Journal of Civil Engineering and Architecture 11 (2017) 1068-1076
doi: 10.17265/1934-7359/2017.12.002

Comparative Study between Waffle and Solid Slab Systems in Terms of Economy and Seismic Performance of a Typical 14-Story RC Building

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Abstract: In order to maximize the return of investments and at the same time improve the quality in the construction industry of midrise buildings, it is very important to derive an optimal solution to the building structural system, which would facilitate faster and easier construction activities with minimal quantity of construction material, while maintaining the satisfactory level of building safety and performance. This paper makes a comparative study between a "solid" and a "waffle" slab system. A typical 14-story RC building structure is selected as an example for this study purpose. The first part of this study is focused in deriving an optimal solution for a solid and waffle slab system which are later on considered as constituents of all stories of the 14-story building. In the second part, it is elaborated the effect of both slab systems over the 14-story building model. This study aims to emphasize the advantages of mid-rise buildings constituted of waffle slab system over the buildings characterized with solid types of slabs, in terms of economy, structural safety and performance.

Key words: Waffle slab, solid slab, RC structure, optimization, seismic analysis and design.

1. Introduction

The benefits of waffle slab systems on building structures with large column-to-column spans are very well documented in literature. But how would waffle slabs perform on residential types of mid-rise buildings with shorter column-to-column spans? Would they outperform the classical type of solid slab system in terms of economy and safety when column span is merely 6 m or 7 m? This paper aims to answer these questions by adopting a typical 14-story RC building as a study case (Figs. 1 and 2). This building structure has column spans of 6.5 m on both orthogonal directions and an assumed story height of 3.0 m. The structural system of the building is a frame system with two bays in both X and Y orthogonal directions. The slab system is considered to be a solid slab in the first case (Fig. 1) and a waffle slab system in the second (Fig. 2). For both cases, the boundary conditions, material characteristics, load types and all added load intensities are identical. In respect to the global structural behavior of the 14-story building, different analysis techniques have been performed and finally a design of the structure has been done in full compliance with the provisions of Eurocode 0, 1, 2 and 8.

Before analyzing and doing comparative research on the 14-story building with two different slab systems, in the subsequent Section 2 has been conducted a study on deriving optimal cross-section geometry to beams and slabs of both solid and waffle slab systems. The optimization process was based on the criteria of applying minimal material quantity that would satisfy the safety and serviceability criteria of the respective slab system.

Once the most optimal slab systems are adopted, in the subsequent Section 3 they are considered as

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constituents of the 14-story building slabs. Characteristic structural analysis and design results of the 14-story building, under consideration of both solid and waffle slab types, are presented in Section 3 of this paper.

2. Slab System Optimization

In order to compare two "optimized" solid and waffle slab systems in terms of economy and performance, there were considered several slab systems with variations in cross-section geometry of their bearing members, respectively slabs, beams and joists. Consequently, for the solid slab "SS" system were considered three types of slabs with various slab thicknesses, i.e., SS-14, SS-16 and SS-18 (Fig. 3a). The number following the "SS" initials represents the slab thickness in "cm" units, for instance, SS-16 is a slab system with a thickness of 16 cm.

Additionally, for the waffle slab system were considered five types of slabs with various number of joists between column bays, i.e., WS-5, WS-6. WS-7, WS-8 and WS-9 (Fig. 3b). The number following the "WS" initials represent the number of joists in one bay (between two columns), for instance, WS-6 is a waffle slab system with 6 joists in each bay in each orthogonal direction.

Cross-section dimensions of beams for all three types of "SS" slabs are with height h = 50 cm and width b =50 cm. Cross-section dimensions of beams for all types of "WS" slabs are with height h = 30 cm and width b = 50 cm. Lastly, cross-section dimensions of joists for all types of "WS" slabs are with height h = 30cm and width b = 15 cm.

Besides the self-weight of slab systems, a uniform load of 2 kN/m^2 was assigned to all slab surfaces for the superimposed dead load case and for the live load as well.

