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Comparative analysis and design of solid ribbed and waffle slabs for residential buildings: A review

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DISCOVERY
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ABSTRACT

The choice of economic reinforced concrete slab for residential spaces has constrained slab types to be rigid with closed supports and framed construction partitions that require demolitions before adjustment or absolutely inhibit a change of use. This restrains slab design to offer lesser clear spans as the most economical option for residential buildings. Most research have considered the use of Ribbed and Waffle slabs for commercial buildings, but this ignored the rising demand for the concept of space adaptability and flexibility of residential spaces. Residential buildings should offer spatial functionality that creates social symbiotic connections between the end-users and the building to avert the loss of value attributed to change of use, cumbersome renovation routines and displeasure of conformations. Structural engineers must integrate structural safety, integrity, stability, economy, aesthetics and user satisfaction, without compromising the ease of construction, sustainability and trending demands of innovation. Using synopses from previous studies, this paper reviewed the comparative analysis and design of conventional solid, ribbed and waffle slabs for a five-storey residential building with respect to an effective, economical, robust and worthwhile option for wide-range residential flexibility. A structural design with the open house concept of clearer-span of residential spaces will enhance sustainability design, produce lightweight structures, minimise cumbersome construction processes and offer multiple user-functionality and long-term satisfaction of residential buildings.

Keywords: Comparative Analysis, Construction, Flexibility and Adaptability, Reinforced concrete Slab, Residential Building, Ribbed Slab, Solid Slab, Sustainability, Waffle Slab

1. INTRODUCTION

A slab is that part of a reinforced concrete building which serves as platform between supports, often subjected to bending (tensile or compressive) but in rare cases, subjected to shear (Olawale and Ayodele, 2014). Reinforced concrete slabs are used in buildings as floors, walls, roof decks, foundations and as bridge decks. The floor slab of the building is the horizontal carrier system whose rigidity is relied upon, to resist the horizontal loads that may affect the structure due to the earthquake and seismic actions (Keleş et al., 2021). The different forms of a building floor system include in-situ solid slab, flat slab (with or without drop panel and column head), ribbed slabs or precast units which may span orthogonally in one or two directions. Slabs may also be supported monolithically on concrete and steel beams, walls or supported by columns (Mosley et al., 2012).

The reinforced concrete slab plays a major role in having clear span in building structures. It relies on thickness for its flexural strength, thereby requiring heavier mass of concrete and reinforcement to cater for its self-weight and supported load (Midkiff and Kramer, 2013). The deadweight of slab ascribed to its greater thickness for strength, makes the slab susceptible to deflection and also necessitates increases in beams, column, foundation sizes and consequent floor-to-floor heights in buildings (Bhade and Barelikar, 2016). Deflection in reinforced concrete slabs is a significant criterion for design. This greatly affects the required thickness, give constrains and limitations on the span length and impacts the choice for slab types and forms. Practically, a deliberate control of deflections is achieved by observing the span/depth ratio rule (Tovi et al., 2017).

2. VARIETIES OF REINFORCED CONCRETE SLABS

Concrete slabs vary by type of frame construction. When designing a traditional flat plate, it is desired to achieve a more open layout by utilizing larger column-to-column spans and reducing the thickness of concrete slabs. However, this has been a competing challenge for designers and researchers in engineering (Midkiff and Kramer, 2013). Commendable efforts have been achieved at comparing the forms and methods of reinforced slab systems. This is intended to reduce the weight of concrete slabs while maintaining the flexural strength, economy and aesthetics, ease of construction and maintenance (Midkiff and Kramer, 2013; Qavi et al., 2018). The risk of deflection and cracking must be carefully noted while achieving a larger or clearer slab span by reducing the bulky mass of slabs (Alfeehan et al., 2017).

This reduction in weight can be achieved by removing part of the concrete below the neutral axis and replacing it with a lighter form of construction. The slab top which is the compression zone is required for fire resistance and flexural strength while the bottom which is the tension zone bonds with reinforcement for rigidity. This becomes economical for buildings with clear spans beyond 5 meters used for light or moderate live loads, such as in hospital wards or sizeable apartment buildings (Mosley et al., 2012).

Slab Spanning Direction

Reinforced concrete slabs are usually classified based on the flexural stiffness of the slab and the span-length ratio in the two principal horizontal directions (Wight and Macgregor, 2012). The type of slab system notwithstanding, this classification determines if the slab would be designed as either one-way or two-way. The span is the route with which the load is being carried. One-way spanning systems are held continuously on the two reverse sides and the applied loads are supported along one direction only. The analogical bending moments and shear forces are minimum along the short span; this consequently results in the frequent spanning of the One-way slabs along the short direction (Bhaduria and Chhugani, 2017).

Considering Figure 1a, the slab panels between the beam supports have relatively short span lengths in one horizontal direction compared to their span lengths in the perpendicular direction. The flexural stiffness of this structure is inversely related to span length and the slab panels would be much stiffer in their shorter span direction than in the longer span direction (Wight and Macgregor, 2012).

Consequently, a higher proportion of the load would be supported in the short span direction as compared to the long span direction. It is common practice therefore, to provide flexural reinforcement to resist the entire load in the short direction for such reinforced concrete floor systems with the ratio of the longer span to the shorter span, greater than or equal to 2. However, it is necessary to provide minimum reinforcement for temperature, cracking and shrinkage effects in the long direction (Wight and Macgregor, 2012; Bhaduria and Chhugani, 2017; Harish et al., 2017). One-way slabs may be solid, hollow or ribbed (Hoffman et al., 1998).

