Subject Review

THE BUBBLEDECK FLOOR SYSTEM: A BRIEF PRESENTATION

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ABSTRACT

The BubbleDeck slab is a floor system of reinforced concrete, containing spherical hollows, as concrete saving elements. The system allows longer spans between columns supports. Usually manufactured partially from precast filigree elements, the BubbleDeck system combines the benefits of factory-manufactured elements in controlled conditions with on site completion with the final monolith concrete, resulting in a completed floor slab. Regarding the BubbleDeck system, numerous experimental research works were conducted, in order to evaluate the performances of this system, subjected to bending loads, shear loads or seismic loads, to determine the time-dependent deformations or the fire reaction, or to study the behavior as support element for fastening elements. The paper present a short synthesis of significant research works performed in prestigious laboratories from Denmark, Germany or Netherlands. Representative applications are also presented.

Keywords: floor system; reinforced concrete; spherical hollows; precast elements; research.

REZUMAT

Sistemul BubbleDeck este un sistem de planşeu din beton armat cu goluri sferice. Sistemul permite realizarea de trame mai mari între stâlpii suport. Realizat de regulă din elemente filigran în soluție parțial prefabricată, sistemul BubbleDeck combină avantajele prezentate de elementele prefabricate produse în fabrică în condiții controlate cu avantajele realizării pe şantier a monolitizărilor. Au fost efectuate numeroase studii experimentale şi teoretice pentru evaluarea performanțelor acestui sistem sub acțiunea diferitelor tipuri de solicitări: încovoiere, forfecare, sarcini de tip seismic, dar şi pentru cunoaşterea deformațiilor reologice, a reacției la foc sau a comportării ca element suport pentru diferite tipuri de sisteme de prindere. Articolul prezintă o sinteză succintă a unor lucrări semnificative de cercetare, desfăşurate în laboratoare de prestigiu din Danemarca, Germania, sau Olanda. Sunt prezentate de asemenea câteva aplicații reprezentative.

Cuvinte cheie: sistem de planşeu; beton armat; goluri sferice; elemente prefabricate; cercetări.

1. INTRODUCTION

1.1. General

The BubbleDeck floor system was invented by the Danish engineer Jorgen Breuning and ensures the reduction of dead weight for the floor slab with more than 30%, allowing longer spans between supports, as well as decreasing over-all costs[1]. The completed floor slab is supported directly on the reinforced concrete columns.

The BubbleDeck structural hollow flat element system consists of reinforced concrete floor slab containing spherical concrete saving cells.

Parts of the system can be realized as prefabricated elements. For that, there are three alternatives, depending on the application type. In the first case, the system can be composed of reinforcement modules, in which the bubbles are trapped between the upper and the lower reinforcement mesh, as shown in Figure 1. In the second case, the system comprises reinforcement modules, but also a prefabricated concrete filigree slab cast on the bottom of the reinforcement mesh, as indicated in Figure 2. This slab represents permanent formwork. The third case consists of precast finished slabs in which the reinforcement modules are embedded into concrete to full finished depth.

In order to ensure the shear capacity and the flexural capacity in zones with concentrated loads, like the vicinity of columns or walls, in such zones the slabs may be not provided with hollows, as shown in Figure 3. The area of the surface without bubbles is determined as a function of loading and slab thickness.

For the first two alternatives that use partially pre-fabricated floor elements, the reinforcement modules or filigree elements are connected together with splice bars and joint mesh, then the concrete is poured to full depth. For the completely pre-cast finished planks, only joints between the planks are filled with concrete.

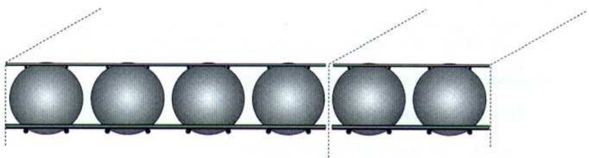

Fig. 1. BubbleDeck element [1]

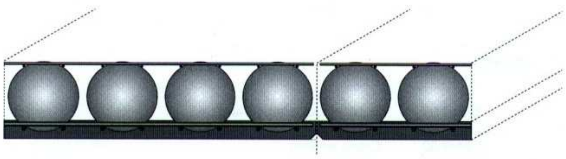

Fig. 2. BubbleDeck element with precast concrete filigree slab [1]

