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Punching shear in reinforced concrete bubbled slabs: experimental investigation

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ABSTRACT: The behavior of twelve reinforced concrete bubbled slabs of dimensions (1500×1500 mm) with thickness of (100 or 130 mm) under concentric load was investigated to study the effect of several variables on ultimate load capacity, central deflection of the slab, strains in flexural reinforcement and in concrete and the value of failure angle. The main variables considered are the diameter of plastic bubbles (60 or 90 mm), the concrete compressive strength (30 or 60 MPa) and the position of bubbles (d or 2d) with respect to the column face. The test results showed that, the ultimate load decreased by about (4.41-18%) and (14.7-29.4%) in specimens containing bubbles at (2d) and (d) from the face of the column, respectively compared with the corresponding solid slabs. Also, the ultimate load increased by about (17.6-58.5 %) by using concrete of (60 MPa) compared with specimens with concrete of (30 MPa).

1 INTRODUCTION

Concrete slabs are classified as one-way or two-way systems depending on the span lengths ratio in two directions. For one-way system this ratio is greater than 2 while its magnitude is less than 2 for two-way slabs, Midkiff (2013). Two way slabs come in many forms like flat plates, flat slabs, slab with beams or waffle slabs. Among all types of slabs the flat plates present the most advantages from technical to functional point of view, Bindea et al. (2013). The main disadvantage of this type is the high weight which limits the span. For this reason, basic research in the field of reinforced concrete structures have focused on enhancing the span, either by reducing the weight or overcoming concrete's natural weakness in tension.

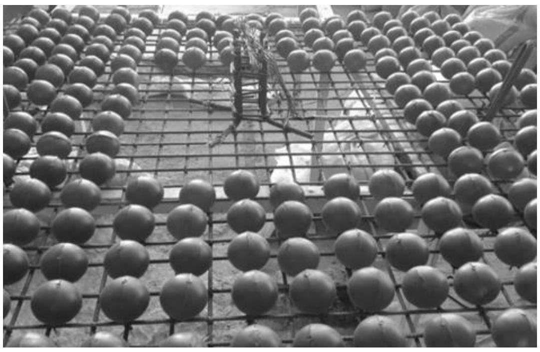
When the flat plates exposed to loads that are greater than their capacity, punching shear would occur. To avoid that, the slab thickness is on increasing resulting in increasing the total weight, Moeinaddini (2012). In order to reduce the total weight, several attempts were done in the last decades through removing concrete from the locations of the slab that are less critical to resist applied loads while maintaining the overall depth of the section and produce slabs with the same section modulus and stiffness if compared with solid slab producing what is called voided slabs or bubbled slab. In the middle of 1990s, a new system was invented by Danish engineer Jørgen Breuning called BubbleDeck technology which locks ellipsoids between the top and bottom reinforcement meshes, thereby creating a natural cell structure, acting like solid slab. This technology consists of spherical balls, to create air voids, made of recycled industrial plastic materials which do not react chemically with concrete and steel. These bubbles may decrease the weight up to 35% and may increase the capacity by 100% with the same thickness. So BubbleDecks can be lighter, thinner, stronger and regular reinforced concrete slabs, Terec (2013).

This paper mainly focuses on the experimental results of BubbleDecks subjected to static loadings. The effect of slab depth, spherical ball diameter and concrete compressive strength will be considered to the overall behaviors of BubbleDeck. The main objective of this study is to investigate experimentally punching shear strength of bubble slab.