The concrete material of all slabs is adopted with class C30/37, while the rebar reinforcement with class S-500.

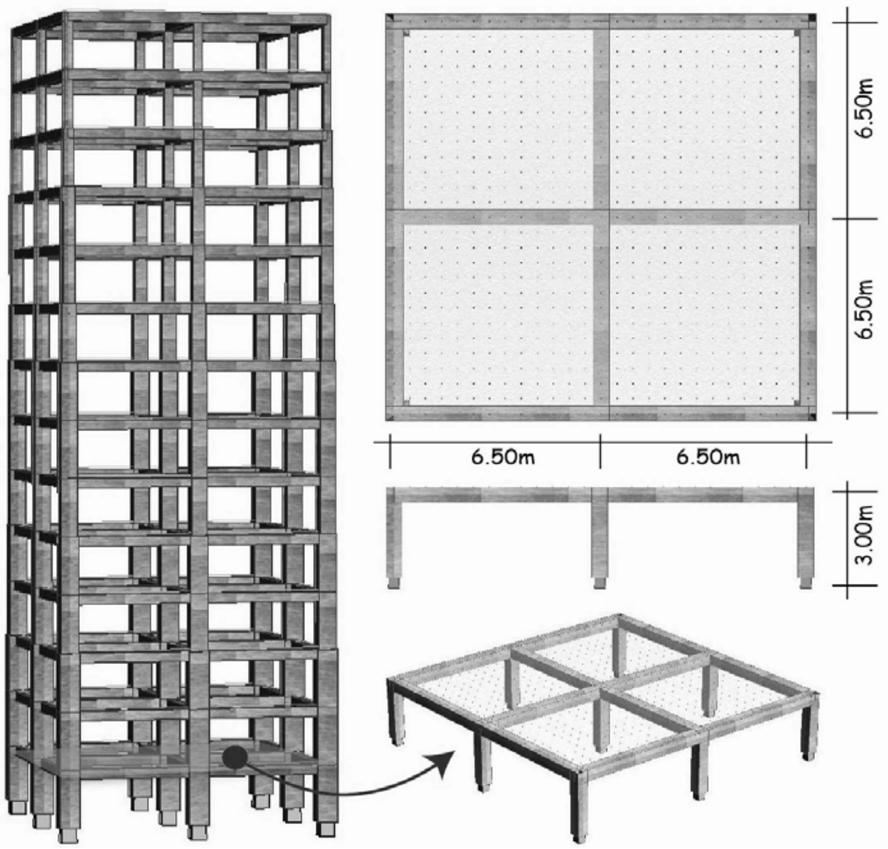

Fig. 1 14-story building with solid slab system.

