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구조요소의 단면특성에 따른 와플슬래브의 동적특성 분석

Study on the Performance of Waffle slab by Variation on the Section Properties of the Constituent Structural Elements

K.K.Choong* Kim, Jae-Yeol** Kim, Kwang-Il*** Kang, Joo-Won****

Abstract

This paper is concerned with the investigation of the structural behavior of waffle structure. Parametric variation on waffle floor thickness, main beam depth and column sizes are imposed to study the effects on mode shapes and natural frequencies of waffle structures. Comparisons between FEM models using shell and 3D-solid elements have also been made.

The analysis result has shown that the mode frequencies increase with i) increase in main beam depth at level 2 and ii) decrease in waffle slab thickness at level 3. Both 3D and 2D model shown similar mode shapes. Besides, there is a consistent difference in mode frequencies between 3D and 2D model ranging from 25% to 36%.

요 약

본 연구는 와플구조의 구조적 거동에 파악하고자 한다. 와플슬래브의 두께, 주요 보의 깊이와 기둥의 크기를 변수로 하여 와플구조의 모드형상과 고유진동수를 파악하고자 하였다. 또한 쉘요소와 입체요소를 사용한 유한요소모델의 해석결과를 비교하였다. i)레벨2에서 주요 보의 깊이가 증가함에 따라, ii)레벨3에서 와플슬래브 두께가 감소함에 따라 모드진동수는 증가하였다. 3차원 모델과 2차원 모델의 모드형상은 유사한 형상을 보였다. 또한, 3차원 모델과 2차원 모델사이의 모드진동수는 25%에서 36%의 차이를 보였다.

Keywords : Waffle structure, mode shapes, natural frequency, impedance, FEM model, free vibration, shell

키워드 : 와플슬래브, 모드형상, 고유진동수, 임피던스, 유한요소모델, 자유진동, 쉘요소

1. Introduction

Waffle slab is one of the structural form commonly selected and preferred in buildings housing advanced technology facilities (ATF) due to its repetitive and high impedance characteristics. Rapid development especially in micro-electric and semi-conductor industries have made the performance of sensitive systems more vulnerable to vibration excitation either internally or externally induced. Those sensitive systems include photo-lithography machines, electron microscopes, atomic force microscopes and etc which have advanced to 0.10μm line width.1) They have made the structural analysis and design being more complex and knowledge based. These machines will generate inertial forces when their internal mechanisms are operating. These forces are

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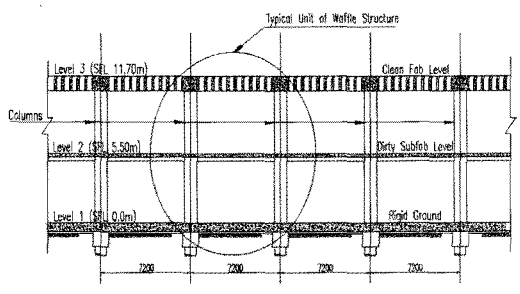
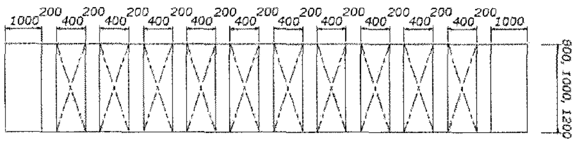
transmitted to the supporting pedestal and finally to the waffle slab below. Hence, the successful operating of the system will depend significantly on the combined impedance of the supporting pedestal, waffle slab and overall interaction of the building structure.

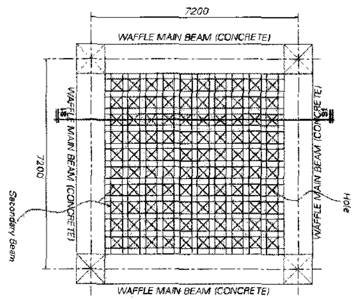
However, limited information and published paper exist that discuss the vibration characteristics of waffle structure in depth. Also, there are no specific code which guide designer through on how to determine the efficiency and sufficiency of waffle structure when subjected to a pre-determined vibration criteria. These special purpose building are well known only to limited consultants thus making the relevant research work sluggish. There are three main objectives for carrying out this study.1),2),3) In the first part, we examine the behavior of waffle structure when



