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Flexural behavior of reinforced bubble arch slabs: A Review

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ABSTRACT

Concrete slabs are essential components of any building structure, providing thermal comfort and enhancing the overall quality of life for occupants. However, concrete slabs require a significant amount of concrete for flooring and roofing, contributing to substantial CO2 emissions—over 5% globally from cement production alone. This study explores the reduction of concrete in slabs through the incorporation of high-density polyethylene (HDPE) hollow spheres. These hollow spheres effectively eliminate non-structural concrete from the slab's middle, reducing its self-weight and increasing efficiency. This technique produces slabs that are 35-50% lighter, reducing loads on columns, walls, and foundations, while also cutting costs and CO2 emissions. Additionally, employing arched shapes, known for their structural efficiency, can further decrease material usage and associated costs. By combining arched and bubble techniques, we achieve our goal of creating lighter, more efficient concrete slabs.

1. Introduction

In the realm of building construction, the slab plays a crucial role as a structural element that requires the largest amount of concrete. Originating from Denmark in the 1990s, Jorgen Bruenig introduced the pioneering biaxial hollow slab, now famously referred to as the bubble deck slab. Distinguished by its innovation, the bubble deck approach surpasses conventional concrete flooring systems in sustainability, boasting reduced concrete usage and minimal CO2 emissions during production. This method aligns with environmental sustainability criteria by incorporating recycled plastic spheres [1].

By enabling the recycling of the spheres even after the building undergoes demolition or renovation in the future, the bubble deck slab dramatically lightens the load by up to 30 to 50% compared to traditional slabs. This reduction in weight alleviates stress on columns, walls, and foundations, benefiting the overall structural integrity. The slab's significance lies in its role as a pivotal structural element that defines the interior space of the building [2]. A slab is a critical component of building construction and a significant structural member that consumes a large amount of concrete. The primary impediment to concrete constructions, particularly horizontal slabs, is their high weight, which restricts their span. Therefore, it is necessary to address the span's weakness, reduce the load, or overcome concrete's inherent tension weakness [3].

In general, as the span of a slab increases, its deflection also increases. Consequently, the thickness of the slab must be increased to counteract this deflection. However, increased slab thickness results in heavier slabs, which can necessitate larger columns and foundations,

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making buildings uneconomical. To circumvent the disadvantages associated with increasing the self-weight of slabs, the voided slab system is used.

An arch is defined as a graceful curve rising upwards, supported at its ends. Its main purpose is to boost the ability to carry heavy loads, taking advantage of the way it stiffens due to a special kind of structural action. This feature lets engineers create expansive roof spans and bridge decks using sturdy materials like concrete, or by utilizing systems that resist compression, such as braced metal structures. These methods effectively counteract the main forces of pressure that build up in the arches. Moreover, by working like an arch, it applies a force that is best suited for concrete materials, which, although not very strong against tension and shearing forces, work well under pressure. [4].

2. LITERATURE REVIEW

a. Literature review (Bubble):

In 2012, Salman [5] fifteen reinforced concrete square slabs measuring (1000×1000 mm) with plastic perforations were investigated both experimentally and analytically. Significant variations were observed in the splitting test specimens, with diameters of plastic spheres ranging from 64, 80, to 100 mm. The critical parameters under investigation encompassed the thickness of the slabs, the area of tensile steel (310, 485, and 698 mm2/m), the method of construction (either simple or filigree/semi-precast), and the percentage of Metakaolin substitution for cement content (5%, 10%, and 20%). The application of load was executed through five hydraulic jacks, as illustrated in **Figure 1.** The results revealed that the slab with plastic perforations exhibited a load capacity approximately between 90-100% in comparison to the standard solid slab with a similar thickness. Additionally, there was a noticeable increase in deflection at 0.7Pu, ranging from 17-27%.

In 2013, Mihai et al [6] the behavior of five spherical hollow flat slabs with dimensions of (1500×2850×310 mm) under concentrated load was examined. The specimens were enhanced with varying proportions of steel reinforcement ranging from 0.18% to 0.63%. Analysis of the test outcomes indicated that the type of failure primarily relies on the steel reinforcement ratio. Specifically, flexural failure was observed in slabs with a steel reinforcement percentage below 0.5%, whereas shear failure was evident in slabs with steel reinforcement percentages exceeding 0.5%.