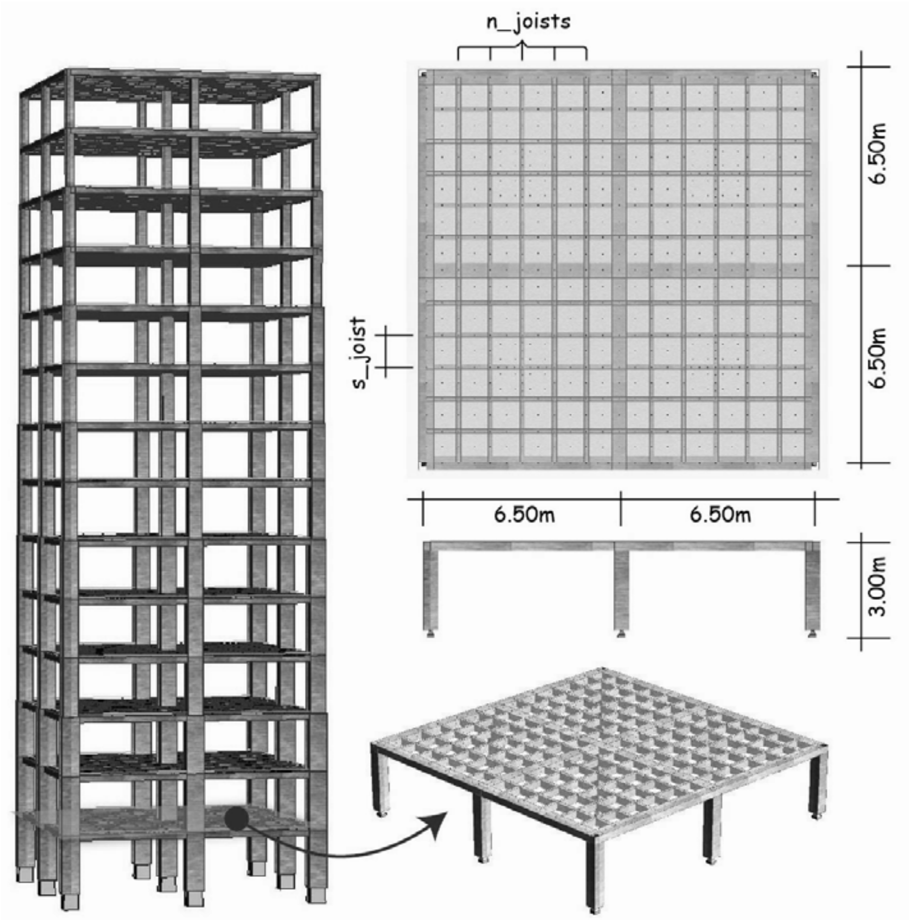

Fig. 2 14-story building with waffle slab system.

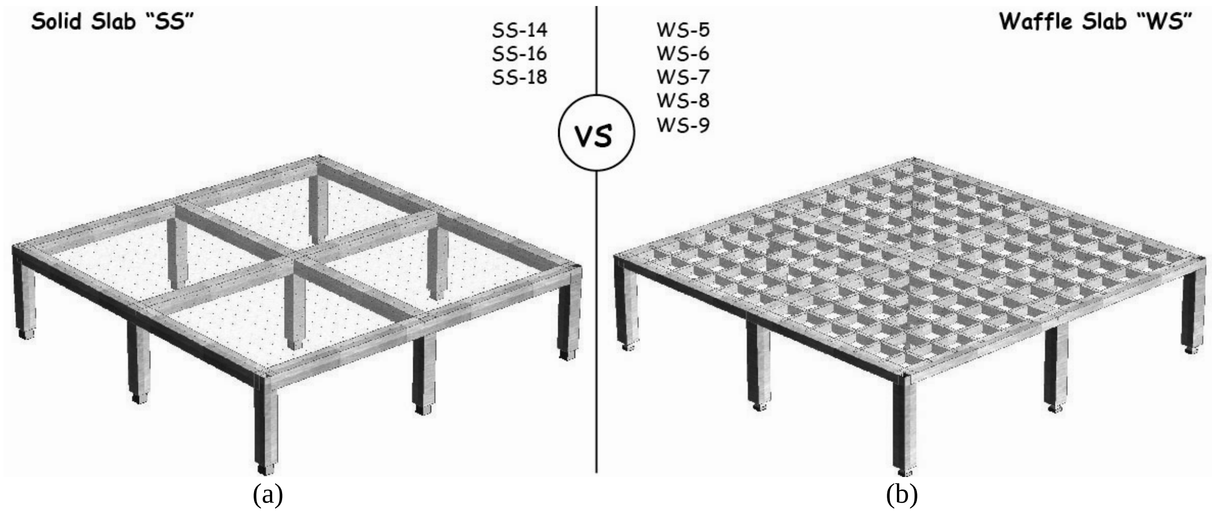

Fig. 3 Comparative study between: (a) solid; and (b) waffle slab system.

Finally, all of the modeled slabs were subjected to linear static analysis based on the presented loading cases and combinations of loads resulting from these combinations [1-4]. The generation of loading combination was done in compliance to EN1991, considering load combination rules for the ULS (ultimate limit states), SLS (serviceability limit states) and ALS (accidental limits states).