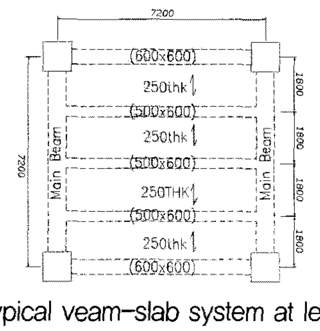
〈Fig. 1〉 Section view of waffle structure



(a) Section S1-S1

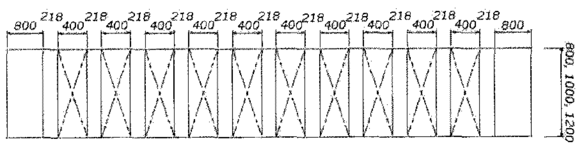


(b) Typical waffle slab panel at level 3.

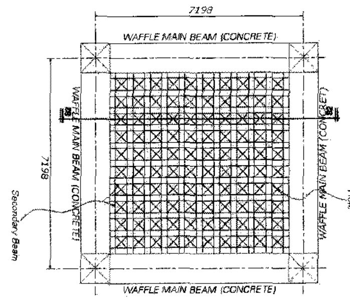


(c) Typical veam-slab system at level 2.

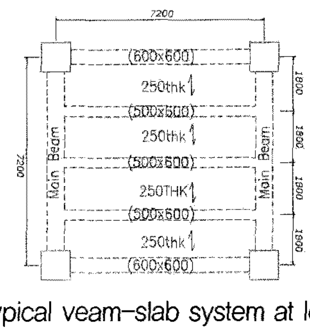
〈Fig. 2〉 Typical layout of a waffle structure with 1000 x1000mm support column



(a) Section S2-S2



(b) Typical waffle slab panel at level 3.

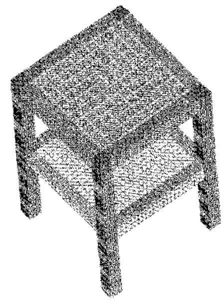


(c) Typical veam-slab system at level 2.

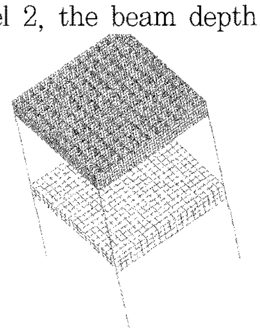
〈Fig. 3〉 Typical layout of a waffle structure with 800 x 800mm support column subjected to uniform normal load and the trend when parametric variation on structural elements has been made. The second part concerns with the mode shapes under free vibration condition. Only the first three modes are studied. The final part begins with the suitability and approximation study of 2D-shell waffle floor compare to 3D-solid waffle floor.

2. Method

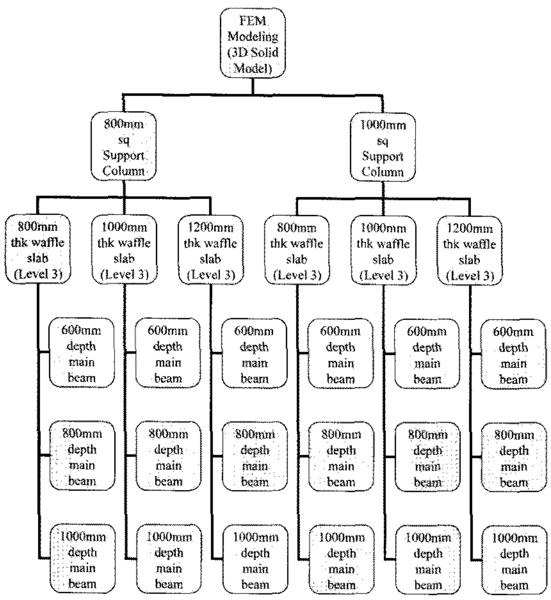
ADINA software was used as the FEM modeling and analysis tools. Two groups of models were built up. The first group of model consisted of 3D solid elements with variations on supporting column sizes, waffle slab thicknesses at level 3 and main beam depths at level 2. Instead, second group of model consists of 2D shell and 1D line elements which possess the section properties of the first group elements.6),7),8) A typical individual of concrete waffle structure with total height of 11.7m was studied (Fig.1.). As depicted in Fig.2. and 3., it was a 7.2m by 7.2m grid with waffle slab at level 3 and beam-slab system at level 2. Two column sizes were chosen, i.e., 800mm and 1000mm square. Three types of waffle slab thicknesses and three types of main beam depth were associated with each column size. The thicknesses of waffle slab selected were 800mm, 1000mm and 1200mm. For main beam at level 2, the beam depth chosen were



