Investigating the Effect of Solid and Lightweight Hollow Block Slabs on Construction Cost

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Investigating the effect of solid and lightweight hollow block slabs on construction cost

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In the design of reinforced-concrete buildings, solid and lightweight hollow block slabs are commonly preferred. In general, it is believed that the cost of lightweight hollow block slabs is higher than that of solid slabs. This research aims to examine the effect of solid and lightweight hollow block slabs on construction cost both in a parametric study and in actual buildings. In the parametric study, both the *x* and *y* directions included a variation of two to four spacings, while on the vertical plane an increase up to ten floors has been taken into account, and accordingly construction costs have been compared. Then, ten structures which have solid slabs, whose number of floors was up to ten and which had been designed in accordance with updated earthquake regulations, were chosen to obtain the cost difference when designed with lightweight hollow block slabs. In all examinations, it has been confirmed that lightweight hollow block slabs cost more than solid slabs, creating a 10·49–21·93% cost difference ratio, and that the cost difference ratios obtained from the actual structures also agree with these findings. The study presents increase curves depending on the slab type, modal analyses and strength comparisons.

Notation

d	thickness of slab
G	dead load
I	building importance coefficient
Q	live load
T_a, T_b	spectrum characteristic periods
V_x	shearing force in x direction
V_y	shearing force in y direction

1. Introduction

Slabs that transmit both vertical load and horizontal load such as earthquakes to the vertical bearing elements of a structure are generally considered two dimensional, for slab thicknesses can be disregarded compared to the other two dimensions. Since slabs support the rigid diaphragm action, the floors provide equal displacement and rotation in the analysis (Park and Gamble, 1995: p. 711; Punmia, 2005: p. 847).

In reinforced-concrete buildings, a solid slab is a conventional slab which is supported by beams and columns, with the load transferred to those elements. This slab type (Figure 1(a)) is classified as either one-way or two-way. The other slab type is a ribbed floor slab consisting of equally spaced ribs, usually supported directly by columns. Slabs are either one-way spanning systems or two-way systems. When the space between beams is filled with lightweight material, they are called lightweight hollow block slabs; the other commonly used name is hordy slab (Figure 1(b)). Hollow blocks are used to fill portions of the slab thickness; this results in a deeper arm for the reinforcement while reducing the amount of concrete and hence the self-weight of the slab. The reinforcement is located between the blocks inside the ribs. A block may be a concrete block, a briquette or styrofoam. When the ribs are in one direction, then it is a one-way hollow block slab, regardless of the rectangularity. When the ribs are in both directions, then it is a two-way hollow block slab. This type of slab has longitudinal voids running through it, which decrease the weight of the slab, as well as the amount of concrete required. These voids can also function as service ducts. A two-way hollow block slab is generally reinforced with longitudinal rebar and can achieve long spans, making it suitable for office buildings, multistorey car parks and so on (Fanella and Alsamsam, 2005). In order to make comparison among the two type of slabs possible, the most common residential building model has been chosen in this paper. Despite their disadvantages, there are certain reasons why lightweight hollow block slabs are widely used, such as their ability to fill big spaces easily, lower formwork cost and smooth surface on ceilings, thereby allowing flexible choice of where to place an interior wall. Another type of slab is the flat slab, which is supported directly by columns without the use of beams. Both vertical and horizontal loads are transferred directly from slab to columns. This type of slab is not as common as the other two types mentioned earlier.

Solid slab systems are known to affect structural ductility because of high diaphragm rigidity, necessary lateral resistance and translational rigidity, and to have an impact on the results of modal analyses (Doğangün, 2004; Lam *et al*., 1998; Matthews, 2004: p. 523). Slabs behave rigidly in the direction of ribs; some problems may be experienced regarding ensuring enough rigidity

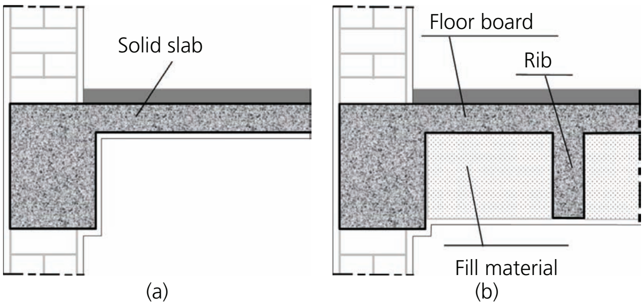


Figure 1. (a) Solid slab type; (b) lightweight hollow block slab type

in a perpendicular position to ribs, since ribs do not fit into beams in that direction.