Table 1 presents the characteristic results obtained from linear elastic analysis and the subsequent design process over all considered types of slab systems. In reference to Table 1, Columns 2, 3, and 4 give the results obtained from the analysis and design process, while the last Column 5 is derived considering the values of Columns 2 and 4 multiplied by their unit prices in Euro.

From results shown in Table 1 are generated several graphs which present a visual comparison of characteristics results between all slab types.

In respect to Figs. 4s and 4c, it is obvious that with the increase of volume of concrete, the maximal slab deflections are reduced, steel reinforcement is increased and also the material costs are proportionally increased as well. A proportional relationship between these four parameters is very obvious from Fig. 4. It can be concluded that the smaller volume of concrete, the more economical are the financial costs. However, there is a limit down to which this economization can extend due to the gradual increase in deflections.

Another interesting observation from Fig. 4 that can be outlined to this point is that waffle slab systems offer a better optimization than solid slab systems in terms of reduction of concrete volume, steel reinforcement and financial costs. In contrast, slab deflections of waffles slabs are higher than the deflections of slab systems. This demonstrates the fact that waffle slab systems are more flexible than solid slab systems.

Based on the obtained values from Columns 2-5 of Table 1 and Fig. 4, as optimal slab types of both solid and waffle slab systems are adopted solid slab "SS-16" and waffle slab "WS-6". Although slab SS14 is more economical than SS16, its deflection seems to start increasing more rapidly. This is why SS-16 is selected as an optimal solution. On the other hand, the determinant factor for the choice of optimal waffle slab type was the "material cost" parameter.

At last, it should be mentioned that the results discussed so far were obtained from elastic static analysis considering only the gravitational loads acting over the slab surface [5, 6]. No seismic actions have been considered in the analysis. On the case when seismic actions are considered in the analysis, the values of deflections and steel reinforcement get increased. In the following section, where SS16 and WS6 slabs are adopted as constituents of the 14-story building structure, seismic actions are taken in to consideration and, as a corollary, the steel reinforcement of slabs is greater than that shown in Table 1 and Fig. 4.

3. Structural Analysis and Design of the 14-Story Building

Benefits of using a waffle slab system over the solid slab system extend further than just achieving a more lighter and economical slab [7-10]. By investigating the overall 14-story building response subjected to both gravitational and seismic actions, further beneficial features of waffle slab systems are observed.

In the following items are elaborated the obtained

Table 1 Characteristic analysis results from considered slab types.

Slab type	Volume of concrete [m^3]	Maximum slab deflection [mm]	Weight of steel [kg]	Material costs [€/m^2]
SS-14	39.3	3.40	3,190	27
SS-16	42.2	2.70	3,295	**28**
SS-18	45.1	2.30	3,270	29
WS-5	30.9	3.30	2,960	23
WS-6	32.5	3.15	2,675	**22**
WS-7	34.0	3.10	2,690	23
WS-8	35.6	3.00	2,860	24
WS-9	37.2	2.95	3,060	26