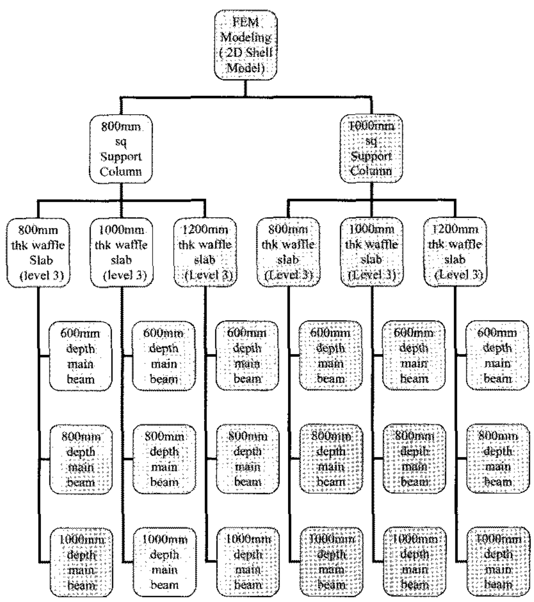
〈Fig. 4〉 Typical generated FEM model using solid element.



〈Fig. 5〉 Typical generated FEM model using shell element



〈Fig. 6〉 Parametric variation of structural elements for FEM models using 3D solid element



〈Fig. 7〉 Parametric variation of structural elements for FEM models using shell element

600mm, 800mm and 1000mm deep. Hence, a total of 36 FEM models were constructed as depicted on Fig.6. and 7. For each model, a normal load of magnitude 13.5kPa and 22.5kPa was imposed onto floor area at level 2 and level 3 respectively. Poisson ratio of 0.2 and Young's modulus of were assumed for all the models. Two types of analysis were carried out. Static analysis was carried to study the efficiency of structural member in transmitting the load while mode shape analysis was carried out to study the free vibration and mode shape characteristics for each model.4),5) A typical generated FEM model using solid and shell element is shown on Fig.4. and 5. respectively.

3. Results and discussion

The characteristics of free vibration modes are tabulated in Table 1, 2, 3 & 4. Table 1 refers to solid FEM waffle structure with 800mm sq. supporting columns while Table 2 refers to solid FEM waffle structure with 1000mm sq. supporting columns. For shell FEM waffle structure, Table 3 and Table 4 correspond to 800mm sq. and 1000mm sq. supporting columns respectively.

In general, the analysis result indicates that the mode shape for mode 1 and 2 is swaying along x- and y-axis respectively while mode 3 is in twisting mode. In solid model, the result in Fig.8.(a)-8.(f) show that the first three mode frequencies increase with the decrease in waffle slab thickness for both 800mm and 1000mm sq. support columns. In shell models, they do agree well in this respect. As shown in Fig.9.(a)-9.(f), the first three frequencies in shell models also increase with the increase in main beam depth. Hence, the shell models also reflect the same trend.

〈Table 1〉 Mode frequency for solid element with 800mm sq. columns

Parameter	Mode Frequency (Hz)		
	Mode 1	Mode 2	Mode 3
main_600_waffle_800	0.3874	0.3941	0.5815
main_600_waffle_1000	0.3746	0.3833	0.5681
main_600_waffle_1200	0.3590	0.3673	0.5480
main_800_waffle_800	0.3847	0.4238	0.5987
main_800_waffle_1000	0.3864	0.4064	0.5915
main_800_waffle_1200	0.3703	0.3895	0.5708
main_1000_waffle_800	0.3977	0.4594	0.6330
main_1000_waffle_1000	0.3897	0.4388	0.6165
main_1000_waffle_1200	0.3735	0.4207	0.5951