The design of a structure must satisfy strength, stability and serviceability. Considering these requirements, it is important to resist safely the stresses which are induced by the loads. The structure must also be economical. Care should be taken to create a safe structure in the most economical way while forming the structural system of the targeted structure (Choi *et al*., 2007). Since the earthquake loads acting on structures depend on the building masses, lightweight hollow block slabs are subject to more earthquake load than solid slabs. Therefore, structures with lightweight hollow block slabs require an increase in the size of vertical bearing elements in order to keep the structures safe against relative floor displacement, which, in turn, affects the construction cost. The general opinion is that the cost of lightweight hollow block slabs is higher than that of solid slabs. However, with the temptation of architectural preferences, the cost increase is often tolerated. The cost increase ratio has been stated to be in a wide range in research studies (Galeb and Atiyah, 2011; Kaveh and Behnam, 2012) and on websites that capture engineers' personal experiences (FYN, 2017; JLC, 2017). The authors have examined ten buildings with up to 16 floors, five of those buildings with lightweight hollow block slabs and the other five with solid slabs, which have been designed in accordance with updated earthquake regulations. As a result of the examination, it has been determined that the cost difference varies between 1·33 and 15·37% when one slab type is replaced with the other (Bikçe and Akyol, 2017).

Engineers have a wide choice of concrete floor systems for buildings. Different forms of slab constructions tend to result in variation in the cost of the slabs for any building project. For this reason, structural engineers should pay more attention to alternatives in order to avoid having the same safety structure at a higher cost, as the type of slabs directly affects the building cost. However, there is a widespread belief that lightweight hollow block slabs cost more compared to solid slabs. Advantages and disadvantages of both lightweight hollow block slabs and solid slabs can easily be found in the literature, while cost comparisons are encountered only on forum websites where the designers' specific experiences can be derived from a wide range of comments. There is no study about the rate of cost surplus. No scientific study has been found regarding the cost surplus except for the examination by the authors, although how the change in slab type would vary depending on the spacing and number of floors is still an interesting and undetermined subject. In this study, the main objective is to compare solid slabs and lightweight hollow block slabs based on cost evaluation both in a parametric study and in actual buildings. The economic comparison made in this study based on the change in the slab type of a newly finished building is important in order to show designers the possibility of the same building being constructed for lower or higher costs.

While investigating the effect of solid and lightweight hollow block slab types on construction cost, a variation of two to four spacings in the *x* and *y* directions and an increase up to ten floors in the vertical plane have been taken into account. The cost difference has been determined for the case when solid slabs in buildings of up to ten floors are changed to lightweight hollow block slabs. Also, the results of a modal analysis and changes in the shearing force for both slab types have been analysed.

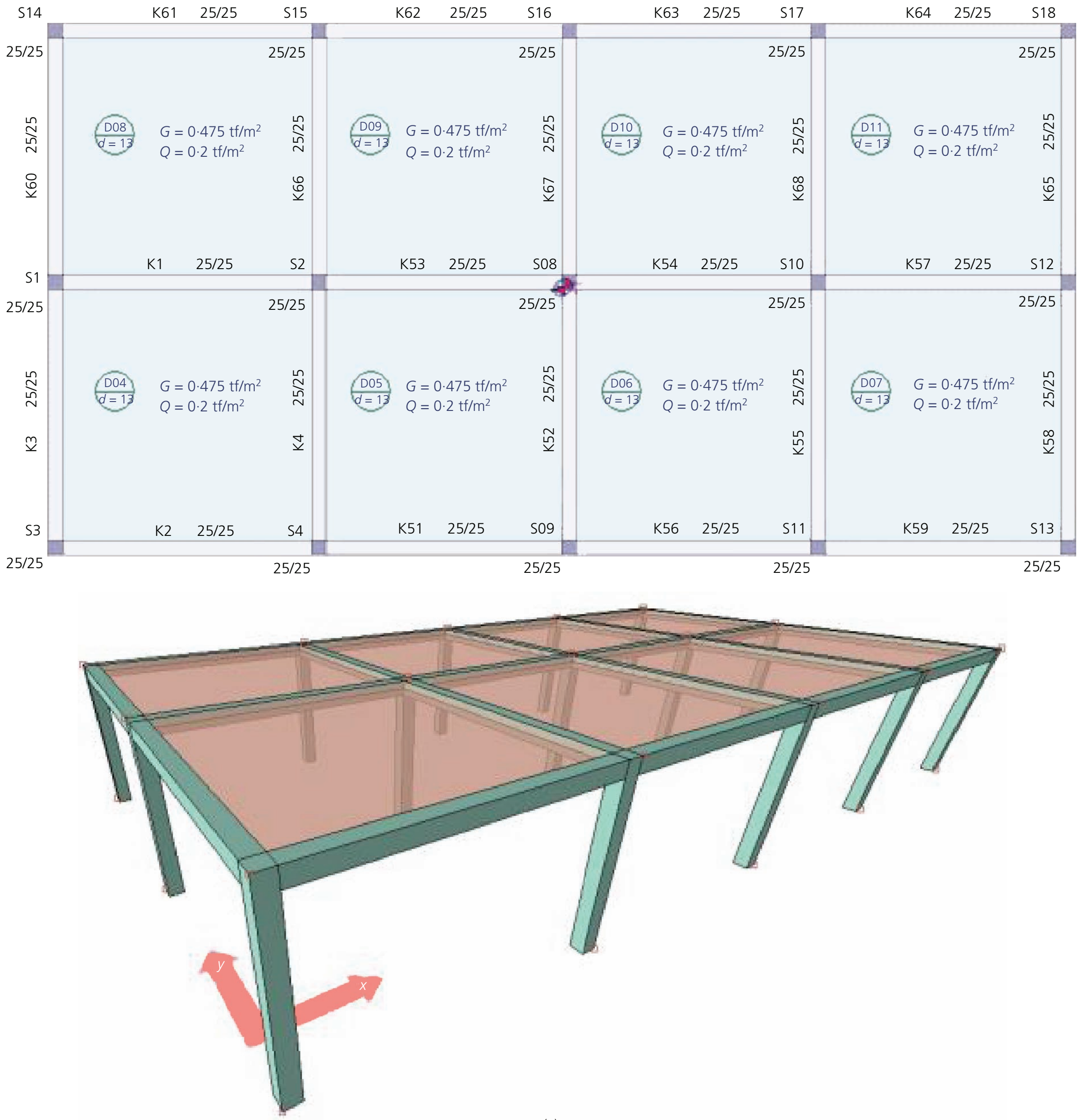
2. Selected structures and their analytical models