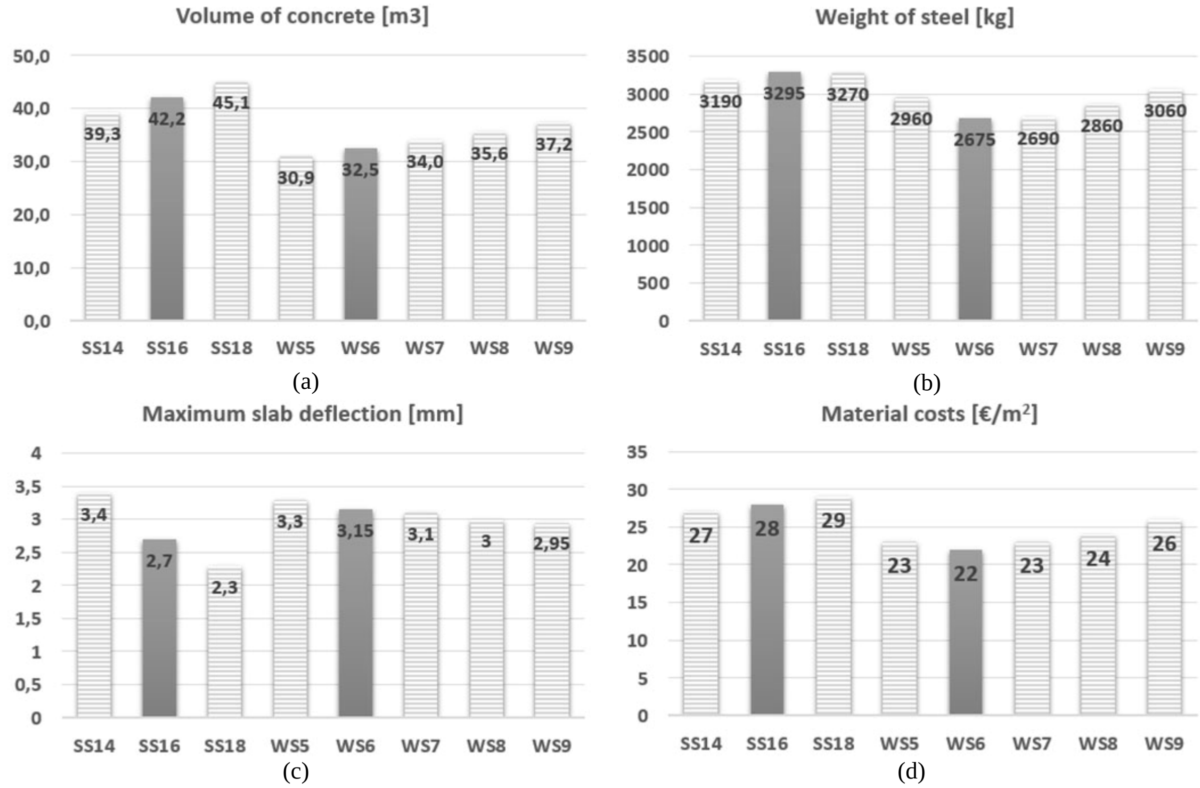

Fig. 4 Characteristic analysis results from considered slab types: (a) volume of concrete; (b) weight of steel; (c) maximum slab deflection; (d) material costs.

results from several analysis techniques, namely linear-static analysis for gravitational loads, modal analysis for determination of basic dynamic characteristics of the building and response spectra analysis for consideration of seismic actions on the building structure. For all types of analysis, the slab system of the 14-story building is considered being both a solid and a waffle type.

3.1 Linear Static Analysis

This is the simplest type of analysis. Based on this type of analysis, the distribution of forces along the building, subjected to gravitational loads, is clearly depicted. These results are directly used for the preliminary member proportioning of vertical bearing elements, namely columns and shear walls.

For the case of the 14-story building with solid type of slabs, the required column cross-section dimensions at the base story level (which would safely withstand the gravitational loads) are b/h = 100 cm/100 cm, and the material quality of concrete must be C50/60 or higher. Along the height of the structure, the cross-section dimensions of the columns are gradually reduced until at the top story level, column cross-section dimensions are reduced to b/h = 40 cm/40 cm (Fig. 1). This same situation holds for the building structure with waffle type of slab system, with the difference that the maximum column cross-section dimensions at the base story level are b/h = 90 cm/90 cm (Fig. 2).

In general, it is obvious that the waffle slab system, being lighter than the solid type of slab system, imposes more flexible bearing elements along the height of the structure, namely columns and walls.

3.2 Modal Analysis

The increased flexibility of the 14-story building structure with adopted waffle system for its slabs, can be clearly depicted from the modal analysis results. In the following Fig. 5 are shown the first nine modal periods of vibration for the building structure considered with both solid and waffle slab system.