Figure 1. Specimen Testing

In 2014 Sakin [7] studied the punching shear strength of five slabs in normal and self-consolidating concrete (SCC) measuring (1000×1000×80mm) was evaluated. Among these, three slabs were Bubble Decks featuring holes with a diameter of 40 mm made through plastic, while the remaining slabs were solid. Steel fiber reinforced concrete with volume fractions of 0.8% and 1% were utilized to reinforce the critical perimeter located at a distance of 2d from the columns faces in this investigation. The results of the tests indicated a decrease in the ultimate load capacity for voided slabs (without steel) by up to 9% and 13% when reinforced with either 1% or 0.8% of steel fiber, respectively.

In 2015, AL-Gasham [8] a research was conducted pertaining to the structural features of reinforced concrete bubble slabs post-fire exposure. The investigation involved nine RC bubble slab samples, each with dimensions of 270x500 mm, having two different thicknesses: 140 mm and 90 mm. The specimens were all constructed using standard concrete with a compressive strength of approximately 25 MPa. Among them, seven samples underwent burning using a diesel furnace, while the remaining two were left unexposed as controls.

The study parameters encompassed various factors such as different fire flame temperatures (200°C, 500°C, and 800°C), distinct cooling methods (gradual air cooling or sudden water cooling), slab thicknesses (90 mm and 140 mm), and exposure durations (1 hour, 1.5 hours, and 2 hours). Following the cooling process, the samples were unidirectionally supported and gradually loaded until failure occurred.

The results of the experiments revealed a decline in the residual strength of the specimens, ranging from 71.8% to 21.6%, as the fire temperature escalated from 200 to 800 degrees Celsius, along with exposure times of 1 to 2 hours. Furthermore, specimens that underwent sudden cooling exhibited enhanced central deflection and residual flexural strength, elevating the residual strength by approximately 45% and augmenting the stiffness of the samples, in comparison to those cooled gradually. Additionally, augmenting the thickness of the bubble slabs by 56% resulted in a lower strength when contrasted with specimens subjected to gradual cooling.

In 2016, Ahmed [9] the study conducted investigations on three Reinforced Concrete (RC) slabs with dimensions of 1000x1000 mm to analyze the punching shear behavior. Experimental factors comprised the slab depth (80 mm and 100 mm), void diameter of 64 mm, and 72 mm spacing between bubbles center to center. Results indicated that RC slabs with bubbles and a bubble diameter-to-slab thickness ratio (B/H) of 0.8 displayed around 92.163% of the maximum load capacity in comparison to standard solid slabs of the same thickness. Furthermore, the bubble-deck slab utilized roughly 74% of the concrete amount needed for similar conventional slabs.

Moreover, there was a minimal rise in deflection at 0.7 times the ultimate load (0.7Pu) by about 0.718%. Nevertheless, the fracture load experienced a reduction of around 6.286% when contrasted with the solid slab configuration. Bubbled slabs showed an increase in maximum load capacity by about 6.4% and a decrease in deformation at 0.7Pu by approximately 1.10%, with nearly the same concrete volume. Additionally, the fracture load was noted to have risen by approximately 10% compared to solid slab systems.

Twenty-four RC slabs (1500x1500 mm) with thicknesses of 100 and 130 mm were examined experimentally by **Luma in 2017[10]** under both concentric and eccentric loading conditions. The key parameters investigated included the type of slab (bubbled or solid), the diameter of plastic balls (60 or 90 mm), the compressive strength of the construction material (30 or 60 MPa), and the position of bubbles relative to the critical section from the column face at either d or 2d.

The results indicated that the maximum load carrying capacity of bubbled slabs compared to solid slabs was reduced by 4-20% and 14.7-29.4% when the bubbles were located at 2d and d, respectively. Furthermore, it was observed that bubbled slabs subjected to eccentric loading exhibited a decrease in ultimate load by 11.8-17.6% in comparison to bubbled slabs under concentric loading conditions.

Oukaili & Husain, (2017) [11], Twelve comprehensive tests were carried out on reinforced concrete bubble slabs, depicted in **Figure 2.** measuring 1500×1500 mm with thicknesses of 100 and 130mm, subjected to concentric loading. The objective was to analyze the performance of such bubble slabs and the influence of various parameters on their maximum load-carrying capacity. The displacement center of the slab, strains in bending reinforcement and concrete, and the extent of cracking angles were scrutinized. The key variables under investigation included bubble diameter (60 and 90 mm), concrete compressive strength (30 MPa, 50 MPa), and the distance of the air-bubble from the column face (d and 2d). The ultimate load capacity experienced a reduction ranging from 4.41% to about 18% for specimens with bubbles positioned at approximately 2d, while it saw an increase ranging from 14.7% to 29% when compared to solid slabs. The significant rise in ultimate load capacity achieved with 60 MPa concrete is noteworthy, as the increase ranged from approximately 17.6% to 58.5% compared to an equivalent specimen utilizing standard (40 MPa or 30 MPa) cover concrete.