2.1 Parametric investigation

Separate models have been prepared for both solid and lightweight hollow block slabs. In each model, the analyses have been repeated, ensuring minimum sections for both the *x* and *y* directions from one to four spacings in the design. On the horizontal plane, a spacing of up to four has been taken into account, and in the vertical plane, analyses have been repeated for an increase up to ten floors. For each slab type, the spacings have been fixed to 5 × 5 m. The images from the analysed models are presented in Figures 2(a) and 2(b) for the solid slab type and in Figures 3(a) and 3(b) for the lightweight hollow block slab type.

2.2 Analysis of the actual buildings

In order to reveal the cost difference, ten different building projects complying with the updated earthquake regulation (Turkish Earthquake Code 2007 (MPWS, 2007)) and standard (TS 500 (TSE, 2000)) of up to ten floors and with solid slabs were chosen. The yield strength of the steel was set as 420 MPa. There are two types of data used for the residential reinforced-concrete building design, which are general building data and characteristic building data for the investigated buildings as shown in Table 1. In order to change the slab type of the selected buildings from solid to lightweight hollow block, two models for each building, one solid and one lightweight hollow block, were designed. As a result of the slab change, there were some deficiencies in the bearing elements in accordance with the updated regulation and standard. Thus the bearing elements were enlarged or made smaller at an optimum level without putting in any additional elements or changing the structural statics in order



(a)

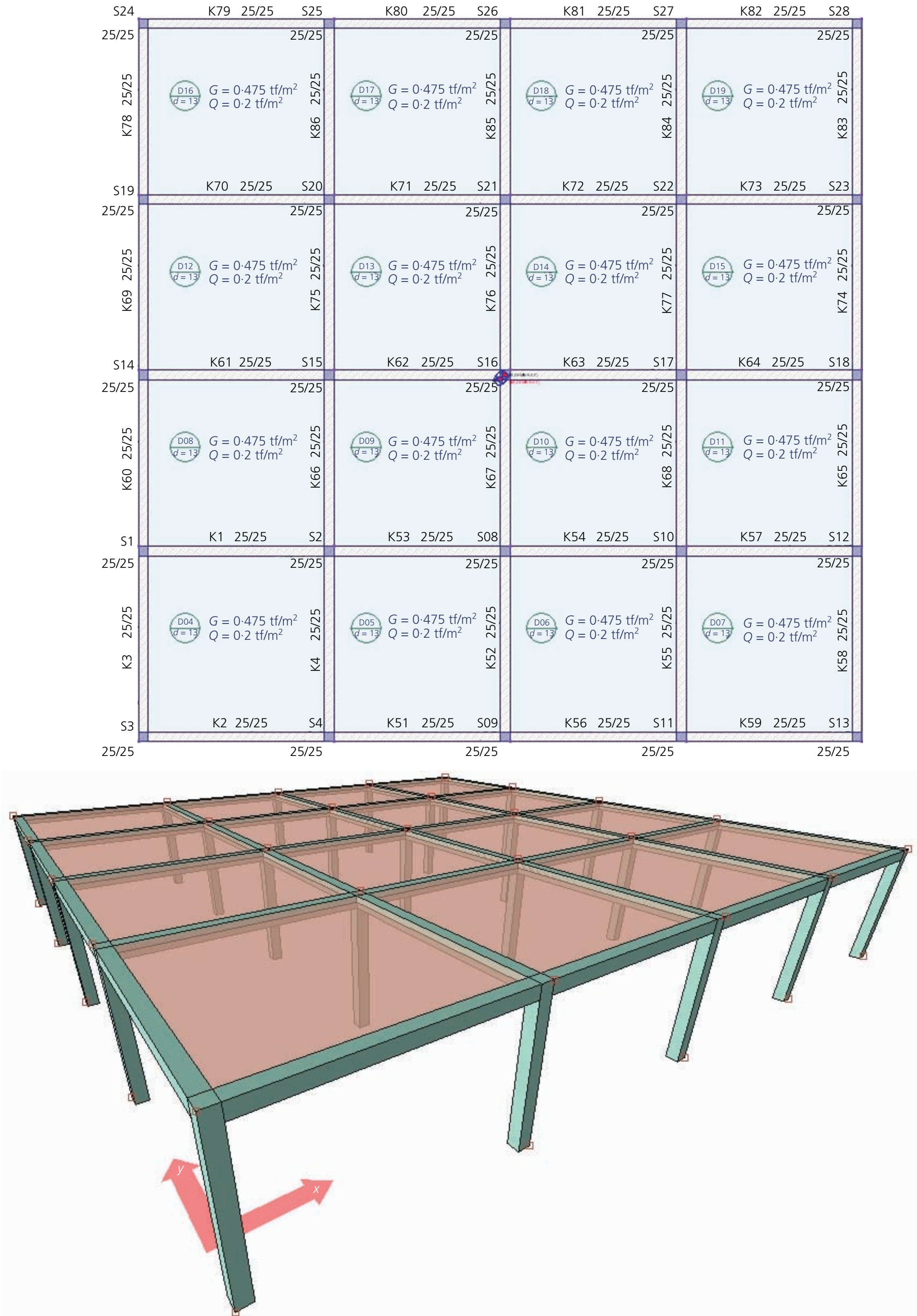
Figure 2. (a) Sample solid slab type model with 2 × 4 spacing; (b) sample solid slab type model with 4 × 4 spacing (continued on next page)