However, two-way slabs are designed such that the flexural reinforcements would be provided in the two principal horizontal directions of the slab panel (Wight and Macgregor, 2012) to enable it to effectively support the applied loads in both long and short directions (Bhaduria and Chhugani, 2017). The ratio of long span to the short span is less than 2 as shown (Figure 1b). This ratio determines the conditions of restraint at each support and the amount of bending in each direction.

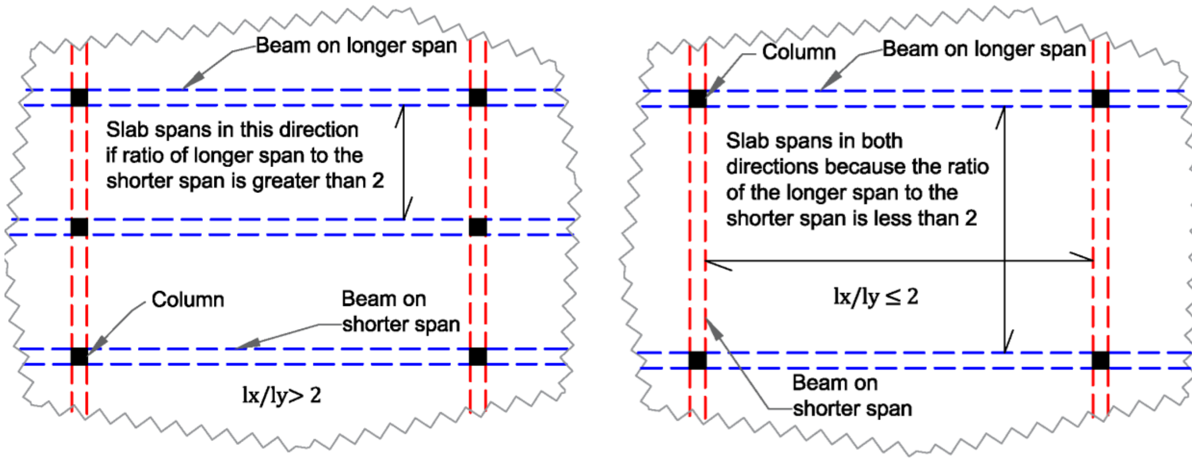

Figure 1 (a) Typical One-way spanning slab system and (b) Two-way spanning slab system

For rectangular shaped slabs as in Figure 2, more than one-half of the loads will be carried in the stiffer, shorter direction and less in the longer direction but if the slab is square and the restraints are similar along the four sides then the load will span equally in both directions. Though the design approach for one-way slabs is easier because less calculation and details are required than the two-way slabs, the load applied to the one-way slab is transferred in one direction to the beams and then to supporting girders and columns. This consequently results in deeper structural members and larger floor-to-floor heights (Wight and Macgregor, 2012). The spanning direction of reinforced concrete slabs is important for all types of slabs as it determines the rigidity of supports and the direction of flexural reinforcement.

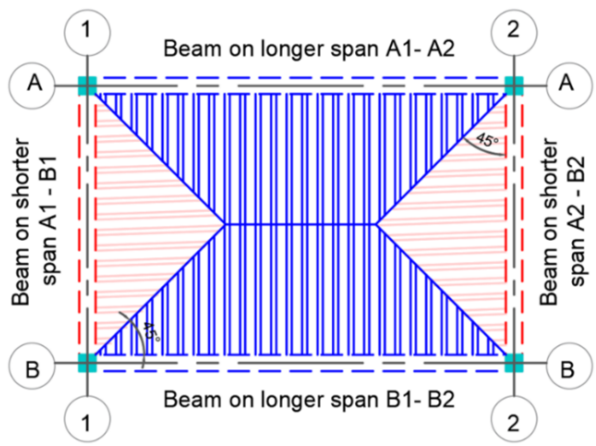

Figure 2 Load magnitudes on supporting beams

The Solid Slab

The solid slab is that conventional slab system, monolithic across its section and transfers its loads on beams or girders. It may either span in one direction or in both directions (Figure 3).

A simply supported slab, transferring its loads on all four sides will deflect about both axes under the corresponding load. The corners will tend to lift and curl up from the supports, causing torsional moments (Wight and Macgregor, 2012).

With proper reinforcement detailing, reinforced concrete solid slabs should be able to offset a clear span (spanning between columns without the support of intermediate beams and girders) of up to 6m by 0.250m thickness or less with the strength benefits of reinforced concrete (Midkiff and Kramer, 2013). But as the superimposed load increases on slabs, the slab thickness also increases with consequent self-weight of the bulk of concrete in order to resist deflection of the slab element (Wight and Macgregor, 2012; Tovi, 2017).