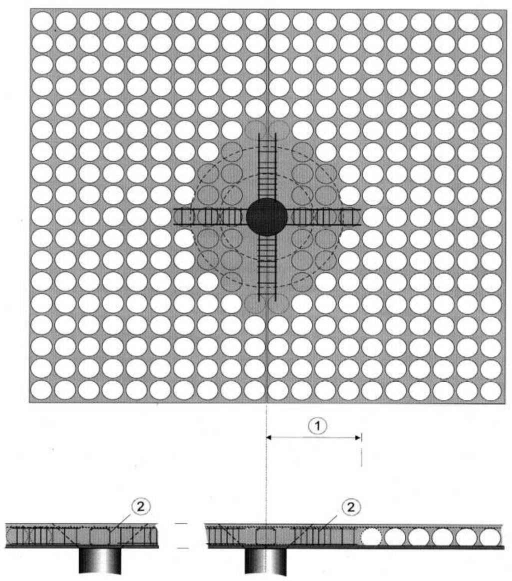

Fig. 3. Slab without hollows in the vicinity of column: 1. Full area 2. Transverse reinforcement [1]

The bubbles are made of a non-porous material that does not react chemically with the concrete or the reinforcement bars. The bubbles have enough strength and stiffness to support safely the applied loads in the phases before and during concrete pouring.

Depending on the bubble diameter, that varies between 180 mm and 360 mm, the slab depth can vary between 230 mm and 450 mm. The distance between bubbles must be greater than 1/9 of bubble diameter. The thickness of the prefabricated filigree slab must be greater than 60 mm.

The concrete for joint filling in the Bubbledeck floor system should have a compressive strength greater than C15/20. It should be mentioned that, usually, self-compacting concrete is used, either for the casting of the prefabricated filigree slab, or for the joint filling on the site. Self compacting concrete can be poured into forms, flow around congested areas of reinforcement and into tight sections, allow air to escape and resist segregation, without the standard consolidation efforts.

As an important advantage of the BubbleDeck floor system, the prefabricated elements can be supplied with prefabricated holes for pipes or electrical boxes.

The lifting, storage and transport should not give the possibility of damaging or splitting the floor elements, which can be stored on bearers or on top of each other. The filigree elements must only be lifted by the lattice beam girder reinforcement. It is important to ensure that BubbleDeck elements are lifted into position in accordance with the planned erection system.

Temporary propping of the elements should be ensured until the concrete poured in situ has gained adequate compressive strength.

2. THEORETICAL STUDIES

In the BubbleDeck system, there are several types of joints. For the case of system comprising reinforcement modules and a prefabricated concrete filigree slab, which is the most frequently used system, a theoretical study regarding the calculation method of the flexural capacity of the BubbleDeck system and of the bond strength of the reinforcement in a joint between the precast slab and the in-situ concrete was carried out by Gudmand-Hoyer [2]. The study is based on the theory of plasticity issued by Nielsen [3]. The special failure mechanisms for the BubbleDeck system are presented in Fig. 4. The bond strength is calculated as a function of the failure mechanism.

In failure mechanisms 1 and 2, yielding is considered as occurring in the joint reinforcement and in the bottom reinforcement. The ductility for this type of failure is usually very large, since yielding is the decisive factor. Therefore, failure mechanism 1 and 2 are often preferred. The bending capacity is significantly influenced by this failure mechanism.

The failure mechanisms 3a, 3b and 3c are different variants of the local failure mechanism where the joint reinforcement is pulled out due to the bending of the slab. Failure type 3a is a dissipation effect, which occurs as a combination of the local failure, splitting failure and reinforcement pull-out. Failure 3b type is a combination of local failure, splitting failure and reinforcement pull-out. If the splitting failure occurs in the construction joint, as shown in Figure 5, the tensile strength should be considered zero. The two prefabricated filigree slab elements will separate and the tension will be carried by the transversal reinforcement, until the pull out of this reinforcement. Failure 3c is a combination of local failure, splitting failure, bending failure and reinforcement pull-out.

Failure mechanism 4 is similar to mechanism 3, but here the pullout of bottom reinforcement occurs. This type of failure is a combination of cover bending failure, splitting failure and transverse reinforcement contribution, depending on its position.

Failure mechanism 5 is a shear failure in the construction joint. A geometrically possible failure mechanism can be a rotation of the compression zone, combined with a displacement of the bottom slab. The interface at the construction joint is assumed to be rough, but it is to mention that the interface area is reduced due to the presence of the spheres.

Failure mechanism 6 occurs by pull out of the reinforcement, like in failure mechanism 3. This failure type is possible if the slope of the crack in tension is equal to the friction angle.

Gudmand-Hoyer has determined, for each type of failure mechanism, the bond strength and the flexural capacity of a joint in the BubbleDeck system, as a function of element geometry, reinforcement and materials characteristics.

