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Human Comfort Assessment of Vibration Behaviour of Office Floors: Before and After

Strengthening Using the Laminated Elastomeric Bearing

Nor Hayati Abd Ghafar[1], Muhammad Imran Rahimi[1], Lyn Dee Goh[2*]

[1]Faculty of Civil Engineering & Built Environment,
Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, MALAYSIA.

[2]School of Civil Engineering, College of Engineering,
Universiti Teknologi MARA, Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, MALAYSIA.

*Corresponding Author

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Abstract: Vibration issues of floor areas in relation to human comfort perception in an open working space are very common. This paper discusses the results of a human comfort assessment before and after strengthening of a a post-tensioned reinforced concrete flooring structure. All floors experience structural vibration, which arises from various sources inside and outside of the building. This paper investigated the vibration issue of a problematic flooring slab area on Level 3 of a four storey building, which vibrations induced by people walking through the working station area. Two types of tests were conducted, namely a (1) shaker test and a (2) walking test. Accelerometers were attached to the floor according to the sensor points and recorded all acceleration responses on the floor system. The highly sensitive KS 48C accelerometer was used in this study. The accelerometers were placed at the same locations for both shaker and walking tests. The floor slab which was initially reported as problematic structure on Level 3 was found that its peak acceleration exceeded the recommended human comfort limitation. A passive vibration isolation technique was used in order to tackle the vibration issue. A laminated elastomeric bearing was chosen as one of the methods in passive vibration isolation. The natural frequency for both results before and after strengthening remained as low-frequency floor classes. However, peak acceleration excitation was reduced after the strengthening work was completed.

Keywords: Floor vibration, human comfort, experimental modal analysis, passive vibration isolation and working space

1. Introduction

In modern construction, designers who desire to increase the span of office floors are renowned for employing current construction techniques and high-strength lightweight material. This design technique has several advantages which includes making an area more usable with fewer columns in a long span, reduced load on the foundation due to the use of lightweight material and lower construction costs (Li, Liu, Cao & Chen, 2018; Silva, Burgos, Duarte & Debona, 2016; Lee, Na, Kim & Hong, 2014). However, utilisation of lightweight materials and modification of slab slenderness with open space often contribute to excessive floor vibration.

**Corresponding author: gohlyndee147@uitm.edu.my*

Floors with lower structure mass easily respond to different excitations such as ambient excitation from the environment and machinery as well as excitation from human activities such as walking. Long and light spans are sensitive to higher excitation, as vibrations from the external sources occur when both structure's mass and stiffness are lower.

Vertical excitation which corresponds to human activity often occurs to floors. Daily activities such as walking, running and jumping, especially in an office environment with high occupancy which contribute to the external forces that exert on the structure, can lead to floor excitations. In an office area, many factors can contribute to excessive excitation. For instance, the operation of machinery such as photocopy machines, fax machines, and computers will also contribute to the floor excitation. In general, humans tend to feel vibration in the natural frequency range between 4 Hz to 8 Hz, as humans are susceptible to dynamic motion (Hassanieh, Chiniforush, Valipour & Bradford, 2019; Setareh, 2012; Murray, Allen, Ungar & Davis, 2009). Even a walking pace of 1 Hz to 2 Hz can cause the floor to vibrate. Humans feel vibration when the floor's resonance merges with excitation caused by human activity at low natural frequency.