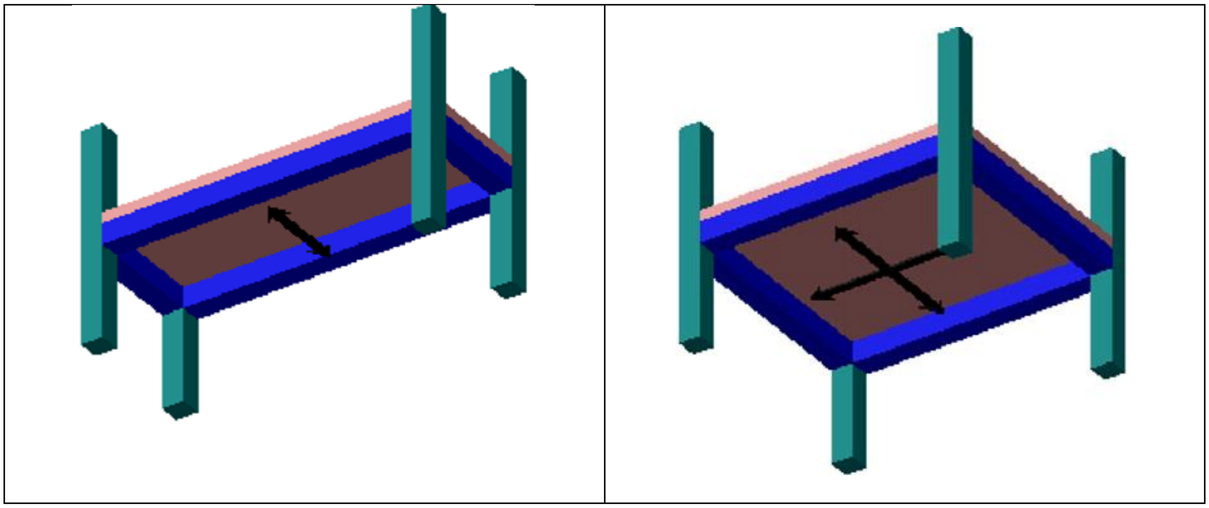

Figure 3 Solid slabs (i) spanning one-way and (ii) spanning in both directions (two-ways)

The consequent increase in solid slab thickness requires more formwork, larger mass of concrete with reinforcement and increase in total weight of the building structure (Midkiff and Kramer, 2013; Bhade and Barelikar, 2016). To achieve a design with considerable savings in construction time and costs, hollows, holes or voids supported by joists or other systems may be created in the slab to deliberately avoid the ineffective concrete in the neutral zone of the slab, thereby decreasing the dead-weight of the slab and increasing the slab efficiency (Shabbar et al., 2010; Dosumu and Adenuga, 2013; Ogyiri, 2014; Bhade and Barelikar, 2016; Abuna, 2017; Bhowmik et al., 2017; Yousuf and Shelar, 2020).

However, two-way solid slabs are known to be more efficient with higher load carrying capacity than the one-way solid slab system. This is because the two-way solid slab transfers its load on both sides (Wight and Macgregor, 2012; Malviya and Tiwari, 2020).

The Ribbed Slab

Ribbed slabs, also called joist slab (Malviya, 2021) are those reinforced slab systems which utilises the supports of parallel reinforced concrete ribs, joists or T-beams which are framed integrally to reinforced concrete girders (Mirza et al., 2021). The slab makes up the flange of the beam while the extended joist or beam which makes up the web is known as the ribs. The joists are wide band beams which run through amid columns, having narrow ribs with equal depth across the orthogonal direction. The concept of the ribbed system is an evolution of solid slab system, whereby the large part of concrete below the neutral axis, which makes little contribution to ultimate strength, is eliminated. The resultant voids reduce the slab thickness and weight, producing a lightened, efficient and economical use of materials (Schwetz et al., 2014).

As in Figure 4, the ribs are usually tapered and spaced uniformly on girders as supports which transfers the slab loads on columns. The rib spacing may be formed by removable forms or shaped by permanent light-weight hollow blocks of standard dimensions (Hoffman et al., 1998; Galeb and Saeed, 2020).

Ribbed slab is quite effective in moment resistance by optimizing the effective depth and the percentage of reinforcement. It is used for larger span of slab and floor where fewer numbers of columns are required (Malviya and Tiwari, 2020).

Figure 4 Ribbed slab with joists spanning one-way with utility groove for Mechanical and Electrical Piping (MEP), constructed with Modular formwork by SKYRAIL® (archiexpo.com)

The Waffle Slab

The waffle slab is like the ribbed slab, but the support joists are deeper and are not in one-direction but intersecting. The mutually perpendicular direction of the bottom grid arrangement of this system looks like a waffle and hence, the name. The waffle slab thickness is controlled by the depth required to transfer shear and near the columns, the full depth is retained for shear transfer of loads from the slab to the columns (Wight and Macgregor, 2012; Midkiff and Kramer, 2013). Waffle slabs contain a skinny topping slab and thin ribs across mutual directions among column heads or band beams. The column heads or band beams contain the identical depth as the ribs. The top surface is flat while the waffle-grid appearance is made by removable fibre-glass or metal-dome moulds temporarily placed with formwork at the bottom (Wight and Macgregor, 2012).

Though the formwork in form of moulds may require large financial investment, it offers greater advantage when reused in repeated works. Vertical penetration between ribs is easy with the Waffle slab offering structural stability with considerable reduction in the use of materials, gives attractive soffit appearance if exposed and reliable for areas largely flat like foundations or larger, clear-span floors and roof construction, with the use of square-grid having pronounced ribs with coffers in the interstices (Sarita et al., 2016; Yousuf and Shelar, 2020).

Waffle slabs are mainly used when span requirement is greater than 12 meters. It is known as the two-way joist slab and its reinforcements are designed to resist flexure in both directions (Midkiff and Kramer, 2013). This two-way spanning direction gives it an edge over other slab types where it is required to support heavy loads along a long clear span. Waffle slabs perform greatly when rigidity and minimal vibration are required, especially in large open-space facilities (Malviya and Tiwari, 2020).

The Waffle slab system reduces the challenges of slab deflections and allows easy installation of mechanical and electrical services, air-handling ducts within the structural depth. The loads are better evenly distributed to the slab supports while all elements of the hollow grid enhance the flexural resistance (Bhatia and Golait, 2016; Harish et al., 2017).