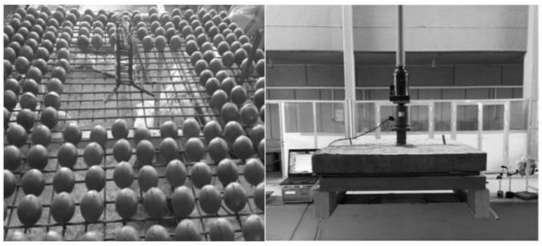

Figure 2. Bubble Slab Design and Test

Hussein, (2018) [12] This research elucidated the structural soundness and performance of unidirectional bubble-infused reinforced concrete slabs measuring 1850 mm x 460 mm x 110 mm. The slabs underwent casting and testing procedures aimed at ascertaining their load-bearing capacity, vertical deflection, compressive strain of concrete, tensile strain of steel, and patterns of cracking. The focal point of examination was:

1- The configuration of the one-way RC bubbled slabs, including simple, filigree, and filigree with a longitudinal joint, is of particular interest.
2- The characteristics of the plastic balls, which can be spherical or elliptical as depicted in **Figure 3.** and the spacing between these balls in the cross-section of slabs, measuring 25 and 70 mm, are crucial factors to consider.

3- The selection of concrete type, whether Normal self-compacted or high self-compacted concrete, along with the decision on the presence or absence of lateral shear reinforcement in the form of a steel cage, significantly impacts the structural behavior.

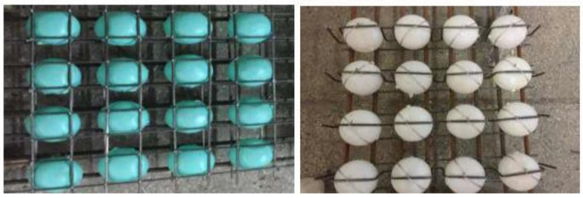

Figure 3. Shape of Ball and Type of Construction

Haitham (2019) [13], The study explored the fascinating dynamics of reinforced concrete bubble slabs exposed to intense fire conditions. Through a series of experiments, nine specimens were cast and subjected to high temperatures while under constant static loads. Each specimen measured 700x450x80 mm and had a uniform compressive strength of 30 MPa, representative of typical concrete. With a ball diameter of 40 mm and a reinforcement ratio of 0.00417 at both the upper and lower parts of the slabs, the trials examined fire flame temperatures of 200, 300, and 400 degrees Celsius, fire durations of 30 and 60 minutes, and concrete cover thicknesses of 20 and 10 mm. The specimens, supported only in two directions, revealed compelling findings.

At 200°C, specimens with a 20 mm cover showed no signs of spalling, whereas those with a 10 mm cover did experience this phenomenon. However, all slabs subjected to 300°C and 400°C exhibited spalling. Interestingly, at 300°C, the spalling damage for a 30-minute fire duration was 32% greater than at 400°C, but for a 60-minute duration, the spalling at 400°C was 49% more severe than at 300°C. Significant deflection during the fire was observed due to the combined effects of static loads and rising temperatures; deflection increased with higher fire temperatures and longer exposure times. Extending the fire duration from 30 to 60 minutes led to an increase in deflection rates by 57%, 79%, and 68% at fire temperatures of 200, 300, and 400 degrees Celsius, respectively, compared to slabs exposed to the same temperatures for only 30 minutes.

In 2021 [14] Jawad studied the punching shear characteristics of strengthened Geopolymer concrete bubbled slabs that have been subjected to a real fire flame comparing with normal and high strength concrete. 28 specimens of 450mm x 450mm x 70mm have been tested with ball diameter 40 mm, reinforcement at top and bottom of slabs was (ϕ3@ 25 mm). Twenty-one slabs exposed to real fire flame and 7 specimens are kept without burning as reference specimens. All specimens were tested under concentrated load at mid span. Variable of experimental works are: concrete types (Geopolymer, normal, high strength and Reactive powder) with compressive strength (30, 30, 60 and 90) MPa respectively, glass fiber content (0, 0.5, 1, and 1.5) %, fire flame temperature (150, 300 and 450) ℃, fire flame duration30-minutes, cooling methods gradually by air. Geopolymer concrete bubbled slabs behave similarly to RC bubbled slabs at 150 °C. In (300 and 450) ℃ the ultimate load decrease by (22 and 34) % respect to control slabs. When the glass fiber content is increased, the ultimate load increases by (14 to 25) % for geopolymer bubble-filled concrete slabs not subjected to fire flame. In all specimens heated to (300 and 450) ℃ the ultimate load decrease by (22 and 34) % respect to control slabs. When the glass fiber content is increased, the ultimate load increases by (14 to 25) % for geopolymer bubble-filled concrete slabs not subjected to fire flame. In all specimens heated to (300 and 450) °C, it was discovered that 300 °C has a greater effect on the maximum load of geopolymer composite bubbled slabs.