In floor vibration design, people accept higher frequency in the frequency-domain evaluation of more than 10 Hz for concrete floors, as mentioned by The Concrete Centre (Willford & Young, 2006). The low-frequency floor refers to floors with a natural frequency below 10 Hz when it is dominated by a resonant accumulation while a high-frequency floor shows a fleeting sequence of the response (Mohammed, Pavic & Racic, 2018). A low-frequency floor with a natural frequency range of 8 Hz to 10 Hz does not affect human comfort. Humans can normally feel vibrations between 4 Hz to 8 Hz (Murray, Allen & Ungar, 2003; Hassanieh et al., 2019). Human comfort can be evaluated by peak acceleration in a time-domain base. Humans are able to feel continuous vibrations below a frequency of 8 Hz at 0.5 g - 1.0 g (% gravity) of peak acceleration (Li et al., 2018). Humans begin to feel uncomfortable in this range as they are quite sensitive. The frequency reacts with the human body and creates feelings of uneasiness. At 0.5 g peak acceleration, the vibration can be distinctly detected by people in an office (Murray et al., 2003). The threshold of human sensitivity of vertical vibration was recommended by ATC (1999), as the baseline required is below 0.01 g for offices or residences to receive the optimum comfort level. This baseline is also employed in this study as the guideline for the floor vibration.

Several modifications can be made for an existing building to keep natural frequency and peak acceleration under control. In this research, passive vibration isolation techniques were used to improve vibration performance. Several studies by Enríquez-Zárate, Abundis-Fong, Velázquez, & Gutiérrez (2019) and Jurevicius et al. (2019) have shown that the usage of these techniques can enhance vibration performance, together with various absorbers such as rubber bearing, ball bearing, sliding bearing and spring. Some researchers use different absorbers such as tuned mass dampers, tuned inerter dampers and tuned viscous mass dampers (Enríquez-Zárate et al. (2019); Lazar, Neild & Wagg (2014); Ikago, Saito & Inoue (2012). Thus, this paper aims to determine the vibration behaviour of an actual office floor slabs which considered problematic as complaints of uneasiness have been received from the building occupants. The vibration behaviour was evaluated through a human comfort assessment. The vibration behaviour of the floor slab was assessed before and after strengthening took placed using Laminated Elastomeric Bearing (LEB) and a comparison is made.

2. Theoretical Background of Floor Vibration Limitation

There is a limit or cut-off frequency for floor vibration depending on the floor material. The cut-off frequency for the floor vibration has been set by different authors and design guidelines. Each of the limits has a different value of frequency to set a boundary between the low-frequency floor and the high-frequency floor. The low frequency floor is a resonant build-up that dominates response while high- frequency is a response due to successive footfall (Mohammed et al., 2018). In earlier research, Ohlsson (1988) had marked the cut off to 8 Hz for limitation on residential or office on lightweight floors. There was an agreement with the cut off between 9 Hz and 18 Hz that indicates reasonable evaluation for the floor (Ohlsson, 1988; Allen & Murray, 1993). Subsequently, the recommended cut-off had been marked at 9 Hz to ensure a comfortable environment and satisfactory for design criterion due to walking (Allen & Murray, 1993).

General floor as office open space area with the concrete material floor including precast is limited to 10 Hz cut-off frequency by Steel Construction Institute 'SCI P345', and it will be limited to 8 Hz for enclosed space (Smith, Hicks & Devine, 2009). The SCI P354 has an agreement on the cut-off with The Concrete Society and The Concrete Center for the general open space area or office area on the frequency limitation at 10 Hz (Pavic & Willford, 2005; Willford & Young, 2006; Smith et al., 2009). For this study, the floor vibration limitation employed is based on the material properties of the floor and the purpose of design in the office area with concrete floor material. Thus, a limitation of 10 Hz limitation will be used as a mark for the serviceability of the floor.

3. Case Study: Office Floor Area

The investigation was performed at a four storey office building in the northern part of West Malaysia. The open office area with slender post-tensioned reinforced concrete slabs receives high excitation from human activities. An open space with a long-span floor consisting of post-tensioned reinforced concrete slabs with a thin floor thickness of 180 mm exposed to vertical vibration from various sources can be disturbing to the consumer. The total test area involved is 255.62 m^2, which includes three workstation areas denoted as Floor A, Floor B and Floor C, as shown in Fig. 1. Employees from the workstation area were reported to feel the most vibration, for example, when their colleagues are walking. This in turn causes the floor and desks to also vibrate. Excessive vibration has a physical impact on the workers at the workstation areas and this leads to an unhealthy work environment.