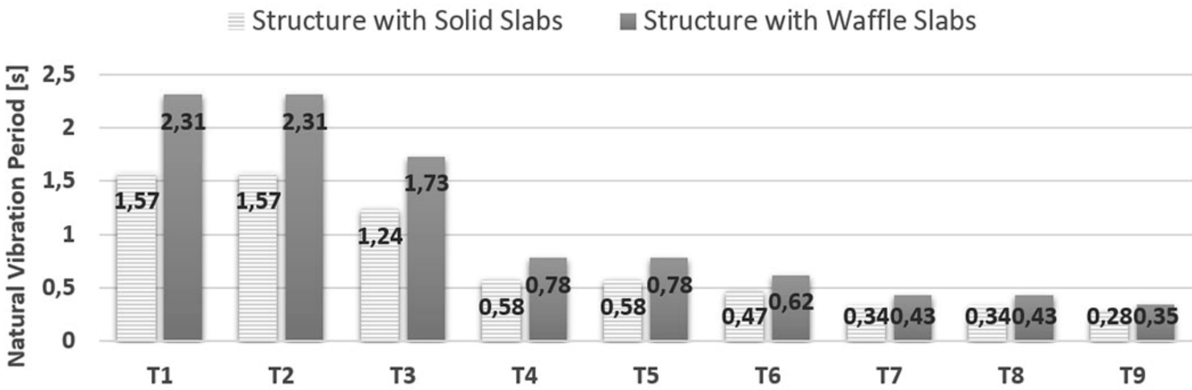

Fig. 5 Natural periods of vibration for corresponding modal modes.

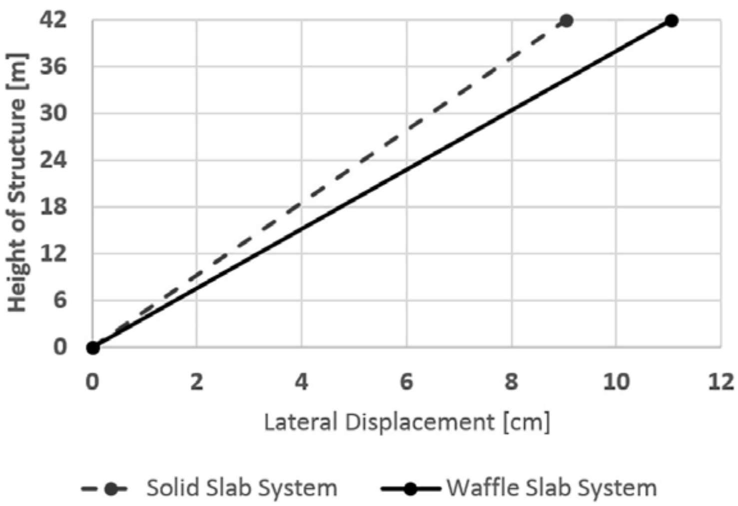

Fig. 6 Lateral building displacement due to seismic design actions.

Fig. 5 shows remarkable differences between the two slab systems. The first vibration periods of the structure with waffle slabs "WS6" show about 150% higher values than for the structure with solid slab "SS16".

This increase in flexibility for the 14 story structure with adopted waffle slab system is not only due to utilization of more flexible columns (columns with smaller cross-section dimensions) but also due to the higher flexibility of the waffle slab connection with the column elements.

3.3 Response Spectra Analysis

In order to consider the seismic action effect in the analysis and design of the 14-story buildings, a response spectra analysis was performed. The analysis results derived from response spectra, Figs. 6 and 7, clearly demonstrate the beneficial effect of the lighter and more flexible structural system in terms of economy, and structural safety.

For both types of buildings, the input parameters of the response spectra analysis were kept identical. The expected seismic PGA (peak ground accelerations) was assumed to be 30% of gravity acceleration g. Moreover, the ductility factor was adopted to be $q = 3$.

Fig. 6 shows the maximal lateral displacements of the 14-story building with consideration of solid and waffle slab system. According to Fig. 6, the building with waffle slab system has larger lateral displacement in respect to the same building consisted of solid slab system due to the higher flexibility of the waffle slab system.

