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Proposed Relationship to Design the Waffle Floor under Harmonic Vertical Loading

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ABSTRACT

The design codes of building are mainly related to the strength of the building and there are no specific codes for the design of building with waffle floors for vibration sensitive equipment. The finite element model, ANSYS, is capable to consider the effects of floor thickness, the size of the bays and stiffness of the columns for analyzing the vibration of the waffle floors and vibration transmission along the waffle floor. Because the finite element analysis is time consuming and it needs enough expertise for modeling, in this study, an approximate relationship is proposed to design the waffle floor based on the comprehensive investigations of different effective parameters in the response of waffle floor. The results obtained from finite element analysis. This proposed relationship comforts the designers of industrial buildings and vibration sensitive equipment to attain a preliminary and appropriate outline to design the waffle floor considering the effective parameters on the floor vibration.

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1. INTRODUCTION

Different machineries used in industry cause diverse dynamic forces due to their specific consumptions. Vibratory motion of mechanical devices has undesired effects in common and if they are not studied precisely, they can lead to defection in their ordinary work and even rupture and breakage of parts. Accordingly, the foundation of such machinery should have enough strength to bear dynamic loads besides static loads. Hence, investigation and analysis of vibration of these structures are among essential concerns which should be considered by designers. The first solution to control these undesired vibrations is to create changes in their production resources. However, this method is not always practical. For example, the impulse resulting from earthquake, atmosphere turbulence, unsmooth state of roads and instability of combustion motors are the factors that they cannot be changed, while in some vibration resources changes can be made. For instance, by good smoothing of the parts surface and using the exact tolerances, the vibration of machinery can be decreased. Moreover, economic concerns should be considered.

Due to the following reasons, the floors of industrial buildings are important:

1- The floors should bear the force produced by machinery.
2- Transmission of vibration from vibration resources (including pumps, pressure machines and walking of human on the floor) to devices that are sensitive to vibration should be minimized.
3- The vibration produced by a mechanical device should not affect exploitation of adjacent devices.

Transmission of vibration in all buildings includes the vibration along waffle floor because it is one of the critical points in designing industrial buildings. These buildings contain a large number of vibratory resources including pumps, pressure machines and other equipments which all are effective in stimulating the floors. The abovementioned vibratory items distribute all over the industrial buildings and their adjacent central buildings and the vibration created cause intensification in adjacent bays. These created vibrations even in low amounts would cause interruption in the work of sensitive devices and irritation in human beings [1].

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Waffle floors are vastly used in industrial buildings due to their remarkable vibration sensitivity. In addition, they provide high strength for producing equipments which are extraordinary sensitive to vibration. Waffle floors can minimize transmission of vibration in buildings and prevent the destructive effect of the vibration created by a device on efficiency of adjacent devices. Thus, investigating the way of transmission of vibration and real behavior of waffle floors by considering parameters effective to respond can lead to optimized and economical designs [1].

Petyt and Mirza used finite element modeling to calculate the mode shapes of floor slabs on four column supports. Several configurations of bays were considered and their results showed that the lowest resonance frequency occurs when adjacent bays are vibrating out of phase. Their work showed that the response of one bay is influenced by the vibration of adjacent bays [2]. Amick et al. presented several models in the field of weakening the vibration along waffle floor by creating distance. However, in none of them module's behavior was included [3]. Howard and Hansen proposed a complicated mathematical model of waffle floor in their research. The presented mathematical model helps designers of industrial buildings to predict transmission of vibration along waffle floor, optimize thickness of floor, stiffness and distance of columns. The mathematical model has been compared to laboratory results and ANSYS model and it has shown great results for responding to displacement in the center of waffle floor and weakening the vibration by getting distance from the vibration resource [4].

The main objective of this research is to analyze vibration of waffle floors under influence of harmonic loads. In line with this objective, the factors contributing to vibration of waffle floors (the most important ones are floor thickness, bay size, column stiffness, and etc.) are analyzed linearly using finite elements software. Then, comprehensive diagrams are presented on the basis of influential parameters in order to show the trend of changes in frequency of floor vibration and displacement. Finally, recommended formulas are presented on the basis of the results achieved by finite elements software. These recommended formulas help the designers present a primary design of waffle floor with consideration to the authorized amount of resonance frequency and displacement. The results achieved by this analysis and presented diagrams can be used to achieve an optimal and cost-effective design for designing waffle floors in vibration-sensitive buildings [1].

