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STRUCTURAL BEHAVIOR OF HIGH STRENGTH ARCHED REINFORCED CONCRETE SLABS

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ABSTRACT

The main aim of this study was to study experimentally the behavior and ultimate strength of concrete arched slabs under flexural load. The main parameters considered in the present investigation were, compressive strength of concrete, thickness of slab, area of steel, arch curvature and support conditions. A total of fourteen samples of the arched slab were constructed and tested under two-point load. The behavior of samples was observed by reading the deflection at mid-span and strains at top and bottom fibers and observed the crack patterns. The behavior of arched slab samples is linear up to first cracking load and still linear up to (35% - 55%) from the ultimate load. The load-deflection curve at the mid-span of the arched slab may be idealized by a bilinear curve. Increasing compressive strength by 116% leads to an increase in the ultimate load by (15% - 25%). Increasing the slab thickness by 43% leads to an increase in the ultimate load by (6% - 17%). Increasing the area of steel by 45% leads to an increase in the ultimate load by (29% - 34%). Increasing the height curvature by 200% leads to an increase in the ultimate load by (6% - 28%). Changing the support from simply to pin-pin support leads to an increase in the ultimate load by (200% - 245%).

KEYWORDS: Arched slabs, High strength concrete, Normal strength concrete, Curvature, Reinforcement.

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1. INTRODUCTION

An arch may be defined as a curved member having convexity upwards, and supported at its ends. The main aim of the arch is to enhance the load carrying capacity, which may come from the stiffening behavior due to membrane action. This characteristic enables the structural engineer to achieve large spans in buildings roofing and bridges decking using materials with efficient compressive strength, like concrete or by using suitable compression resisting systems, like braced and trussed metal structures to overcome the dominant compressive stresses generated in the arches. On the other hand, an axial force is introduced due to the arch action. This state of action is compatible with concrete materials, which are relatively weak in carrying the tension and shear stresses, but adequate in carrying the compressive stresses (Bashar, 2013).

The purpose of this research is to study the behavior and strength of arched slab subjected to flexural load. The influence of the following parameters is considered.

2. BACKGROUND

Arched slabs are structures that derive their strength from form rather than mass. This form enables the structure to have a minimum of material for maximum structural advantage. While a plane element like a roof slab undergoes bending when subjected to vertical loads. The concrete arched slabs construction technique is an important legacy in the history of concrete construction and structures. It was an attempt to cover large spans with the most widely used construction material of the Twentieth Century which produced structures that are now regarded as architectural masterpieces (British Standards Institution, 1990). The design of concrete arched slab also fostered theoretical developments in structural analysis, in the mathematical theories and in the theory of finite elements. it may distinguish roughly two periods in the history of thin concrete arched slabs; a period of precursors before the Second World War with eminent engineers such as Eduardo Torroja (Torroja, 1958) in Spain and Eugene Freyssinet (Femandez Ordoñez 1979) in France, and a period of blooming development after the war.

Al-Rifaie and Al-Himedawi, 2000 studied the structural behavior and ultimate strength of thin ferrocement shell units under a point load positioned at the crown of the shell. Twelve shell units were constructed and tested to failure, the width and the supported span of these shell units were kept constant (0.45 m) and (4 m), respectively while the thickness, mesh layers and the height of the crown were varied. The finite element method (FEM) was used to provide a theoretical basis of comparison up to the first cracking loads by using a computer program STAADIII version 8. The element used was 4-node straight-sided shell element with (6) degree of freedom per node. The results of the study were that the flexural rigidity was increased by increasing the thickness of the shell unit and the number of wire mesh layers and increasing the height of the shell unit tends to increase the cracking and ultimate loads.

Zhang, 1991, studied finite element methods for a class of arch beam models. For both standard and mixed methods, existence and uniqueness results were proved, optimal rates of convergence were obtained and the super convergence property is established. Reduced integration was shown to be an efficient method for arch beam problems and selected reduced integration was found to be identical to the mixed method. The significances of the analysis were: The mixed and the reduced integration methods were converged uniformly at the optimal rate with respect to the arch thickness parameter, so they were locking free. Mixed method and reduced integration keep the super convergence properties of the standard method. Finally, this was the first attempt to investigate the super convergence of finite element methods for arch beam problems.

Wang et al., 2007 made short-term experimental studies undertaken on two shallow parabolic reinforced concrete arches with span to rise ratios of 18.8 and 25.0. The two supports of each arch were connected by a steel tie. The arches failed in an antisymmetric bifurcation buckling mode well before the maximum stress in the concrete reached its compressive strength. Both the load–deflection response and the buckling load are compared with theoretical predictions that incorporate various degrees of nonlinearity in their formulation. The average stress in the arches was only about 40% of their compressive cylinder strength indicating that the material response and so the buckling behavior was close to being elastic.