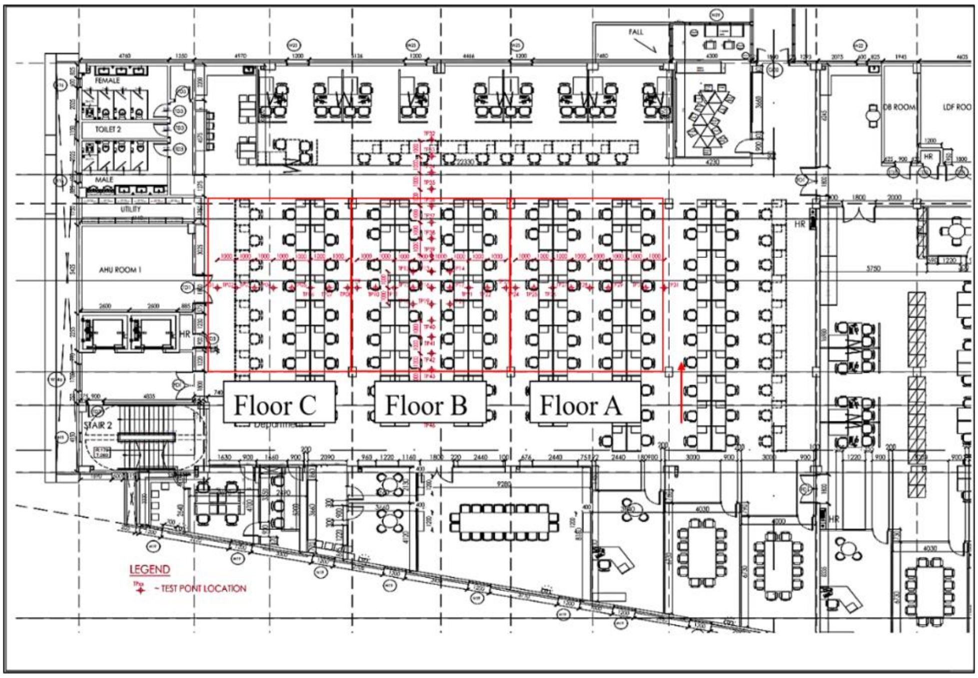

Fig. 1 - Plan layout of vibration test on Level 3

3.1 Strengthening of Office Floors

The passive vibration isolation technique is one of the methods for improving vibration performance by using LEB to enhance vertical movement rigidity. LEB´s essential function is to support vertical load with minimum deflection and to allow horizontal movement with minimal resistance to absorb excessive vibration with low damping. LEB reduces a structure's load capacity in a lightweight structure as the isolation damper is applied after construction (existing building). The overall LEB dimension is 310 mm x 310 mm x 110 mm, with three internal elastomers measuring 8 mm thick, as shown in Fig. 2 and Fig. 3. The design parameters include a total load of 25 kN and an allowable rotation of ±0.00010 rad. Shear and compression stiffness of the LEB are 0.88 kN/mm and 10.8 kN/mm, respectively. As shown in Fig. 4, LEB was installed in the middle of the problematic floor (column to column) on Floor B. LEB was installed with 200 mm x 200 mm steel columns to support the system, as shown in Fig. 5.