to comply with the earthquake regulation. The aim is to reveal the minimum cost difference occurring as a result of changing the slab type of the buildings.

3. General information regarding the analyses

The comparison of the minimum cost differences resulting from the conversion of the selected solid and lightweight hollow block slab types is the aim of this study. Therefore, care has been taken to ensure that necessary changes to the reduction or increase in the cross-sectional dimensions of the bearing elements according to standards resulting from the conversion of slab types are kept at an optimum level. In order to reveal the cost difference, all other variables such as number of floors and material properties are kept constant while converting the slab types of the investigated buildings. In the design of lightweight hollow block slabs, the height of ribs is limited to the level of the beams, and edge beams have been formed as commonly preferred wide beams. In the design, up-to-date and commonly used building materials have been preferred.

Briquettes are preferred to have sizes of 25 × 40 × 20 cm and are produced from lightweight concrete and widely used in the market as a filling material for lightweight hollow block slabs (ACI 318-05 code and commentary (ACI Committee 318, 2005)). In the analysed buildings, the coefficient of concrete safety is 1·5,



(b)

Figure 2. Continued

(a)

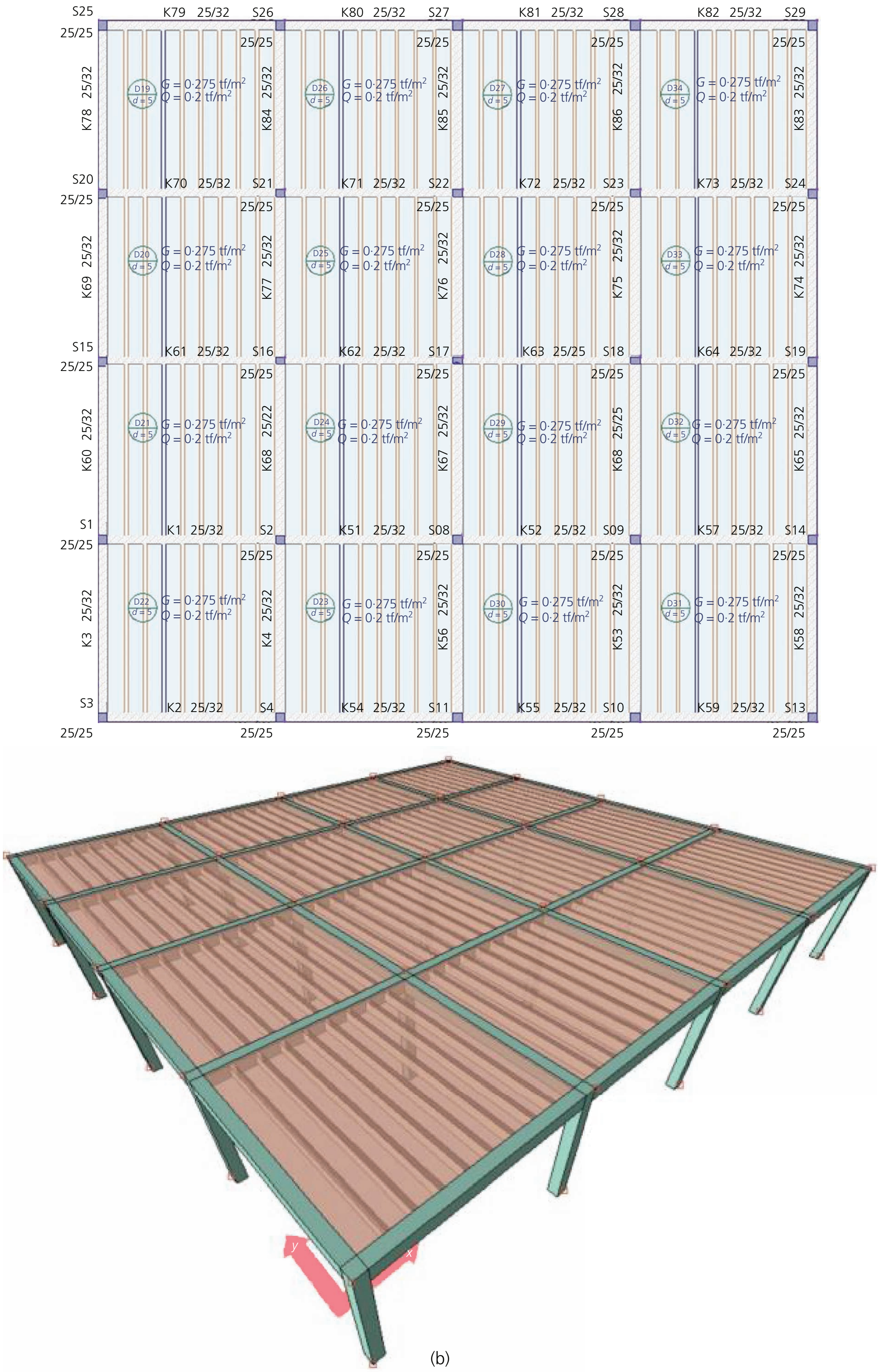
Figure 3. (a) Sample lightweight hollow block slab type model with 2 × 4 spacing; (b) sample lightweight hollow block slab type model with 4 × 4 spacing (continued on next page)