In 2021 [15] Jabir in this study Bubble slabs and solid slabs were experimentally compared under restricted repeated four-point loads. It was thus required to manufacture six identical slab strips, except for the cross-section type. Because 70 mm diameter balls had been placed into three of them. Additional research was done on the shear span to actual depth ratio (a/d). Consequently, one slab from each kind was evaluated, with the a /d (2, 3.5, 5). To determine the maximum load, the ACI-19 code calculated that the slabs would be subjected to 10 cycles of 25 KN, which is 70% of the total load. Regardless of the a /d ratio, the presence of the balls caused slabs to break suddenly owing to shear mode. Increases in a /d decreased the strength, stiffness, and hardness of the same slab type while increasing ductility had the reverse effect. A significant decrease in mechanical properties, excluding service stiffness, was seen in the bubble slabs. Stiffness, on the other hand, decreased by less than 15%. The reductions in CO2 emissions and embodied energy consumption of roughly 14% and 10% compared to solid energy consumption, respectively.

In 2022 [16] Abdul Hassan studied the Fire and Water-Cooled Glass Fibers Bubble Deck Slab Punching Shear Behavior. This investigation used 15 panels to perform tests. Additionally, the models illustrate the interior column guidance zonation for bubble slabs with negative bending moments. The specimens of slab tests were investigated at ambient temperature, and the other three different cooling conditions for high temperatures reached. The test loads were gradually raised until the carrying capacity reached its maximum. The objective of the experiment is to find out various parameters such as Ultimate punching shear, deflections, and crack patterns.

b. Literature review (Arch):

Al-Rifaie & Alihmedawi, (2000) [17] This study presents experimental research conducted on twelve cylindrical ferrocement shell models. These shell units were cast, built, and tested until failure during the experiments. The supported span was kept constant, while the thickness, number of mesh layers, and elevation of the crown were varied. A point load was applied to the crown of each shell unit. The performance of these models was evaluated based on load-deflection responses, first-cracking strength, ultimate strength, failure mechanisms, and crack patterns observed at failure.

Teng et al. (2004) [18] proposed a reinforced concrete composite curved roof, known as the Comshell roof, designed for covering large spaces. This roof system was constructed using a thin, rigidized steel shell that served both as permanent formwork and as a tensile reinforcement, with concrete applied on top. The steel shell was composed of modular units bolted together with a foundation plate, edge plates, and reinforcement in both horizontal and vertical directions. The study described a two-stage construction process aimed at minimizing sheeting thickness and reducing the need for temporary supports during construction.

In the first stage, steel-concrete composite arches were cast over selected rows, which reinforced the base shell and allowed for optimal pouring of the remaining concrete. During this phase, the stability of the standalone bolted steel arches under the load of wet concrete was a critical concern. The second stage of casting was crucial for ensuring the buckling behavior of the steel shell segments between two composite arches and for proper load transfer, which determined the overall strength of the structure.

After construction, the primary failure mode anticipated was overall buckling of the roof under gravity loading. Another potential failure mode identified was unilateral buckling of the base plate, observed during Comshell roof tests. To investigate this buckling issue, three laboratory model base shells were tested experimentally. In the first two tests, local buckling of stiffeners and the base plate initiated failure, followed by stable post-buckling deformations and ultimate collapse due to overall buckling. In contrast, the third specimen experienced sudden overall buckling without any preceding local buckling. **Figure 4. and Figure 5.** illustrate an arch with a steel base and long connection bolts, and a scenario of composite arch failure, respectively.

Figure 4. Steel Arch Structure with Extended Connecting Bolts

Figure 5. Structural Failure in Composite Arches

Husain and Al-Feehan, 2010 [19] The study explored a novel construction technique known as the Shell-Slab Roofing System (SSRS). This system features a precast thin shell of reinforced concrete in a cylindrical form, with a flat slab constructed on the bottom side. The flat slab, which acts as the roof, is prefabricated at a factory and illustrated in **Figure 6.** as a roof modular unit. The slab is positioned atop the cylindrical casing at its highest point and is secured to the casing by steel rod connectors on two opposite sides. The steel plate strips attached to both surfaces serve as external tensile reinforcement and contribute to punching shear protection around the supplementary bar link connections. The height of the shell was designed to be 0.1 times its length.