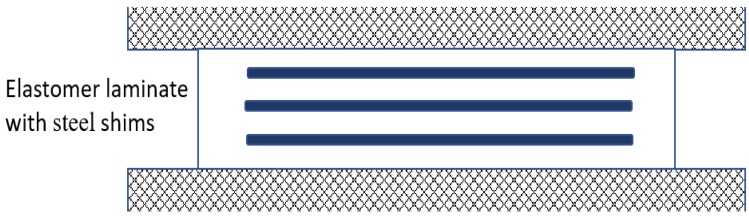

Fig. 2 - Typical LEB detailing

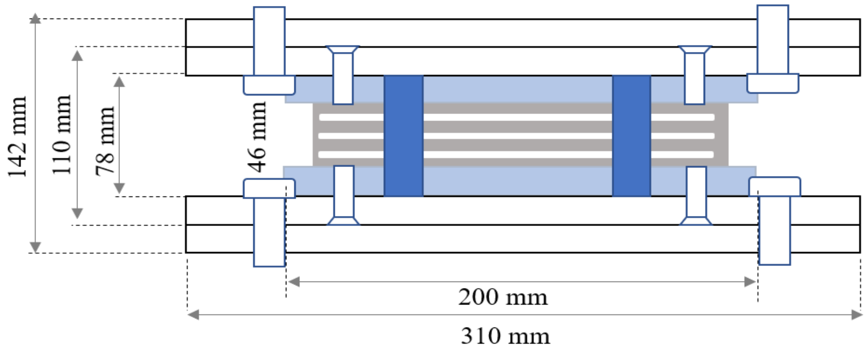

Fig. 3 - LEB cut section detailing

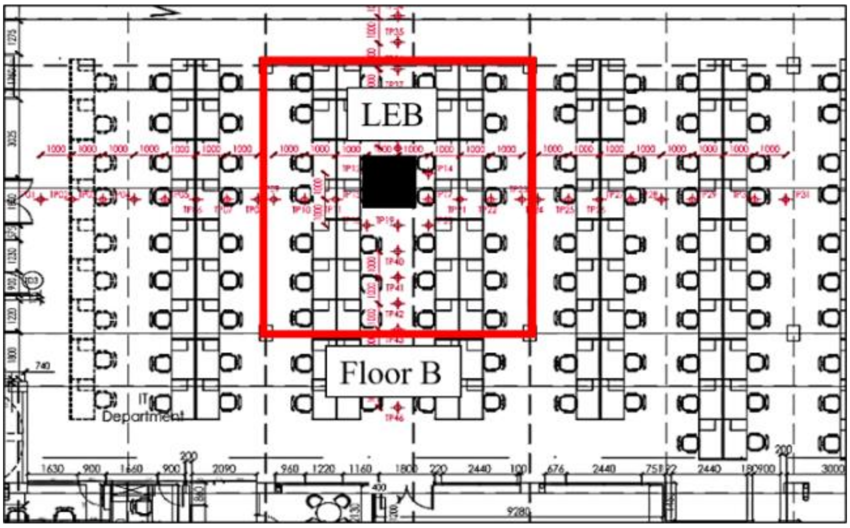

Fig. 4 - LEB point location

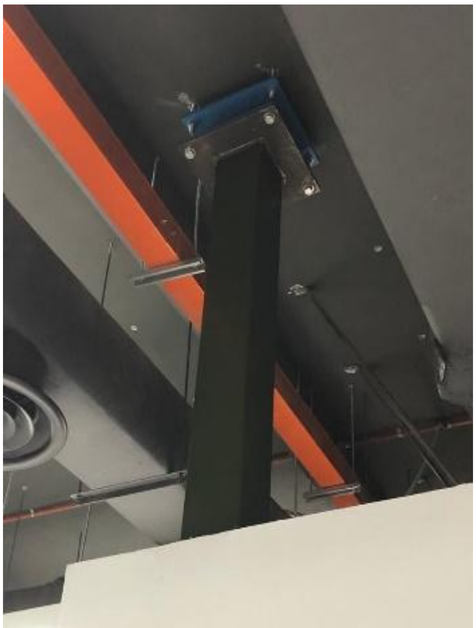

Fig. 5 - Actual LEB with 200 mm x 200 mm installed at steel columns

4. Experimental Modal Testing & Results

The tested floor span measured 8 m per bay (column to column). Three bays of the floor were selected for testing to determine the vibration properties of the problematic slab. The floor areas were denoted as Floor A, Floor B, and Floor C, as described in Fig. 1. The two tests, namely the shaker test and the walking test, were conducted at Level 3 which included adjacent floors to the problematic slab. An electrodynamic shaker was placed on the Floor B area whereas accelerometers were attached to the floor according to the sensor points to record all acceleration responses on the floor. Locations of accelerometers for Level 3 are shown in Fig. 1. The highly sensitive KS 48C accelerometer was used in this study. The accelerometers were placed at the same locations for both tests.

