Two-Way Bubbled Slabs Strengthened by Prestressing Strands

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Abstract. Nine proposed two-way simply supported slabs were numerically tested by finite element method using ABAQUS commercial software to investigate the behavior of two-way slabs strengthened by prestressing strands, one-third of them were solid and the other two-third were bubbled. All slabs have the same dimensions of (1600 ×1600 ×140) mm. Some of these specimens were strengthened by using two or three strands with nominal diameter (6.4) mm in both directions. The slabs were divided into three groups depending on the type of slab (solid or bubbled) and the bubble diameter to slab thickness ratios (D/H). From the numerical tests, it was found that the ultimate load capacity for the bubbled slab at D/H ratio 0.64 and 0.80 was decreased to 12.6 and 14% respectively, while, the maximum deflection for bubbled slab at D/H ratio 0.64 and 0.8 was increased to 3-4 times as compared with the conventional solid slab.

Keywords: Two-way slabs, bubbled slabs, prestressed strands, flexural failure.

1. Introduction
Implementation of plastic balls in reinforced concrete (RC) two-way slabs is considered one of the latest ways to reduce slabs weight. This type of slabs is called bubbled slab system which is widely used in Europe, that’s due to a reduction in self-weight up to 35%, increasing the span of slabs and reducing the total cost of the building [1-5]. When long spans are required, post-tensioned prestressed strands could be used to control the deflection and to increase slabs capacity [6, 7, 8, 10, 11]. Many studies and tests were performed to investigate the flexural and shear behavior of bubbled slabs. It was found that the Bubble Deck slab for the same strength of solid slab had (87, 66) % bending stiffness and concrete volume respectively [12]. Due to the presence of the plastic bubbles which affect negatively on shear strength as a result of removing a significant amount of concrete, the reduction factor for the bubbled slab shear capacity is taken (0.6) of the solid slab [13]. For this reason, it is recommended to remove the bubbles around the columns, as shown in Fig. 1 [7].

2. Proposed Slab Models
Nine two-way RC slab proposed models were numerically tested in this research. These slabs are with proposed dimensions of (1600×1600×140) mm and are divided into three groups depending on their type (solid or bubbled). Group one includes three solid slabs. While, Group two and Group three consist of three slabs having a bubble diameter of 90 mm and 112 mm, So the bubble diameter to depth ratio (D/H) are 0.64 and 0.8 respectively, for each group, one slab is considered without strengthening and the others are supposed to be strengthened with 2×2 or 3×3 unbonded prestressed strands. Table (1) describes the proposed slabs designations and details.
Table 1. Characteristic of the proposed tested slabs

| Group | Design specimen | Type of Specimen | Bubble Diameter (mm) | Number of Bubbles | Weight reduction (%)** | Number of strands in both directions |
|-------|----------------|-----------------|----------------------|-------------------|------------------------|--------------------------------------|
| I     | SD1            | solid           | N.A                  | 0                 | N.A                    | N.A                                  |
|       | SD2            | solid           | N.A                  | 0                 | N.A                    | 2                                    |
|       | SD3            | solid           | N.A                  | 0                 | N.A                    | 3                                    |
|       | BD1            | bubbled         | 90                   | 0.64              | 169                    | 27.25                                | N.A                                  |
|       | BD2            | bubbled         | 90                   | 0.64              | 169                    | 27.25                                | 2                                    |
|       | BD3            | bubbled         | 90                   | 0.64              | 169                    | 27.25                                | 3                                    |
|       | BD4            | bubbled         | 112                  | 0.80              | 100                    | 33.61                                | N.A                                  |
|       | BD5            | bubbled         | 112                  | 0.80              | 100                    | 33.61                                | 2                                    |
|       | BD6            | bubbled         | 112                  | 0.80              | 100                    | 33.61                                | 3                                    |

* refer to a bubble diameter to slab thickness ratio

** % reduction in weight = (w. solid slab - w. bubbled slab) / w. solid slab x100, [9]

3. Proposed Specimens Details

All slab models are proposed to be designed with rebar Ø 4 @ 50 mm for the main reinforcement in both directions. This reinforcement produced a steel ratio of 0.0022 which is more than the minimum reinforcement as recommended by the ACI Code 318M-2019 [14]. The concrete compressive strength fc’ and steel yielding stress fy are considered to be 25 and 420 MPa respectively. For strengthening slabs, while, the prestressing strands grad 250 low relaxation with nominal diameter (6.4) mm respectively.

4. Modeling of Specimens in ABAQUS Computer Program

Three proposed groups of two-way RC simply supported slabs are implemented in the finite element analysis (FEA) using ABAQUS computer program. As mentioned before, each group consists of three specimen models, one is without strengthening and the others are strengthened with 2x2 or 3x3 unbonded prestressed strands. Depending on bubble to depth ratio (D/H), Group one (G1) having B/H=0 (solid slabs) and group two (G2) having B/H=0.64 (slabs with 90 mm bubbles), while group three (G3) having B/H=0.80 (slabs with 112 mm bubbles). Figures 2, 3, and 4 show the details and finite element modeling for the proposed slabs. Moreover, these slabs are analytically subjected to five concentrated loads up to failure, one of these loads is subjected at the center of the models and the other four loads are subjected at the middle quarter of the model slabs. To prevent local failure, steel plates of dimensions (100 ×100 ×10) mm are located under the applied loads. While, steel plates with dimensions (140 ×70 ×10) mm are located at the ends of each strand and contacted the model side face.
Figure 2. Slab models of group one G1.
Figure 3. Slab models of group two (G2) (D/H=0.64).
Steel strands are modeled as shown in Fig. 5. The strand is modeled through a cylindrical sheath having a diameter 2 mm larger than the diameter of the proposed strand to simulate the actual behavior.
of the unbounded prestressed strands. It is worth to mention that each proposed strand is stressed at a level of 65% from its yield stress.