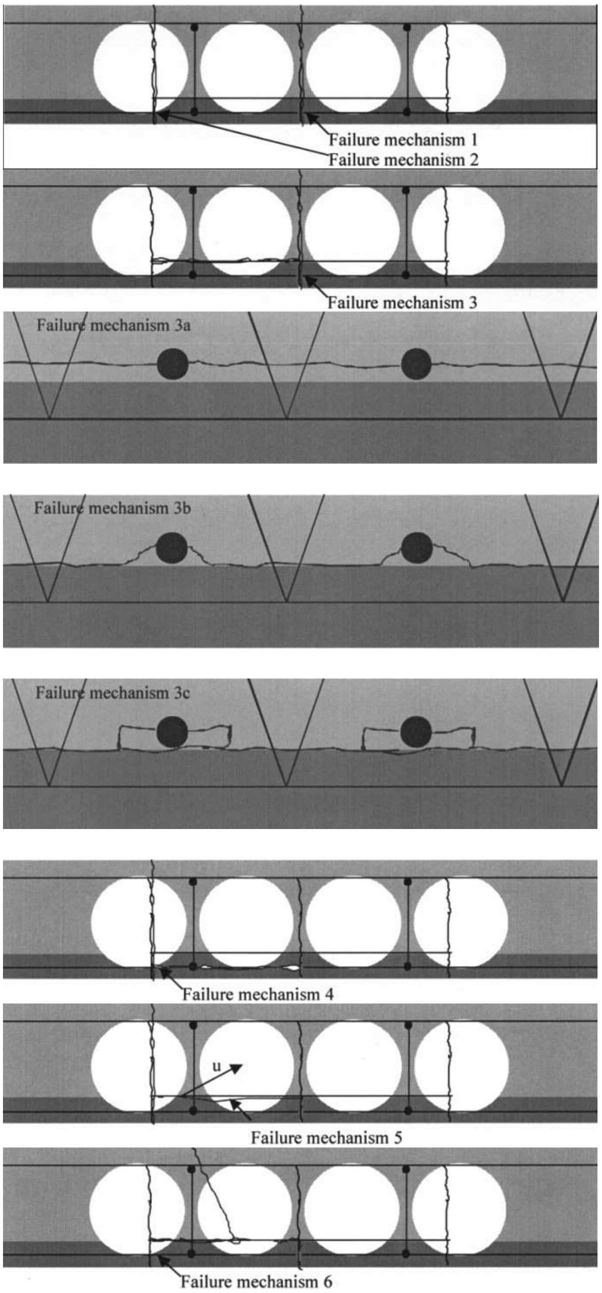

Fig. 4. The special failure mechanisms for the BubbleDeck system [2]

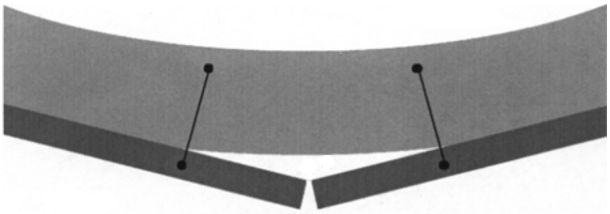

Fig. 5. Separation due to bending [2]

A study regarding the evolution of the neutral axis for an inner middle span of an edge strip of a BubbleDeck slab under various load levels was performed by Bindea et al. [4] at the Technical University of Cluj. In the analysis, the calculating methods specified in the following provisions were considered: Eurocode 2 [5], the FIB Model Code 2010 [6] and the Guide for design of slabs in seismic zones [7]. The results of the comparative study evidenced that EC2 flexural design model may be used for the design of BubbleDeck slab with reinforcement ratios lower than 0,5% and subjected to medium load levels, in the cases when the neutral axis is placed on the top of the bubbles.

3. EXPERIMENTAL STUDIES

3.1. Behavior under bending and shear loads

Comparative studies between BubbleDeck slab and solid slab, regarding the flexural capacity and the punching shear capacity, respectively, were performed by Schmidt et al [8] at Technical University of Denmark, and also by Schnellenbach-Held et al [9], [10] and [11] at Technical University from Darmstadt.

Bending tests were performed on three rectangular bubble slabs, with marginal beams. The dimensions of the models were 1540 × 3080 × 188 mm. The concentrated load was applied centrically.

Shear tests were conducted on three square bubble slabs with dimensions of 1540 × 1540 × 188 mm, with beams along the edges. The load was applied eccentrically on the slab. Punching shear capacity was determined on eleven square bubble slabs at dimensions as above, simply supported along all edges. Shear tests on corners were also performed, on nine square bubble slabs simply supported at the corners. For these tests, three marginal conditions were analyzed: slabs with \beams along all edges, slabs with extended links and no edge beams and slabs with U-shaped stirrups at edges and no edge beams.