The study investigated the impact of a uniform static load on the structural response of the SSRS. The laboratory work involved fabricating six identical segments, scaled down to 25% of the full size for simulation purposes. Vertical deflections were observed at specific locations on these models. The concrete used had a water/cement ratio of 0.5 and a cement to sand ratio of 1:2. For large-span roofing applications, the design—featuring only 12 rod couplings and minimal reinforcement density—proved sufficient to carry live loads.

The study concluded that this composite system, which combines a slim concrete casing with a flat concrete slab reinforced with small-diameter steel, is particularly effective for creating broad-span roofing systems. The profile depth of these materials remains low relative to their longitudinal length, which is beneficial for large-span structures, especially those where the height-to-span ratio (h/c) is less than 0.1.

Figure 6. Thin Concrete Shell with Reinforcement and Flat Slab Construction

Zeman and Co GesellschaftmbH, (2012) [20] A new composite flooring solution was proposed for building and industrial construction, combining Slim Floor ceilings—a hybrid system with integrated steel girders that reduce overall floor height and include inbuilt fire protection—with a self-sustaining, trapezoidal-arched sheet design.

The trapezoidal arched floor structure includes steel primary beams spaced at intervals of approximately 4000 to 6000 mm. Positioned along the bottom flange of these beams are sheet elements with a "trapezoidal arch" shape, which serve as the shuttering for the concrete bearing ceiling, resulting in a Concrete Arch Ceiling. The reinforced concrete slab also functions as the top flange of the composite beams, integrating smoothly with the tapered steel girders. **Figures 7. and 8.** illustrate the construction principles of the arch deck system from top and bottom views, respectively.

The design of the floor slab includes a narrow neck that minimizes bending moments across the span. A thickness of just 60 to 80 millimeters, combined with a stiff and flat steel sheet on the trapezoidal arched profile plate beneath, is sufficient to handle span moments with minimal reinforcement. Additionally, the tapered design ensures that the concrete has a sufficiently large cross-section at the supports.

The compression forces in the concrete are effectively transferred through direct fastening to the steel girder network, while the tensile forces from above are managed by the corresponding reinforcement. The design creates a relatively large lever arm, reducing the amount of reinforcement needed.

Compared to traditional floor systems, the arch deck system demonstrates superior performance, particularly with a load capacity exceeding 5 kN/m².

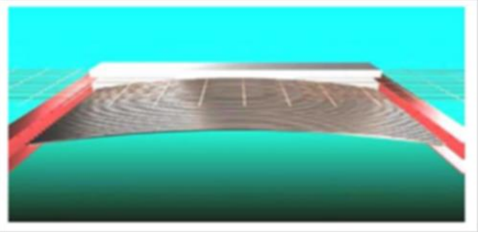

Figure 7. Top View of the Construction Approach

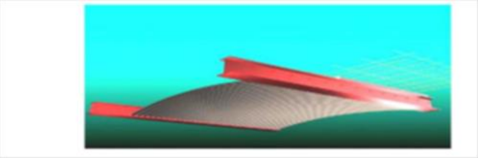

Figure 8. Bottom View of the Construction Approach

Fattah et al., 2015 [21] This study investigated the use of Reactive Powder Concrete (RPC) in conical shell bases as a potential alternative construction material. A comprehensive structural frame system was developed and manufactured for the research. Laboratory tests were conducted to assess the influence of various factors on the behavior of conical shell foundations, including the volumetric proportion of steel fibers, the inclusion of silica fume in the mix, load offset, and the ratio of shell rise to base radius.

The experimental results from tests on wire-reinforced, scaled-down concrete prototypes of conical bases under load revealed significantly higher load capacities compared to predictions made using traditional membrane theory for conical foundations. Specifically, increasing the height-to-radius ratio of the shell foundation from 0.25 to 0.75 led to an approximate 15% increase in the ultimate load capacity of the footing. Additionally, the conical shell footing exhibited resilience against lower accidental load offsets, such as those caused by unanticipated moments, indicating its robustness in practical applications.

Abd, (2016) [22] The experimental analysis aimed to evaluate the structural performance and mechanical characteristics of hemispherical Reactive Powder Concrete (RPC) shells, as illustrated in **Figure 9.** The study involved designing, casting, and testing five thin shells made of ferrocement (as a reference) and RPC to assess their structural behavior. The focus was on understanding how the volume fraction of steel fiber, concrete compressive strength, and shell thickness influenced the structural performance.