Sadjad, 2009 derived a new stiffness matrix for arch beams using finite element method. Transverse shear deformation was included in the derivation. The presented stiffness matrix could be used in both linear and nonlinear analysis of concrete and steel arch beams. The new stiffness matrix had been used in some applications of both curved thick and thin arch beams. The conclusion shows a very good agreement between the presented study and the results of exact solution of other researchers. The maximum difference in deflection was found to be (9%). Also, the influence of shear deformations was found to be significant in the thick arch example with a ratio of (10%).

Maryam and Nameer, 2018 presented a study that include an experimental and numerical investigations for the behavior and the load carrying capacity of simply supported beam with segmental arch bottom of high strength concrete (HSC) subjected to static loading condition. The goals were to evaluate the effect of arch dimensions on the behavior of beam with the same volume of concrete and amount of steel reinforcement and to find the optimum ratio of the arch length to beam span for the maximum load capacity as well as to validate the numerical results taken from the finite element model. The experimental program consists of testing four simply supported beams containing arch at the bottom face and tested under two-point load. The beams are different spans of arch (1.18 m, 0.9 m, 0.74 m and 0.6 m). Among conclusions of this work, it is concluded that the increase of the arch length to beam span ratio increased the ultimate load capacity to more than 60%. FEM appears efficient and gives good accuracy through comparison with the experimental results where the maximum difference in the ultimate load value was less than 4%.

Alireza, et al., 2019 presented an experimental investigation on the behavior of RC arches strengthened by Glass Fiber Reinforced Polymer (GFRP) composites. Twelve samples were tested in order to determine influence of arrangement and number of GFRP layers on RC arches having different steel reinforcement ratios. The arches were tested under centrally concentrated point load using displacement control condition. Load-deflection behavior, failure mode, GFRP debonding, angle between hinge formation and supports and crack propagation pattern are studied extensively. Based on test results, extrados strengthening is much more effective than intrados strengthening in increasing ultimate load carrying capacity which can reach up to 200%.

3. EXPEREMENTAL PROGRAM

3.1. Details of Tested Specimens

All the samples have length of span of 2 m and width of 0.6 m. The details of the models are shown in Fig. 1. The main properties of the tested models were given in Table 1. Five main parameters are chosen to study the behavior and ultimate strength of arched slabs which were thickness of slab, curvature of arched slab, area of reinforcement steel, compressive strength and support condition.

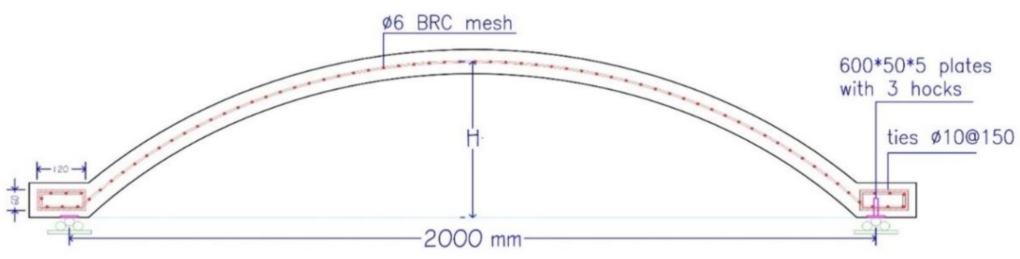

Fig. 1. Details of the Specimens.

Table 1. Main Properties of the Arched Slab Models.

No.	Symbol	Slab Thickness (mm)	Height of Curvature (mm)	Area of Reinforcement Steel (mm)	Compressive strength (MPa)	Support condition
1	N-10-15	100	150	255	30	Hinge - hinge
2	N-10-45	100	450	255	30	Hinge - hinge
3	N-7-15	70	150	255	30	Hinge - hinge
4	N-7-45	70	450	255	30	Hinge - hinge
5	H-10-15	100	150	255	65	Hinge - hinge
6	H-10-45	100	450	255	65	Hinge - hinge
7	H-7-15	70	150	255	65	Hinge - hinge
8	H-7-45	70	450	255	65	Hinge - hinge
9	H-T-15	100	150	368	65	Hinge - hinge
10	H-T-45	100	450	368	65	Hinge - hinge
11	H-S-15	100	150	255	65	Simply supported
12	H-S-45	100	450	255	65	Simply supported
13	H-C-15	100	150	255	65	Simply supported with tension member
14	H-C-45	100	450	255	65	Simply supported with tension member

3.2. Materials

The used materials and their properties are listed in Table 2.

Table 2. Description of Mix Materials.