The deflections were measured by two transducers mounted on each side of the loading line in bending tests, by one transducer at the center of the slab for shear tests, respectively by one transducer at the bottom surface at the centre of the slab, in punching shear tests. For all type of tests, the deflections at the supports were determined with one or two transducers at each support.

Cracking occurred, as expected, when the tensile stress exceeded the tensile strength of concrete. The bending tests showed that the BubbleDeck slabs have much larger capacity than the theoretical values for the solid slabs. The experimental results demonstrated, as well, that the BubbleDeck slabs have considerable smaller deflections under service load than expected by comparing with calculated values for solid slabs with the same amount of concrete and the same reinforcement ratio. Therefore, the flexural rigidity resulting from experimental tests was more than six times greater than the calculated value. The ultimate load values obtained in bending tests were up to 90% greater than the calculated ultimate load value.

Because of the three–dimensional structural behavior of the BubbleDeck slab, the shear tests showed satisfactory values, compared with the theoretical ones. The effective value of the shear resistance of a BubbleDeck slab was at least 70% of the shear resistance of a solid slab at the same thickness.

Experimental tests regarding the shear behavior and the shear capacity of the BubbleDeck slabs were performed by Bindea et al [12], on four slabs with dimensions of 1500 × 2850 × 310 mm or 1500 × 2750 × 310 mm, with reinforcement ratios varying between 0.18% and 0.52%. During the tests, the vertical deflection, the evolution of cracks on the lateral side of the slabs and the strains in the transversal direction were studied. A comparative study between a BubbleDeck slab with reinforcement ratio of 0.52% and a solid slab, regarding the shear capacity, was also performed. It is to mention that the ultimate shear force of the studied BubbleDeck slab was 97% of the ultimate shear force for the similar solid slab.

3.2. Time dependent behavior

In order to evaluate the creep and shrinkage, comprising early shrinkage, drying shrinkage, chemical shrinkage respectively carbonation shrinkage, of a BubbleDeck element and to compare it with the similar deformations of a solid concrete, important experimental research programs were performed by Grube [13] and Schnellenbach-Held et al [14], respectively.

A BubbleDeck element with two spherical hollows was compared with a solid concrete block, of the same dimensions and the same concrete. The samples were kept at a constant temperature of 20ºC and atmospheric humidity of 70%. The difference between the shrinkage strains of the two blocks was measured on the marginal side. The evolution of shrinkage deformations is presented in Figure 6.

The results show that the BubbleDeck element has a negligible larger marginal shrinkage strain than a solid slab with equivalent dimensions and the same concrete performances, under the same exposure to environmental conditions. An additional analysis performed with finite element method and with three-dimensional elements confirmed these results.

The influence of carbonation shrinkage can be neglected in the design of concrete structures with BubbleDeck system, because only small parts of the concrete cross-section are exposed to this kind of shrinkage.

The geometry of a BubbleDeck influences creep in the same way it influences shrinkage. The creep coefficient and the moment of inertia influenced by the geometry enlarges creep by a negligible amount, whereas the small dead load of the BubbleDeck reduces it. In each case, the dimensions of the BubbleDeck and the influence of the geometry on the creep coefficient must be considered in the design of the elements.

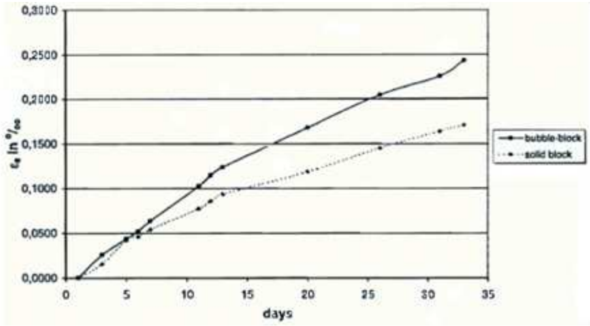

Fig. 6. Shrinkage deformations [13]

3.3. Behavior under seismic loads

A non-linear dynamic analysis was conducted by Gislason [15] at Sigillum Universitatis Islandiae, on a 16-storey office building structure, planned to be build in Reykjavik, Iceland. The building was designed with BubbleDeck floor system, as the first one in Iceland, having biaxial hollow slabs with spherical bubbles. Additionally, a comparison on the earthquake effects on buildings for several floor systems was conducted, and the impact of placing the building in Selfoss, a stronger earthquake zone in South-Iceland, was studied. The main conclusions have evidenced the following aspects:

- two floors can be added for a fixed total height of the building, if BubbleDeck are used instead of normal slabs;
- the building will sustain considerably smaller earthquake forces, as a result of using BubbleDeck instead of normal slabs;
- due to large wall surfaces, wind load is dominant for lateral load design.