〈Table 2〉 Mode frequency for solid element with 1000mm sq. columns

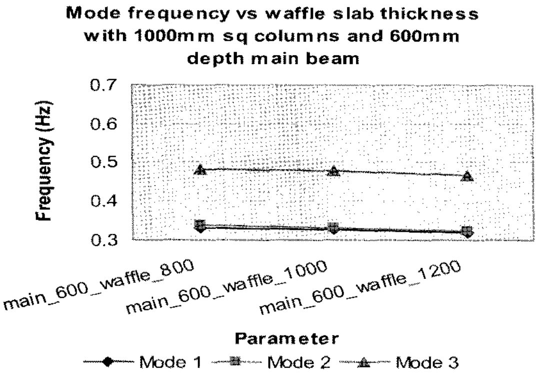
Parameter	Mode Frequency (Hz)		
	Mode 1	Mode 2	Mode 3
main_600_waffle_800	0.4573	0.5166	0.7623
main_600_waffle_1000	0.4391	0.4923	0.7104
main_600_waffle_1200	0.4284	0.4841	0.7090
main_800_waffle_800	0.4873	0.5235	0.7761
main_800_waffle_1000	0.4681	0.5073	0.7500
main_800_waffle_1200	0.4573	0.4937	0.7316
main_1000_waffle_800	0.5087	0.5465	0.8013
main_1000_waffle_1000	0.4885	0.5273	0.7743
main_1000_waffle_1200	0.4778	0.5142	0.7558

〈Table 3〉 Mode frequency for shell element with 800mm sq. columns

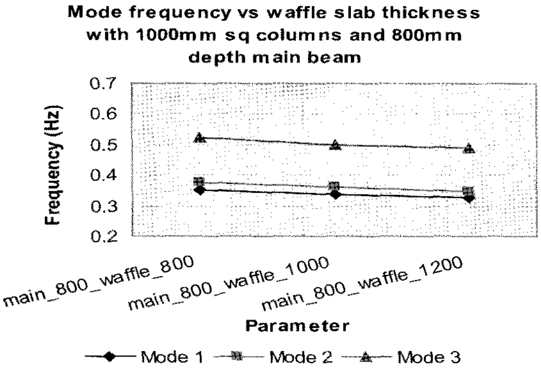
Parameter	Mode Frequency (Hz)		
	Mode 1	Mode 2	Mode 3
main_600_waffle_800	0.2778	0.2851	0.4114
main_600_waffle_1000	0.2659	0.2728	0.3963
main_600_waffle_1200	0.2553	0.2619	0.3827
main_800_waffle_800	0.2893	0.3096	0.4344
main_800_waffle_1000	0.2769	0.2963	0.4185
main_800_waffle_1200	0.2659	0.2845	0.4042
main_1000_waffle_800	0.2938	0.3385	0.4578
main_1000_waffle_1000	0.2812	0.3242	0.4413
main_1000_waffle_1200	0.2701	0.3115	0.4264

〈Table 4〉 Mode frequency for shell element with 1000mm sq. columns

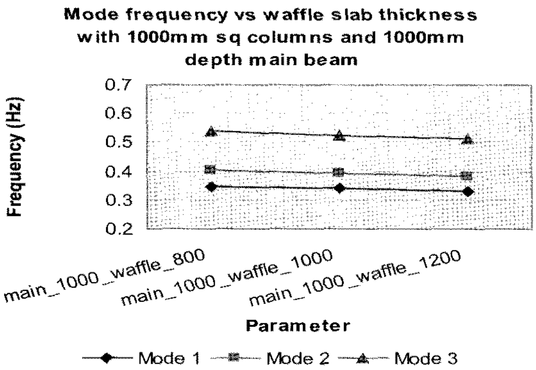
Parameter	Mode Frequency (Hz)		
	Mode 1	Mode 2	Mode 3
main_600_waffle_800	0.3309	0.3370	0.4844
main_600_waffle_1000	0.3279	0.3322	0.4798
main_600_waffle_1200	0.3184	0.3229	0.4657
main_800_waffle_800	0.3506	0.3768	0.5215
main_800_waffle_1000	0.3361	0.3596	0.5008
main_800_waffle_1200	0.3269	0.3495	0.4888
main_1000_waffle_800	0.3479	0.4029	0.5365
main_1000_waffle_1000	0.3397	0.3924	0.5245
main_1000_waffle_1200	0.3304	0.3812	0.5119



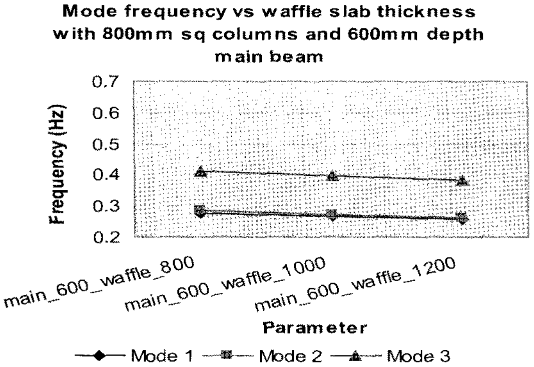
(a)



