Manual mechanical prestressing system of thin shallow curved slab

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Abstract. A manual mechanical prestressing system was manufactured which used to apply a post-tension force to the high-stress steel wires in the curved slab member. The study aims to experiment with the use of a mechanical prestressing technique of thin curved sections to assess the prestressed force influencing the behavior of a curved slab at the initial and final loading stages. Two advantages achieved in the system; pulling the steel wires at all positions simultaneously and application of the pulling force perpendicular to the cross-section of the curved slab. To check the efficiency of the prestressing system, two reactive powder concrete curved slab members were cast and tested under a uniformly distributed load. The first one is reinforced with micro steel fibers while the second one is reinforced with micro steel fibers in addition to four high-stress steel wires. The experimental results showed the applicability and facility of using this manual mechanical system to perform the post-tension forces of thin curved slabs. Applying the post-tension prestressing force in the curved slab member increased the cracking and ultimate loads to about 311\% and 381\% respectively compared to the non-prestress curved slab, whereas the failure mode was occurred by flexural-tensile stress near the edge beams for both curved slabs.

Keywords: prestress, mechanical system, curved slab, reactive powder concrete, thin shell

1. Introduction

A shell is a Three-dimensional spatial structure made up of one or more curved slabs or folded plates whose thicknesses are small compared to their other dimensions [1]. Shell structures are characterized by their three-dimensional load-carrying behavior, which is determined by the geometry of their forms, by how they are supported, and by the nature of the applied load. They can span large distances with a minimal amount of material, in addition to maintaining these light forms, aesthetic, and sculptural appeal [2]. The ultra-high-strength ductile concrete produced from Reactive Powder Concrete (RPC) is mostly used in thin shell concrete structures [3]. Due to the very high compression strength of RPC, the span length of the concrete arch may be increased, therefore reducing the total construction cost. RPC is also
used to increase the resistance to freeze-thaw cycles, increase abrasion resistance, reduce chloride permeability, and enhanced durability by decreasing maintenance costs and lengthens the service life of a structure [4]. Concrete structures with thin sections are reinforced by using advanced reinforcing materials such as steel fibers, where the traditional steel reinforcements can not be used without achieving the minimum concrete cover (2–3cm) [5]. These materials are suitable for shell structures due to their excellent mechanical properties and their pronounced ductility. The inclusion of steel fibers with RPC in the shells can improve the tensile strength, and also makes it possible to obtain the required level of ductility [3]. Recently, a new technique is used to reinforce thin concrete structures by using post-tension steel wires. It can be used in the flat and curved structural elements to provide internal initial stresses opposite to the external load stresses. This increases the section ability to resist the forces generated from the applied loads and improves the efficiency of the structural section by reducing the crack propagation and the contribution of concrete in tensile resistance under the neutral axis [5]. In the flat structural elements such as beams and floors, the prestressed wires are straight and the pull force at the ends of the structural element transfers from the wires to the concrete section with the full force, but in the curved structural elements such as arches and shells, vertical or horizontal compound forces are generated from the initial tensile force that attempt to overturn the structural element and make it unstable. Accordingly, a new mechanical prestressing system was manufactured to apply a post-tension force to the thin shallow cylindrical curved slab members. The study aims to experiment and check the efficiency of the manual mechanical prestressing system in the thin curved sections. For this purpose, two RPC curved slab specimens were cast and tested to study the effect of mechanical prestressed force on the curved slab behavior.

