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EXPERIMENTAL EVALUATION OF THE SHEAR STRENGTH OF THE UNIDOME SLAB SYSTEM

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Abstract. *In this study, the principal objective was to obtain the ratio between the shear strength of Unidome Slab System (USS) and assess the applicability of the ACI 318 Code Provisions for estimating the shear strength of the USS. Four specimens were fabricated and tested including a reference conventional solid slab and three identical USS. The slabs were tested under 3-point loading setup with a single loading applied uniformly across the width (a/d = 4). The results showed that all slabs have experienced typical shear failure modes with sudden failure near the support accompanied by formation of large diagonal major crack. Prior to failure, cracks were developed mainly as diagonal-web shear cracks in the shear zone as well as flexural cracks near the mid region. The overall response of the solid slab was almost linear up to ultimate, whereas the USS response was almost linear up to about 40% of the ultimate load followed by a non-linear response up to failure. The ultimate strength of the USS was 0.71 of the conventional solid slab, and the stiffness and toughness of the USS were 0.88 and 0.96 of the reference solid slab. Based on the results and findings, it was concluded that the ACI-318 Code equation for estimating the design shear strength (V_n) of one-way solid slabs can be safely used for the USS with a modification factor of 0.70. In addition, the USS can be designed in terms of deflection limit as a solid system with a modifier in stiffness.*

1 INTRODUCTION

The Unidome Slab System (USS) is a new system that is sustainable and can provide significant reduction in the self-weight of the structure. The shear strength of Unidome slab system of 20 cm thickness was evaluated experimentally in order to obtain the ratio between the shear strength of slabs cast with Unidome system and companion solid slabs. The specimens were fully-fabricated, casted, cured, and tested after 28 days at the Structural Laboratory at the Jordan University of Science and Technology (JUST). Four specimens were fabricated and tested including a reference solid slab without the Unidome system and three identical slabs with the Unidome system. The width, length, and thickness of the four slabs are 80 cm x 195 cm x 20 cm, respectively. The geometric and reinforcement details are shown in Fig. 1. The concrete mixture was selected to ensure that the 28-day compressive strength is 25 MPa, which was verified prior to testing of the slabs using 100x150 mm cylinders taken at the time of casting and match-cured with the slabs. Reinforcing steel bars were conventional steel with yield strength of 420 MPa. The four slabs were cast at the same time using ready-mixed concrete truck to avoid any variation in the concrete. All practices were conducted according the relevant ASTM standards [1]. Fig. 2 shows portion of the preparation and casting practices of the slabs. A digitally-controlled universal testing machine of a capacity of 2000 kN was used for testing the slabs and the load and mid-span deflection data were continuously recorded using a data acquisition system. The mid-span was measured using LVDT. The slabs were tested under three-point loading setup with a single loading applied uniformly across the slab width using a spread beam. The applied loading was at a distance of 68 cm from the nearest support (span length = 155 cm) resulting in a/d = 4, where d is the slab thickness. Fig. 3 illustrates the loading setup and shows actual setup of one slab.

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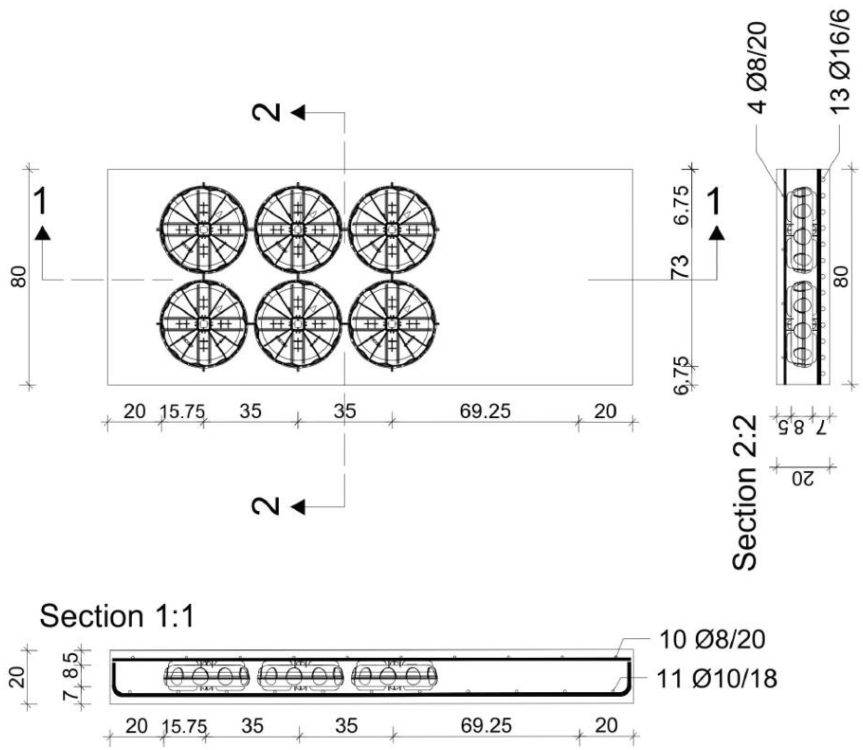