the coefficient of steel safety is 1·15 and the concrete unit volume weight is taken to be 2·5 t/m^3. During the static and dynamic analyses, the updated earthquake regulation and standard have been taken into account (MPWS, 2007; TSE, 2000). The up-to-date unit prices for materials considered in the cost comparison are presented in Table 2.

In all elements, it has been presumed that the size and material properties do not change along the element. In the calculations, a building with 285 00 MPa elasticity modulus of concrete, 0·2 Poisson's ratio and 420 MPa outflow strength of steel has been considered to be in the first-degree seismic zone, and the local soil class, as one of the parameters, has been selected as Z1 (MPWS, 2007).

Reinforced-concrete buildings are analysed and designed using the ideCad (2017) software package. ideCad (2017) is an integrated packaged software program that can perform three-dimensional analysis. The analyses for both slab models have been repeated, and the results provided from the software have been multiplied by the unit prices presented in Table 2 to get the building costs.

For the selected building in the parametric study, the slab size is 5 × 5 m, the storey height is 3 m and the smallest size of a column is



(b)

Figure 3. Continued

Table 1. General residential building data

NF	CG: MPa	BA: m	SZ	FUW: t/m	CSR: t/m	ABP: t/m	ST
1	25	252	2	2·2	4000	22	Z3
2	30	304	2	2·1	5500	20	Z2
3	25	451	1	2·2	4000	19	Z3
4	25	723	1	1·9	3500	19	Z3
5	25	902	1	2·1	6000	17	Z3
6	30	1315	4	2·0	2500	25	Z2
7	25	1726	1	2·1	4000	26	Z3
8	25	2516	4	2·0	7000	25	Z2
9	25	3043	4	2·1	9000	30	Z2
10	30	3416	4	2·1	2500	15·6	Z3

ABP, allowable bearing pressure; BA, building area; CG, concrete grade; CSR, coefficient of soil reaction; FUW, foundation unit weight; NF, number of floors; ST, soil type; SZ, seismic zone

Table 2. Current unit prices of building materials

Reinforcement: \$/t	Concrete: \$/m^3	Briquettes: \$/unit	Formwork: \$/m^2	Labour cost: \$/m^3
431·31	30·35	0·32	4·15	25·6