2. DESCRIPTION OF THE MODEL

The studied floor is a waffle floor which includes rectangular beams and a surface layer. This composite section can be transformed into an equivalent plate section of constant thickness, by equating the cross-sectional moments of inertia of the composite section and a plate section of unit width [1, 4]. Note that the steel reinforcing bars that are within concrete sections are ignored, as they do not significantly alter the flexural rigidity of the floor. This reduction of the complex cross-section geometry into an equivalent flat plate can only be made when the moments of inertia along the x and y axes are the same. If the waffle has different cross-sectional moments of inertia along each axis, then the transformation is invalid [5]. Waffle floor can be modeled as a flat floor with simple backrest which is lying on columns, and harmonic loads are applied in a spot on the floor. Columns are models from linear elastic springs that are applying a strong force along perpendicular axis and strong torque around two cycling axis. Specifications and mechanical behavior of materials were assumed isotropic in ANSYS software, elasticity module equal to 26 Pascal, Poison Coefficient as 0.15 and density was selected 2323 Kg/m^3 [1, 6].

3. FINITE ELEMENTS MODEL

As being observed in Figure 4, ANSYS modeled a floor by 9×9 bays and a number of columns. In order to model the floor, the SHELL63 element is used which has capacity to change thickness. This element has three freedom degrees along x, y, z and three rotational freedom degrees around x, y, z axis and also capacity of huge ductility. Furthermore, in order to model linear springs, Spring-damper 14 element is used. This element has longitudinal and Torsional capacities in 1D, 2D and 3D. The option of Torsional Spring-damper is a completely rotational element with three freedom degrees in each node and the rotation is done around x, y, z axis. The Spring-damper element doesn't have any mass. Concentrated 1 N harmonic load is applied in the center of waffle floor and the frequency areas of 0-50 Hz with 100 steps of design are defined for the software. The software considered the first 50 vibrations and solved harmonic load for all consumed frequencies based on the number of step and provides the results based on frequency and displacement. The results have been copied in Excel software and frequency-displacement chart is drawn. In addition, in each analysis step, the rate of natural frequency for the structure can be extracted from ANSYS software by taking to account the type of modeled structure [7].

One of the contributing factors is the size of elements (mesh). So, first the effect of this factor on different models is studied using finite elements software. To do so, three models of waffle 9×9 floors with bay size of 7 meters were modeled. 7 elements were used in each 7-meter bay size in the first model, 14 elements were used in each 7-meter bay size in the second model, and 28 elements were used in each 7-meter bay size in the third model. The achieved results are shown in Table 1 and Figures 1, 2, 3.