2 EXPERIMENTAL PROGRAM

In order to investigate the behavior of BubbleDecks using traditional spherical balls, the experimental program was carried out at Laboratory of Full – Scale Testing, Civil Engineering Department, University of Baghdad. The experimental work consists of a series of tests carried out on twelve half-scale two-way slab specimens of dimensions (1500×1500 mm) with total depth of (100 or 130 mm) which were tested as simply supported over an effective span of 1400 mm in order to evaluate the effect of several variables on punching shear strength of solid and bubbled flat plates. The specimens, with total thickness of 100 mm, were reinforced with bottom mesh steel reinforcement of (6 mm) diameter at (50 mm) c/c. The steel yield strength is 627 MPa. While the specimens, with total thickness of 130 mm, were reinforced with bottom mesh steel reinforcement of (10 mm) diameter at (70 mm) c/c. The steel yield strength is 480 MPa. In each slab, the magnitude of the cover was (20 mm). The diameter of the bubbles used in this study was (60 mm and 90 mm) while the distance between bubbles is (15 mm). The bubbles were tighten with the flexural reinforcement by using tighten wires. Plate 1 and Table 1 show the details of the specimens, where (SD) means solid deck, (BD) means bubbled deck and (d) represents the effective depth of the slab. All slabs were simply supported along the four edges. In each direction, the applied supports allowed angular movement in one end and both horizontal and angular movement of the specimen at the other end, and, hence simulated simply supported scheme. All slabs were loaded using one concentrated loads applied at midspan. The test was conducted using closed loop ram with 50 ton capacity actuator (Plate 2). Specimens were subjected to a monotonically increasing load to failure using a load control test. All measurements, such as slab deflections, strains in concrete and steel were recorded twice, immediately after the application of the load and after 10 minutes later. The total testing time took an average of three hours, depending on the strengthen of the specimen.

(a) Formwork for solid slab



(b) Formwork for bubbled slab

Plate 1. Prefabrication of solid slab (a) and bubbled slab (b).

Table 1. Details of the experimental specimens

Slab designation	Compressive Strength (MPa)	Total Thickness (mm)	Position of bubbles
SD1	30	100	-
SD3	30	130	-
SD5	60	100	-
SD7	60	130	-
BD1	30	100	2d
BD3	30	130	2d
BD5	30	100	d
BD7	30	130	d
BD9	60	100	2d
BD11	60	130	2d
BD13	60	100	d
BD15	60	130	d

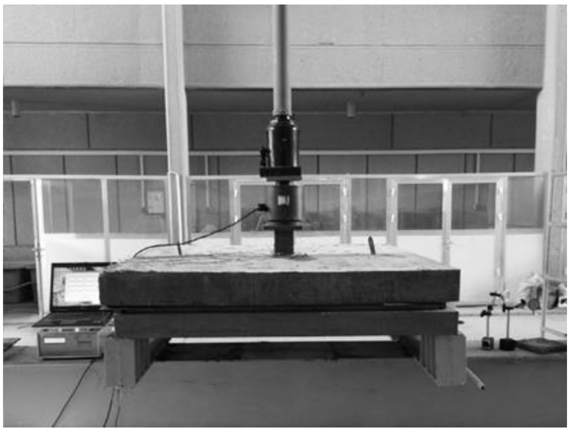


Plate 2. Test setup.