Material	For Normal Strength Mix	For High Strength Mix
Cement	Sulfate-resisting cement type V	Sulfate-resisting cement type V
Gravel	Crushed coarse aggregate with a maximum size of 10 mm	Crushed coarse aggregate with a maximum size of 10 mm
Sand	Natural sand (from Al-Najaf region) with a maximum size of 4.75 mm	Natural sand (from Al-Najaf region) with a maximum size of 4.75 mm
Silica fume	---	Gray densified micro-silica fume
Superplasticizer	---	Master Glenium 54, BASF, Ludwigshafen, Germany

3.3. Mix Proportions

The mix proportions were selected according to multiple trial mixes and the final mix proportions are presented in Table 3.

Table 3. Concrete Mix Proportions.

Mix	C.A. kg/m^3	F.A. kg/m^3	Cement kg/m^3	Water L/m^3	W/B	Silica kg/m^3	Glenium 54 L/m^3	gravity Kg/m^3	F'c MPa
Normal strength	1100	800	335	165	0.5	---	---	2400	30
High strength	1250	470	520	150	0.3	60	15	2445	65

3.4. Reinforcement Details

The used reinforcement in the arched slabs samples were square B.R.C mesh of 15×15 cm opening and diameter 6 mm. Two symmetric layers were used to get cross-section steel area of 255 mm², and three symmetric layers were used to get cross-section steel area of 368 mm². Also, a 10 mm diameter bar used for making stirrups at the rectangular parts at the ends of slab where the supports should be placed. Fig. 2 shows the reinforcement of the samples. The steel is tested according to ASTM A 370-17 (ASTM A 370-17, 2017) [9] the test shows that the Fy=210 MPa and Fu=570 MPa

Fig. 3. Reinforcement of the Samples.

3.5. Testing Procedure

The hydraulics machine was used in the test of the arched slab specimens and two-point loads were applied on the arched slab as shown in Fig. 3. Mid span deflection, strains at both top and bottom fibers, and cracks widths were recorded. Fig.4 shows the sample on the testing machine.

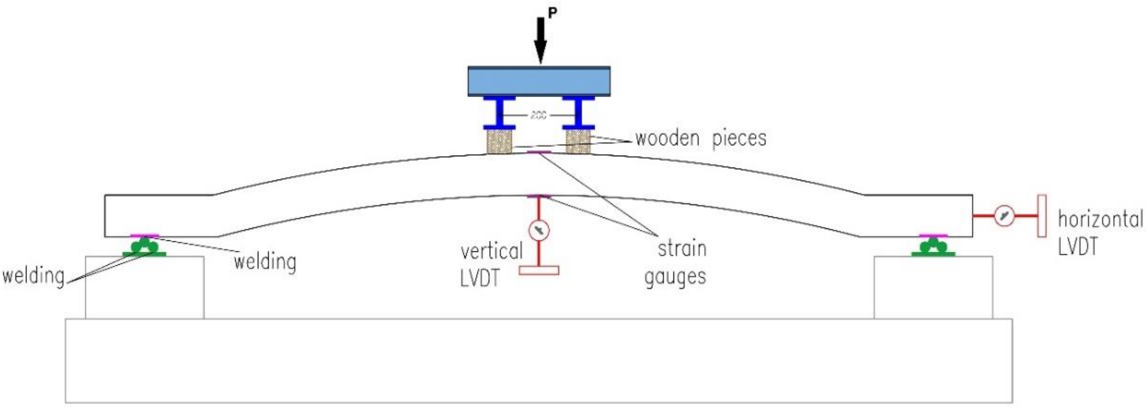

Fig. 3. Test Setup Details.

Fig. 4. The Sample on the Testing Machine.

4. RESULTS

In general, the first crack was initiated at the bottom face of the concrete arched slab at the mid span or under the two-line loads or both. After applying higher loading, there were propagation cracks with an expansion in the first crack horizontally over the bottom face of the concrete slab and vertically towards the top face of the concrete slab. During that deflection were increasing continuously. Finally, a plastic hinge was formed at mid span. After this stage of loading, the loading was dropped down and the last load recorded by the reader of the testing machine was considered the ultimate load. The main experimental results are summarized in Table 4. Where Pcr = load of the first crack at the bottom face of the concrete slab, Δcr = the mid-span deflection at the load of the first crack, Ps = the service load (which equal to about 70 % of the ultimate load), Δs = the mid-span deflection at the service load, Zs = the width of the first crack at service load, Pu = the ultimate load of the sample, Δu = the mid-span deflection at the ultimate load, Zu = the width of the first crack at ultimate load.

Table 4. The Results Summary of Experimental Test.