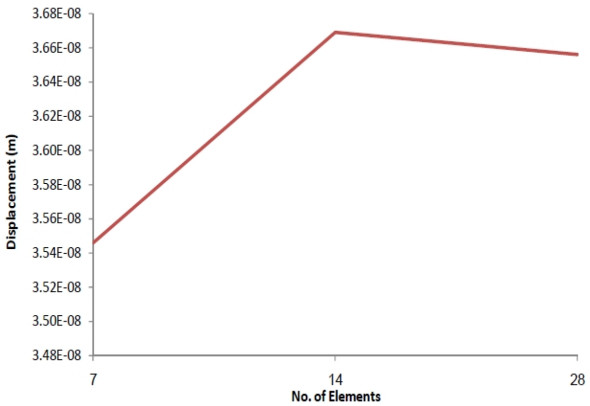

Figure 1. The number of element in bay to displacement

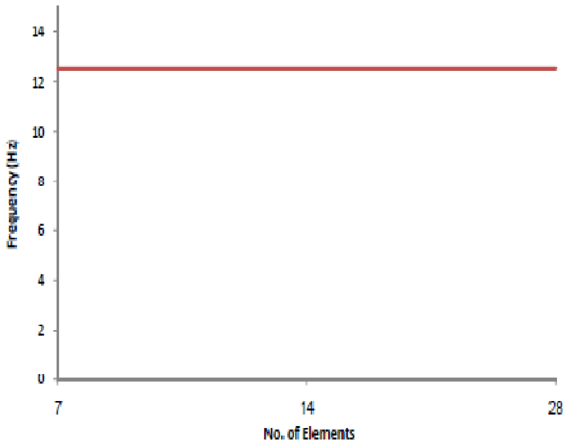

Figure 2. The number of element in bay to resonance ferequency

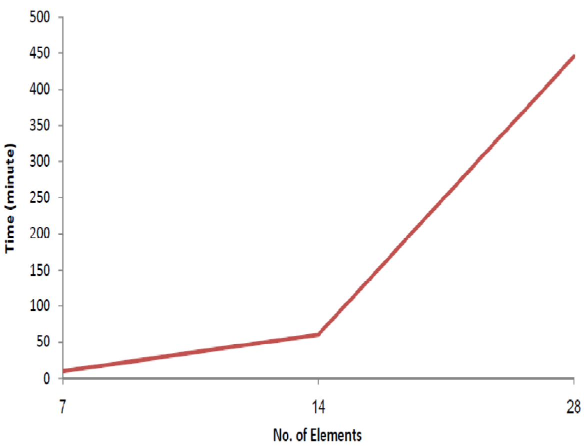

Figure 3. The number of element in bay to time of analysis

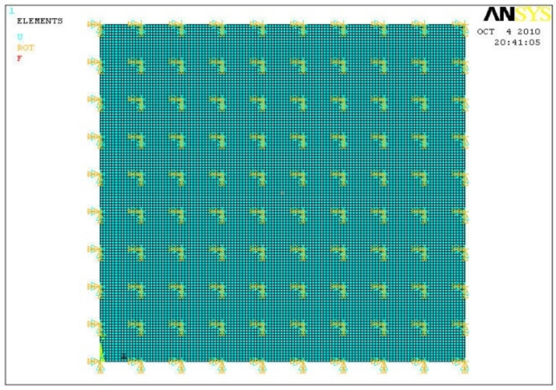

Figure 4. ANSYS model for waffle floor

TABLE 1. The influence of meshing in finite elements to structures response

Description	Mod. 1	Mod. 2	Mod. 3
Bay size (m)	**7**	7	7
The number of elements along bay size	**7**	14	28
The time of analysis (min)	10	60	445
Displacement (m) $\times 10^{-8}$	3.546	3.669	3.656
Resonance ferequency (Hz)	12.5	12.5	12.5

According to the achieved results and diagrams, we can conclude that displacement response in the second model (14 elements) does not considerably differ from the third model (28 elements), but has increased the time up to 7 times. Therefore, to save time, the second model (14 elements in each 7-meter bay size) has been used in all models of this research [1].

4. COMPARISON OF RESULTS

In the first step, validity of the results achieved by finite elements software is investigated with consideration to experimental results and the results achieved by other researchers. First, modeling method and waffle floor results are tested in laboratory. Then, the results achieved by Howard and Hansen finite elements software are presented and the validity of the results is investigated.

The impedance measurements were made using an instrumented sledgehammer to strike the floor. The vibration response of the floor was recorded with a spectrum analyzer. Another instrument that is commonly used to excite the floor in a building is an electrodynamics shaker. Figure 5 shows the equipment that was used to perform the measurements. The sledgehammer has a large steel mass (7.8 kg) that was used to strike 25 mm thick rubber pads that rested on the waffle floor. The accelerometer attach to the back of the mass (model 4373). The accelerometer (model W8318c) rested on the floor and was used to measure the vibration response of the floor when it was struck with the instrumented hammer. The signals from the accelerometer on the hammer and the response accelerometer on the floor were conditioned by charge amplifiers (model 2635) and processed by a Data Physics ACE portable digital spectrum analyzer. The force exerted by the hammer on the floor is calculated by multiplying the acceleration of the hammer with its mass. It is preferable to measure the impact force directly with a force transducer attached to the hammer head. However, many comparisons with the instrumented sledgehammer and an impact hammer with a calibrated force transducer (PCB piezotronics model 086C20) showed identical results, except at low frequencies where the sledgehammer was able to provide greater excitation. The point impedance is measured by striking the hammer against the floor and measuring the vibration response adjacent to where the hammer strikes the floor. The transfer impedance is measured by striking the hammer on the floor at one location and measuring the vibration response at another location on the floor. Point impedance and transfer impedance measurements were conducted on several waffle floors, to quantify the transmission of vibration along the floors [5]. In Figure 6, the curve gained from linear analysis of waffle floor is indicated next to laboratory and ANSYS model of Howard and Hanson. The combination of investigated results indicates that the conducted linear analysis has acceptable accuracy.

