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Response of Post-Tensioned Two Way Flat Slabs to Vibration

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ABSTRACT

As PT floor slabs become thinner, a doubt about its vibration behavior and comfort of occupants arises. This paper investigates several approaches for determining the post-tensioned slabs behavior for human induced vibrations which can give a high accuracy for determining the vibration behavior and can be considered as a simple tools and a guide for designers. It also studies the vibration behavior of slabs with different span length, and thicknesses and relates vibration response to natural frequency of floor. The results show that the frequency of the slab is increased by decreasing the span length or increasing the slab thickness. The peak acceleration is mainly decreased achieving acceptable vibration behavior by increasing the slab thickness to length ratio for all span lengths studied. The results also indicate that PT floor slabs with practical thickness-span ratios and designed for deflection are expected to be acceptable for vibration. The limits of natural frequency for vibration validity of floors are also discussed.

1. Introduction

Nowadays vibration problem becomes so frequent as the design methods, materials and construction technology produce slender, economical, and efficient designs which also meet the architectural requirements. So, many vibration problems related to high rise buildings, long span bridges and slender floors are reported in recent years than previously [1]. Recently, Post-tensioned floors are vastly used and have various applications due to their advantages related to cost, time, and structural behavior [2]. The Performance of post-tensioned (PT) concrete floors in Vibration are now being raised as pre-stressing allows relatively flexible and light solutions for long spans [3,4].

In this paper, the perception of human to vibration is discussed, the design criteria behind vibration analysis is observed and different methods for vibration evaluation are illustrated. The effect of span length and slab thickness on the vibration characteristics of PT floors are also discussed.

2. Human induced vibration

In 1831, it was recognized that human footfall can produce loading cause exaggerated vibration of structures when the soldiers marched on a cast iron bridge. They generated vibrations caused a bridge to fail [5]. Human loads cover the major portion of live loads in residential and office building`s floors. In assembly structures such as grandstands, health clubs, ballrooms, and pedestrian bridges the main source of vibrations is the human dynamic loads. There are two wide categories of human live loads:

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moving and in situ. Unexpected standing up of an assembly, irregular in-site activities and Cyclic jumping due to music are samples of in place human live loads. Running, walking, and marching are samples of moving human live loads [6]. A major interest in the small frequencies values of vibrations for the thin floors which induced by the traditional human activities as walking primarily but also jumping and running due to children playing for an example. Walking steps produce a frequency about 1.6‑2.4 Hz [7]. Many studies in the previse works are found which interested in the human consciousness for the vertical vibrations Reiher et al. [8] accomplished one of the major studies which investigate the acceptance scale of the human perception which expressed by peak deflection. Wiss et al. [9] improved an equation to expect human response degree to transient vertical vibrations depending on peak displacement, frequency, and damping ratio. The base acceleration value that can be realized mainly depends on the human body`s direction effect. A main coordinate system is used as shown in Fig. 1. (Z-axis compatible with the human`s spine direction) [10].

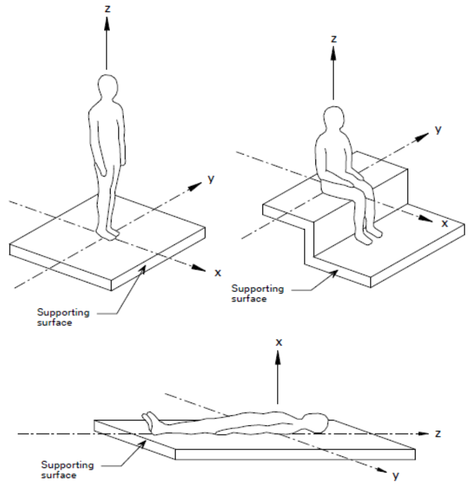


Fig. (1) Directions for Vibration [11, 12, 13 and 14].

Generally, walking activity is not continuous. It is intermittent by its nature. More reliable levels of perceptive tolerance can be determined from a cumulative measure of the intermittent vibrations response [15]. Human perception cause a Normal footstep rates range from 1.5 to 2.5 Hz [16].