2. Materials
RPC is an ultra-high-strength and high ductility cementitious composite with advanced mechanical and physical properties [6]. Type I Portland cement from Tasluja Cement Company under the ASTM C150 [7] with very fine sand passed on 600 µm sieve from Al-Ukhaidir quarry in Iraq were used in this work. Silica fume was used to improve the mechanical characteristics of concrete with a particle diameter of 0.2 µm, complying with the ASTM C1240 [8]. A superplasticizer BETONAC-1030 from LEYDE Company in Iraq complies with ASTM C494 [9] was also used in the RPC mix to maintain workability without segregation and achieving high early compressive strength. Micro steel fibers of 13 mm length and 0.2 mm diameter were used to reinforce the reactive powder slurry. Table 1 shows the percentages of the RPC mixture components that were used in this study. High tensile stress steel wires with a bar diameter of 5 mm were used as prestressing steel reinforcement. The experimental test values of ultimate and yield tensile strength of post-tension steel wires were found based on ASTM A881 [10]. The properties of steel fibers and steel wires are shown in Table 2.

| Material                                               | Quantity                      |
|--------------------------------------------------------|-------------------------------|
| Ordinary Portland Cement Type I                         | 1000 kg/m³                   |
| Fine Sand (passed from 600 µm sieve)                    | 1000 kg/m³                   |
| Silica Fume (0.2 µm) 8% of wt. of Cement               | 80 kg/m³                     |
| w/c                                                    | 0.25                          |
| Superplasticizer (1.1 kg/liter) 6% of Cementitous Materials | 58.9 liter/m³               |
| Micro Steel Fiber (7800 kg/m³) 1 % of Total Volume     | 78 kg/m³                     |

Table 1. Components of reactive powder concrete mixture.
Table 2. Properties of steel fibers and high-tensile steel wires.

| Type of Steel           | Yield Strength MPa | Ultimate Strength MPa | Modulus of Elasticity MPa |
|-------------------------|--------------------|------------------------|---------------------------|
| Prestressed Wires       | 2292               | 2587                   | 202746                    |
| Steel Fibers*           | -                  | 2600                   | 250000                    |

* according to the manufacturer

Compressive strength, splitting strength, modulus of rupture, and modulus of elasticity of concrete specimens complied with ASTM C39 [11], ASTM C496[12], ASTM C78 [13], and ASTM C469[14] respectively are listed in Table 3.

Table 3. Mechanical properties of reactive powder concrete.

| Compressive Strength \(f'_{c}\) MPa | Tensile Strength \(f_{t}\) MPa | Modulus of Rupture \(f_{r}\) MPa | Modulus of Elasticity \(E_{c}\) MPa | Density kN/m³ | Poisson Ratio |
|-------------------------------------|-------------------------------|----------------------------------|------------------------------------|--------------|--------------|
| 70.5                                | 8.6                           | 10.5                             | 44130                              | 22.5         | 0.248        |

3. Experimental Program
The geometry of the curved slab specimen is shown in Figure 1, while the description of the proposed curved slab member is detailed in Table 4.
Table 4. Description of the curved slab member.

| Property               | Value       |
|------------------------|-------------|
| Inner Radius           | 908.3 mm    |
| Central Radius         | 923.3 mm    |
| Outer Radius           | 938.3 mm    |
| Thickness              | 30 mm       |
| Start Angle            | 56.6°       |
| End Angle              | 123.4°      |
| Cross-sectional Area   | 12000 mm²   |
| Rise                   | 150 mm      |
| Chord Length           | 1000 mm     |
| Width                  | 400 mm      |
| Height of Edge Beam    | 150 mm      |
| Width of Edge Beam     | 80 mm       |

3.1 Mechanical Prestressing System

In this experimental work, a manual mechanical prestressing system was manufactured to apply a post-tension force to prestressing steel wires in thin shallow cylindrical curved slab member as shown in Figure 2. The system was used to apply the tensile force to all the steel wires simultaneously. The system consists of:

1. Supporting steel frame to carry the concrete curved slab and provide fixed supports to the edge beams of RPC curved slab.
2. Hydraulic hand pump with a measuring watch and a high-pressure rubber hose.
3. Special steel block wedge to convert the oblique force to axial force in the direction perpendicular to the shell cross-section.
4. Fixed steel frame at the dead end and moveable transverse steel beam at the live end.
5. Steel plate of 8 mm thickness to distribute the post-tension forces on the transverse face of RPC edge beam.
6. Sixteen post-tension wedges and barrels to fasten the ends of the prestressing steel wires.
7. Eight triangular prism steel wedges to adjust the angle of the steel wires from both ends.