5. RESULTS

Factors are influencing the floor's vibration that investigating all of them takes a long time. For this reason, in this research, efforts are taken to study the factors having maximum influence on the floor's vibration. After modeling of different samples of waffle floor by taking in to account the effective factors in floor's vibration in ANSYS software, the linear analysis of sales in the format of resonance frequency and displacement were drawn. The presented results are indicating some predictions from displacement in the waffle floor for ANSYS model and vibration's respond in industrial buildings. Details of the models analyzed in limited components software together with dimensional details are shown in Table 2.

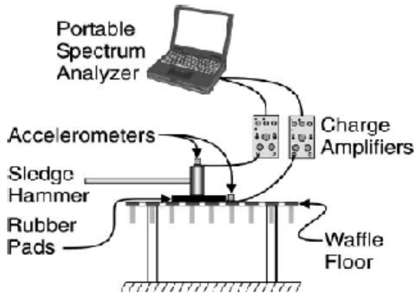

Figure 5. Equipment used to perform experimental measurements.

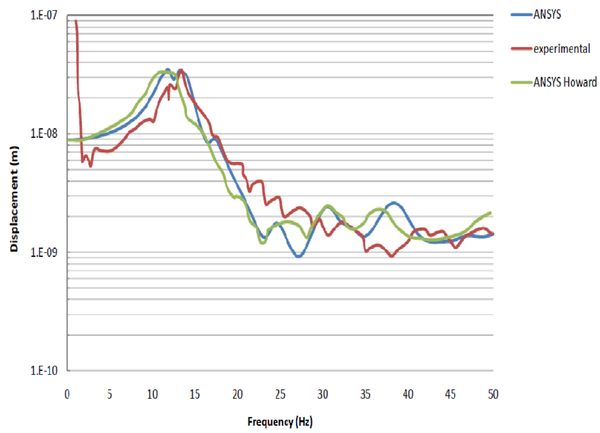

Figure 6. The curve gained from linear analysis in conjunction with laboratory and ANSYS model

TABLE 2. Parameters used in the analysis.

Description	Units	Mod. 1 (Figure 7)	Mod. 2 (Figure 8)	Mod. 3 (Figure 9)	Mod. 4 (Figure 10)	Mod. 5 (Figure 12)
Bay size	m	7.3	4-8	7	4	4
Floor thickness	m	0.347	0.347	0.15-0.6	0.15-0.6	0.347
Coulmun axial stifness	N/m	1×10^9	1×10^9	1×10^9	1×10^9	1×10^9-5×10^9
Location of driving force	---	Center	Center	Center	Center	Center
Magnitude of driving force	N	1	1	1	1	1
Density of the plate	Kg/m^3	2323	2323	2323	2323	2323
Poisson's ratio of the plate	---	0.15	0.15	0.15	0.15	0.15