Sample	Pcr (kN)	Δcr (mm)	Ps (kN)	Δs (mm)	Zs (mm)	Pu (kN)	Δu (mm)	Zu (mm)	Pcr/Pu %	Δu/Δcr	Δu/Δs
N-10-15	24.5	4.05	24.56	4.25	0.5	35.08	18.6	5.5	69.8	4.59	4.37
N-10-45	24.2	5.6	26.2	6.2	0.2	37.43	19.6	4.25	64.6	3.5	3.16
N-7-15	11.5	1.6	21.03	6.75	2.4	30.04	19	7	38.2	11.87	2.81
N-7-45	9.4	0.9	24.16	6.25	0.78	34.52	21.3	3	27.2	23.66	3.4
H-10-15	25	0.46	28.08	2	0.8	40.12	16	7.2	62.3	34.78	8
H-10-45	25.3	0.63	31.34	1.4	1.4	44.77	20.5	9	56.5	32.54	14.6
H-7-15	23.3	3.3	26.83	6.9	0.48	38.33	15.3	5	60.7	4.63	2.21
H-7-45	22.2	2.5	29.34	4.15	0.43	41.92	16.8	6	52.9	6.72	4.04
H-T-15	29.4	4.9	37.8	7.3	0.7	54	17.5	10	54.4	3.57	2.39
H-T-45	32	2.3	40.42	5	4.15	57.74	21	8.4	69.3	9.13	4.2
H-S-15	7	1.35	8.15	2.3	6.65	11.64	10	10	55.3	7.4	4.34
H-S-45	7.6	4.6	10.41	6.95	4.05	14.87	13.9	14	51.1	3.02	2
H-C-15	15	2.96	19.8	4.4	0.58	28.34	8	6.5	52.9	2.7	1.81
H-C-45	16.5	1.61	21	1.92	1.25	30	6.5	5.3	55	4.03	2.76

5. DISCUSSION

The results of the experimental test were discussed according to the parameters. The discussion was classified to five groups according to the effect of the variables taken into consideration.

5.1. Group 1 (Effect of Compressive Strength)

This group contains eight samples that differ in the compressive strength of concrete mix, four samples (N-10-15, N-10-45, N-7-15 and N-7-45) have a normal compressive strength of 30 MPa, the other four samples (H-10-15, H-10-45, H-7-15 and H-7-45) have a high compressive strength of 65 MPa. Fig. 5 shows the difference in the behavior of each couple of samples.

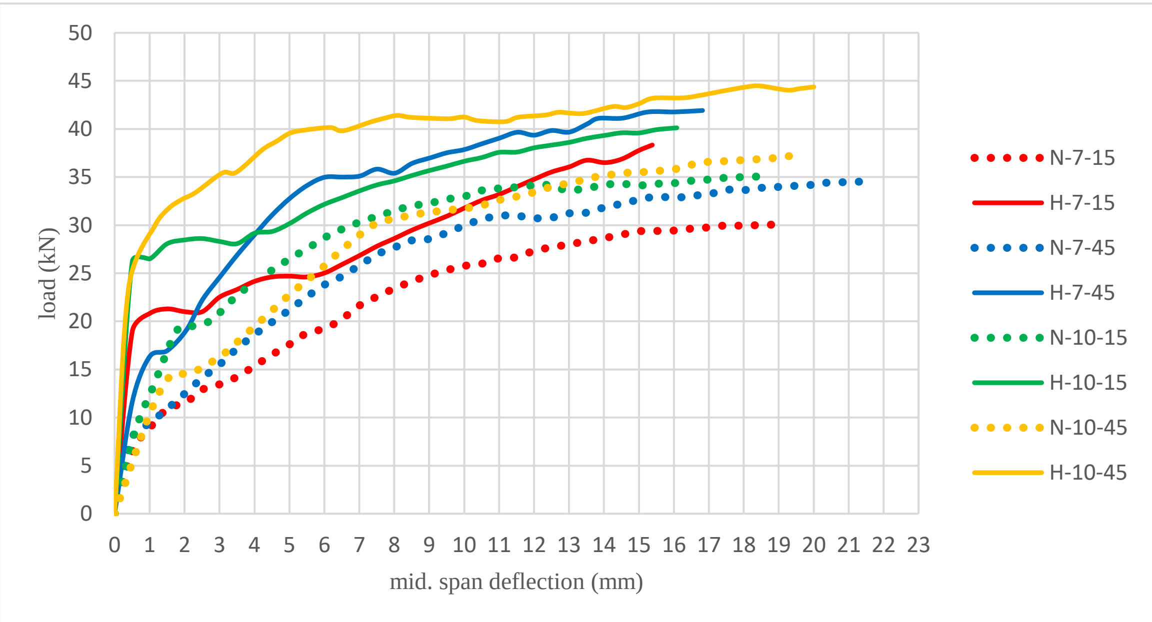

Fig. 5. Effect of Compressive Strength on the Behavior of Arched Slabs.