Waffle slabs have economical and constructional benefits. They perform showing higher stiffness with little deflection favourable for heavyweight loads and large spanning structures (Ghanchi and Chitra, 2014; Bhatia and Golait, 2016). The waffle slab is aesthetically pleasing and ideal solution for larger clear spans and therefore adaptable, energy efficient and seismically safe for public and residential buildings. The typical utility groove for MEP is as in Figure 5 (Malviya and Tiwari, 2020).

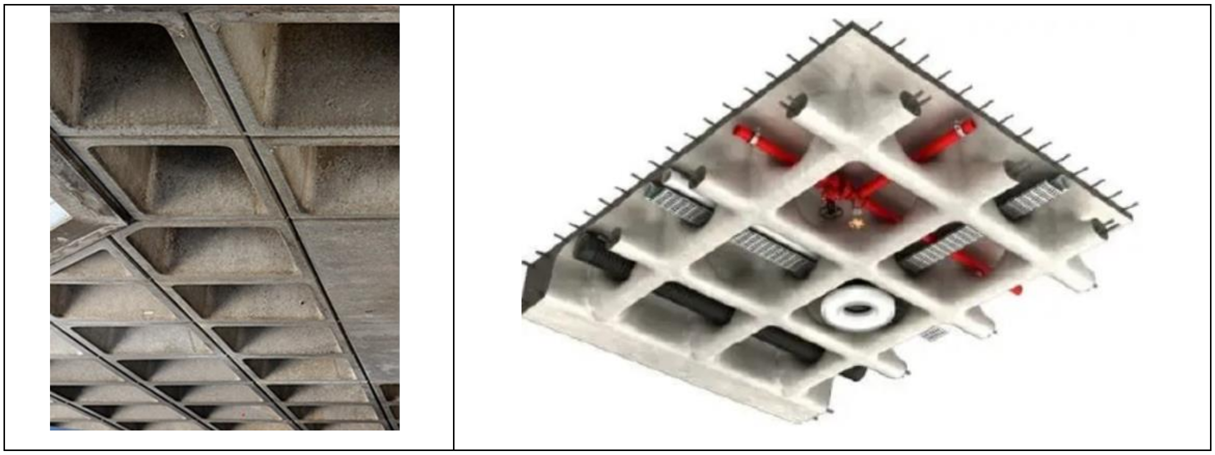

Figure 5 Typical Waffle RC slab (a) plain (Malviya and Tiwari, 2020), (b) with utility groove for Mechanical and Electrical Piping (MEP)

Essential Characteristics of a Robust Reinforced Concrete Slab

New or recent investors who seek to maximize profit, time and achieve cheaper projects in real estate berate the value of design in which their actual profit could be rooted if they are up on professional knowledge of design variation and construction economics (Kekanović et al., 2017). Solid slab deflection increases as more loads are required to be supported by the slab, especially with clearer span between columns and supports. The consequent increase in solid slab thickness requires more formwork, larger mass of concrete with reinforcement and increase in total weight of the building structure (Midkiff and Kramer, 2013; Bhade and Barelikar, 2016).

Researchers are concerned and efforts are intensified at reducing the deadweight of slab (Shabbar et al., 2010; Alfeehan et al., 2017). This can be done by the reduction of the concrete below the neutral axis (Wight and Macgregor, 2012; Dosumu and Adenuga, 2013; Bhowmik et al., 2017; Malviya and Tiwari, 2020). This reduction could be up to fifty percent (50%) to deliberately create a smaller column size and foundation because leaner floor slabs will automatically provide lower building weight and more headroom (Bilek et al., 2005; Bhade and Barelikar, 2016). This intentional reduction of slab construction expenditures and a corresponding reduction in other structural elements will yield an economic savings with associated time, labour and wide range of cost and other construction benefits (Midkiff and Kramer, 2013; Adenuga and Sotunbo, 2014; Anjaneyulu and Prakash, 2016; Bhatia and Golait, 2016; Bhowmik et al., 2017).

For residential buildings, the design and construction of solid reinforced concrete slab with required thickness of minimum 20 centimeters has no justification as such floor slab thickness hinders architectural creativity by limiting the clear distance between columns, load-bearing walls and other types of supports. Beyond this hinderance to space flexibility and adaptability, massive slab thickness also directly amplifies the seismic impetus it precipitates and produces high heat capacity (Aladžić et al., 2019).

Financial Efficiency

Execution of tasks in a well-timed, cost-effective manner with suitable estimation plays a major role in building construction from project conception, through the planning phases, executing, monitoring, controlling and up to the project culmination. The different available construction methods, procedures and techniques form the variation in the overall quantity and cost of projects (Nassar and Al-Qasem, 2020).

Relatively, the cost of structural slabs towers statistically beyond other structural elements of a building. This is because most of the structural framework is usually attributed to the largest component and the horizontal elements. Consequently, the choice of the structural slab system and type is usually the imperative design tool for economic considerations in design and construction (Anjaneyulu and Prakash, 2016).

The form of use, span directions, mode of support, production and construction method employed in the use of reinforced slabs constitutes the variation in costs which in turn affects the overall costs of building projects (Dosumu and Adenuga, 2013). Therefore, any savings achieved from the floor system will substantially reduce the overall building cost (Adlakha and Puri, 2003; Ogyiri, 2014).