Figure 1. Geometric and reinforcement details of the Unidome slabs.

Figure 2. Portion of the preparation and casting practices of the specimens.

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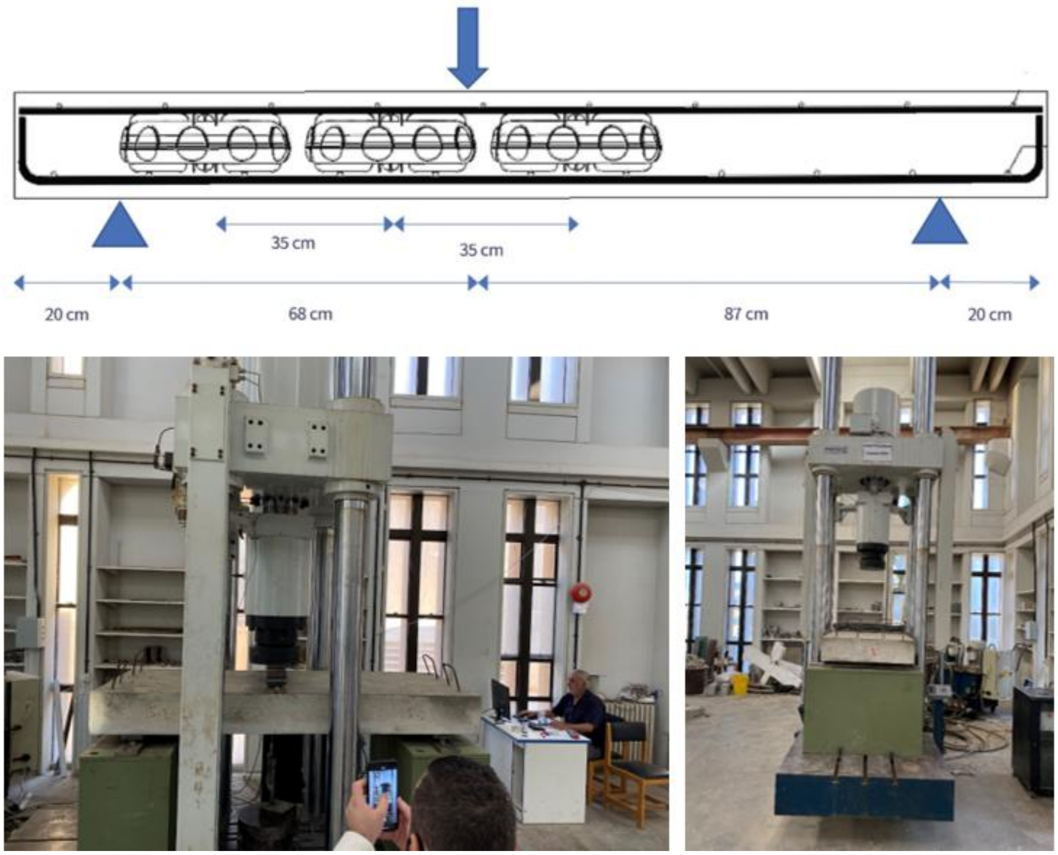

Figure 3. Loading setup.

