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Performance of Structural Behaviour of Bubble Deck Slab: a Review

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Abstract: ***Bubble deck slab can be achieved by reducing the weight of the slab by eliminating unwanted concrete which is not playing the role in the interlocking of aggregate for shear resistance and the remaining concrete act as the compression block for flexural resistance. Further, the larger spans with less design loads to the columns and footings without compromising flexural strength of the slab with minimum deflections are possible with this renowned technology. This paper presents a comprehensive review of the structural behaviour of bubble deck slab. The analytical and experimental studies on bubble deck slabs under general loading to know the structural behaviour has been presented in this article. The structural behaviour of the bubble deck slab has been assessed through flexural strength, shear strength, punching shear, anchoring, crack pattern, fire resistance, creep, crack pattern. From the review of literature, it has been concluded that the bubble deck slabs are more economical and efficient with respect to structural integrity while comparing with conventional slabs.***

Index Terms: ***Bubble deck slab, HDPE spheres, Flexural strength, Shear strength, Punching shear.***

I. INTRODUCTION

In the world, low-cost housings are major leftovers, a big challenge for Civil Engineers and many governments, particularly in the emergent countries of the world like India. The crisis is aggravated by fast escalating population, migration of rural masses into the urban and industrial centres, which demands for the better eminence of existence. Due to this insufficiency of conventional building construction systems, new building systems appeared at the beginning of the 20th century. During 1999 the government has conducted government-sponsored contest on the topic of new habits of constructing buildings. In this contest, the bubble deck technology was accepted and become popular in Europe and around the world as large scale profit-making construction [1].

Fig. 1: Bubble deck slab

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In bubble deck slab construction, in addition to HDPE (High-Density Poly Ethylene) hollow spheres, all other materials are the same as the conventional solid slab. The reinforced steel which is fabricated in two layers for lateral support and diagonal girders for vertical support of the bubbles which are made from recycled high-density HDPE. In this process, the bubbles are placed firmly in between the top and bottom reinforcement as shown in Fig. 1.

A. Bubble Deck Slabs

As per the bubble deck [2], bubble deck slabs can be categorized into filigree elements, reinforcement modules, and finished planks. The size of all form of slabs is limited to 3 m for easy transportation and installation although the capacity may not differ after connection all the panels [3].

In case of filigree elements type of bubble deck slab, the layer of concrete act as both part of the finished slab and also as the formwork bought on site with the bubbles and steel reinforcement separated. Before pouring the concrete temporary stands are used to keep the bubbles in their position, extra steel is also introduced if necessary [3].

In the case of reinforcement modules group of bubble deck, the steel mesh and plastic bubbles are packed together. The other way of identification of reinforcement modules are called as “Bubble Lattice” which are directly bring to the site and laid on conventional formwork connected with the other panels with additional reinforcement and concreting is done. This type is more suitable for the structures have less work area since these panels can be stacked on top of one another for storage until needed [4]. When compared to the above types module can be pre-fabricated by concreting the module bubbles fitted with a reinforcement mesh and delivered on the site which is best for shorter spans and limited work area which is called finished planks [5].

B. Advantages of Bubble Deck

The amount of the concrete used in bubble deck slab is 35-50% less than the conventional solid slab. The amount of non effective reduced concrete is replaced by HDPE hollow spheres leads to the usage of less reinforcement because of the reduction in the dead load from the slab which is more useful for low-cost housing [6]. Load bearing walls are not necessary because of the reduced dead load from the slab and its two-way spanning action [5]. Support beams and girder members can also be eliminated if the bubble deck is designed as a flat slab bubble deck which results in the reduction in some of the structural requirements of the columns and foundations [7]. Out of all types of bubble deck