An electrodynamic APS 113 long stroke shaker was used to extrude the floor's vibration force with a 200 Hz sample rate. The shaker is placed at about one-third of the floor span. The accelerometers were applied to record all responses from Floor B as it was suspected to be the problematic slab. Due to the limited number of accelerometers, roving accelerometers were used to ensure all selected points were recorded. The test was repeated five times. The walking test was conducted with an adult walking along a designated path, as shown in Fig. 6. The person who engaged in the walking test walked randomly at a walking pace between 1.7 Hz to 2.5 Hz from one corner to the next along the path.

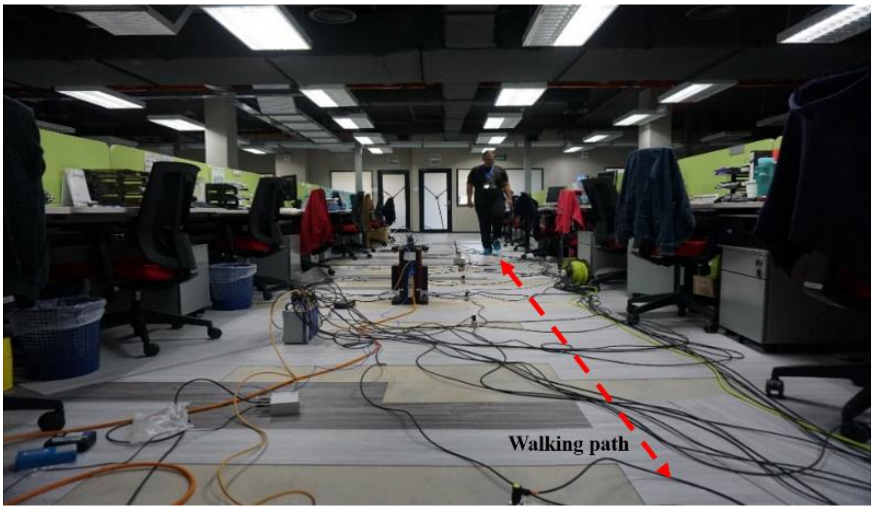

Fig. 6 - Walking test

4.1 Before Strengthening

The study was conducted on three floor areas to determine the problematic slab. Time-domain based evaluation was performed to obtain peak acceleration (g) on each floor area. The human comfort evaluation is based on ATC's (1999) design guide on human recommended tolerance. The frequency-domain based evaluation involved the Fourier Transform (FT) to gain the peak frequency to determine floor frequency classes. According to SCI P354, the floor's cut-off natural frequency with concrete material for general floors as open space areas is limited to 10 Hz (Willford & Young, 2006; Pavic & Willford, 2005; Smith et al., 2009). The floor's natural frequency below 10 Hz is classed as a low-frequency floor.