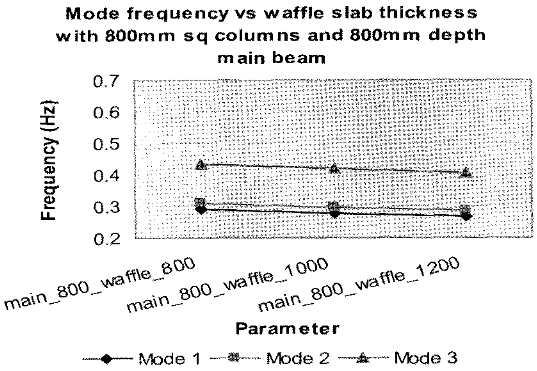
(b)



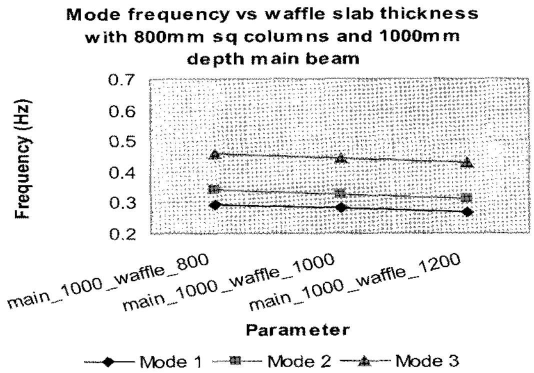
(c)



(d)

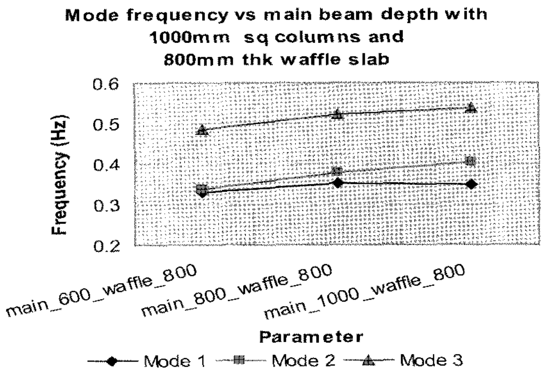


(e)

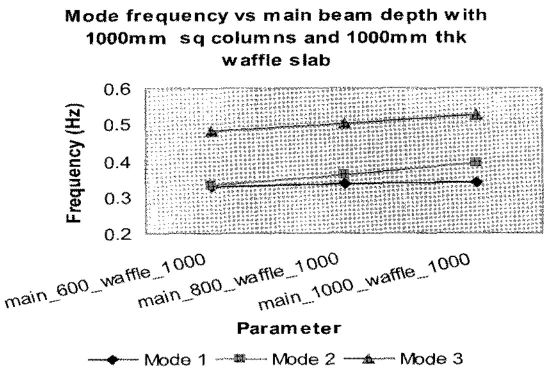


(f)

〈Fig. 8〉 Mode frequency - Waffle slab thickness



(a)



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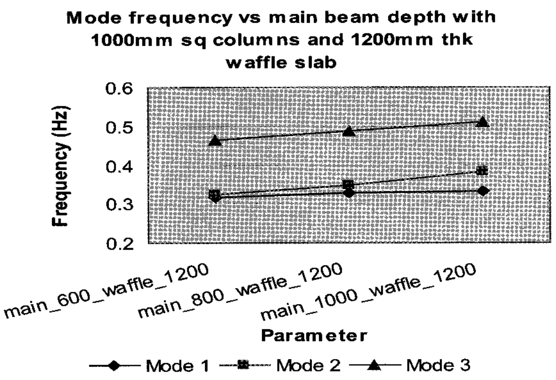

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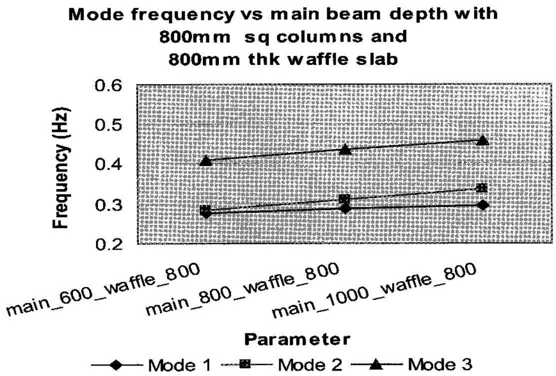