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slab, the finished planks technology is more time-saving process when compared to filigree elements and reinforcement modules. Because this is a type of construction like a precast can be cast in the workshop which leads to the fast erection of column [8]. Bubble deck slab is not only time-saving construction, but it also has a very good impact on cost saving due to a reduction in self-weight. Further, it would be easier to lift the panels thereby it reduces the labour costs. Slight rise in the cost for HDPE hollow spheres can be overcome by saving in transportation, material, time and labour [9]. According to the bubble deck company, the reduction in weight of passive concrete may save up to 40% on embodied carbon which can help in reducing global warming and useful for carbon credits. Generally, for every 5000 m^2 of bubble deck slab area, one can save up to 1000 m^2 of on-site concrete. The benefits in the form of 166 concrete truck trips, 1798 tons of foundation load, 1745 GJ of energy used in concrete production & transportation and 278 tons of CO_2 emissions respectively (Bubble Deck*-UK) [10].

II. APPLICATIONS

Reducing self-weight as the positive attributes for encouraging efforts to use voided slabs. This division discusses the idea of creation of voided slab and figures out the historical applications of voided slab [3].

Applications of voided slabs in history

The first use of voided slab through back to 1900s. Most of the voided slab systems were developed in the 1900s although it was utilized for centuries ago.

Fig. 2: The Pantheon
(Source: https://en.wikipedia.org/wiki/Pantheon, Rome)

The Pantheon is one of the ancient voided slabs constructed in the period of 113-125AD. Fig. 2 shows The Pantheon, which is having 43.3 meters dome diameter which is the very week in cracking but because of the presence, several coffers which are voids on one side of the slab reduced weight for the proper function of the dome. Precast Floors Corporation of New York has developed a new type of voided floor system in 1929 consisting sections having a depth of 15 cm, 20 cm, or 25 cm and 30.5 cm as width and hollow section in the middle. The pre-cast units shipped in three sections with the center unit in standard lengths, end sections were custom lengths depending on the construction because of the less weight with these sections we can maintain larger spans. Figs. 3, 4 show the section through a Miller system unit and an isometric of Miller system units prior to being joined.

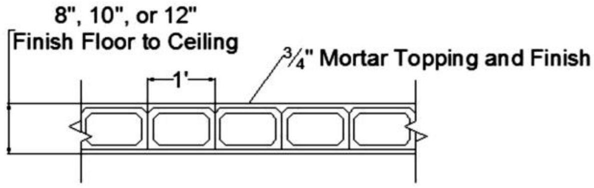

Fig. 3: Section through a miller system unit

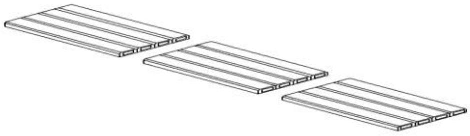

Fig. 4: An isometric of Miller system units prior to being joined

Similar floor system to the miller system a new type of voided floor system was developed which consist of hollow formed precast units having 1.2 m to 1.8 m in length which was called Porete Floor System with this system we can continue a span ranging from 3 m to 7.6 m. Like the previous two systems another third system providing a depth of 10cm to 15 cm and width of 30cm to 45cm having lengths up to 2 m which can be united to form longer spans can be obtainable by using pyrobar precast roof. In 1950s F & A System is another type of voided slab system has come into existence providing high strength with t-joints, hollow concrete blocks and concrete toppings to form a slab with low weight. Fig. 5 shows F & A System.

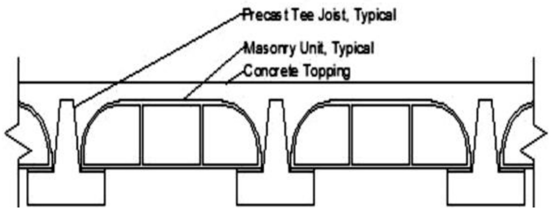

Fig. 5: F & A System

III. VOIDED SLABS USING PLASTIC

With the introduction of plastic voided slab systems to the construction industry as an alternative to the conventional concrete slab which is significantly lighter leads to have larger spans. we can replace 100 kg of Concrete with 1kg of replaced plastic. This part discusses the construction practices of Plastic voided slab systems

Bubble Deck is the company which focuses on special construction techniques founded by Jorgen Breuning has got the first breakthrough in 1999 with fulfilling the flexibility, sustainability and material reduction by creating a natural cell structure acting as a solid slab by locking the Plastic Hollow spheres in between the top and bottom reinforcement.