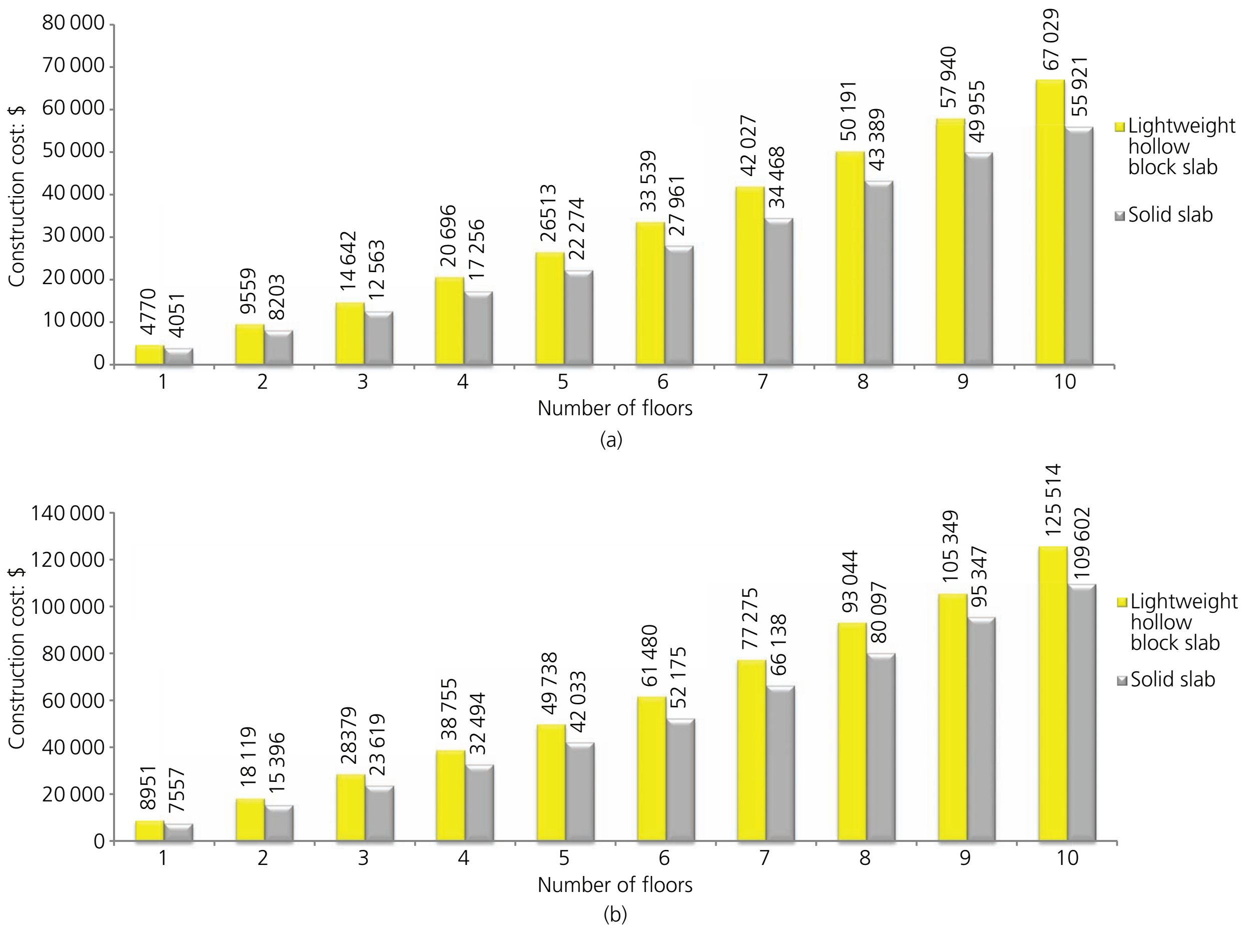


Figure 4. (a) The cost curves of solid and lightweight hollow block slabs with 2 × 4 spacing; (b) the cost curves of solid and lightweight hollow block slabs with 4 × 4 spacing

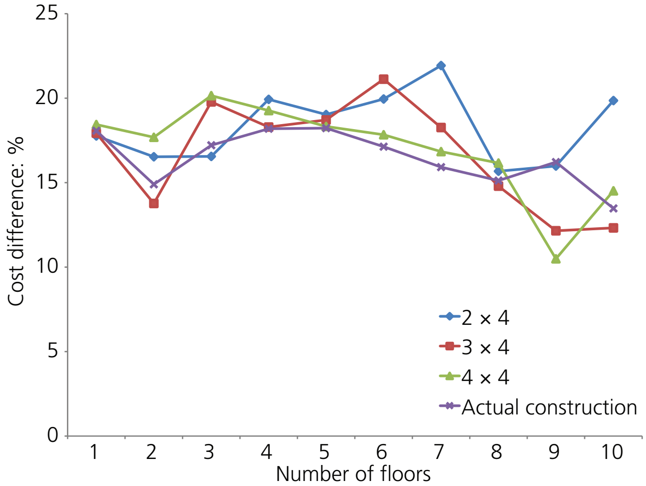


Figure 5. Cost surplus ratios between lightweight hollow block slabs and solid slabs in all buildings

25 cm. For both slab types, the material feature of the structures is C25-S420. In addition, the earthquake parameters taken into account in the analyses are as follows: the building importance coefficient (I) 1, the eccentricity ratio 0·5, the earthquake zone 1 and the effective ground acceleration coefficient 0·40. Also, the foundation parameters are as follows: soil class Z4, spectrum characteristic periods T_a 0·20 and T_b 0·90, allowable bearing value 15 t/m^2, soil predominant period 0·25 s, coefficient of soil reaction 2500 t/m^3 and soil group A (MPWS, 2007; TSE, 2000). The infilled walls and coating weight have not been taken into account in the design.

4. Cost comparisons

In the parametric examination, analyses for both slab types of the structures with the same number of floors have been carried out, and the graphs showing the cost differences are presented in Figures 4(a) and 4(b). The differences in construction methods between different forms of slabs presented in the following figures tend to result in variation in the cost of the slabs. As clearly shown in the figures, the cost of lightweight hollow block slabs is higher than that of solid slabs.

In all of the buildings that have been analysed, lightweight hollow block slabs cost more than solid slabs. The graph showing the comparison ratio regarding the cost differences is provided in Figure 5.