2 EXPERIMENTAL RESULTS

The conducted testing protocol with the used a/d ratio of 4 reflects the shear strength of the slabs, which is confirmed in the failure mode and cracking patterns for all slabs as shown in Fig. 4. All slabs experienced typical shear failure modes with sudden failure near the support accompanied by formation of large diagonal major crack. Prior to failure, cracks were developed mainly as diagonal-web shear cracks in the shear zone as well as flexural cracks near the mid region.

Fig. 5 shows plots of the response of each slab in terms of the load versus mid-span deflection. The overall response of the solid slab was almost linear up to ultimate, whereas the Unidome slabs response was almost linear up to about 40% of the ultimate load followed by non-linear response up to failure. It can be seen that the responses of the three slabs with the Unidome system showed high agreement with minor variation. Therefore, the average of the three Unidome slabs was considered for comparison with the response of the reference solid slab.

Table 1 shows the ultimate load, stiffness, and toughness (area under the load-deflection curve) of each specimens obtained from the load-deflection responses. The average ultimate strength of the Unidome slabs was 242.2 kN and the ultimate strength of the solid slab was 340.8 kN. This indicates that the shear strength of the Unidome slab is 0.71 of the shear strength of the reference solid slab. The average stiffness and toughness of the Unidome slab were 0.88 and 0.96 of the reference solid slab. The stiffness and toughness results of the Unidome slabs were close to the solid slab which attest to the structural integrity and soundness of the Unidome slab. Fig. 6 shows the four slabs after testing.

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Figure 4. Typical shear failure and cracking patterns.

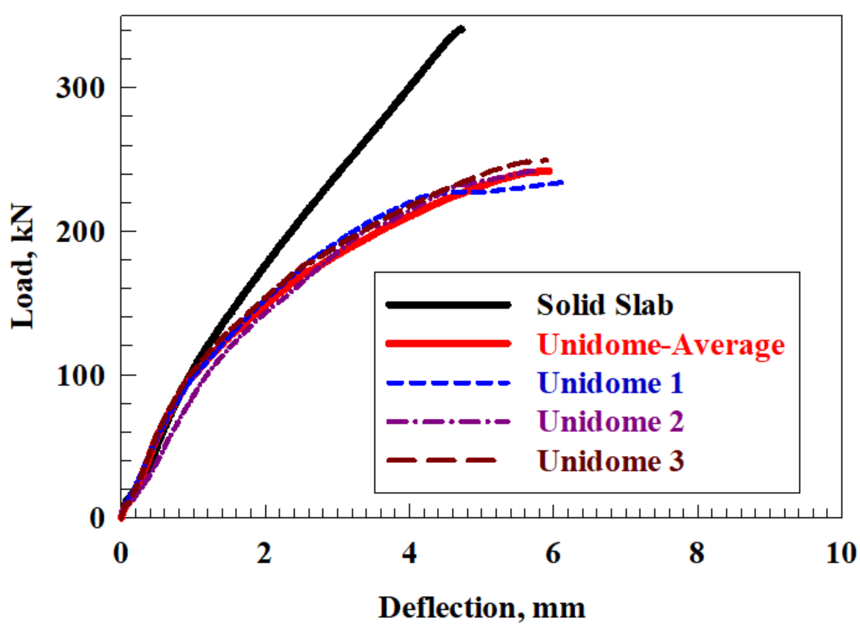

Figure 5. Load versus mid-span deflection for each slab.

Table 1: Ultimate load, stiffness, and toughness results

Slab	Ultimate load (kN)	Experimental Shear Strength $V_{Exp.}$ (kN)	Stiffness (kN/mm)	Toughness (kN.mm)
Solid Slab	340.8	191.2	103.0	906.4
Unidome #1	234.7	131.7	91.1	888.9
Unidome#2	242.3	135.9	81.5	855.6
Unidome#3	249.5	140.0	98.3	863.8
Unidome (Ave.)	242.2	135.9	90.3	869.5
Unidome/Solid	0.71	0.71	0.88	0.96