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Cobiax Technology is based on generating specific hollows inside a reinforced concrete slab. Massive concrete is replaced by synthetic void formers and remains only in statically relevant areas. Thus, it is possible to construct buildings with flat slabs while allowing for a remarkable span width. This method is more complicated than the bubble deck because it requires more form work.

An Italian company Daliform come up with the usage of another shape of plastic voids other than Spherical voids in 2011 and called u-boot beton has creates many I- Sections and is cast entirely on site provides good transport and stacked efficiently [11].

A. Applications of Plastic Voided Slabs

This section reviews projects that used plastic voided slabs and discusses the reasons, why plastic voided slabs are used rather than a more traditional slab system.

Bubble deck was first used in United States of America in the construction of La Bahn Arena which is women hockey arena in the University of Wisconsin at Madison it took significantly shorter period than conventional slab (Bubble Deck North America, 2012). Cobiax plastic voided slab system faced a challenge in 2013 in the construction of Miami Art Museum in Miami, Florida having an extent of 18580 m^2 and with limited number of columns and it should have a greater cover over the reinforcement in the slab against the corrosion because of the close proximity to Miami harbour because of the voided slab the weight of slab reduced drastically and leads to higher spans compared to conventional slabs. York University in York, Ontario had made decision to make use of a bubble deck Plastic voided slab system in the construction of new life science building in June 2012 because of more live loads and dead loads due to the presence of lecture halls, laboratories, etc.., for research (Blackwell Bowick, 2012).In the construction of Abuja tower hotel in Abuja, Nigeria in the year 2006 with 22 floors including commercial spaces like shopping areas and restaurants came up to use U-Boot Beton system to reduce the load to provide scope for maximum space utilization. Union of European Football Association (UEFA) Nyon, Switzerland near the beginning 2009 wanted to construct a building in circular similar to the shape of a doughnut, and provided only to structural columns at the ends by avoiding the intermediate columns with the use of Cobiax system maintained larger spans with a free workspace. Cobiax system made not only the structure it also constructed two-story parking with a maximum number of parking slots by minimizing the number of columns... With thirty-nine floors and a height of 162 m started in the year 2008 and completed by 2010, a skyscraper in Milan, Italy which is located in the seismic zone had switched to Cobiax voided slab system from conventional slab system, which becomes an advantage for saving of a large amount of concrete.

IV. STRUCTURAL PROPERTIES AND DESIGN

Denmark, Germany and the Netherlands has become the major origin for Research on the mechanical and structural behaviour of bubble deck slab include flexural strength, shear strength, deflection, punching shear, fire resistance and sound.

A. Stiffness and Deflection

Report from the Eindhoven University of Technology the Netherlands – Enclosure A1 has compared the conventional slab and bubble deck slab both theoretically and practically shown in the Table I (Source: Based on the report, articles have been published in the: *“Darmstadt Concrete” (Annual journal on Concrete and Concrete Structures) - Enclosure A3*, summarizing several tests)

Table I: showing results from practical tests on bubble deck *vs.* solid deck

In % of a solid deck	Bubble deck *vs.* Solid deck		
	Same strength	**Same bending stiffness**	**Same concrete volume**
Strength	100	105	150*
Bending Stiffness	87	100	300
Volume of Concrete	66	69	100
*On the condition of same amount of steel. The concrete itself has 220% greater effect.			

When considering stress block in Eurocode 2 below the neutral axis flexural stiffness in bending is contributed by bottom reinforcement steel whereas the concrete remains ineffective in centre of the flexural slab which is replaced by HDPE hollow spheres. By using EC2 and BS8110 bubble deck slab is designed. Fig. 6 shows a Standard stress block (Eurocode2) [12].