Table 1 - Natural frequency and peak acceleration before strengthening

Floor	Natural frequency, f_n (Hz)		Peak acceleration, a_{peak} (g)	
	Walking test	Shaker test	Walking test	Shaker test
Floor A	7.48	7.66	1.78×10^{-3}	1.46×10^{-3}
Floor B	7.48	7.62	8.67×10^{-3}	5.27×10^{-3}
Floor C	7.65	7.69	2.99×10^{-3}	1.56×10^{-3}

The result in Table 1 shows that the natural frequency of all three floor areas were below 10 Hz. Therefore, they can be classified as low-frequency floors which having a high probability of exposing to floor serviceability issues. Based on the peak acceleration, Floor B had the highest peak values at 8.67×10^{-3} g and 5.27×10^{-3} g for the walking test and the shaker test, respectively, compared to Floor A and Floor C. Both test methods recorded a peak acceleration above 0.5 g which exceeds the recommended peak acceleration important for human comfort. Thus, Floor B was classified as a problematic floor that leads to an uncomfortable environment for users based on the result from the analysis.

4.2 After Strengthening

The second assessment on the vibration properties was only conducted after the LEB installation on the problematic floor area was completed. The accelerometers' locations remained at similar positions as the vibration test was done before the strengthening work was carried out.

Table 2 - Natural frequency and peak acceleration after strengthening at Floor B

Floor B	Before strengthening		After strengthening	
	Natural frequency, f_n (Hz)	**Peak acceleration, a_{peak} (g)**	**Natural frequency, f_n (Hz)**	**Peak acceleration, a_{peak} (g)**
Walking Test	7.49	8.67×10^{-3}	9.37	3.4×10^{-3}
Shaker Test	7.62	5.27×10^{-3}	9.54	2.17×10^{-3}

The natural frequencies and peak accelerations from both the shaker and walking tests for Floor B are presented in Table 2. A comparison with the previous results obtained from the earlier shaker and walking tests are also presented. The natural frequencies from both tests (shaker and walking tests) increased to about 1.88 Hz and 1.92 Hz, respectively, after the strengthening work took place underneath the Level 3 (to support the floor slab from Level 2). However, from the results obtained, Floor B on Level 3 was still categorised as a low-frequency floor, as the cut-off frequency for post-tensioned floors is 10 Hz, as suggested by Pavic & Wilford (2005). The peak accelerations decreased after LEB installation as the stiffness of the floor increased. The strengthening result showed that both peak accelerations in Table 2 are below the recommended peak acceleration limit of 0.5 g. The peak acceleration dropped to 60.7% and 58.8% for both tests, which shows an effective vibration isolation system that absorbs more than 50% of excessive vibration.

Table 3 - Comparison of damping ratio

Floor B	Damping ratio (%)	
	Before strengthening	After strengthening
Walking test	1.456	5.847
Shaker test	2.502	2.122

As shown in Table 3, the damping ratio showed an increase from 1.456% to 5.847% after the LEB installation. A damping ratio of 2% was recommended by Murray et al. (2003) for open office areas with the least non-structural elements whereas a damping ratio of 5% was recommended for height partition in residences and offices. Thus, after strengthening, the damping ratio exceeded both recommended percentages at 2% and 5%. As for the shaker test, the damping resulted in a different reaction from the walking test. Continuous forces which were applied until resonance was achieved during the shaker test influenced the damping ratio. The shaker caused unstable damping due to the noise in acceleration data excitation from 0 Hz to 200 Hz compared to a walking pace of 1.7 Hz to 2.5 Hz.

5. Discussion

The natural frequency was slightly increased while the peak acceleration is decreased after strengthening works was completed in the problematic area using passive vibration isolation as compared to before strengthening works were carried out. The LEB reacts by absorbing vibration from the elastomeric material to decrease the peak acceleration excitation from the problematic slab. Furthermore, the LEB helps reduce excitation by excellent energy absorption at a minimum rated reaction force with the layer of elastomer and steel to increase vertical stiffness. Peak acceleration showed a decrease of more than 50%, which indicates that the floor had become more stiff and rigid. The excitation from human activity is reduced when the stiffness of the floor increases.