Key findings from the study include:

Effect of Thickness: Increasing the shell thickness from 15 mm to 20 mm led to a significant rise in maximum load capacity—approximately 92.63% for a steel fiber volume fraction (Vf) of 1% and 108.33% for Vf of 2%. The ultimate load increased by about 22.95% for shells with a thickness of 20 mm and 13.68% for those with a thickness of 15 mm when the steel fiber volume fraction was raised from 1% to 2%.

Effect of Concrete Compressive Strength: As the concrete compressive strength increased from 40 MPa to 130 MPa, the maximum load capacity increased by approximately 232.72% for shells with a thickness of 20 mm and Vf of 1%. The increase in load capacity was around 309.1% for the same thickness and fiber volume fraction when the compressive strength was raised from 40 MPa to 195 MPa.

Effect of Axial Displacement: Increasing the shell thickness from 15 mm to 20 mm resulted in a reduction in axial displacement of the RPC shells. As the concrete durability of the shells increased from 40 MPa to 130 MPa and 195 MPa, there was a trend towards greater plastic deformation. Additionally, an increase in the volume fraction of steel fiber from 1% to 2% also contributed to a decrease in axial displacement. However, changes in concrete durability had a minor impact on failure behavior.

Overall, the study demonstrates that increasing shell thickness and concrete compressive strength significantly enhances the maximum load capacity and reduces axial displacement, while higher steel fiber content also contributes to improved performance. The concrete durability, while influencing structural characteristics, had a lesser effect on failure behavior.

Figure 9. Thin Shell

Maryam and Nameer, (2018) [23] The study involved both experimental and numerical investigations to assess the behavior of a structural beam with an arched bottom segment made of high-strength concrete (HSC) under static stress conditions. The research aimed to explore the effects of arch length and beam span on load capacity, while keeping the concrete volume and steel reinforcement ratios constant. The goal was to identify the optimal ratio between arch length and beam span for maximum load capacity, with results validated through finite element analysis (FEA).

The experimental program focused on testing four structural beams, each with an arch at the underside, subjected to dual-point loading. The arch spans varied at 1.18 m, 0.9 m, 0.74 m, and 0.6 m. A key finding was that increasing the arch length relative to the beam span resulted in a nearly 60% increase in peak load capacity. The FEA proved to be a highly precise method, with the ultimate load values in the numerical simulations closely matching the experimental results. The maximum difference between calculated failure loads in the FEA and experimental data was less than 4%, demonstrating the effectiveness of the numerical modeling.

In 2020 [24] Alireza, et al., Experimental Study on RC Arch supported with GFRP. The influence of number and arrangement GFRP layers was evaluated on RC arches with different ratios for steel reinforcement in constructive tests performed over twelve samples. Center-point loads were applied to the arches using displacement-control conditions. These measures included investigating the load-deflection characteristics, failure-modes of reinforced systems and a unique aspect related to GFRP debonding phenomenon in addition to its opening angle with respect to hinge-formation as well as supports/crack propagation patterns. Extrados strengthening, on the other hand appeared to be much efficient compare with intrados strengthening in improving maximum load-carrying capacity (as shown from test results) where it has reached up to 200%.

In 2021[25] Fakhri Performed experimental study on the behavior of concrete arched slabs under flexural load until failure was pertain to its ultimate strength. In this inquiry, the most influencing items in structural behavior were selected as compressive strength of concrete, slab thickness and steel area reinforcement besides these parameters' arch curvature and support conditions. Fourteen replicates of the curved slab samples have been manufactured and subjected to dual-point load testing. Specimens performance recorded by monitoring the deformation at the center and stress levels at the topside and underside of the fiber, crack patterns. There is initial cracking load linear behavior up to (35% - 40%) of the maximum strength for the arched slab samples. The mid-span of the arched slab load-deflection curve can be an idealized as a bilinear one. Increases in the ultimate load of (15% to25%) were obtained by increasing compressive strength 116%. The geometric bearing increases the ultimate load by (6% ha 17%) on increasing the thickness of slab to respectively 43%. Upsizing the amount of steel by 45% results in an (29%-34%) improvement in ultimate load. If we increase it up to 200% then the ultimate load may grow from (6%-28%). If the support is changed to pin-

pin from simply supported then ultimate load will increase by (200% - 245%).

C. Literature review (Arch with Bubble slab):

In (2018) Alfeehan and Alzubaidi [26] used in this experimental work two directions of the voids system with two types of the voids shape in each direction The study explored the impact of different void shapes and orientations on the structural performance of cylindrical shells under load. Circular and squared voids were used as continuous voids in the uniaxial direction, while spherical and cubic voids were employed as separate voids in the biaxial direction. Both circular and spherical voids had a diameter of 70 mm, and the squared and cubic voids had an equivalent side length of 62.5 mm. The research investigated various shell types, void orientations, void shapes, and the number of steel reinforcing layers, with configurations including reinforcement at the bottom only or both top and bottom.