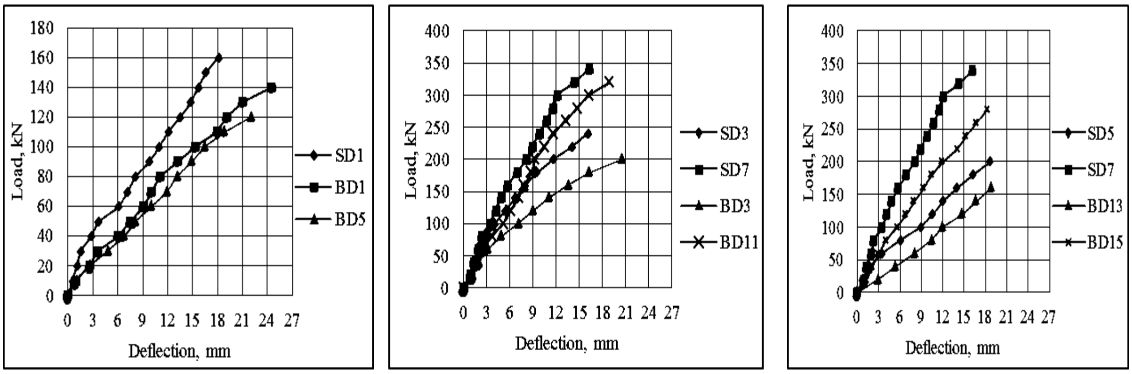
3 RESULTS AND DISCUSSIONS

3.1 Load-deflection relationships

The vertical deflection was measured at the center and at one third the span at each direction using dial gauges of 0.01mm sensitivity. The load-central deflection response of the slabs is shown in Figure 1. The slope of the curves at the beginning are almost identical for all slabs as it depends on the stiffness of the slab, arrangement of supports and type of load. After the formation of first crack, the deflection increases until failure associated with an increase in the number of cracks. It was noticed that, due to the existence of the bubbles, the ultimate loads of bubbled slabs are lower than that of solid slabs. Meantime, the ductility of bubbled slabs is higher than that of solid slabs (Fig. 1a). However, by using high strength concrete, the strength of the specimen increased (Fig. 1b). Also, an increase in the total capacity was observed when the total thickness increased from 100 mm to 130 mm (Fig. 1c).

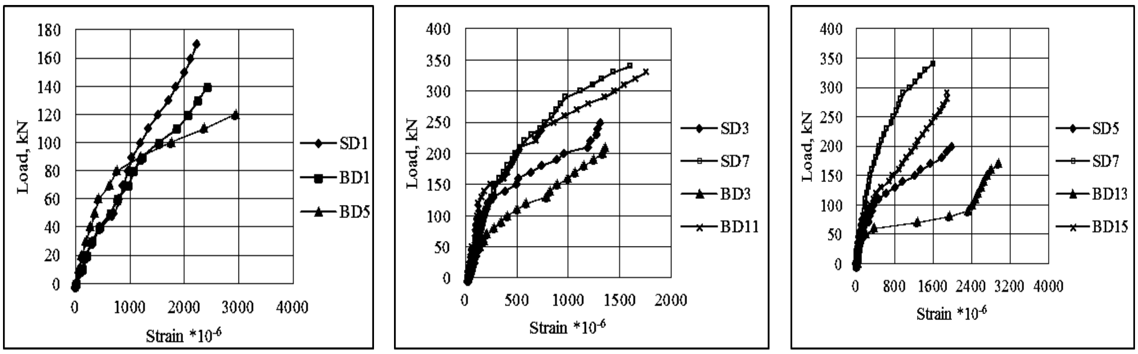
3.2 Load-steel tensile strain relationships

The strain of flexural steel reinforcement was measured at each load stage using four electrical strain gauges at sections located at (d) and (2d) from the face of the column on two orthogonal directions. Figure 2 shows load-steel strain relationships of some slabs at section located (d) from the column face in one direction only. It was found that, the magnitude of strain in steel reinforcement is influenced by the presence of the bubbles (Fig. 2a). Ultimate strain in flexural reinforcement at section (d) from the column face in BD1 and BD5 is higher than that of SD1 by about (12.6% and 36.6 %), respectively. This may be due to the reduction in stiffness in bubbled slabs. On the other hand, by using high strength concrete, the steel tensile strain of the specimen increased at ultimate load (Fig. 2b). Also at service and ultimate loads, a decrease in the steel strain was fixed when the total thickness increased from 100 mm to 130 mm (Fig. 2c).



(a) Effect of bubbles location (b) Effect of concrete strength (c) Effect of slab thickness

Figure 1. Load-deflection relationships for experimental specimens.