As shown in the figure above, it can be noted that the maximum effect of compressive strength on the ultimate load appeared in samples H-7-15 and N-7-15, generally, for samples with less thickness of slab; the effect of compressive strength on the ultimate load and deflection is more obvious than the samples with higher slab thickness. Also, the effect of compressive strength seems clearer at the linear stage than at the non-linear stage.

The effect of increasing compressive strength from 30 MPa to 65 MPa on the ultimate load can be summarized as following: -

- Increasing the ultimate load by 14% for samples with 100 mm thickness and 150 mm curvature.
- Increasing the ultimate load by 19% for samples with 100 mm thickness and 450 mm curvature.
- Increasing the ultimate load by 27% for samples with 70 mm thickness and 150 mm curvature.
- Increasing the ultimate load by 21% for samples with 70 mm thickness and 450 mm curvature.

5.2. Group 2 (Effect of Slab thickness)

This group contains eight samples which differ in the thickness of the slab, four samples (N-10-15, H-10-15, N-10-45, and H-10-45) have a thickness of 100 mm, the other four samples (N-7-15, H-7-45, N-7-45, and H-10-45) have a thickness of 70mm. Fig. 6 shows the difference in the behavior of each couple of samples.

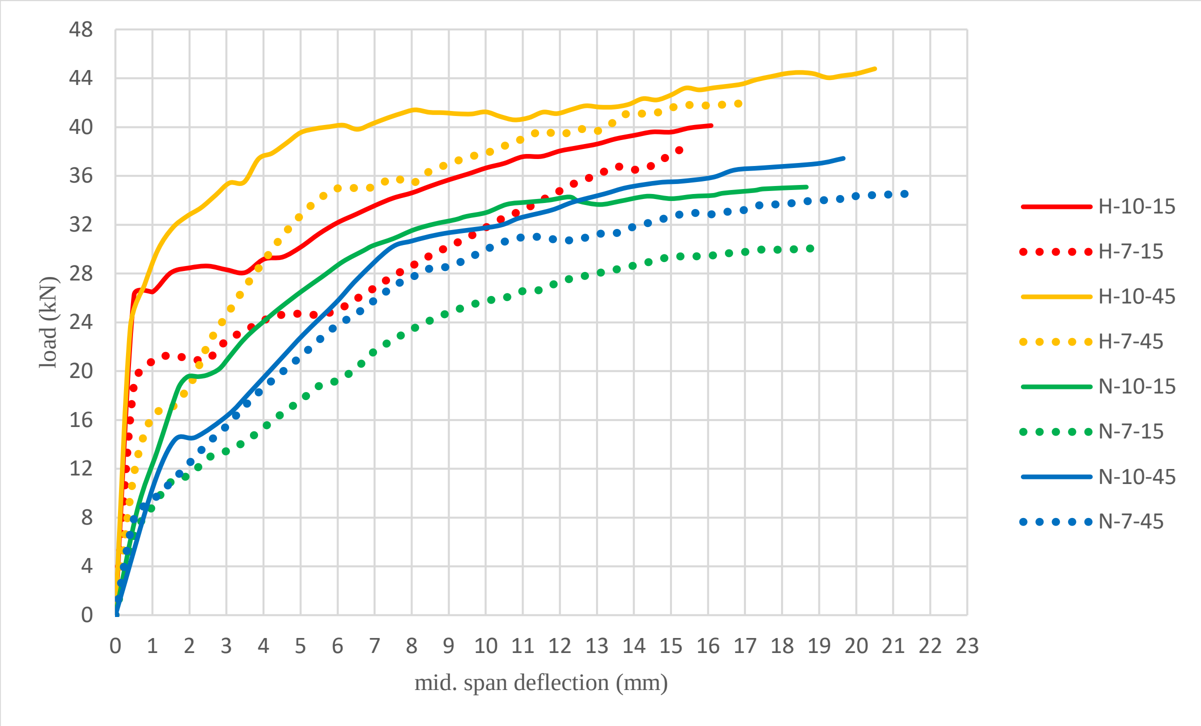

Fig. 6. Effect of Slab Thickness on the Behavior of Arched Slabs.

As shown in the figure above, it can be noted that the maximum effect of slab thickness on the ultimate load appeared in samples N-10-15 and N-7-15. In general, the stiffness of each couple is almost similar at the linear stage. Also, it can be recognized that the effect of slab thickness on the load-deflection is more obvious at the elastic-plastic stage.

The effect of increasing slab thickness from 70 mm to 100 mm on the ultimate load can be summarized as following: -

- Increasing the ultimate load by 17% for samples with 30 MPa compressive strength and 150 mm curvature.
- Increasing the ultimate load by 8% for samples with 30 MPa compressive strength and 450 mm curvature.
- Increasing the ultimate load by 4% with 65 MPa compressive strength and 150 mm curvature.
- Increasing the ultimate load by 6% for samples with 65 MPa compressive strength and 450 mm curvature.