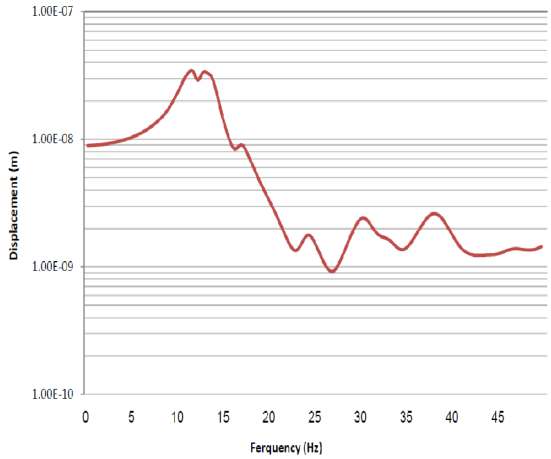

Figure 7. Resonance frequency and displacement at the center of waffle floor

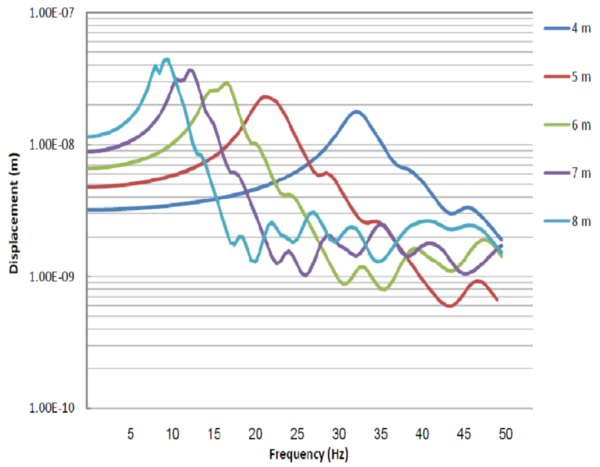

Figure 8. Influence of bay size on displacement and resonance frequency

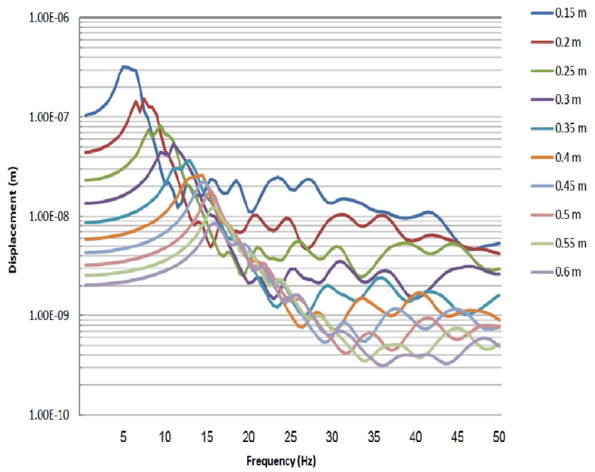

Figure 9. The influence of equivalent floor thickness on displacement and resonance frequency for bay size 7m.

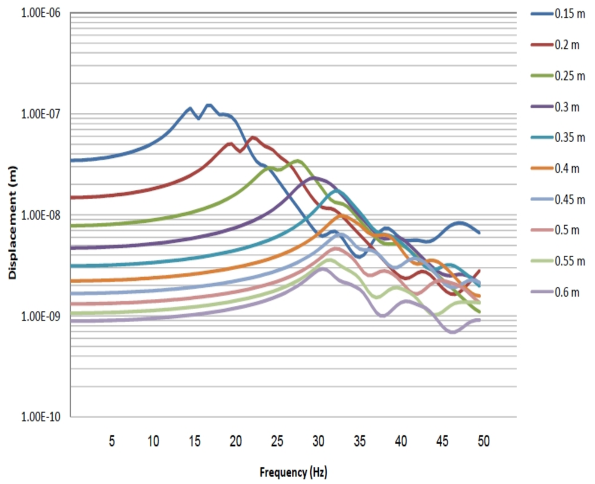

Figure 10. The influence of equivalent floor thickness on displacement and resonance frequency for bay size 4m.

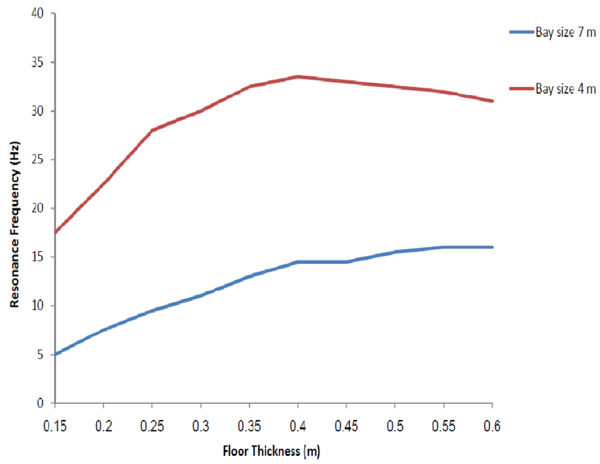

Figure 11. Reduction in resonance frequency of floor by increase of thickness over 0.4m.