3. Design criteria:

Several researchers have discussed different suggestions for the floor design criteria of the floor vibration over the years. Talja et al. [17], Ohlsson [18] and Wyatt and Dier [19] provided a deflection and acceleration boundaries for the floors with large and low frequencies. An ease criteria are expressed for vibration to use the floors. An ease design approach for calculating the intensity of vibration due to the human vibration is produced to check the vibration criteria. This design approach “Vibrations of Floors” has been produced, validated, and then used in the field of RFCS-project “Research Fund for Coal and Steel” [20]. Following are the most common methods used for vibration evaluation of floors.

First Approach: OS-RMS 90 Method:

The method is based on calculating the one step- Root mean square value “OS-RMS” value which used to determine the slab class. OS-RMS value can be determined using the floor modal mass and frequency [20].

Modal mass and corresponding frequency for regular, simple systems can be calculated by the following equation.

$$f = \frac{\alpha}{l^2} \sqrt{\frac{Et^3}{12\ m\ (1-\nu^2)}} \qquad \text{eq. 1}$$

$$M_{mod=\beta.\ M_{tot}} \qquad \text{eq. 2}$$

α : A factor detected from a chart “The chart is selected according to the support condition” by knowing (λ).

λ : A Ratio equal (L/B) “Slab longer span length/ slab shorter span length”.

L: The floor longer span.

E: Modulus of elasticity [N/m²]

t : The plate thickness [m]

m: The floor mass including finishing and the corresponding amount of imposed load [kg/m²]

υ : Poisson ratio

β: A factor detected according to the support condition.

M: The floor total mass including finishes and the corresponding amount of imposed load. [kg]

When frequency and modal mass are determined, the perception classes and the OS-RMS90-value can be determined as shown in Fig. 2. The selection of figure is according to the floor damping characteristics (considering finishes and furniture). The floor modal mass is defined on x-axis and the floor frequency on the y-axis. The acceptance class and OS-RMS value can be obtained from the intersection of extensions of the model mass and the corresponding frequency.

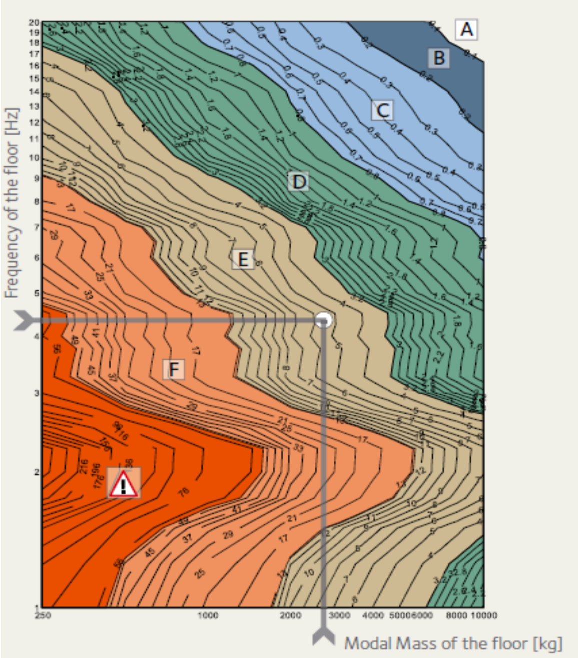
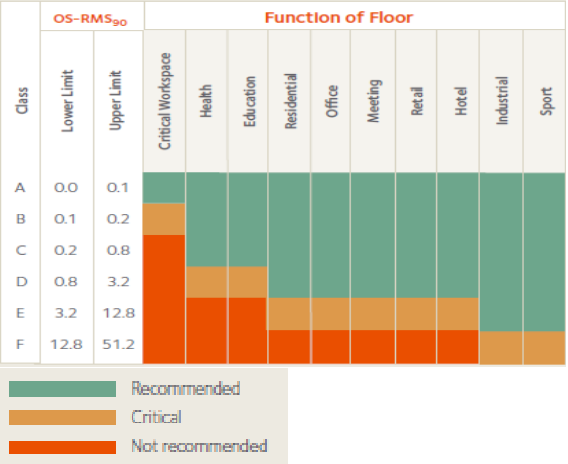


Fig. (2) Human perception classes [20]

The following table categorizes vibrations into a number of classes and also gives commendations for the classes respecting to the purpose of the studied floor.

