents the graphical data for Point 1 which consist of jumping and walking test result. It contains complete time series for 10 seconds period, Fast Fourier transform (frequency domain) and vibration criteria curve. The result clearly shows that jumping exerted higher vibrations response on slab compared with walking.
By referring to the frequency graph, the result clearly shows that the investigated slab is response to human-induced vibrations at the range of frequency between 15Hz to 20Hz where the peak is closely to 20Hz. This peak value is quite similar with the first natural frequency value as shown in table 3 which is about 20.148Hz. Its shows that the finite element modelled was successfully according to the actual structural component. Besides, the graphical data clearly shows that input data is greater than output. By referring to VC- curve graph, the result indicate that there is a slightly different between the one third octave bands data at the range of 15Hz to 20Hz as mentioned earlier.

5. Conclusions

From the measurement data, it indicated the quite similar response on vibration signal as referred to the input and output results. The overall value for the vibration criteria of the beam and block precast slabs due to human induced vibration is 3 µm/s between 1 and 80 Hz where it falls below of VC-E. Besides, the vibration criterion obtained for investigated precast structural slab can be concluded as acceptable and satisfied which it was not over the limit which according to the comparison of several guidelines. Concerning to the masonry type structural, vibration response of the particular structural component is an enormous issue. VC-E obtained represents that the slab can be considered very sensitive regarding to vibration stimulation due to human-induced vibrations. The vibration incurred by the slab have no impact to the structure or even give discomfort to occupancy inside the building. The slab structure is most suitable place to accommodate very sensitive equipment or as a cleanroom area for a sensitive laboratory.

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