5.3. Group 3 (Effect of Area of Steel)

This group contains four samples which differ in the area of reinforcement steel, two samples (H-10-15 and H-10-45) have area of steel of 255 mm², the other two samples (H-T-15 and H-

T-45) have an area of steel of 368 mm². Fig. 7 shows the difference in the behavior of each couple of samples.

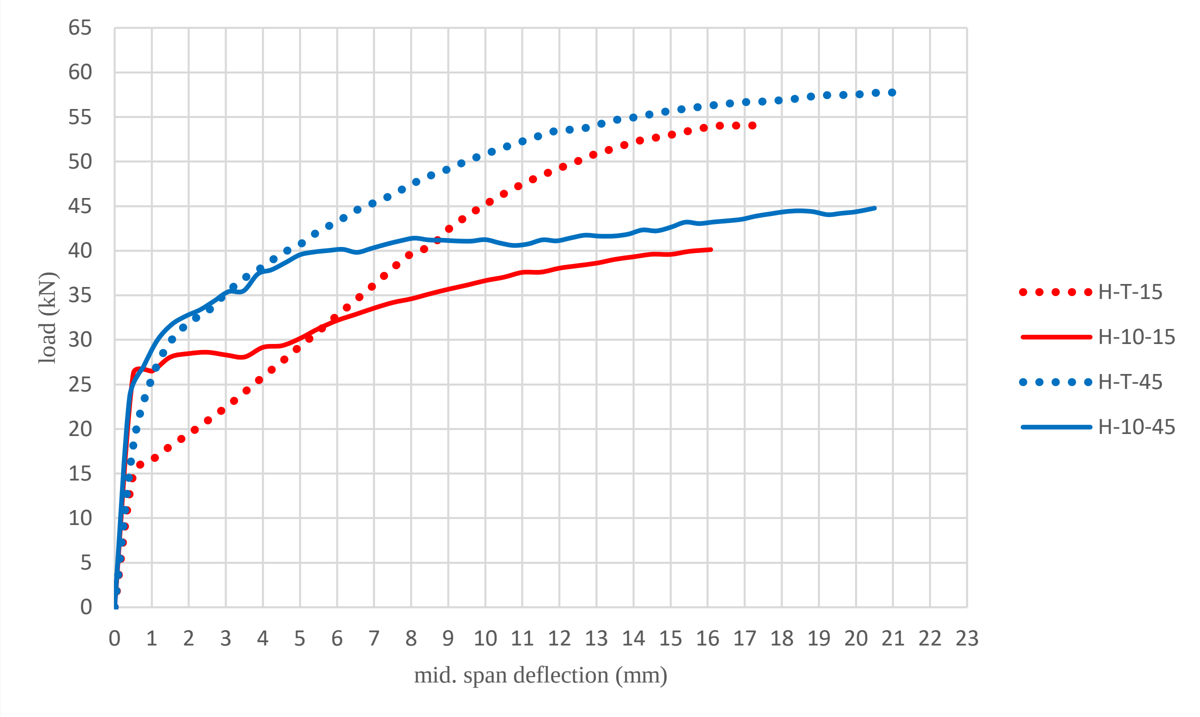

Fig. 7. Effect of Area of Steel on the Behavior of Arched Slabs.

As shown in the figure above, it can be noted that the maximum effect of steel area on the ultimate load appeared in samples H-10-45 and H-T-45. It can also notice clearly that the effect of steel area is so explicit after the linear stage (at the ono-linear stage). And we can recognize the difference in the effect of steel area on the deflection between the service load stage and ultimate load stage, where there almost no obvious change in the mid-span deflection at the ultimate load, while there is an exaggerated change in the mid-span deflection at the service load.

The effect of increasing area of steel from 255 mm2 to 368 mm2 on the ultimate load can be summarized as following: -

- Increasing the ultimate load by 34% for samples with 65 MPa compressive strength, 100 mm thickness and 150 mm curvature.
- Increasing the ultimate load by 29% for samples with 65 MPa compressive strength, 100 mm thickness and 450 mm curvature.

5.4. Group 4 (Effect of Curvature)

This group contains ten samples that differ in the curvature of the arched slab, five samples (N-10-15, H-10-15, H-T-15, H-S-15 and H-C-15) have mid-span height of arched slab of 15 cm, the other five samples (N-10-45, H-10-45, H-T-45, H-S-45 and H-C-45) have mid-span height of arched slab of 45 cm. Fig. 8 shows the difference in the behavior of each couple of samples.