5. 1. Resonant Behavior of the Floor Figure 7 indicates displacement at the center of waffle floor, where a harmonic load of 1 N has been applied. The results indicate that the responses peak of resonance is created in 12.5 Hz

5. 2. Influence of Bay Size The bay sizes has the maximum effect on the lowest resonance frequency of the floor. Figure 8 indicates displacement at the center of waffle floor for stimulating harmonic load of 1 N, when the bay size varies from 4 m to 8 m with step like motion of 1 m and floor thickness of 0.347 m. The results indicate that by increase of bay sizes from 4m to 8m, displacement at the center of waffle floor and resonance frequency have been increased 60% and 70% if being compared with the primary state, respectively.

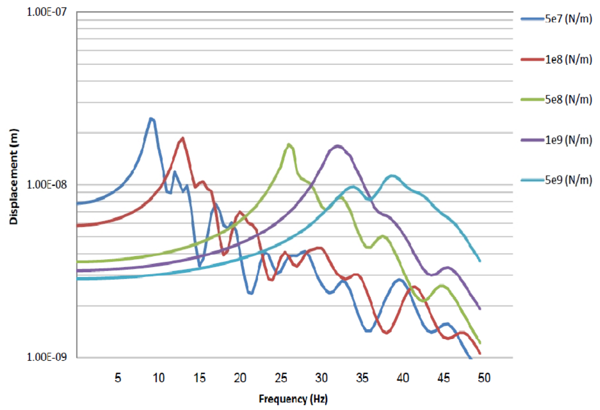

Figure 12. The effect of columns' axial stiffness on displacement and resonance frequency.

5. 3. Influence of Equivalent Floor Thickness Figure 9 indicates displacement at the center of waffle floor for floor thickness ranging from 0.15 to 0.60 m with step like motion of 0.5 m for bay size of 7×7 m and column stiffness of 1×10^9 N/m. The results indicate that increasing of the floor thickness from 0.15 to 0.60 m, which more conforms to a sectional moment of inertia, has been associated with 97% decrease in the displacement at the center of reticulated floor and 69% increase in the resonance frequency of being compared to the primary state 0.15 m. Similar procedures for bay size of 4×4 m are observed that is shown in Figure 10. Moreover, when the floor thickness increases, resonance frequency is not highly increased by the stiffness and in return, its reduction commences by increasing the thickness, as observed in Figure 11.

5. 4. Influence of Columns' Axial Stiffness Figure 12 shows the displacement of waffle floor for several columns' axial stiffness. The bay size is 4×4 m and the thickness is 0.347 m. The results indicate that by increasing of columns' axial stiffness from 5×10^7 N/m to 5×10^9 N/m, the rate of displacement at the center of waffle floor is reduced 54% compared to the primary state (5×10^7 N/m) which the resonance frequency is increased 76%.

6. PROPOSED RELATION TO DESIGN THE WAFFLE FLOOR

By considering the time taking state of analyze in ANSYS software and the need for sufficient skill for modeling in this software, in this part of the paper, some formulations are proposed for designing waffle floor. The proposed formulations would help designers of industrial buildings to propose a primary design from waffle floor (by taking to the effective parameters on floor's vibration into account). In order to gain formulations of designing waffle floor, totally 250 analysis were done in ANSYS software. In these analyzes, parameters such as floor's thickness, bay size and stiffness of column were studied. For each amount from mentioned parameters, the amounts of resonance frequency and displacement at the center of waffle floor (under applied load) were calculated.

In order to gain the abovementioned formulations, two models of waffle floor were studied. The first model of waffle floor with simple backrest and second model of waffle floor with complete girder around the perimeter of the floor were modeled. For each model, 125 analyses was conducted in ANSYS software, in a way that for each model 5 amounts of floor's thickness (0.2, 0.25, 0.35 and 0.4) and 5 amounts of columns' axial stiffness (5×10^7, 1×10^8, 5×10^8, 1×10^9 and 5×10^9 N/m) and 5 amounts of bay size (4, 5, 6, 7 and 8 m) were considered. The waffle floor was analyzed for all abovementioned variables and for each analysis, the amounts of resonance frequency and displacement at the center of waffle floor has been calculated. Using the results and the available software, following equations are proposed for designing a waffle floor.