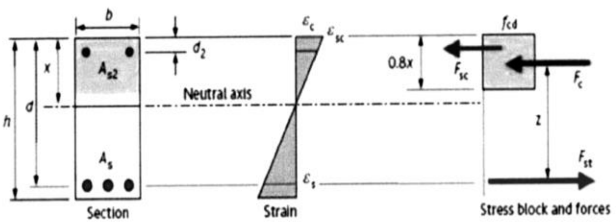

Fig. 6: Standard stress block (Eurocode 2)

The plastic voids in the bubble deck slab do not lead to weakening the strength of the slab further also provides support by forming arch like fashion.

B. Shear Strength

The reduction factor 0.6 to be used for shear strength in bubble deck slab because of the presence of the plastic bubbles the bubble deck slab shear strength was determined to be 60-80% of the solid slab has observed when shear capacity is tested for two ratios of a/d shown in the table as shown in Table II. High shear in the flat plate slabs is concreted in the region where floor and column are connected. In case the applied shear is less than the shear capacity of bubble deck slab spheres surrounding the column have to be omitted as shown in Fig. 7 and in case

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the shear resistance of the solid concrete portion is below then applied reinforcement for shear to be provided. [13]. Table II shows shear capacities.

Table II: Shear capacities

Shear capacity (in % of solid deck)	a/d=2.15	a/d=3.0
Solid deck	100	100
Bubble Deck, secured girders	91	78(81)[1]
Bubble Deck, loose girders	77	

C. Punching Shear

The punching shear becomes the common concern for flat plate floor systems since there is a highly concentrated reaction from Column on to slab which is associated with failure from extreme, localized forces. The design for punching shear for bubble deck slab closely follows that of a flat slab. If applied shear is greater than the shear capacity of bubble deck slab, then providing drop panels or flared column heads or by increasing the depth of the slab reduces the problem. Fig. 7 shows Floor to column modification (Bubble Deck International) and Fig. 8 shows cross-section of bubble deck slab [14].

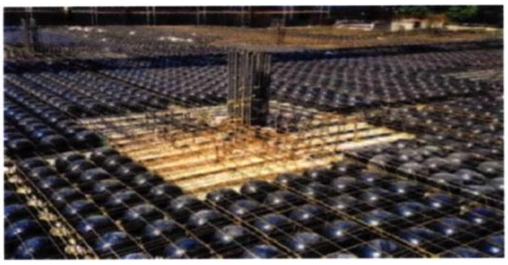

Fig. 7: Floor to column modification (Bubble Deck International)

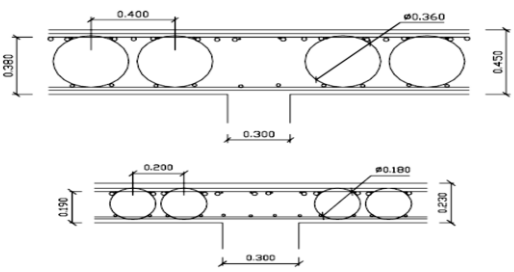

Fig. 8: cross-section of bubble deck slab

Martina Schnellenbach-Held *et al.* (2002) had made investigations to check the validity of German design code DIN 1045 for the structural behaviour of bubble deck slab and concluded that mode of failure of both bubble deck slab and solid slab are similarly based on the previous investigations and modification was made for the available design rules. In many design codes punching resistance is treated as a shear resistance that acts as a section, the so-called control perimeter. This control perimeter does not have any physical. It is necessary to reduce the shear area by area A of the intersection of the control perimeter with bubbles. If any of the bubbles are situated in between the control perimeter and the border of the column, (Eq. (1)), [15].

$$A = uh_m - \sum(d_k^2\pi/4) \qquad \text{(Eq. (1))}$$

D. Moment Capacity

Tim Gudmand-Hoyer **(**2003) has stated that it is impossible to use the code rules directly to find the load carrying capacity of a bubble deck slab using the theory of plasticity. They are different kinds of joints in the construction of bubble deck slab. The bond strength of the bubble deck slab (Filigran type deck) is influenced by the casting joint between the precast and the in-situ concrete and also demonstrates that having a theory instead of relying on empirical rules is more advantage [16].