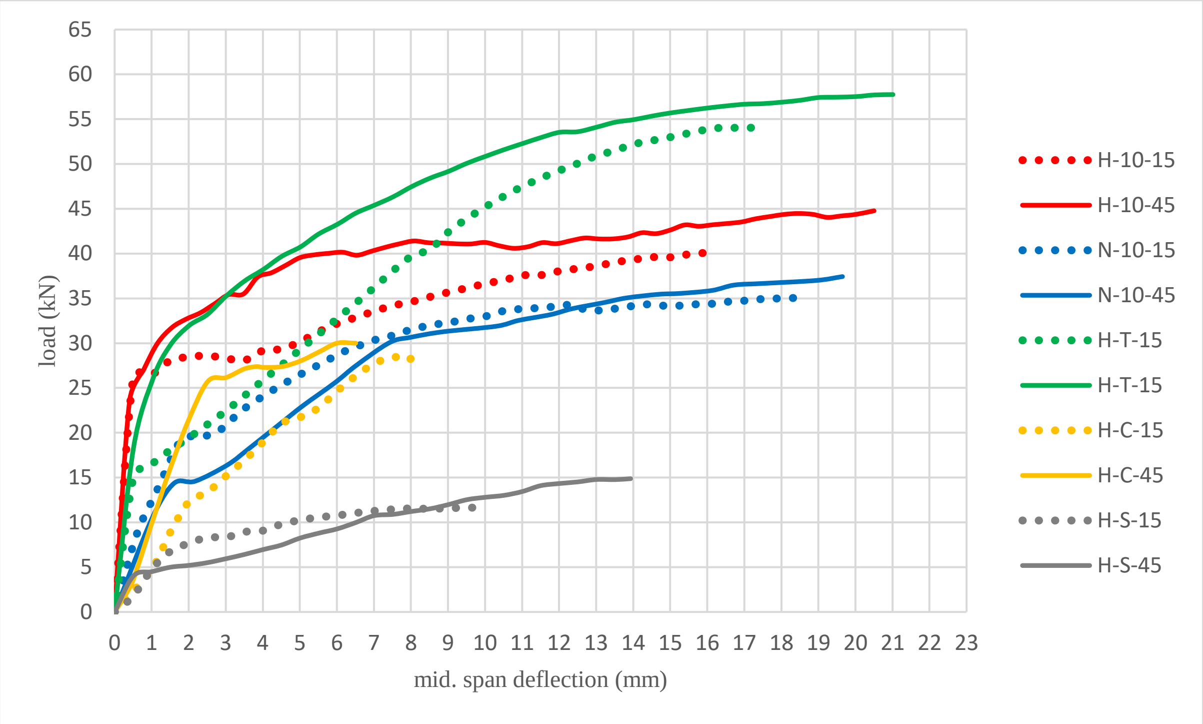

Fig. 8. Effect of Curvature on the Behavior of Arched Slabs.

As shown in the figure above, it can be noted that the maximum effect of curvature on the ultimate load appeared in samples H-S-15 and H-S-45. In general, it can be recognized that the effect of curvature appears at the both linear and non-linear stages. Also, there is a typical effect of curvature on the behavior for all couples except the simply supported samples where there is a clear difference in the effect of curvature, this deference can be described as the leading of the specimen with 15 cm curvature on the specimen with 45 cm curvature in the load-deflection curve till late stages of the plastic behavior of the two simply supported arched slabs.

The effect of increasing the mid-span height of arched slab from 150 mm to 450 mm on the ultimate load can be summarized as following: -

- Increasing the ultimate load by 7% for samples with 30 MPa compressive strength, 255 mm2 steel area and pin-pin support.
- Increasing the ultimate load by 12% for samples with 65 MPa compressive strength, 255 mm2 steel area and pin-pin support.

- Increasing the ultimate load by 7% for samples with 65 MPa compressive strength, 368 mm2 steel area and pin-pin support.
- Increasing the ultimate load by 28% for samples with 65 MPa compressive strength, 255 mm2 steel area and simply supported.
- Increasing the ultimate load by 6% for samples with 65 MPa compressive strength, 255 mm2 steel area and simply supported with tension member.

5.5. Group 5 (Effect of Support Condition)

This group contains six samples that differ in the support condition of the arched slab, first couple of samples (H-10-15 and H-10-45) have a pin-pin support, a second couple of samples (H-S-15 and H-S-45) are a simply supported, the third couple of samples (H-C-15 and H-C-45) are also simply supported but they contain a tension member connect between the two ends. Fig. 9 shows the difference in the behavior of each couple of samples.