Table (1): The floor response classification of and recommendation [20]



Class	OS-RMS$_{90}$		Function of Floor									
	Lower Limit	Upper Limit	Critical Workspace	Health	Education	Residential	Office	Meeting	Retail	Hotel	Industrial	Sport
A	0.0	0.1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
B	0.1	0.2	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
C	0.2	0.8	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
D	0.8	3.2	🟥	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩
E	3.2	12.8	🟥	🟥	🟥	🟧	🟧	🟧	🟧	🟧	🟩	🟩
F	12.8	51.2	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟧

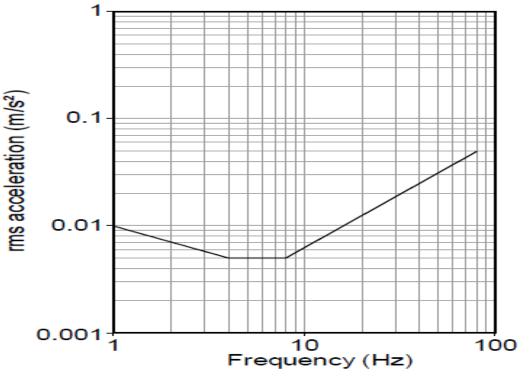
🟩 Recommended
🟧 Critical
🟥 Not recommended

Second Approach: R.M.S Acceleration Method:

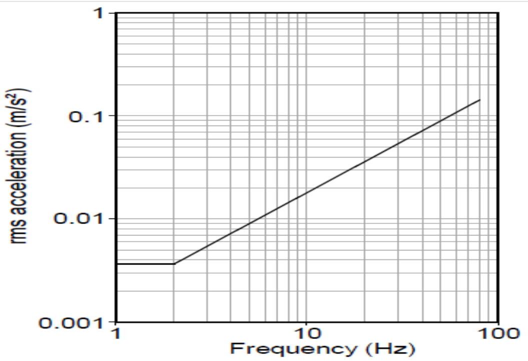
This method is used In the United Kingdom, other suitable method like the BS 6472[13]. This method presented other boundaries for acceptable magnitude of vibration which are represented by a weighted frequency and a sequence of multiplying factors. In Fig. 3. The main vibration curves in x, y and z direction are shown. The curves depends on the following base values:

- a_{rms} = 5×10-3 m/s² for vertical vibrations “z-axis”
- a_{rms} = 3.57×10-3 m/s² for horizontal vibrations “x- and y-axis”

A constant level of human perception is represented by the lines which are recognized as an iso- perceptibility lines. The area under the line represents the imperceptible level of the human perception due to vibration and the area above the line indicates high level of human perception.



A- z- axis base curve



b- x, y- axis base curve

Fig. (3) “A, b” the vibration perception base curves according to BS 6472

For this approach there are another scale which called “the response factor”. The response factor represents a multiple of the level of vibration that is barely perceivable to a human. A response factor of 1 indicates a vibration that is just perceivable. The following table lists some common response factor limits mentioned in BS 6472 and ISO 2631-2 for some different environments.

$$Response\ factor = \frac{a_{w,rms}}{0.005} \qquad \text{eq.3}$$

Table (2): Recommended response factor limits for various environments. [21]

Environment Response	Factor Limit	Description of Use
Workshops, Office	8-10	Perceptible vibration, suitable for non-sensitive areas.
Residential	4-8	Possible perceptible vibration, suitable for sleep areas in most cases.
Operating rooms	1-4	Near the limit of perception, appropriate for sensitive sleep parts and in most cases for microscopes to 100x and other low sensitivity equipment.
Sensitive Equipment rooms	0.0625-1	Suitable for sensitive equipment, electron microscopes, etc.

Third Approach: Peak Acceleration Method:

Another simple approach depends on expeditious first estimates for the vibration response of the studied floor. This approach shows whether the floor design is compatible with the serviceability requirements for the floor vibration in a conservative way or more detailed analysis is needed.