(a) Effect of bubbles location (b) Effect of concrete strength (c) Effect of slab thickness

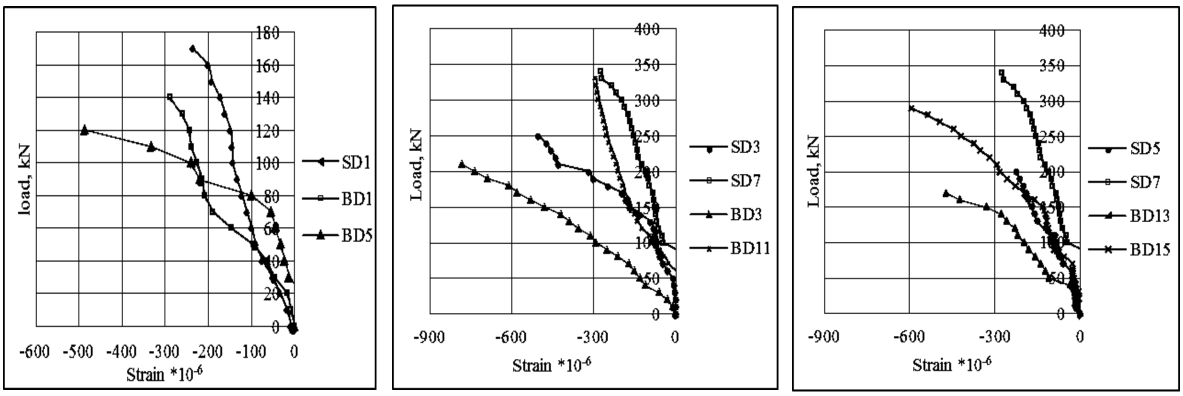
Figure 2. Load-steel tensile strain relationships for experimental specimens.

3.3 *Load-concrete compressive strain relationships*

The compressive strain of concrete is measured at each load stage using six electrical strain gauges at sections located at (d) and (2d) from the face of the column on diagonal and two orthogonal directions. Figure 3 shows the load-concrete compressive strain relationships for some slabs, where the strain in these slabs measured at section located at (d) from the column face in one direction only. As shown in (Fig. 3a), the magnitude of compressive strain in concrete was affected by the presence of the bubbles. Concrete ultimate compressive strain at (d) from the face of the column in BD1 and BD5 is higher than that of SD1 by about (23.2%-106.6%), respectively. This may be due to the reduction in stiffness in bubbled slabs. However, by using high strength concrete, the concrete compressive strain of the specimen decreased (Fig. 3b). Also at ultimate loads, an increase in the concrete strain was noticed when the total thickness increased from 100 mm to 130 mm (Fig. 3c).

3.4 *Ultimate load capacity*

When the load was applied on the slab, the initial crack of all tested specimens was firstly observed in the tension zone near one or more of column corners. With further loading, cracks increased in number at the central region of the slab and extended towards its four edges. In general, the first flexural cracking load initiated at (24.6%-36.8 %) of the ultimate load (see Table 2). From Table 2, it was noticed that, there was a reduction in the load capacity of the bubbled slabs compared with the corresponding solid slabs. This reduction is between (4.41%-18 %) and (14.7%-29.4 %) in bubbled slabs containing bubbles at sections located (2d) and (d) from the column face, respectively. This indicates that the specimens with bubbles located at (2d) from the column face behave as solid decks with a small reduction in punching shear capacity. When the total thickness increased from 100 mm to 130 mm, the ultimate load increased by about (46.4%-80.6 %). This is due to the increase in slab overall stiffness. On the other hand, increasing the concrete compressive strength of slabs resulted in an improvement in their performance. When the concrete compressive strength increased from 30 to 60 MPa, the ultimate load increased by about (17.6%-58.5 %). This confirms that the use of high strength concrete improves the punching shear resistance allowing higher forces to be transferred through the slab-column connection.



(a) Effect of bubbles location (b) Effect of concrete strength (c) Effect of slab thickness

Figure 3. Load-concrete compressive strain relationships for experimental specimens.