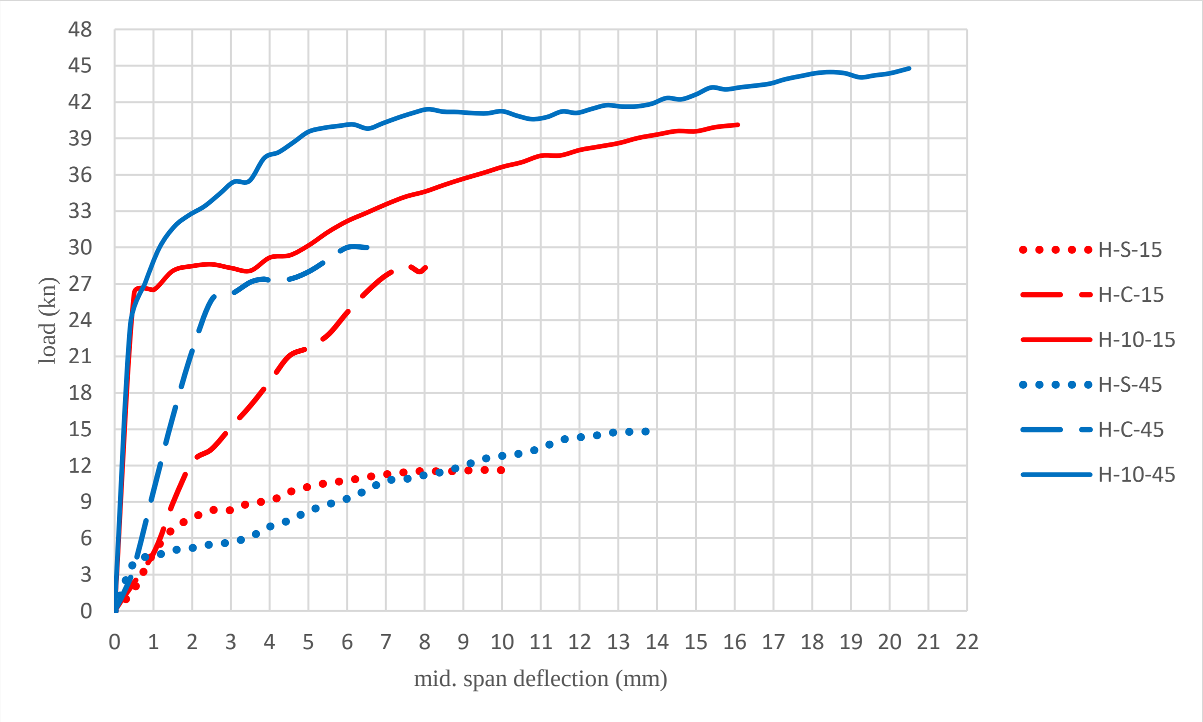

Fig. 9. Effect of Support Condition on the Behavior of Arched Slabs.

As shown in the figure above, it can be noted that the widest effect of the support condition appears at the linear stage. Also, it can be recognized the effect of tension member on the behavior; where there is almost a matching in the load-deflection curve between the simply supported samples with and without tension member till the end of the elastic stage of the sample without tension member. It can be noted there is no wide variance in the effect of support condition on the ultimate load between the two triplex groups of 15 cm and 45 cm curvature. Also, there is a similarity in the behavior at plastic stage between H-10-45 and H-C-45 on the contrary of the behavior at plastic stage between H-10-15 and H-C-15.

The effect of changing the support condition on the ultimate load can be summarized as following: -

For samples with curvature of 150 mm

- The ultimate load would be decreased by 29% when changing the support from pin-pin to simply supported with tension member.
- The ultimate load would be decreased by 71% when changing from pin-pin to simply supported.
- The ultimate load would be decreased by 59% when removing the tension member from the simply supported sample.

For samples with curvature of 450 mm,

- The ultimate load would be decreased by 33% when changing the support from pin-pin to simply supported with tension member.
- The ultimate load would be decreased by 67% when changing from pin-pin to simply supported.
- The ultimate load would be decreased by 51% when removing the tension member from the simply supported sample.

6. CONCLUSIONS

The conclusions reached through the experimental results are:

1. The behavior of arched slab samples is linear up to (35% - 55%) from the ultimate load. The load-deflection curve may be idealized by bilinear curve.
2. Effect of increasing f'c from 30 MPa to 65 MPa on ultimate load ranged between 15% to 25% (increasing), and on ultimate deflection ranged between 55% to 73% (decreasing).
3. Increasing the thickness by 42% tends to increase ultimate load which is ranged by 6% to 17%, and tends to decrease ultimate deflection which is ranged between 17% to 64%.
4. Increasing area of steel by 45% leads to increase ultimate load by about 30%, and leads to decrease ultimate deflection by 49% to 67%.

5. Increasing the curvature from 15 cm to 45 cm leads to an increasing in ultimate load ranged between 6% to 28%, and leads to a decreasing in ultimate load ranged between 22% to 41%.

6. A significant effect of support condition on ultimate load, where the minimization of horizontal reaction stiffness leads to a decreasing of about 30% in ultimate load, while the removing of the horizontal force leads to a high decreasing exceeded 65%.

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