The importance of flexibility of the structure may be even better demonstrated in Fig. 7, where along with the magnitude of building loads and generated seismic shear forces, is also shown the ratio of seismic shear forces in relation to the modal load at the base of the structure. In Fig. 7 can be seen that the ratio of the seismic shear forces over the modal loads of the 14-story building with solid slab system is about 14%, while for the same building with adopted waffle slab system is minimized down to about 9%. This means that the building with adopted waffle slab system, being lighter and more flexible absorbs smaller seismic shear forces in comparison to the same building with adopted solid slab system. More specifically, according to Fig. 7, in the building with solid slab is generated about 411 t of shear force at the base of the structure, while for the building with waffle slabs is generated somewhat less than half its value, respectively 211 t. In other words, the absorption of seismic actions in this building is almost doubly reduced by slightly simultaneously reducing the building mass and increasing its flexibility, respectively by changing the slab system from solid to waffle type.

4. Comparative Study of Results

After completion of all structural analysis techniques, the design process considering all of structural members of the 14-story building has been performed. The design criteria of all structural members, i.e., slab, beams and columns, were in full compliance to the Eurocode 1, Eurocode 2 and Eurocode 8 design provisions. As a result, besides the determination of the volume of concrete for the entire structure, it was also estimated the quantity of the steel reinforcement for the overall structure. In addition, considering the material costs of both concrete and steel reinforcement, and also considering the quantity of concrete and steel used in the building, it was derived the cost of utilized material per square meter.

These parameters have been defined for the 14-story building with consideration of both solid and a waffle slab systems. These results, presented in Fig. 8, clearly depict the beneficial features of the 14-story building with waffle slab system in terms of economy.

According to Fig. 8, by replacing the solid slab system of a 14-story building (Fig. 1) with a waffle slab system, there are 20% of savings in concrete volume and 27% of savings in steel reinforcement. Considering the prices of 65 €/m^3 for concrete and 730 €/t for steel reinforcement, the financial savings for adopting a waffle slab system over the solid type of slab are 14 €/m^2.

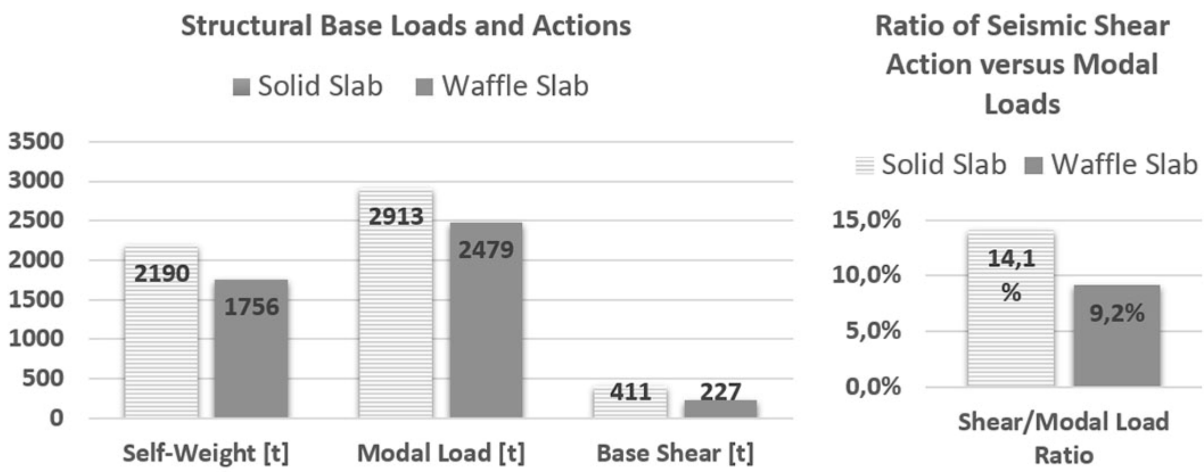

Fig. 7 Structural base loads and ratio of seismic base shear vs. modal loads.