Proposed formulations for designing waffle floor with simple support:

$$d = \frac{at^b \times k^c}{L^e} \tag{1}$$

$a = 3.72\times10^{-10}$ $c = 0.0279$
$b = -2.72$ $e = -1.454$

$$F = \frac{at^b \times k^c}{L^e} \tag{2}$$

$a = 49.485$ $c = 0.0978$
$b = 0.807$ $e = 1.544$

Proposed formulations for designing waffle floor with fix support:

$$d = \frac{at^b \times k^c}{L^e} \tag{3}$$

$a = 4.65\times10^{-11}$ $c= 2.12\times10^{-5}$
$b= -3.01$ $e= -1.73$

$$F = \frac{at^b \times k^c}{L^e} \tag{4}$$

$a = 1236.94$ $c = 0.0199$
$b = 0.964$ $e = 1.59$

In proposed formulations above, d is displacement based on m, F is frequency based on Hz, t is floor's thickness based on m, L is bay size based on m and k is axial stiffness of the column based on N/m.

The recommended formulas help the designers of industrial buildings to propose a primary design of waffle floor. The waffle floor has to be designed for use in industrial buildings or in vibration-sensitive floors. The authorized resonance frequency and displacement of this floor has been extracted on the basis of relevant directives and the floor's intended use. The procedure is that the authorized resonance frequency and displacement of this floor is given to the relevant formulas and then floor thickness, column stiffness and the bay size are calculated with consideration to the authorized amount and at last the final design of waffle floor is achieved using accurate designing formulas. Furthermore, the validity of recommended formulas is investigated and acceptable results with minor error are achieved for primary design which enables accurate designing. The recommended formulas are used only for primary design of dimensional specifications of waffle floor with consideration to authorized resonance frequency and displacement. The results achieved are not final, but often accurate answers are given.

7. CONCLUSION

Doubling of the bay size, results in 60% increase in the amount of displacement at the center of waffle floor and 70% decrease in the frequency of intensity.

By four times increase in floor's thickness, the amount of displacement at the center of waffle floor has been increased about 97%, while the resonance frequency has shown 69% decrease.

By 100 % increase in axial stiffness of the column, the amount of displacement at the center of waffle floor is 54% decreased and resonance frequency is 76% increased.

ANSYS model of described waffle floor can help designers of industrial buildings to predict transmission of vibration along waffle floor, optimized floor's thickness, stiffness and distance of columns. In addition, it gives acceptable results to get respond to the displacement at the center of waffle floor and weakening of the vibration by increasing of the distance from vibration resource.

Proposed formulations help designers of industrial buildings to provide a primary design of waffle floor. The proposed design is compared to ANSYS software and indicates acceptable results to respond the displacement at the center of waffle floor.

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چکیده

آیین‌نامه‌های مهندسی عمران برای طراحی ساختمان‌ها، عمدتاً به مقاومت ساختمان برای تحمل بارهای زلزله و استاتیکی پرداخته و آیین‌نامه جامعی برای طراحی ساختمان با کف مشبک برای تجهیزات حساس به ارتعاش موجود نمی‌باشد. مدل اجزای محدود ANSYS برای تحلیل ارتعاش در مرکز کف مشبک و انتقال ارتعاش در امتداد کف مشبک می‌تواند اثر ضخامت کف، اندازه دهانه‌ها و سختی ستون‌ها را لحاظ کند. با توجه به وقت‌گیر بودن آنالیز در نرم افزار اجزای محدود و نیاز به مهارت کافی برای مدل سازی، در این مطالعه با بررسی جامع پارامترهای مختلف موثر در پاسخ کف مشبک به بار هارمونیک و استفاده از نتایج بدست آمده از تحلیل اجزای محدود، فرمولی تقریبی برای طراحی کف مشبک پیشنهاد شده است. این رابطه پیشنهادی، به طراحان ساختمان‌های صنعتی و دستگاه‌های حساس به ارتعاش کمک می‌کند که طرحی اولیه و مناسب را برای طراحی کف مشبک با توجه به پارامترهای موثر بر ارتعاش کف بدست آورند.

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