Peak acceleration calculated from the floor first natural frequency as shown in equation. 4 [22].

$$\frac{a_p}{g} \le \frac{P_0\, e^{-0.35fn}}{\beta W} \qquad \text{eq.4}$$

ap : peak acceleration
g : gravitational acceleration [9.81 m/sec2]
Po: constant force representing the walking force
β : modal damping ratio
W: effective panel weight and the superimposed dead load
f_n : first natural frequency

The response acceleration should be checked with the acceptable limits as shown in equation 5 and the perceptibility classes (Fig. 4) which show the beginning of human perception to vertical vibration.

$$f_n \ge 2.86 \ln\left(\frac{K}{\beta W}\right) \qquad \text{eq.5}$$

K: a constant (table3)
β: modal damping ratio (table 4)
W: the panel area weight influenced by the point load (heel drop)
fn: minimum frequency

Table (3): Constant K for Minimum Acceptable Frequency [22]

Occupancies	k	
	kips	kN
Offices, residences, assembly halls	13	58
Shopping malls	4.5	20

Table (4): Damping Factors for Various Occupancies [22]

occupancy	Damping factor β
Bare concrete floor 0.02	0.02
Furnished, low partition	0.03
Furnished, full height partition	0.05
Shopping malls	0.02

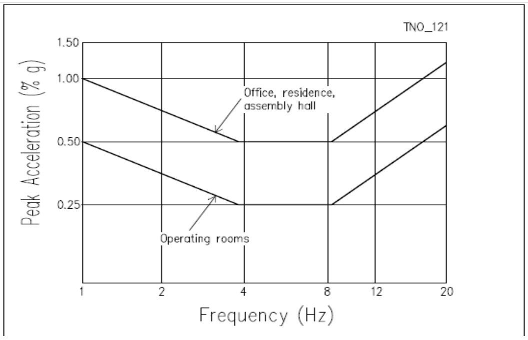


Fig. (4) Threshold of human sensitivity to vertical vibration (ATC). [22]

Intermittent vibrations

In the fact the walking activities are not continuous as assumed in previous approaches, but they are intermittent by their nature. The perceptive tolerance levels became more reliable by using a cumulative measure of the response [23]. A guide of intermittent vibrations by using the vibration dose values (VDVs), which illustrate the perception levels due discontinuous short-duration vibrations as shown in BS 6472 [13] and ISO 10137 [24]. That's give a more accurate vibration levels than the thresholds calculated from the continuous vibrations which give a higher level of vibration. For using this approach, the location of walking corridors should be known and that is considered a difficult requirement in the early design stage as some flexibility in the layout of floor is normally required [23]

4. Parametric study:

- **Comparison between different approaches:**

A problem with practical dimensions 9m composed of post-tensioned floor of three equal spans in each direction is selected to be solved using the previous approaches. The slab is designed to be safe for the loads of (its own weight, super imposed dead load which equal 5 kN, live load which equal 2 kN and the pre-stressing force)The concrete properties is shown in table 5. Low Relaxation, seven wire strand with diameter 12.7 mm is used for pre-stressing reinforcement with a tendons distribution as shown in Fig. 5. The distribution is kept the same for both directions.

The pre-stressing reinforcement have Modulus of elasticity equal 195000 MPa and Ultimate strength for steel (f_{Pu}) equal 1860 MPa. The Non-pre-stressing reinforcement have Modulus of elasticity equal 200000 MPa and Ultimate strength for steel (f_{Pu}) equal 420MPa. The problem is also solved by using finite element method using RAM Concept software. The results of different approaches and finite element method is summarized as shown in Table 6 which indicate similar results for all approaches used. The values of natural frequencies range from 6.59 to 7.4 with variation of not exceeding ±10% compared to the finite element method. Other parameters which varies for different methods lead to the same conclusion that the floor is accepted for vibration.

Table (5): Concrete properties

Concrete properties	Value
Unit weight (γc)	24.5MPa
Cylindrical strength at 28 day (F`c)	35MPa
Cylindrical strength at transfer (F`ci)	20 MPa
Modulus of elasticity at 28 days (Ec)	27805 MPa
Modulus of elasticity at transfer (Eci)	21019 MPa

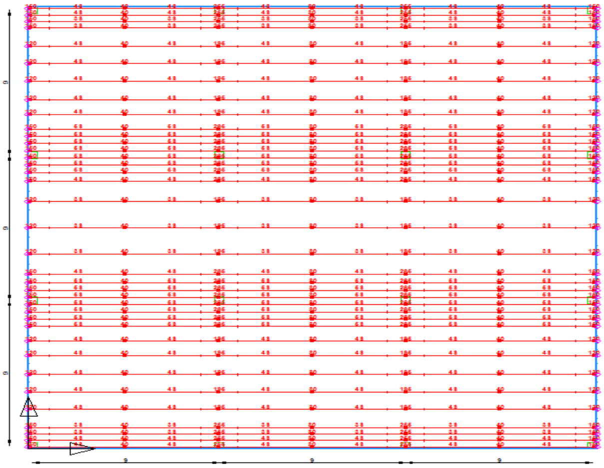


Fig. (5) Tendons layout (x-direction).