The cylindrical shells were tested under a single-point load at the crown, with simple support at the ends. Results indicated that a 37% reduction in concrete volume led to a 35% decrease in ultimate load capacity. Voids aligned in the biaxial direction showed improved structural behavior compared to uniaxial voids, which formed a hollow core section. Additionally, square or cubic voids provided better structural performance than circular or spherical voids in both orientations. The findings underscore the significant influence of void shape and orientation on the overall structural performance of cylindrical shells.

3. TYPES OF BUBBLE SLAB

The different kinds of bubble deck slab systems have been brought to light. There are three types of bubble deck slabs [27][28]: reinforcing modules, filigree sections, and finished planks. Each type has its own unique characteristics. The bubble deck slab combines constructed and unconstructed elements. In this slab, a 60mm thick precast concrete layer is placed locally with unattached bubbles and structural reinforcement. The plastic bubbles are kept steady with the help of temporary stands on the precast concrete layer and held in position by a honeycomb of interconnected steel mesh.

3.1 Reinforcement Modules:

Bubbled RC Slab Type A is a new self-developed and patented reinforced system, bubble lattice reinforcement network composed of pre-fabricated layer of steel grid combined with plastic bubbles. These ingenious elements are transported to the construction site, based on ordinary formwork, complemented if required by an extra reinforcement and finally filled with concrete following traditional methods shown in **Figure 10**. This modular system is especially well suited for sites where space is limited since the modules can be stacked when they are not in use [29].

Figure10. Reinforcement Modules

3.2 Filigree Elements:

Bubble Deck system Type B (Bubbled RC slab) includes both constructed parts as well as unconstructed ones. The design incorporates a 60mm thick precast cementitious slab that serves as the casting mold and portion of the final depth. As illustrated in **Figure 11**. the precast layer is transported to the site without bubbles and steel reinforcement connected. These bubbles then rested on temporary supports above the precast layer and attached to an interlocking steel mesh honeycomb. Reinforcement design data will specify additional steel can be added as required. Standard concrete finishing follows to expose the full depth of slab. Bubbled RC slab of this type is particularly best suited for new construction where position and layout of bubbles are within the scope to be determined by designer at design stage [29].

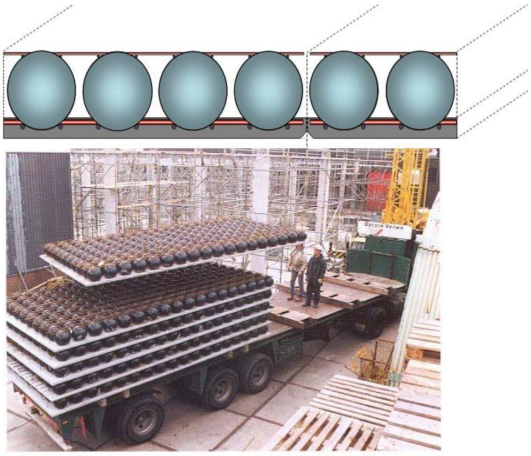

Figure 11. Filigree Elements

3.3 Finished Planks:

Shop-fabricated type is bubbled RC slab Type C in its finished form, which will include a certain plastic sphere with mesh reinforcement and concrete **Figure 12**. The module is produced complete to final site depth, i.e., as a plank. It is a one-way spanning type and unlike types A/B, support beams or load bearing walls are required. For short spans and where time factor in construction is the main constraint, this type of bubbled RC slab can be considered [29].

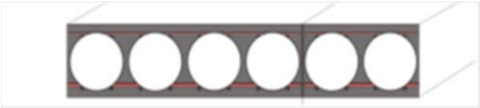

Figure 12. Finished Planks

4. Materials Required for Bubbled Slabs

The three types of materials listed below are utilized to build a Bubble Deck slab:

4.1 Spherical Plastic Bubbles

The bubbles are fabricated from high-density polypropylene. This material is typically non-porous and does not chemically react with steel bars or concrete. To safely support the imposed loads, the bubbles must be stiff and robust. The most popular bubble diameters used in the Bubble Deck system are 180, 225, 270, 315, or 360 mm, corresponding to total slab depths of 230, 280, 340, 390, or 450 mm, respectively. The clear space between bubbles should be no smaller than 1/9th of the bubble's diameter. The bubbles may have either an ellipsoidal or spherical shape [30].