E. Shape of Voids

Chung *et al.* (2010) had made many investigations on 250mm thick hollow slab using finite element method program on several hollow slabs with different hollow sphere shapes were analyzed to compare with structure capacity and failure mode by using finite element method program and optimal hollow sphere shape could be derived. From the results corner radius, hole diameter and volume of the hollow sphere were closely related to the shape of the hollow spheres and it also relates to the failure mode and capacity. For 250 mm thickness of slab, the deflection of the hollow slab was higher when the hole diameter of the hollow sphere was smaller. In 250 mm thick hollow slab hollow spheres having a corner radius of 50mm are appropriate and proved that rectangular doughnut having D=50mm is optimal hollow sphere shape [17]. Based on the results of test conducted by Chung *et al.* (2011) with test parameters included shapes parameters donut, non-donut forms and materials parameters general plastic and glass fibre plastic of plastic balls conclude those shear capacities of the hollow sphere slab are influenced by the shape and material of the hollow especially, for the shear capacity shape of the hollow sphere plays a prominent role. The shear strength of the slab with donut-shaped spheres increases the shear strength of about 20% when compared to the non-donut shape hollow sphere. Fig. 9 shows Donut type hollow sphere shape.

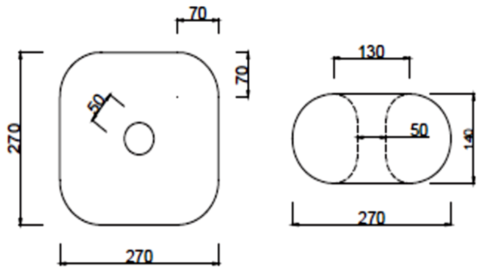

Fig. 9: Donut type hollow sphere shape

It can be increasing the shear strength about 20% rather than hollow slab which is applied non- donut shape hollow sphere. The shear strength of the hollow slab is increased by providing a hole in the center of the hollow sphere as shown in the fig.4.4 and shear strength of the hollow slab is dependent on the hollow sphere material [18].

F. Crack Pattern

Ibrahim (2012) made investigations to verify the flexural behaviour of R.C two ways hollow slab of plastic sphere voids and results shown the void diameter to slab thickness ratio plays a major role in the flexural behaviour and crack pattern. It is clear that the stiffness values of bubble deck slab and solid slab are not similar. It is observed that deflection under service load and concrete compressive strain of a bubble deck specimen are higher than equivalent solid specimen [19].

Chung (2011) has made investigations on the biaxial hollow slabs with donut type hollow spheres for shear capacities and observed that in both hollow slab with donut type plastic voids and equivalent solid slab has similar crack pattern as the shear load carried by a direct compression strut between the loading point and the support all specimens were failed when diagonal shear cracks occurred and broaden out [18].

V. OTHER INVESTIGATIONS

Pisanty (1992) has tested ten slab specimens in failing in shear mode to investigate the shear strength of extruded prestressed precast hollow-core slabs and concluded that FIP (Fair Information Practice) can be modified for an improved approximation of the test results. To bring the equation for shear capacity in shear tension mode a reduction factor is necessary as shown in the Eq 5.1. [20].

$$V_{uk} = 0.75\frac{I\sum b_w}{S}(f_{ct,sp}^2 + \alpha\sigma_N f_{ct,sp})^{1/2} \qquad \text{Eq:5.1}$$

Alnuaimi (2008) after testing seven hollow and seven solid reinforced concrete beams with a cross-section of 300x300mm and length of 3800mm. For a hollow beam internal core is 200 × 200 mm creating a wall thickness of 50mm made a comparison and studied the main variables studied were ratio of bending to torsion varied between 0.19 and 2.62 and smaller the ratio larger the differences in failure loads between hollow and solid beams, the ratio of shear stress due to torsion to shear stress due to shear force varied between 0.59 and 6.84. Whereas the longitudinal steel yielding while the transverse steel experienced lower strain values. And it is observed that major cracks have been developed in the solid beams than in the hollow beams.[21]