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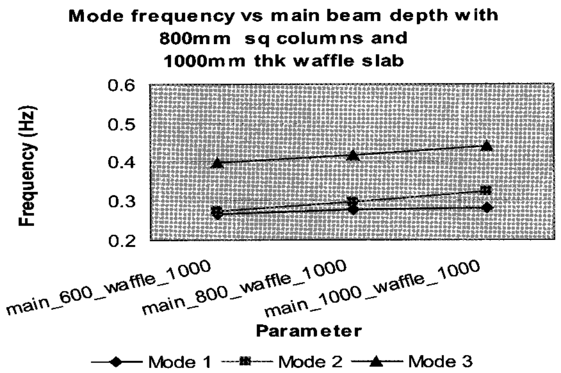

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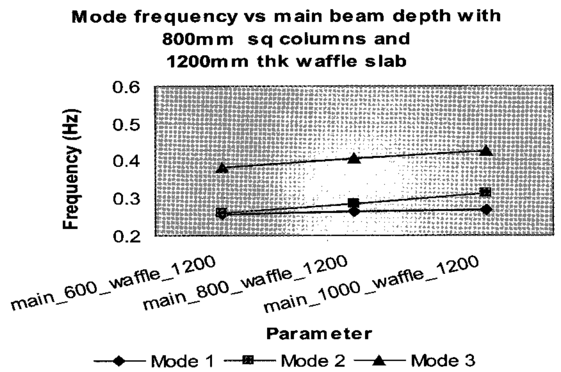
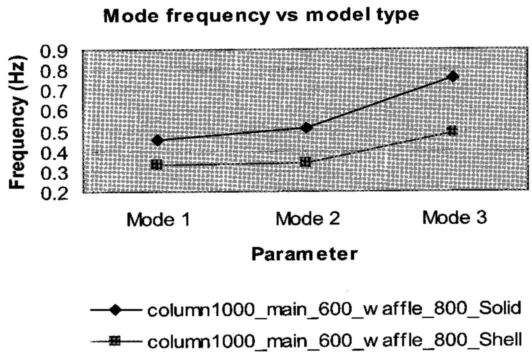
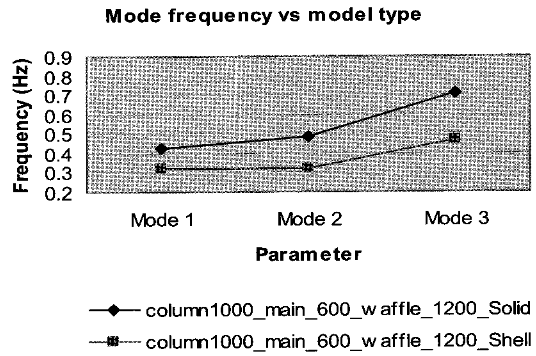


(f)

⟨Fig. 9⟩ Mode frequency - main beam depth



(a)



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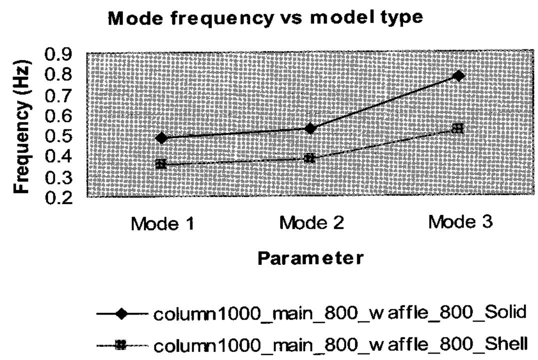
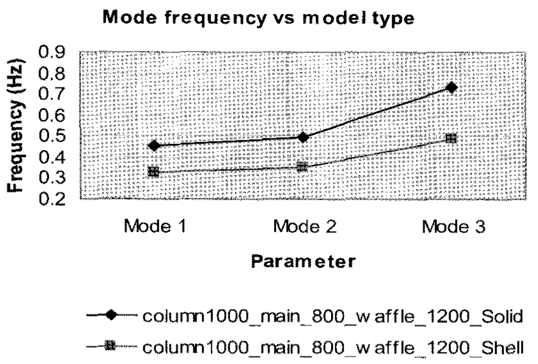