Table (6): Results of different approaches

	OS-RMS 90 Method	R.M.S Acceleration Method	Peak Acceleration Method	Finite element Method
Frequency	6.59	7.4	7.2	6.85
OS – RMS 90	0.6 mm/s	----------	----------	-------
a_w rms	-------	0.0332 m/sec2	----------	0.04
ag/g	-------	-----------	0.0011	-------
Response Factor	-------	6.64	-----------	8
Floor status	accepted	accepted	accepted	accepted

- **Parametric study:**

In practice, limits need to be established for vibration acceptance of PT floors similar to that found for defection. Thus, the following study is presented to investigate how the vibration parameters (frequencies and peak acceleration) are affected by the floor span and thickness. The third approach that uses the peak acceleration is used as human perception is sensitive mainly to acceleration. Spans studied varies between 7 and 10 meters as found frequently in construction practice. The span/thickness ratios considered range from 29.2 to 47.6 to cover the practical range with small margin.

5. Results and discussion:

The frequency behavior of PT slabs is investigated in fig. 6 which show the relation between the slab thickness and its fundamental frequency. The figures show that the frequency of the slab is mainly increased by increasing the slab thickness while the frequency is increased by decreasing the span length for the same thickness. Although many span lengths and slab thicknesses are studied in our paper, a frequency of 10 Hz which was recommended by khan et al [25] to avoid the structure resonance has not been reached as it requires more increasing of slabs thickness to extremely unpractical values.

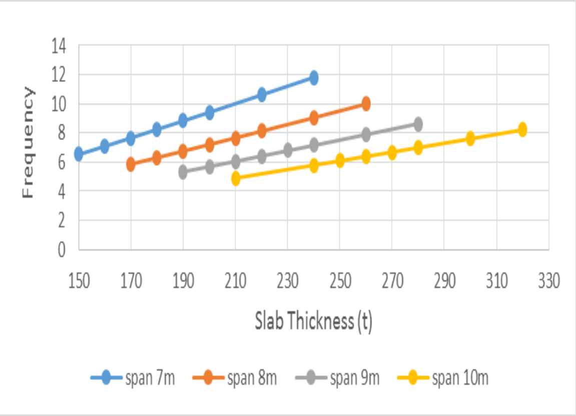


Fig. (6) Relation between slab thickness and fundamental frequency.

To investigate how the peak acceleration is affected by slab thickness, Fig. 7 shows the relation between the slab thickness and the peak acceleration as ratio of the earth's gravity. The increase of peak acceleration indicates undesired response of floors to vibration. The figure shows that the increase of slab thickness leads to better behavior of slab as the peak acceleration is decreased. On the other hand the peak acceleration is increased by increasing the span length for the same floor thickness as expected.

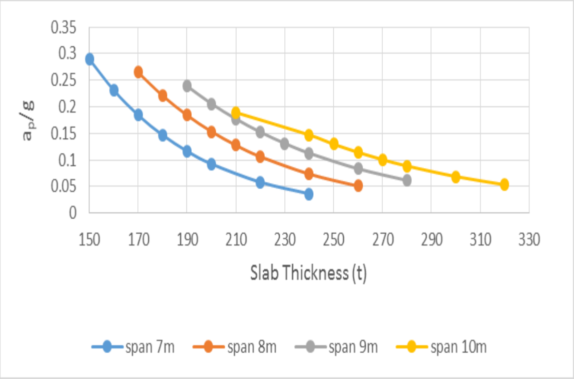


Fig. (7) Relation between slab thickness and (a_p/g) Ratio.