![Hole in concrete 6.5mm Strand](image)

Figure 5. Proposed strands modeling in ABAQUS computer program.

5. FEA Results

5.1. Ultimate Load Capacity

Table 2 illustrated the results of ultimate load capacity and deflection for slabs numerically tested by finite elements analysis, FEA. Where group one B/H (0), showed a higher ultimate load than the other two groups (G2, G3), B/H (0.64, 0.80) by (14.5-16) % respectively. And group three showed dropping in ultimate load than the group two by 2% when increasing the ratio of bubble diameter to slab thickness from (0.64 to 0.80). From the other hand, there is increasing in ultimate load for slabs in the same group when increasing the number of prestressing strands, from (0 to 3) in both directions, this increase can be evaluated as below: The group one G1, there is an increase by (88-98)% for SD2 and SD3, respectively. Group two G2, the increase is (56-73) % for Bubbled Deck (BD2, BD3), respectively, and group three G3, the increase is (40-55) % for Bubbled Deck (BD5, BD6) Sequentially.

| Group | Slab designation | B/H | Ultimate load (kN) | Ultimate deflection (mm) | Camber (mm) | Net deflection (mm) |
|-------|------------------|-----|--------------------|--------------------------|-------------|---------------------|
| 1     | SD1              | 0   | 285                | 8.3                      | ---         | 8.30                |
| 1     | SD2              | 0   | 538                | 6.5                      | 0.0524      | 6.45                |
| 1     | SD3              | 0   | 564                | 5.4                      | 0.0918      | 5.30                |
| 2     | BD1              | 0.64| 249                | 6.5                      | ---         | 6.50                |
| 2     | BD2              | 0.64| 389                | 8.5                      | 0.0808      | 8.42                |
| 2     | BD3              | 0.64| 430                | 9.0                      | 0.123       | 8.88                |
| 2     | BD4              | 0.80| 245                | 7.3                      | ---         | 7.30                |
| 3     | BD5              | 0.80| 345                | 7.9                      | 0.0885      | 7.81                |
| 3     | BD6              | 0.80| 380                | 7.32                     | 0.135       | 7.20                |

5.2. Load-Deflection Response

Deflections are read at the center of the slabs model. The load-deflection curves are plotted to show the behavior of the slabs when using prestressing strands as shown in Fig. 6. Also, the results showed there is a decrease in deflections for all groups when increasing the number of strands from (0 to 2×2 or 3×3) as following; G1 by (55-65) %, G2 by (50-70) % and G3 by (60-63) %. On the other hand, an increasing number of strands from (2×2 to 3×3), cause an increase the camber of the prestressed solid slab by (75) % and by (52) % for both types of Bubbled slabs of ratios of B/H (0.64, 0.80). While Fig. 7 introduces the effect of D/H ratio. The results showed an increase in the deflections of the Bubbled slabs in comparison with solid slabs by (3-4) times the deflection of solid slab, and an increase deflection with
increasing the ratio of D/H from (0.64 to 0.80) by 28%, when reading deflections at 60% of the ultimate load.

**Figure 6.** Load-deflection curves for slabs (Effect number of strands).
5.3. Cracks Pattern

After reviewing the failure patterns of the models shown in Fig. 8, the following conclusions are noted:

- The mode of failure is almost the same for all slab’s models will be flexure failure. The cracks appear as a green region start from the center and extend diagonally toward the corner to make (x) shape.
- For the slabs models without strengthening, (SD1, BD1, BD4), the cracks manifest clearly and with great intensity as wide strip forming (x) shape. These cracks decrease and diverge among themselves with an increase in strands number from (0 to 3), this because of the prestressing tendon effect significantly on increasing the flexure stiffness of slabs and decreasing the cracks.
- The number of cracks were increased with increasing of the bubble diameter to slab thickness ratio (B/H) as compared with the conventional solid slab.

6. Summary and Conclusions

From the analytical results obtained in this study the following conclusions can be drawn:

- The weight of bubbled slabs with bubble diameter to slab thickness ratio (D/H), 0.64 and 0.80 can be reduced to 27% and 34% respectively, as compared with conventional solid slab.
• The Bubbled slabs that have ratios of D/H (0.64, 0.80) % can carry (87, 85) % respectively of the ultimate load capacity compared with the reference solid slab.

• Strengthening the Bubbled slabs have ratios of B/H (0.64, 0.80), by increasing the number of prestressing strands from (0 to 3) enhance the ultimate load capacity by (40-73) % and reducing the deflection by (50-70) %. The same applies to the solid slabs when increasing the strands from (0 to 3) in both directions leads to increasing the ultimate load by (88-98) % and reducing the deflection by (67-70) %.

• The mode of failure for all slabs is the flexural mode and the pattern of the cracks takes the form of a letter (x) that extends to the corners of the models.

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