The concrete mass, reinforcement and formwork constitute the cost function for the slab. The required cost of floor slabs is influenced by increases in span length of slabs and compressive strength of concrete increases (Flynn and Kulzer, 2012; Anjaneyulu and Prakash, 2016; Zekirija and Isak, 2017; Galeb and Saeed, 2020).

Ease of Construction and Environmental Impact

Studies on return on investment (ROI) as well as quality improvement in the construction of midrise buildings, faster, easier construction method and reduced quantity of materials to curb environmental impact have been relatively scanty for the building construction phase (Paik and Seunguk, 2020), compared to other stages of development (Stuart and Kate, 2012). This can be optimised while maintaining the satisfactory quality of building safety and performance (Zekirija and Isak, 2017).

A process-based quantitative model which was used to evaluate the environmental impact of different slab construction methods in a building revealed the environmental impacts from the conventional solid slab are the highest over other types of voided or hollow slab systems (Paik and Seunguk, 2020).

Seismic Performance and Safety

Heavier structures are more susceptible to seismic forces and the need to fortify the structure with a lateral force resisting system, heightening the affordability of residential structures. This vulnerability among other reasons prods engineers towards the reduction of weight in slabs. Lighter structures are preferable than heavier ones because larger dead load increases the magnitude of inertia forces which the structure must resist due to the higher seismic weight implied by large dead load. Increasing the seismic performance of slabs consequently requires the reduction of the dead loads, leading to smaller components and reasonable cost savings (Midkiff and Kramer, 2013).

Flexibility and Adaptability

Owing to complex cues from economic adjustments, improved technologies, intensified environmental concerns, growing customer expectations, dire market competitions and the cultural revolutions of the contemporary society, residential construction is being greatly influenced to motivate research and development of design adaptability (AD) as an emerging paradigm for engineering design (Hashemian, 2015).

Several quantitative and qualitative studies are proving that residential end-users will eventually change their floor plan arrangements in the events of time (Esin-Altaş and Özsoy, 1998; Larissa, 2013; Minami, 2016; Aladžić et al., 2019; Femenias and Geromel, 2020; Kamara et al., 2020). Flexibility has turned out to be a significant modernist term in residential architecture. The concept of flexible architecture is pertinently dynamic; in place and in time, in size/shape and in purpose, free of borders (Larissa, 2013).

Beyond other transformations are the family crux and the several activities executed in living spaces. Residential design and construction must, therefore, offer the possibility of housing flexibility and structural modification which attempts to satisfy the numerous needs of users by reconfiguring their living spaces and functions over time. This is based on extending the lifespan of residences by avoiding obsolescence due to changing needs and embracing sustainable consumption that conforms to recycling and waste management. Therefore, flexibility permits a long-term use and relevance of residential buildings by means of adaptations with assurance of continual utilization (De-Paris and Lopes, 2018).

Residential spaces should not be rigid but offer chances for adjustment of spaces to the need of the user and enable flexible structures whose parts could be easily replaced, reused or recycled (Nwadiogwa, 2011). Such slab systems with longer clear spans affords architectural freedom as it allows for less columns and supports while it offers more interior space (Midkiff and Kramer, 2013).

Space flexibility and adaptability and lifecycle consideration of residential spaces is therefore, necessary for clients, designers, construction managers and investors as it aids optimum floor systems, with increased sustainability and reduced environmental impacts. The whole lifecycle impact of construction and serviceability phases have been considered as it reduces the needs for new raw materials after demolitions, repartitioning and remodelling of internal walls (Wang et al., 2018).

Adaptability is the quality of a building which by design, intentionally provides for subsequent adjustments and alterations to be made to its physical fabric (Sundharam et al., 2004). Being able to adjust to different user functions (Kielion, 2008), adaptability in its versatility, averts the consequences of climate change and building redundancy, encourages sustainability through prolonged building serviceability and useful life with minimal use of resources. Adaptability is therefore, a design approach with focus on deliberately designing for change with the Open Building concept (Kamara et al., 2020). A sense of space satisfaction would be created for end-users when they are directly connected to structural flexibility and considered during initial design that they might customize their space layout in future (Abbasian et al., 2017).

3. COMPARATIVE REVIEW OF REINFORCED CONCRETE FLOOR SLABS

Adenuga and Sotunbo, (2014) assessed of time variation in solid and hollow floor construction in Lagos State. Their work surveyed the variations in the cost of construction methods for ribbed slabs and normal Solid slabs in Lagos state. Utilising a quantitative survey via structured questionnaires, site investigation and review of past projects, journals, conference proceedings articles and the internet. The survey tools were tested via non-probabilistic and specifically convenience sampling technique (descriptive tools such as frequencies, percentage and mean values). The study showed the economic relief of using the ribbed slabs instead of Solid slab and recommended adequate and careful analysis in the choice of floor system being adopted for any project.

Kibkalo et al., (2016) explored coffered slabs as a perspective type for reinforced concrete structures. The article reviewed the technology of construction arrangements of Ribbed and Waffle slabs as coffered slabs. Cast-in-place and precast ways of coffered slab were reviewed with the aim of expressing the economic and technical advantages of the Ribbed and Waffle slabs over the normal reinforced solid slab. They recommended that the reinforced solid slab which declines in effectiveness with clear-span greater than 4.5 meters can be replaced with Ribbed and Waffle slabs, with reduction of self-weight from 40% - 60% while rigidity of the slab is increased.