It is important to note that, the measured deflections from the experimental testing are not a direct and accurate evaluation mean for the deflection since: The deflection limit should be measured as a flexure failure; not as a shear failure. The specimens' steel ratio was increased to avoid any flexural failure that can happen and to have accurate shear failure limitations. However, in general the deflection results in this test can give a good indication for the deflection limit that will be considered for the design of the Unidome slab system. Table 2 shows the measured deflections for the four slabs at failure, at 132 kN press load (referred to as the cracking load), and at 88 kN press load (referred to as the service load). These values were obtained from the load-deflection response shown previously in Fig. 5. In Table 2, the deflections at the failure loads of the solid and Unidome slabs cannot be compared since the deflection values occurred at different ultimate loads. For the sake of relevant comparison, the loads that caused the first flexural crack in the three Unidome slabs were marked on the specimens during the testing. The cracking loads in the three Unidome slabs were 118, 110, and 171 kN, with an average of 132 kN. Again, for the sake of providing useful comparison, the service load is then taken as the cracking load divided by 1.5 kN. Comparing the deflection values at the service load shows that the solid slab and Unidome slabs experience similar deflection at service loads.

Table 2: Measured deflections

Slab	Ultimate Deflection at failure load (mm)	Ultimate Deflection at load 132 kN (mm)	Service Deflection at load 88 kN (mm)
Solid Slab	4.73	1.30	0.80
Unidome #1	6.13	1.57	0.75
Unidome #2	5.79	1.70	1.00
Unidome #3	5.90	1.50	0.70
Unidome (Ave.)	5.94	1.59	0.82
Unidome/Solid	---	---	1.02

3 COMPARISON

The ACI-318 Code provisions [2] allow the use of the following equation for estimating the nominal shear strength (Vn) of one way solid slabs:

$$\boldsymbol{V_n = \frac{1}{6}\sqrt{f'_c}b_w d} \tag{1}$$

Where b_w is the width and d is the effective depth.

The ACI Code uses the design shear strength (V_u) which is calculated by multiplying the shear strength reduction factor ($\boldsymbol{\varphi = 0.75}$) by Vn as follows:

$$V_u = 0.75x\frac{1}{6}\sqrt{f'_c}b_w d \tag{2}$$

From the test setup (Fig. 3), the experimental shear strength ($V_{Exp.}$) can be calculated from the load at failure (P) as: $V_{Exp.} = 0.561P$. The resulting values are listed in Table 1. In the case of the tested slabs, f 'c = 25 MPa, b_w = 800 mm, and d = 162 mm. Using Equation 1, the estimated V_n is 108 kN for solid slab, which is 0.56 of its $V_{Exp.}$ = 191.2 kN. Also, Using Equation 2, the estimated Vu is only 0.42 of its $V_{Exp.}$. This comparison is intended to show the major precautions the ACI-318 Code as well as other Codes are imposing on the shear design of flexural members due to the sudden nature and dangerous shear failure. These precautions include: 1) ignoring the contribution of the steel bars to the shear strength, 2) considering the ultimate shear stress to be on 0.166 times the square root of f'_c, and 3) not considering the diagonal failure plain. Most importantly, the average experimental shear strength of the Unidome slabs (135.9 kN) is 1.68 times V_u = 81 kN calculated using the ACI-318-318 Code. With the use of 0.70 as a reduction factor in the calculation of the shear strength of the Unidome slabs, the resulting shear strength is V_u = 0.7*81 = 56.7 kN, which is about 42% of the experimental press load (56.7/135.9). Therefore, Equation (3) can be safely used for calculating the shear strength of Unidome slabs:

$$V_u = 0.7 * 0.75 * \frac{1}{6}\sqrt{f'_c}b_w d \tag{3}$$

4 CONCLUSION

A total of four full-scale slabs including one reference solid slab and three slabs with the Unidome system were evaluated experimentally in this study. Based on the results and findings, it can be concluded that the shear strength of the Unidome slab can be safely estimated as 70% of the shear strength of the companion solid slab, and thus Equation (3) can be used for calculating the shear strength of the Unidome slabs. The Unidome slabs system is a sound system structurally and provides significant reduction in the self-weight of the slab. The Unidome system can be designed in terms of deflection limit as a solid system with a modifier in stiffness based on the selected void size. Useful publications [3-6] relevant to voided slab systems are listed in the references section.

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