Table 2. Cracking and ultimate loads and their corresponding deflections

Slab designation	Cracking load (kN)	Ultimate load (kN)	Deflection at cracking load (mm)	Deflection at ultimate load (mm)
SD1	55	170	5.43	19.45
SD3	80	250	3,0	17,8
SD5	65	200	4,55	18,7
SD7	95	340	2,93	16,2
BD1	40	140	6,0	24,5
BD3	70	205	3,7	20,45
BD5	40	120	6,73	22,1
BD7	70	190	4,72	20,9
BD9	50	180	5,65	22,1
BD11	80	325	3,7	18,88
BD13	45	170	5,75	20,22
BD15	85	290	4,5	19,75

3.5 Crack patterns

The behavior of bubbled slabs was almost the same as the behavior of solid slabs. The first crack appeared around the sides of the column on the tension face of the slab. Also, the width of the first crack in each specimen is approximately (0.05 mm). By increasing the load, other cracks formed at the central region of the slab and extended towards the edges of the specimen. It was noticed that the number of the cracks in bubbled slabs are higher than those noticed in solid slabs. At ultimate load, punching shear failure occurred. It should be mentioned that this failure was more ductile than punching shear failure occurred in solid slabs. On the compression face there were only cracks which formed due to the penetration of column inside the slab. Plate 3 shows the crack patterns of the tested slabs.

3.6 Area, perimeter and failure angle of the tested slabs

The punching failure mode was typically in the shape of pyramid making an angle with the bottom face of the slab. This angle depends upon the nature and the amount of reinforcement in the slab. It may range between about 20° and 45°, Darwin et al. (2016).

The failure angles and the failure punching pyramid zone were measured by considering the dimensions of the crushed zone at the centerline passing through the loaded area. For the tested specimens area, perimeter and failure angle of the punching failure zone are presented in Table 3.

It is worth to mention that the perimeter of failure zone in bubbled slabs is larger than that in solid slabs by about (4.2%-41.7 %). This indicates that the bubbled slabs are more ductile than solid slabs. As a result, the value of failure angle in bubbled slabs is lower than that in solid slabs. Also, when the concrete compressive strength increased from 30 to 60 MPa, the perimeter of failure zone decreased while the values of failure angle increased except those for BD9. On the other hand, when the total thickness increased from 100 mm to 130 mm, the perimeter of failure zone decreased and failure angle increased.