Singh and Joshi, (2019) reviewed seismic analysis of high-rise building structure, considering flat and grid slabs. In a bid to understand the potential of different slab systems and their utilisation in structural analysis and design, the study investigated up to seventeen previous publications in related quest for efficiency of different type of reinforced concrete slabs over different structures. Their analysis distinguished Grid slab systems which include the Ribbed (one-way) slab and the Waffle (Two-ways) slabs for better performances than the normal solid slabs.

Qavi et al., (2018) researched the comparative analysis and design of flat and grid slab system with conventional slab system. Using the ETABS software, a comparative study of the normal solid slab, flat slab and grid slab (ribbed or waffle slab) in multi-storey building, in respect to their resistance to wind loading and seismic behaviour was researched. The analysis of slab system proved the grid slab system develops the least values in the building torsion, best suitable slab structure for low, medium and high-rise building construction and also, the most economical for all span considered in the analysis. The work also proved use of structural design and analysis software as a very essential tool for quick and accurate results.

Keleş et al., (2021) researched on evaluating the effects of different slab types on static and dynamic characteristics of structures. With the aid of SAP2000 finite element software, the rigidity of beamed decks, flat slabs, ribbed slabs and waffle slab were investigated in relation to the dynamic response of building structures to lateral loading due to the effect of several forms of floor slab systems. The authors modelled some 3, 4 and 5 storey buildings with the beamed slab, flat slab, one-way ribbed (hollow) floor and waffle deck on each structure for comparison. The study proved that horizontal rigidity of building systems is better formed by beams, columns and walls created in beamed slab, ribbed slab and waffle slab systems.

Shabbar et al., (2010) studied the comparison between ribbed slab structure (using lightweight foam concrete) and solid slab structures (using normal concrete) to validate the fact that one-way ribbed slab made of lightweight foam concrete can be used to cut-down the dead load on normal solid slab concrete structure. Their methodology included some laboratory tests for both density and compression strength and the analysis and design made using the ESTEEM® software. The result showed that for the construction of multi-storey residential buildings, one-way ribbed slab with beam is more cost efficient than the two-way solid slab with beam. However, the study did not consider the clear span of the slab and reduction of column supports.

Galeb and Saeed, (2020) explored the optimum design of reinforced concrete one-way ribbed employing the concept of genetic algorithms by the ACI method of coefficient with the aid of a MATLAB computer program. Their research compared the optimum design outcomes of one-way spanning ribbed floors with the two-way spanning ribbed floors and four cases of flat slabs. Their result showed that the one-way ribbed slab is more cost-effective compared to the doubly-spanning ribbed slabs with a clear-span of 7-12meters; the one-way ribbed slab is also more efficient when compared to the flat slab without edge beam at a clear-span of 12meters; and for clear-span 10meters, the one-way ribbed slab is more economical than the flat slab with edge beams and flat plate with and without edge beams. Also, this research did not consider the adaptability and flexibility of spaces in residential buildings beyond 12meters of clear span.

Though Galeb and Saeed, (2020) and Shabbar et al., (2012) agreed that the one-way ribbed floor is more cost-effective compared to the waffle slab for low-cost residential building with the span length ranging from 7-12meters, they affirmed that the slab cost escalates with longer and clearer span length.

Malviya and Tiwari, (2020) reviewed the behaviour of flat slab, waffle slab, ribbed and secondary beam in a multi-storey building under seismic response. Their article explored the benefits of using flat slabs, ribbed and waffle slabs in multi-storey residential and multi-storey residential plus commercial buildings for clear-span slab and the use of the secondary beam to optimize larger spans under seismic hazards. The analysis was carried out with rigid frame structure under seismic response. Seventeen articles were reviewed, giving affirmations to the preferential use of flat slab, waffle slab, ribbed over the conventional solid slab for large-span structures. The work proved that both waffle slab and ribbed slabs offers effective architectural-aesthetic purposes but the waffle slab exhibits load carrying capacity that is greater than the other types of slabs along with savings on weight and materials, while exhibiting good vibration control capacity and also impacting on fast and speedy construction. They also recommended the adoption of the secondary beams along with the main beam where large span is required to be over 12 meters.

Olawale and Ayodele, (2014) performed a comparative study on the flexural behaviour of waffle and solid slab models when subjected to point loads. The work determined the deflections, crack width, bending moments and examined the structural characteristics of both waffle and solid slab models in reaction to axial load. The work analysed the difference that may occur between theoretical and experimental results, despite the different theories and equations, if the equations may give true representation. Their methodology compared the flexural moments, deflections and crack width at failure of ten different models, each of waffle and solid slabs structures, while the specimens were subjected to an incremental axial loading of 1kN interval after 28 days of curing age. The support conditions notwithstanding, solid slabs failed earlier, had higher deflections, showed early loss of stiffness and formation of large crack width at failure load while Waffle slab displayed greater flexural moments. The work further showed that waffle has higher structural stiffness. The behaviour of solid slabs in deflection and earlier failure demerits its use for large span floor, giving a greater advantage to waffle slabs.

Kekanović et al., (2017) studied the problems of floor slab design in terms of capacity, safety and energy efficiency. The objective function highlights the importance of the load bearing capacity, safety and energy efficiency as key emphases as the design and construction of buildings are being analysed from all possible aspects. The work modelled and compared the waffle slab, ribbed and solid slabs in terms of weight, reaction to seismic actions and accumulation of energy in the Republic of Serbia. This attributes greater stiffness, stability and better resistance during seismic activities to the ribbed and waffle slab due to lower horizontal forces and reduction in self-weight of up to 50% compared with solid reinforced concrete slabs. Aesthetic credits were given to the ribbed and waffle slab in the use of Stirofert-technology, built-in-place with structural expanded polystyrene into the formwork during construction. But the Solid slab is rated low in energy efficiency demand.