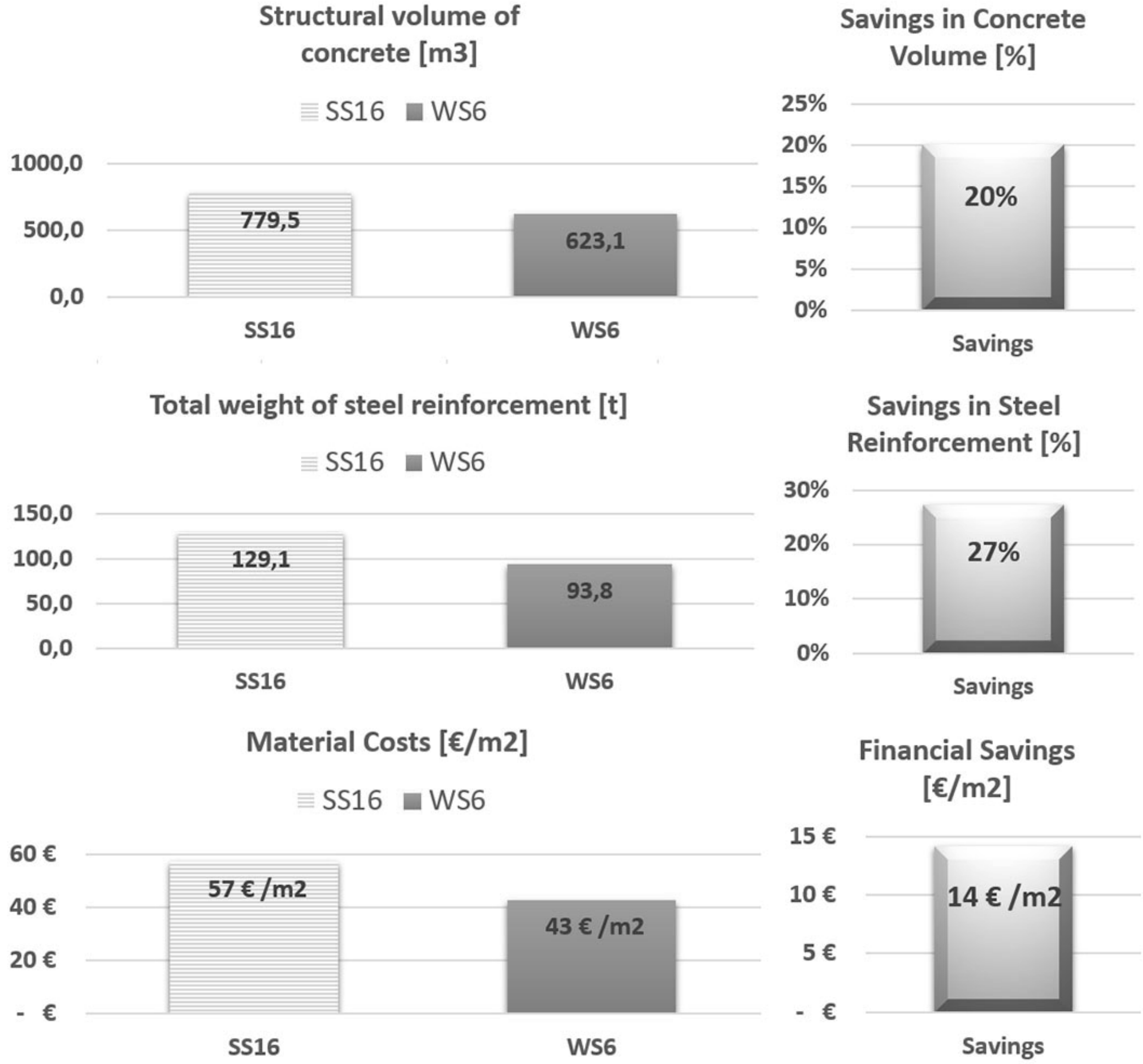

Fig. 8 Solid vs. waffle slab comparative results in terms of material and financial savings.

5. Conclusions

As a closing remark it can be reiterated that the benefits of using a waffle slab system over the solid slab system are significant not only in the sense of achieving a lighter and economical structure but also in the sense of providing a safer structure with improved level of seismic performance in seismic design situations.

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