Cost surplus ratios between lightweight hollow block slabs and solid slabs were between 10·49 and 21·93% in the parametric

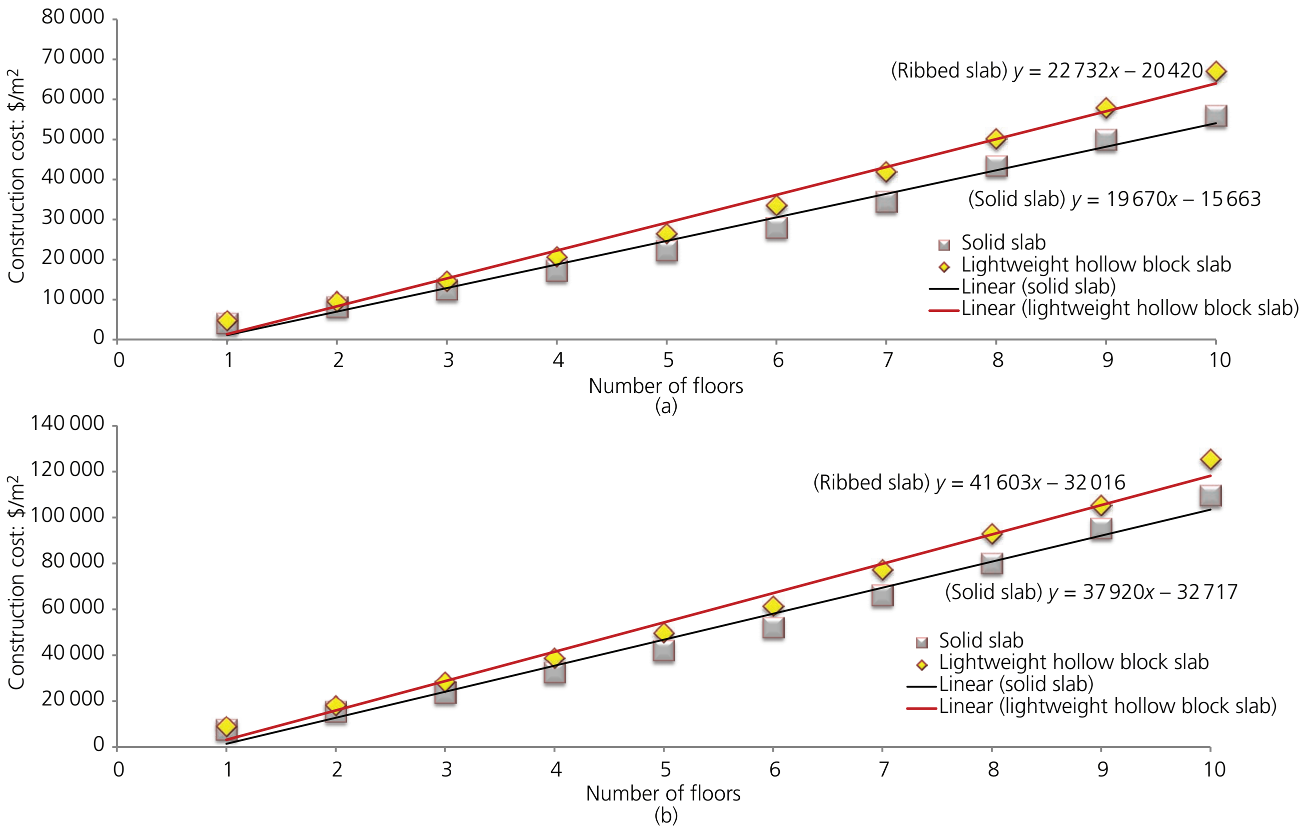


Figure 6. (a) The cost curves of solid and lightweight hollow block slabs with 2 × 4 spacing; (b) the cost curves of solid and lightweight hollow block slabs with 4 × 4 spacing

study and 13·48–18·23% in the actual buildings. The fact that the ratios for the actual buildings remain between the ratios obtained from the parametric study demonstrates that the study is proportionately compatible.

The curve equations formulating the cost differences of the same type of slabs according to the number of floors are presented in Figure 6.

5. Modal analysis and strength comparisons

As a result of the modal analysis, the difference in periods depending on the difference in the slab type is demonstrated in Figure 7.

As can be seen in Figures 7(a) and 7(b), the buildings with lightweight hollow block slabs have reached higher periods compared to the ones with solid slabs. As a result of the change in the slab type, the change in the shearing force obtained at the corner column base in the dynamic analysis is presented in Figures 8(a) and 8(b).

The buildings designed with lightweight hollow block slabs appear to have higher shearing force values than the ones with solid slabs (Figures 8(a) and 8(b)). Also, as a consequence of the analyses, it has been understood that this applies to the interior columns.

6. Conclusions

In this study, the effect of solid and lightweight hollow block slabs on construction cost both in a parametric study and in actual buildings has been investigated. The study conveys the following conclusions.