Paik and Seunguk, (2020) worked on the comparison of environmental impact of three different slab systems for life cycle assessment of a commercial building in South Korea. Using the Life-Cycle Assessment (LCA) methodology (ISO 14044), an assessment and analytic comparison of the environmental impacts of conventional solid slabs, the flat plate slab and the hollow floored system (Ribbed and Waffle slabs) at the construction stage, improvement and application of novel construction techniques and methods was carried out through a three-fold quantitative model evaluation (Process-based analysis, Economic input–output analysis and a Hybrid approach) for environmental impacts. The environmental impact pointers indicated the decline in tendency from the ribbed and waffle slabs (rated as voided slab systems) while the normal solid slab indicated the highest tendency.

Sarita et al., (2016) explored a comparative study of waffle with flat slabs and conventional RCC Slabs. With the IS 456-2000 guidelines for the design of solid slab, flat and waffle slabs for a particular building, the results of the analysis and design of the various slab systems were compared. The waffle floor requires lesser floor thickness than other floor slab system but may require more investment in formwork moulds which may be reused and offers greater aesthetic values. The authors rated waffle as a better option for reinforced concrete slab system in terms of loading, large spans, aesthetic appearance.

Zekirija and Isak, (2017) carried out a comparative study between waffle and solid slab systems in terms of economy and seismic performance of a typical 14-storey RC building. The objective function was to derive an optimal solution to the building structural system in order to adopt faster and easier construction activities with considerable reduction in the use of construction material, even as the level of building safety and performance is greatly maintained satisfactorily. Their paper made a comparative study between Solid and Waffle slab system using a typical 14-story RC building structure. An optimal solution for a solid and waffle slab systems were derived and the solid slab and Waffle slabs were analysed and designed in compliance with the provisions of Euro code (1, 2 and 8). The various effects of both slab systems on the general building model was later compared and analysed in terms of structural performance, economy and structural safety (Singh and Joshi, 2019). The research showed an improved level of seismic performance in seismic design situations and savings in concrete volume by 20% and 27% of savings in the rebar by replacing the solid slab floor system of a 14-storey building with a waffle slab system.

Harish et al., (2017) worked on the analysis and design of grid slab in building using response spectrum method. With the aid of ETABS software, A G+4 (Ground plus four floor storey) building was analysed and designed for gravity, seismic and wind loading conditions in accordance with the IS codes. The seismic integrity of the ribbed slab and waffle slab with respect to seismic activities was analysed, using the Equivalent method and Response spectrum method. The authors recommended the design of multi-storey and complex slab systems with Software loads.

Aladžić et al., (2019) studied the Traditional thick concrete floor slabs–an obstacle to the flexibility, energy efficiency and seismic safety. The objective function demonstrated the simultaneous synergy and correlation between flexibility-adaptability, energy efficiency and seismic safety and self-weight in the design and constructing of floor slabs in residential buildings. Their research related mass of solid slab to high volumetric heat capacity as it also directly intensifies the seismic forces it induces. The authors skilfully explored the contemporary concept of living space flexibility through inhabitant-based spatial model analysis of same architectural plan in twelve different layouts. They prescribed an equation-based reduction analysis of a lightened waffle slab up to 45% of the conventional thick, solid concrete slabs. They recommended the open-plan design with two-way spanning waffle slabs for higher spatial flexibility and adaptability of the residential building. This review is a key-link between the choice of lightened slab thickness with larger clear-span of the open plan structure and the design concept of architectural flexibility and adaptability.

Review of the Concept of Flexibility and Adaptivity of Spaces

Adaptive reuse of buildings is a major criterion to sustainability. From the concept of adaptability and flexibility, the interstitial space provides the virtual elimination of obstructions caused by columns, mechanical shafts and other vertical supports in building structures (Sundharam et al., 2004). Therefore, a regard to this concept is quite germane for the design and choice of reinforced concrete slab for residential building. A review of relevant articles is highlighted as follows.

Larissa, (2013) worked on flexible architecture for the dynamic societies; reflection on a journey from the 20th Century into the Future. Through theoretical concepts and objective case-studies, the research evaluated the relationships and disparities of flexible architecture between the 21st century and modernism. Adaptability also characterizes the future as infinite and must adjust to the prevailing user-functions activities. Though buildings may initially have distinct purposes, must be open to operate for all kind of different others. This adaptability function classifies such structures as open building, with loose-fit space that can be easily accommodated at the later stage. The open building strategy considered the most formalized strategy for adaptable structure. The process of change can be continuous and on-going, as it involves different participants to interact in the design of desired space and at different times of building existence. This process is seen as the most momentous attribute to adaptable architecture. The flexibility of the possible layouts gives freedom for users and inhabitants to choose own designer and freedom for the designer to create the desired space the client needs.

Minami, (2016) investigated the efforts to develop more durable life housing with adaptability in Japan. The research investigated the life of housing and its adaptability over time in Japan in response to the Long-Life Housing Law in 2009. Using a review two experimental projects in Japan and questionnaire technology in researching the product outcomes to determine viability of the intended adaptability over the thirty plus years of occupancy. The research confirmed the effectiveness of the concept of Open Building with movable partitioning system and a conventional remodeling system, which focuses on adaptability with time, as an ace player in Japan's future.