The results before strengthening showed that the natural frequency was nearly the same for three floor areas. All three floor areas were classified as low-frequency floors. However, the problematic floor was confirmed through different peak acceleration values. The problematic floor exceeded the recommended limit for human comfort during both the walking test and the shaker test at 8.67×10^{-3} g and 5.27×10^{-3} g, respectively. The LEB installation reduced the peak acceleration values resulting in an acceptable limit for consumers' comfort level. Compared to the natural frequency, both tests recorded results below 10 Hz, resulting in low-frequency floor classes.

Perception of vibration and whether or not it is annoying or objectionable is highly subjective. The threshold of human sensitivity of vertical vibration was recommended by ATC (1999) for comparison before and after strengthening, as presented in Fig. 7. The peak accelerations for Level 3 (Floor B) after strengthening are below the threshold of human sensitivity for offices and residences. Thus, the floor is suitable for office or residences in terms of human comfort.

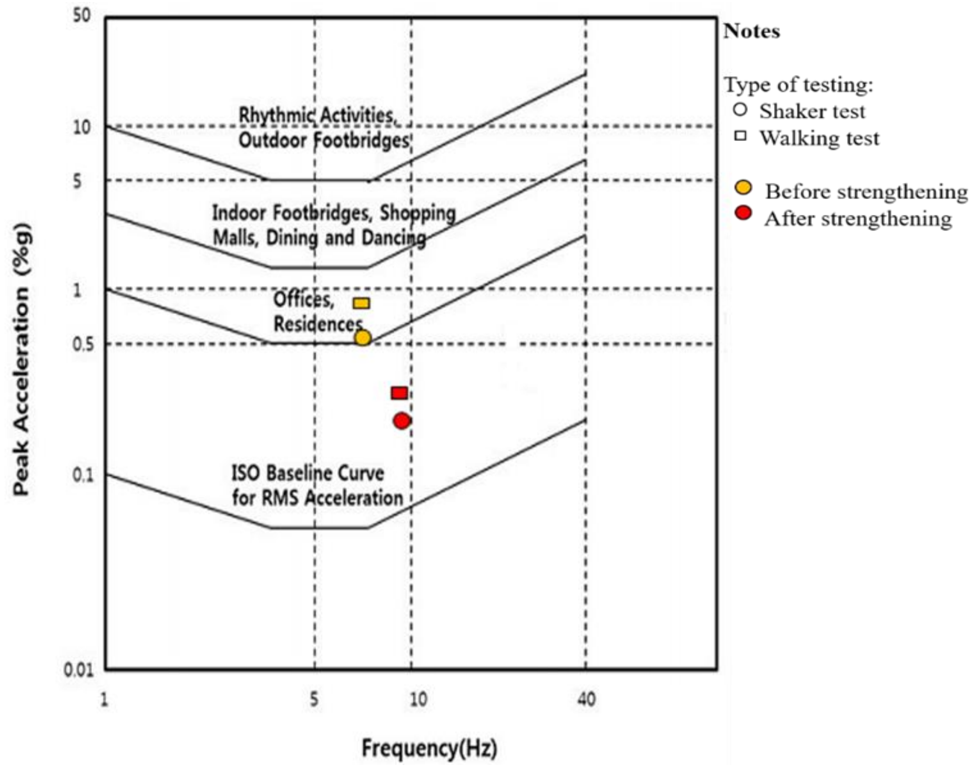

Fig. 7 - Comparison of floor response before and after strengthening with the threshold of human comfort perception

6. Conclusion

The results obtained in from this vibration study on the post tensioned concrete flooring system showed that the natural frequency for Floor B increased after strengthening. The floor's final natural frequency in this study was 9.5 Hz, which can still be categorised as a low-frequency floor. The peak acceleration of Floor B was found to be under the threshold of ATC limitations and is thus considered as an acceptable comfort level. Therefore, the floor is suitable for use in offices or residences.

It is good to remark that the structural engineer should address the vibration issues during the conceptual and design stages by balancing the choice of the structural elements in the design with the structural loads to ensure no human comfort issue to be jeopardised at later stage.

7. Acknowledgement

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