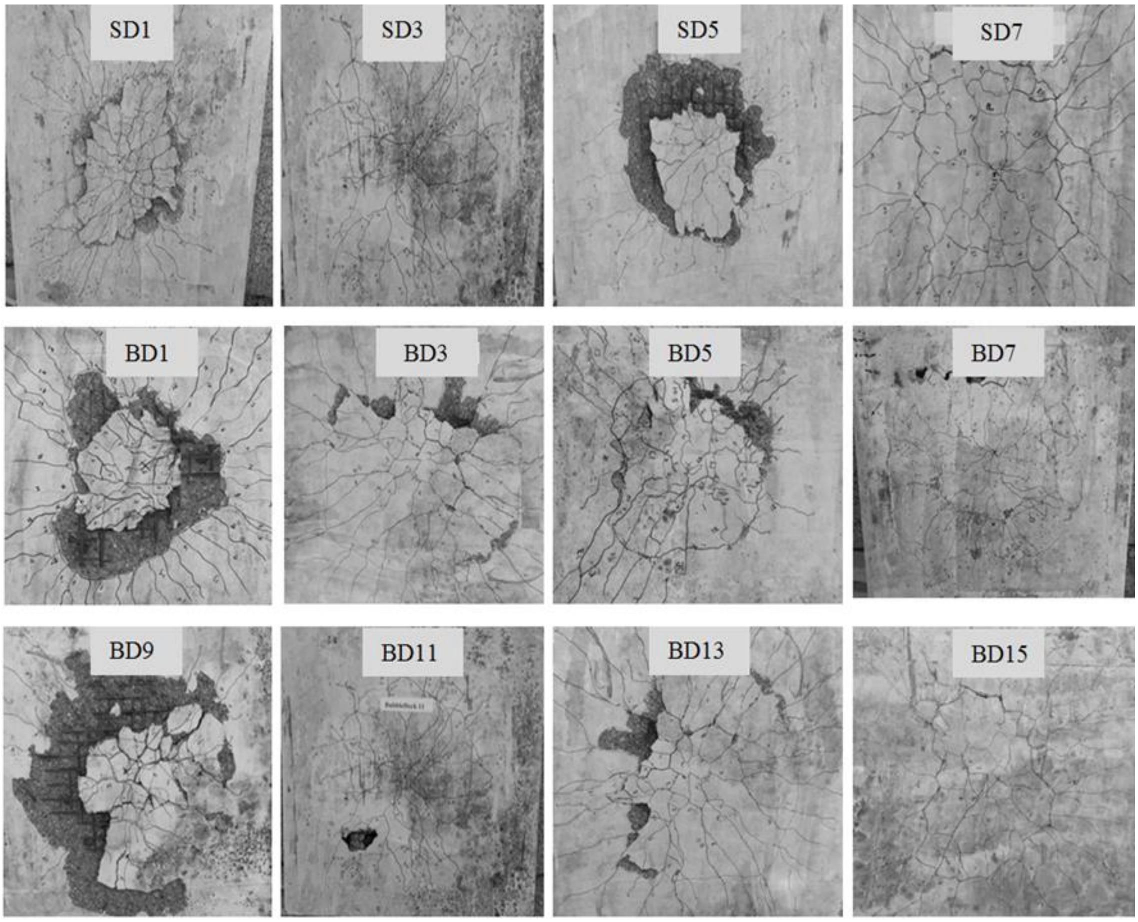


Plate 3. Typical crack patterns of tested specimens.

Table 3. Area, perimeter and failure angle of the specimens

Slab designation	Area (mm^2)	Perimeter (mm)	Failure angle (Ø˚)
SD1	580120	2700	19.7
SD3	497359	2500	33
SD5	458366	2400	29
SD7	458366	2400	45
BD1	669247	2900	20,3
BD3	623887	2700	31,8
BD5	814873	3200	12,5
BD7	764740	3100	23,4
BD9	919916	3400	14,0
BD11	497359	2500	33,0
BD13	716197	3000	17,9
BD15	580120	2700	24,1

4 CONCLUSIONS

Based on the studied parameters, the following conclusions can be drawn:

1. At ultimate the tensile strain of flexural reinforcement of bubbled slabs is higher than that of solid slabs by about (12.6%-36.6 %). While this ratio was about (23.2%-106.6 %) for concrete compressive strain. This may be due to the reduction in stiffness of bubbled slabs.
2. The first cracking load initiated at (24.6%-36.8 %) of the ultimate load.
3. There is a reduction in the load capacity of the bubbled slabs compared with the corresponding solid slabs. This reduction is about (4.41%-18%) and (14.7%-29.4 %) for bubbled slabs containing bubbles at sections located at (2d) and (d) from the column face, respectively. This indicates that the specimens with bubbles located at (2d) from the column face behave as solid decks with a small reduction in punching shear capacity.
4. When the total thickness increased from 100 mm to 130 mm, the ultimate load increased by about (46.4%-80.6%). This is due to the increase in slab overall stiffness.
5. When the concrete compressive strength increased from 30 to 60 MPa, the ultimate load increased by about (17.6%-58.5 %). This indicates that the use of high strength concrete improves the punching shear resistance allowing higher forces to be transferred through the slab-column connection.
6. The presence of bubbles in the specimens increases the deflection at the same stage of loading in comparison with reference solid specimens.
7. The behavior of bubbled slabs was almost the same as the behavior of solid slabs. However, the number of the cracks in bubbled slabs are higher than those noticed in solid slabs.
8. The perimeter of failure zone in bubbled slabs is larger than that in solid slabs by about (4.2%-41.7 %).

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