Esin-Altaş and Özsoy, (1998) worked on spatial flexibility and adaptability as variables to measure users' satisfaction for quality housing. The adaptability of the original plan arrangements of 16-20 years old dwellings within two regions in Istanbul were investigated by evaluating the social characteristics as well as the physical characteristics of the settlements. The methodology comprised the data of several statistical analyses, physical, as well as spatial analyses of four plan types having 2-bedroom units in critical size evaluation for the user's degree of satisfaction. The Contextual assumptions for space consciousness were functions of dwelling size and space size, space organizations and spatial changes and alterations. The research emphasised the complex relation between the perceived space and real dwelling size in terms of space organization and recommended the proper design of open plans and spatial freedom as incentives for flexibility and adaptability in residential structures.

Akindamini, (2020) reviewed flexible housing; a solution to housing problems in Nigeria. The objective function reviewed the studied cases in relevance to the housing situations by examining the cost analysis of user-changes in buildings and the climatic implication of the cases studied if adopted. The research highlighted six motivations for flexibility in design of buildings in terms of enhancing the efficiency of limited space, economical consideration, modernity, user participation (choice and interior variability), function uncertainty in the future and adapting to the upgrading of building facilities. Mass housings being deserted for lack of functionality, thereby wasting limited urban spaces, building reconstruction/remodeling and dire use of natural resources can be curbed by offering the typological variety of initial and permanent flexibility as a design concept. The paper discussed the concept of design based on four themes: Structural system, service spaces, architectural layout and furnishing for flexible use.

Femenias and Geromel, (2020) explored adaptable housing. A quantitative study of how end-users' reconfiguration affects contemporary apartment layouts. The study delved into a search for quantitative correlations of spatial layout and its general or polyvalent use and in contrasting perspective, between the form and layout of residential apartments and their potential compliance with future changes. The methodology comprised an empirical study documenting the renovations conducted by the end-users in a modern Swedish residential apartment with the aim of highlighting the synergy between the design of spatial layout and their adaptability over time. A questionnaire enquiry revealed the layout transformation of recently built apartments by wall restructuring and remodeling which led to material flows and consequential climate impacts, which could be averted with intentional spatial design for functional qualities, adaptability and flexibility of such apartments. The initial design of residential buildings should henceforth acknowledge end-user's motivations for rearranging their living space, which eventually would avert the limitations in choosing a suitable apartment and control changing household needs.

Abbasian et al., (2017) studied the use of flexible structures in Tehran residential spaces to respond better to the changing needs of its residents. The objective enhanced space satisfaction by applying the technology of movable structures in housing, to create spatial flexibility and mobility for intended spaces in anticipated response to end-user's need. The methodology assessed the qualitative indices of a targeted survey of four groups to evaluate their tendencies towards the dynamic or the static space arrangement in residential dwellings. The research distinguished the end-user's functionality aspects as a major uncertainty in the original design and recommends the factors of flexibility as the need to provide possible essentials for spatial flexibility according to the anticipated need of the end-users and thereby, exploiting the space optimally.

4. ROBUST FLOOR SLAB DESIGN FOR RESIDENTIAL DEVELOPMENT

From the comparative review of reinforced floor slabs generally, the right selection of slab system for weight reduction and the achievement of clearer span creates many benefits that is worthy of consideration by Engineers determining the structural system of buildings (Midkiff and Kramer, 2013). Therefore, lighter-weight slabs are imperious choices, not just for economic impacts but also for social and environmental impacts in building construction (Wang et al., 2018). Nevertheless, the serviceability of such lighter-weight slabs must be considered because of vibration forces. Engineers must strategically determine the correct configurations, members and component sizes of the structure to resist the required loads while minimizing project costs without compromising in any way, the structural integrity of the building (Flynn and Kulzer, 2012). Hence, the flexural rigidity of the slab system in use must also be thoroughly considered (Aladžić et al., 2019). Rigid slabs reduce the expansion of foundations and give respite for resistance against slab vibration that occurs in large spanned structures (Ribbed and Waffle slab Construction, 2021).

5. CONCLUSION

This review work has demystified the vintage pursuit for spatial functionality of residential buildings with respect to adaptability and functionality. The floor slab of a building is the horizontal carrier system element that provides space, functional connection and rigidity to the structure. The choice of a floor slab greatly affects the overall building weight, the entire building height and cost of the building. The average residential building receives the demolition blows more than the commercial types because of rigidity of space and functionality that short-lived the varying needs and satisfaction of the end-users. However, the evolution of the conventional reinforced concrete slab offers more options of lightweight slab systems that are financially efficient, ease of construction and maintenance, averts incessant environmental impacts and overuse of raw materials involved in building reconstruction, reduction of demolition noises, assures safe seismic performance and the innovative choice of adaptability and flexibility of space for user-satisfaction.

Despite vast information from previous studies on the use of improved slab systems like the ribbed and waffle slab which offers greater advantages than the solid slab, developers still defy their use in preference to solid slab due to the perspection of high construction cost, need for construction moulds and the comfort of familiar construction method of the solid slab. To fill this gap, this elaborate review of the synopses of previous research has linked the various needs for a robust floor slab design for residential development and hopefully dissolves the myth that the option of grid floor slabs of greater clear-span than 12meters is not economical for residential buildings, there by rendering the conventional solid slab as the tenable choice. Contemporary structural designs must integrate safety and stability with economy, aesthetics and user satisfaction, without neglecting the ease of construction, reuse of formwork, sustainable developmental goals and trending demands of innovation.

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Data and materials availability

All data associated with this study are present in the paper.

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