The same relation is sown in normalized form by investigating the relation between the span/thickness ratio and the (ap/g) divided by limiting value which defined as the acceleration response ratio as shown in Fig. 8. While the span/thickness ratio is considered a representative practical parameter, the (ap/g)/Limiting is the resulted response indicator. The limiting value is extracted from the chart of “Threshold of human sensitivity to vertical vibration (ATC)” shown in Fig. 4. Such that the investigated response ratio that exceed the value 1.00 is considered not acceptable As shown in the Figure, the acceleration response ratio are found to increase with increasing the span/thickness ratio which means that spans with more span/thickness ratio is prone to vibration. Floors with different spans show similar behavior referring to the span /thickness ratio. The minimum safe thickness in vibration which give acceleration response ratio less than unity is found to be 1/43.7, 1/44.4, 1/47.3, 1/50 of the span length for spans 7, 8, 9, 10, respectively. It can be concluded from this relation that PT floor slabs designed with practical dimensions to be safe in deflection are also safe in vibration as the suitable Span to thickness ratio for the deflection equal (40-45). [26] It can be also concluded that for smaller span length, more thickness to span ratio is required for acceptable vibration behavior.

Some investigations refer to the floor fundamental frequency as an indicative measure of vibration validity. Thus, Fig. 9 shows the relation between the slab fundamental frequency and the acceleration response ratio. The figure shows that the peak acceleration is decreased by increasing the slab frequency. For lower values of fundamental natural frequency, the floor is more prone to vibration. The peak acceleration exceed the limiting value at a frequency equal 7 Hz for the span length of 7m, 6 Hz for the span length of 8m, 5.4 Hz for the span length of 9m and 4.5 Hz for the span length of 10m. This indicates that the limit of natural frequency for vibration validity depends on the geometry and span length. It indicates also that more values of fundamental natural frequency are required for safe vibration if the floor span length becomes smaller. The result also concluded that the limit of 10 Hertz natural frequency [25] may be limited and not applicable to wide variety of floor configurations.

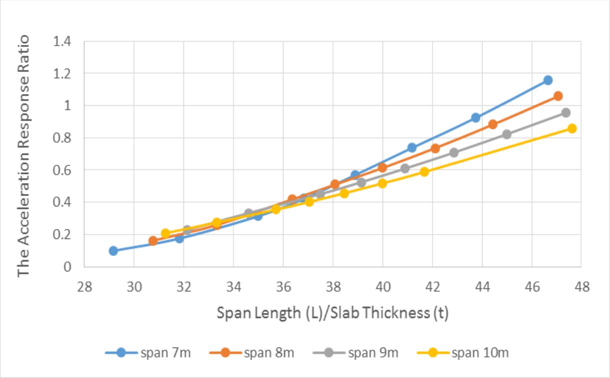


Fig. (8) Relation between (span length/ slab thickness) ratio and the acceleration response ratio

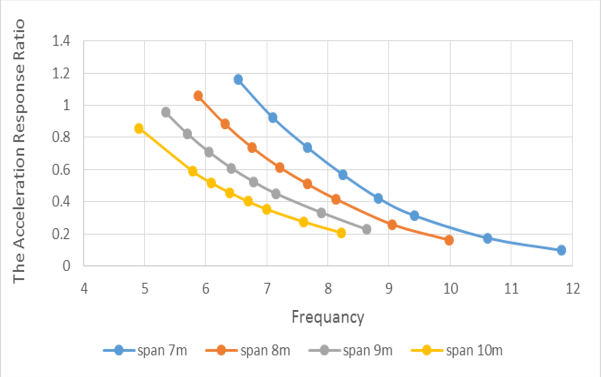


Fig. (9) Relation between Frequency and acceleration response ratio.

6. Conclusion

Regarding the shown approaches of solving the vibration problems and the parameter`s studied about the effect of span length and slab thickness on floor vibration it can be concluded that:

1- The shown approaches in this paper are considered as simple tool to the designers who do not have an enough knowledge about the vibration behavior of the slabs. They enable the designers to judge floors for human induced vibrations. these approaches lead to relatively similar results

2- The frequency of the slab is increased by decreasing the span length or increasing the slab thickness.

3- The peak acceleration of the slab is decreased leading to better response to vibration by increasing the slab thickness/span ratio.

4- The slab which is designed to be safe for deflection, is expected to have satisfactory response to human induced vibration.

5- The peak acceleration of the slab is mainly increased by decreasing its natural frequency. The limit of minimum natural frequency 10 Hertz as limit for vibration acceptability is not applicable to all spans and configuration

6- For smaller span length, more thickness to span ratio and more fundamental frequency is required for acceptable vibration behavior

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