4.2 Concrete

The Bubble Deck Slab method requires concrete with a grade higher than C25. Self-compacting concrete can be used for both the site-based joint filling and the casting of prefabricated filigree slabs. The nominal maximum size of the aggregate is governed by the relationship between the bubble diameter to the slab thickness (B/H) [31].

4.3 Steel Bars

Steel reinforcement must have a tensile strength of at least 414 MPa. There are two styles of steel reinforcement: meshes for lateral assistance and lattice frames for vertical assistance of the bubbles. **Figure 13.** [32][33] visually represents how steel and bubbles are arranged in a Bubble Deck slab. Due to their spherical shape, the bubbles cannot be stacked. Steel cages are the best way to keep the bubbles in place. Mesh reinforcements are necessary to securely lock the bubbles [34]. The top and bottom reinforcements are connected by inserting diagonal lattice girders between them. The spacing between rebar is determined by the diameter of the bubbles being used and the amount of reinforcement needed from the transverse ribs of the slab [31].

Figure13. Bubbles and Steel Arrangement

5. ADVANTAGES

i) Structural-

- Reduced weight
- Eliminates need for beams
- Minimal columns necessary

- Freedom to choose any shape
- Allows for large variety of shapes

ii) Construction-

- Decreased weight at construction site
- Lightweight, reducing equipment needs
- Simpler and lighter on-site tasks
- Accelerated construction process

iii) Economy-

- Significant materials savings of up to 50%
- Reduced transportation costs
- 35% decrease in required concrete
- Reduced workforce needs, no carpentry, no beams, and fewer skilled workers needed

iv) Environmental-

- Less carbon emission
- Less energy consumption

6. STRUCTURAL PROPERTIES OF BUBBLE DECK SLABS:

A. Compressive strength and Flexural capacities

The concept of a Bubble Deck slab involves removing a significant volume of concrete from the central core, wherein the slab typically faces less flexural stress than in a solid slab. In this innovative system, the thickness of the concrete layer that is compressed is typically just a fraction of the total slab depth. With the concrete remaining interposed within the spheres and the top surface, there is no notable discrepancy in performance between a Bubble Deck slab and a conventional solid slab. The critical components are the steel on the section under tension and the external concrete 'shell' on the compressive zone. Regarding resistance to bending, the moments of strength are on par with those of a solid slab.

B. Durability

The durability of a Bubble Deck slab is fundamentally comparable to that of conventional solid slabs. The concrete employed is of normal grade, and when incorporated with appropriate bar cover, it ensures durability on par with conventional specifications for solid slabs. Through the creation of filigree slabs, the reinforcement structure and balls are rhythmically incorporated into the concrete, facilitating consistent compaction. This process produces a surface concrete density that is at least as impermeable and durable as that of solid slabs. Bubble Deck slab joints feature an internal chamfer, ensuring that concrete surrounds each bar, preventing direct exposure of the rebar to air. This design primarily enhances fire resilience but also contributes to overall robustness.

C. Fire Resistance

The fire resistance of a Bubble Deck slab is a challenging issue, primarily relies on the capability of the steel reinforcement to sustain adequate strength throughout a fire. As the temperature rises, the steel heats up and loses significant strength. The temperature of the steel is influenced by the intensity of the fire and the shielding provided by the concrete. In the event of a fire, air within the slab would likely escape, reducing internal pressure. If the conventional bubble material is employed, the resulting combustion byproducts are rather harmless. During a protracted, fierce fire, the plastic spheres would liquefy and gradually turn into charcoal without any notable or noticeable impact. The fire-retardant nature of the slab is determined by the thickness of the concrete cover, usually varying between 60 and 180 minutes.

Bubble Deck slabs, though not intentionally crafted for thermal insulation with air bubbles enclosed within the concrete, boast 17% to 39% greater thermal resistance than a solid slab of equal thickness. Therefore, Bubble Deck slabs can contribute to the overall thermal insulation of a building.

7. Conclusion

After reviewing the literature on Bubble Deck slabs, we can conclude that:

- The concrete required for Bubble Deck slabs is less compared to reinforced concrete slabs, resulting in a lower overall weight.
- The reduced weight of the Bubble Deck slab means that the load transferred to the columns, walls, and foundation is less, allowing for a building foundation design that accommodates a smaller dead load.
- The overall construction cost is reduced by using Bubble Deck slab technology due to the decreased amount of concrete and materials needed.
- Bubble Deck slabs are more beneficial and economical compared to traditional reinforced concrete slabs, offering advantages in terms of material efficiency, cost savings, and structural performance.

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