3.4. Fire resistance

On the basis of tests performed at Weena Tower Rotterdam on BubbleDeck slabs with 330 mm-thick and with a concrete cover of 20 mm, the research report issued by TNO Rotterdam determined for these slabs a fire resistance of 60 minutes. The TNO report specifies, for 230 mm-thick BubbleDeck slabs with a 35 mm cover, a fire resistance of 120 minutes.

An important experimental program regarding the influence of the cover thickness on the fire resistance of BubbleDeck slabs was performed in the laboratory "Material Research and Test Office for Construction Leipzig". The tests were performed in accordance with the requirements of DIN 4102-2 and of ISO 834-1 respectively.

The design recommendations issued by the above laboratory indicate the minimum value of cover thickness that must be ensured, as a function of fire resistance, (Table 1).

Table 1. Minimal concrete cover thickness (mm), BubbleDeck Technical Manual and Documents [1]

Steel stress (MN/m^2)	**Fire resistance (minutes)**				
	30	60	90	120	180
≤ 190	17 mm	17 mm	17 mm	17 mm	-
≤ 286	17 mm	29 mm	35 mm	42 mm	55 mm

3.5. Fixings into BubbleDeck slabs

In order to evaluate the influence of BubbleDeck slab configuration on fixing systems pullout capacity, BubbleDeck Netherlands company ensured the performing of a comparative study concerning the pullout capacity of fastening anchors embedded in solid blocks with full section and in BubbleDeck blocks with the same reinforcement respectively. The experimental results evidenced the same pullout capacity.

4. CONCLUSIONS

The theoretical and experimental studies performed in Germany, Denmark, Netherlands and Romania had as objective the analysis of BubbleDeck systems behavior, under different loads, in comparison with cast-in-place slabs of full section.

The studies have demonstrated that, with the same amount of concrete and the same reinforcement as the solid slab, the BubbleDeck configuration allows the obtaining of a much-improved flexural capacity and stiffness and a shear capacity of at least 70% from that of a solid slab, realizing 30-50% concrete economy, in comparison with the solid slab. Another advantage of BubbleDeck system is the significant cost saving, because of the possibility of obtaining great spans with less support elements.

The numerous applications in European countries, in Canada and USA, the results of research works performed and the issued regulations highlight the viability and the efficiency of this system.

In the last years, more than 1,000,000 m^2 were built in several countries in the world by using the BubbleDeck system.

In order to indicate the high degree of conformity and use of this type of slab, aspects regarding installation and images from applications are presented in Figures 7…12, courtesy of BubbleDeck Netherlands Company.

Considering the advantages offered by this system, but also the seismic specificity of Romania, it is mandatory to perform theoretical and experimental studies, in order to establish the influence of several parameters (loading level, reinforcement ratio, dimensions ratio, joint configurations) on the behavior of BubbleDeck systems subjected to seismic loads. An experimental and theoretical database will allow the implementation of this system in Romania.

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Fig. 7. Placing of self-compacting concrete for the filigree slab. Gelissen Precast Factory (Holloweg)

Fig. 8. Reinforcement spacers introduced in the self-compacting concrete. Gelissen Precast Factory (Holloweg)

Fig. 9. Realization of precast concrete filigree slab Installation of reinforcement and of the spheres, prior to pouring the self-compacting concrete. Gelissen Precast Factory (Holloweg)

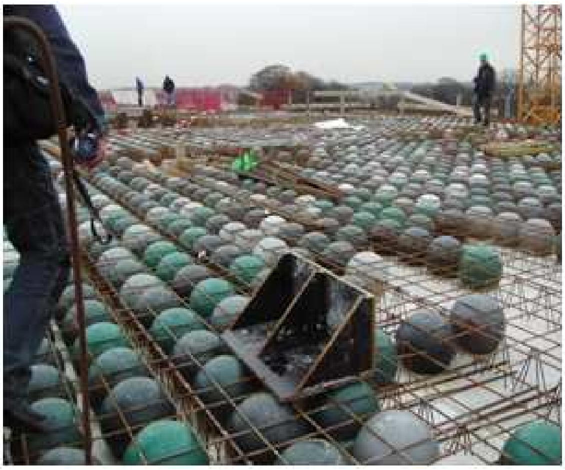

Fig. 10. RCAM (Smalle Pad Amersfoort)

Fig. 11. Retailpark Schaarbroekerweg (Roermond)

Fig. 12. ABC Education Building (Utrecht)

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