Aurelio Muttoni (2008) presented on the basis of the opening of a critical shear crack explained the phenomenon of punching shear in slabs without transverse reinforcement which leads to new failure criterion for punching shear based on the rotation of the slab and also proposed a simple mechanical model with very low coefficient of variation (COV). The punching shear strength of a flat slab is shown depending on the span of the slab, rather than on its thickness. By providing the punching shear reinforcement can get a satisfactory level of ductility [22].

Sergiu Călin **(**2009) had made economic analysis to make bubble deck into existence in all the rest of the nation whereas its existence only in the countries like Austria, Belgium, Denmark, Germany, Iceland, Italy, United Kingdom, Holland, also in other continents, in Canada or USA. Tests have conducted on the bubble deck slab to known behaviour in bending, reaction to shear force, performance of mountings, resistance to fire and the acoustic behaviour of floors and concluded that bubble deck in any way act follow same rules and regulations as solid deck and leads to considerable saving [4].

Prabhu Teja (2012) made compression between solid slab and bubble deck slab by making two way spanning floor 3d model of both in SAP2000 which was based on finite element method [23]. In the bubble deck floor system bubbles are arranged in such a way to avoid the impact the punching shear. After comparison found that solid slab is only 6.43% higher in the behaviour of bending whereas deflection of bubble deck slab is 5.88% more than the solid slab because of reduced stiffness with presence hollow sections, Shear resistance of bubble deck slab is 0.6 times and the weight reduction is 35% of the solid [24].

Hai (2013) has made experiments on them to find the behaviour of bubble deck slab and compared with the finite element program using ANSYS to find the behavior of bubble deck slab with traditional hollow spheres and elliptical spheres and concluded that better load-bearing capacity is achieved by using the hollow elliptical spheres Fig. 10 shows the Shape and Dimension of Plastic Balls [25].

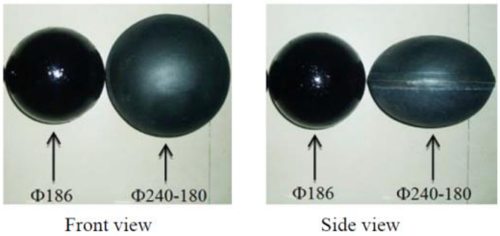

Fig. 10: Shape and Dimension of Plastic Balls

Bindea (2015) had made parametric study on flats slabs with spherical voids for shear force behaviour by making a 3d model with a scale 1:1 in the Atena 3D finite element Design Software and found that flat slabs with spherical voids don't fail to shear force under a longitudinal reinforcement rate of lower than 0.50%, as the reinforcement rate increases shear force decreases in comparison with solid slab [26]. Sagadevan (2019) had conducted non-linear finite element analysis and study showed the void slab also can withstand the load that is carried by a solid slab. However, reduction in stiffness of void slab leads to an increase in deflection because of stress concentration at the corner of the cuboid shape void slab with cuboid shape void carries less load than slab with other void shapes. Slab with sphere shape void shows better results in terms of load carrying capacity as well as serviceability criteria [27].

VI. CONCLUSION

The literature on the bubble deck slab has reviewed. From the literature, it is clear that voided slab is very common in olden days and it is improving day by day and at present bubble deck are effective in load carrying capacity, shear capacity, flexural capacity, fire resistant and moreover we can reduce the weight and increase the span of the slab. Bubble deck slab has not got widespread in India because most of the design is based on the DIN codal provision and lack of BIS codes and specifications regarding the use of technology which is discussed only in IRC SP 64-2005, meant for bridge superstructures. It will come into the competition in India like the pre-stressed concrete, which is using almost all the metro, tall structures, and bridges a lot nowadays but not popular before.

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