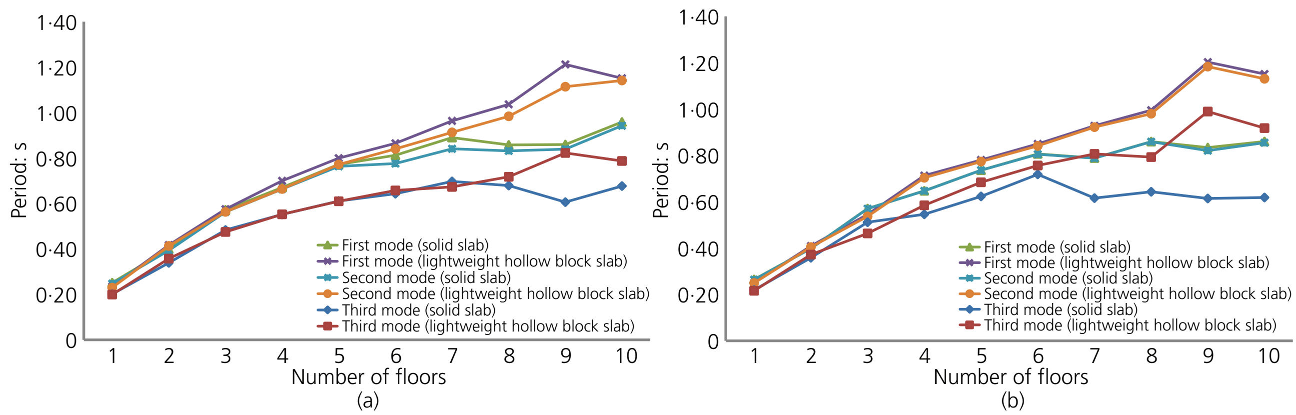


Figure 7. (a) First three mode changes depending on the floors of solid and lightweight hollow block slabs with 2 × 4 spacing; (b) first three mode changes depending on the floors of solid and lightweight hollow block slabs with 4 × 4 spacing

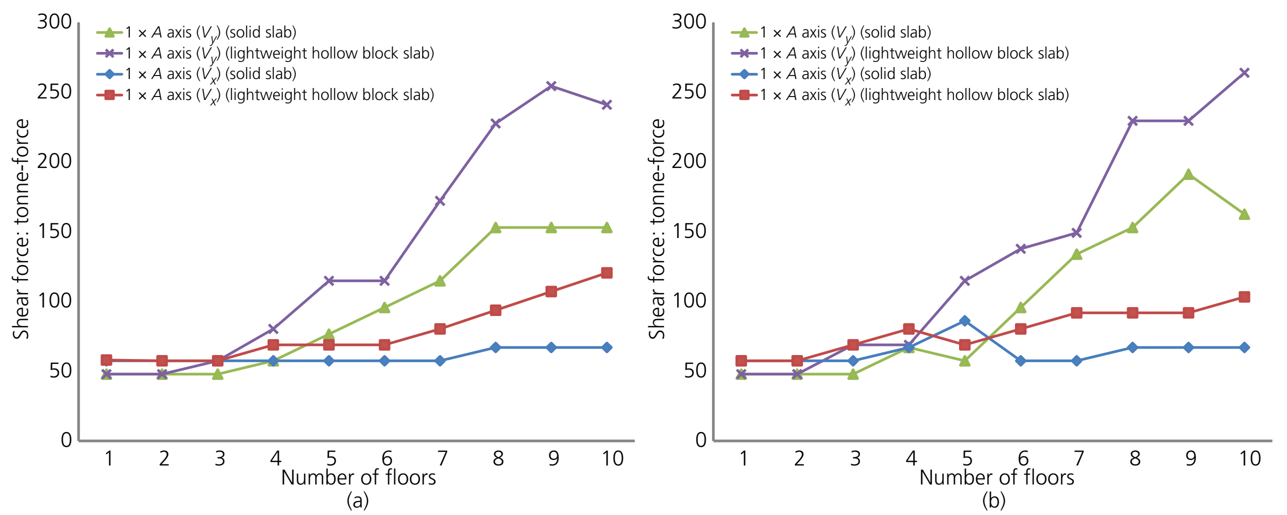


Figure 8. (a) The change in shearing force of solid and lightweight hollow block slabs with 2 × 4 spacing; (b) the change in shearing force of solid and lightweight hollow block slabs with 4 × 4 spacing

- In all of the cases examined, the cost of the building with lightweight hollow block slabs is more than the cost of the building with solid slabs.
- According to the results of the parametric study, it has been determined that lightweight hollow block slabs cost 10·49–21·93% more than solid slabs. The examination of actual buildings has also shown a similar ratio of cost differences.
- The ratio of cost differences varies depending on not only the slab type, but also numerous other parameters such as structural geometry, material properties, the number of floors, architectural obligations and most importantly the design of the structures by engineers. Hence, in order to build a structure with the same architecture and safety at a lower cost, it is essential to investigate alternative slab types.
- It has been concluded that the buildings with lightweight hollow block slabs have reached higher periods and had higher shearing force values. Depending on the increase in floor weight of the hollow block slab, it is expected that the structure's relative storey displacements and period will increase.
- There has been a considerable increase in the number of commercial buildings. Therefore, further studies are required to quantify and investigate the effects of different structural systems and configurations and occupancy types. It would be useful for evaluating structural alternatives under different seismic intensities and related cost-management studies.

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