(c)

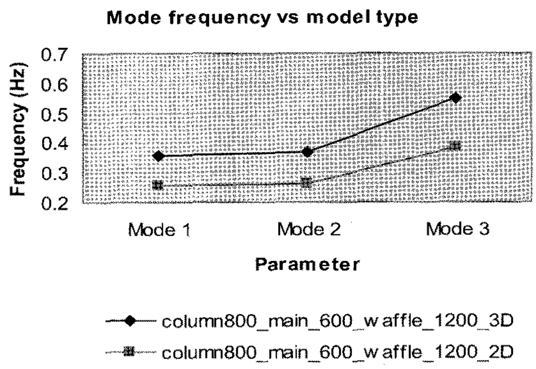
Analysis result for both 3D and 2D models indicate similar patterns of mode shapes for the first 3 mode. However, there is a consistent but large difference in mode frequency when comparison is made. The results are shown in Fig.10.(a)-10.(l). The differences may range from 25% to 36%.

4. Conclusion

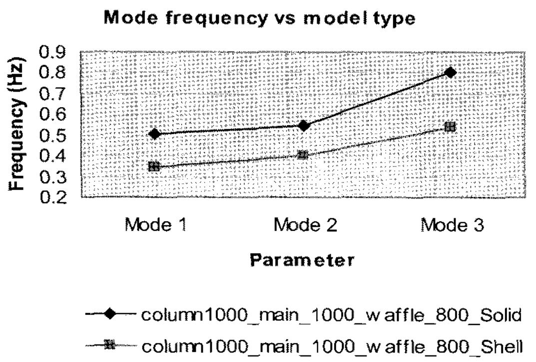
It can be concluded that stiffening of main


Mode frequency vs model type
Frequency (Hz)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Mode 1
Mode 2
Mode 3
Parameter
column1000_main_800_waffle_1200_Solid
column1000_main_800_waffle_1200_Shell

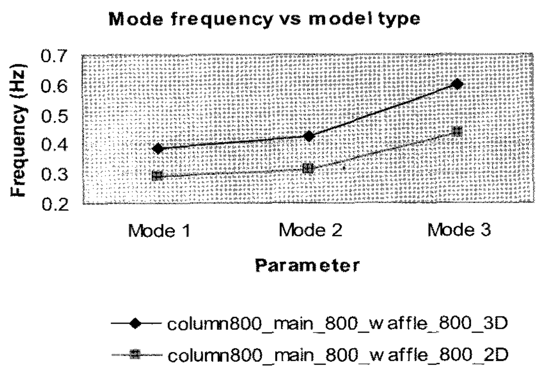
(d)


Mode frequency vs model type
Frequency (Hz)
0.7
0.6
0.5
0.4
0.3
0.2
Mode 1
Mode 2
Mode 3
Parameter
column800_main_600_waffle_1200_3D
column800_main_600_waffle_1200_2D

(h)


Mode frequency vs model type
Frequency (Hz)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Mode 1
Mode 2
Mode 3
Parameter
column1000_main_1000_waffle_800_Solid
column1000_main_1000_waffle_800_Shell

(e)


Mode frequency vs model type
Frequency (Hz)
0.7
0.6
0.5
0.4
0.3
0.2
Mode 1
Mode 2
Mode 3
Parameter
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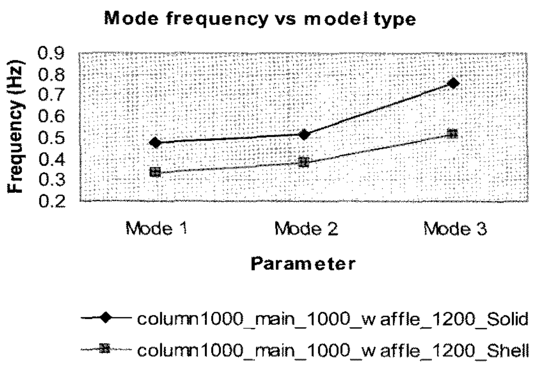
column800_main_800_waffle_800_2D

(i)


Mode frequency vs model type
Frequency (Hz)
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0.5
0.4
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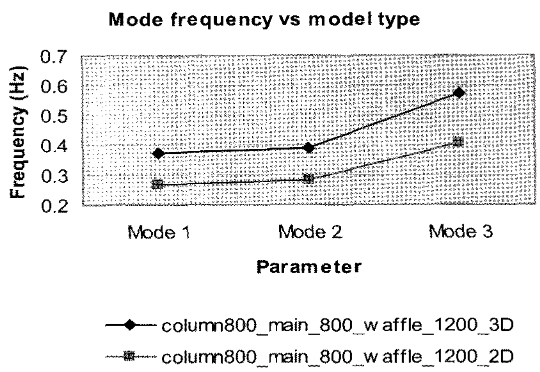
(f)


Mode frequency vs model type
Frequency (Hz)
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0.4
0.3
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Mode 1
Mode 2
Mode 3
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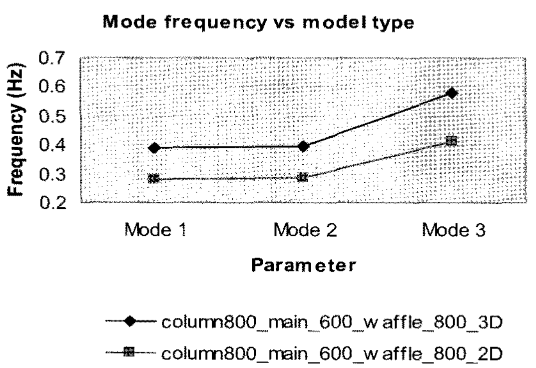
column800_main_800_waffle_1200_2D

(j)


Mode frequency vs model type
Frequency (Hz)
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0.5
0.4
0.3
0.2
Mode 1
Mode 2
Mode 3
Parameter
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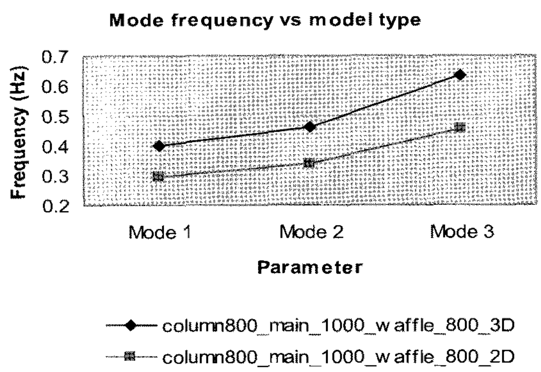
(g)


Mode frequency vs model type
Frequency (Hz)
0.7
0.6
0.5
0.4
0.3
0.2
Mode 1
Mode 2
Mode 3
Parameter
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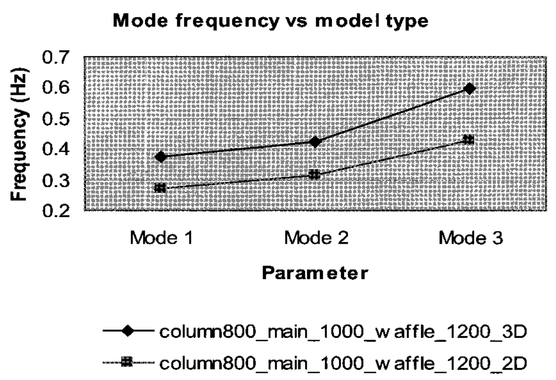
column800_main_1000_waffle_800_2D

(k)



(l)

〈Fig 9〉 Mode frequency - model type

beam at level 2 helps in increasing the efficiency of overall mass concentration at lower ground floor and stiffening effect contributed by deeper main beam to restraint the overall waffle structure, especially the supporting columns. In contrast, thickening of waffle slab do not much improve the overall mode frequency. These may be attributed to the structural behavior of waffle structure.

Both solid and shell element models show similar patterns of mode shape. Although, the mode frequencies exhibited by shell models are lower than solid models, ranging from 25% to 36%, they do show a consistent trend in variation from lower mode to higher mode.

5. Recommendation

Further investigations should be carried out in order to study more in depth the structural behavior of waffle structures. These suggestions are as follows:

a) Shear wall may be included to study the overall behavior of waffle structure. The locations, orientations and dimensions of shear wall do play a significant role to enhance the structural performance of waffle structure.

b) Only free vibrations are studied in this project. Further works can be extended to forced synchronized vibrations and random sources of vibrations.

c) Research work can be extended to larger scale of model by repetition of single prototype of waffle unit. The interplay between adjacent waffle units may serve as an interesting topic.

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