Figure 2 Mechanical prestressing system.
The main distinguishing characteristics of this prestressing system are as follows:
1. The prestressing force is applied manually.
2. The stress level of steel wire can be controlled by a measuring watch.
3. The system is lightweight and can be installed without using heavy lifting equipment.
4. All of the post-tension steel wires were tensioned together simultaneously from the live end.
5. The steel wires were pulled by a force perpendicular to the cross-section of the shell with the same direction of the curvature.
6. Releasing of the prestressing steel wires is accomplished under a slow strain rate.

3.2 Initial Prestress
To check the efficiency of the prestressing system, two reactive powder concrete curved slab members were cast and tested under uniformly distributed load. The first one which coded CS (Curved Slab) is reinforced with micro steel fibers (1% ratio of micro steel fibers of the total volume), while the second coded PTCS (Post-Tensioned Curved Slab) is reinforced with micro steel fibers in addition to four high-stress post-tension steel wires. Each of the prestressing steel wire was tensioned with a force of 30 kN which equals to the stress of about 1528 MPa ($0.59f_{pu}$). This value is lower than the maximum permissible tensile stress in post-tension reinforcement immediately after force transfer at post-tensioning anchorage device ($0.7f_{pu}$) [15].

3.3 Prestressing Procedures
The prestressing method was done by placing the concrete curved slab inside a manufactured supporting steel frame so that the edge beams of the RPC shell were fixed. All of the components are installed successively according to the following order:
1. Inserting the steel wires inside the RPC shell through plastic tubes that are previously placed into the shell mold in appropriate positions.
2. Placing the triangular prism steel wedges from both sides of the curved slab to keep the wire extending in the same direction of the shell curvature.
3. Fastening the steel wires with a set of steel wedges and barrels at both dead and live ends. The wedges at each end consist of two inner and outer rows, each row consists of four holding steel wedges. The outer row of the holding wedges at the live-end is attached to a movable transverse steel beam which is connected to the hydraulic jack head while the outer row of the holding wedges at the dead-end is attached to a non-movable steel frame which welded to the fixed test apparatus wagon, Figure 3.
4. Applying the initial post-tension force by using a hydraulic hand pump equipped with a measuring watch to determine the initial stress of the steel wire reinforcement.
5. After the prestressing level is achieved, the steel wedges in the inner rows are pushed toward the RPC shell at both ends before releasing the prestressing system.
6. Releasing of the prestressing system is done through a safety valve in the hydraulic pump causing to transfer of the stress from reinforcing steel wires to the RPC shell.
7. Cutting the prestressing steel wires beyond the first row of the wedges and barrels from each end. Figure 4 shows the post-tension curved slab member after cutting the prestressing reinforcements.
3.4 Instrumentation and Test Setup

The experimental test was conducted in the Laboratory of constructions of Civil Engineering Department at Mustansiriyah University. Figure 5 shows the test setup of the RPC curved slab under a vertical monotonic load. A manufactured steel arch bridge is used to distribute the concentrated load which is applied by the testing device on the outer shell surface. The central deflection of the arch was measured by using a dial gauge with a sensitivity of 0.01 mm at the bottom surface of the RPC curved slab.
4. Results and Discussion
The load-midspan deflection of curved slab members with and without post-tension steel reinforcements are shown in Figure 6 and Table 5. By post-tensioning steel reinforcements, the cracking and ultimate loads increased compared to the non-prestress control member as follows:

![Figure 6 Load-deflection curves of curved slab specimens.](image)

| Coding Specimen | Cracking Load 
(P<sub>c</sub>) kN | Ultimate Load 
(P<sub>u</sub>) kN | Cracking Deflection 
(Δ<sub>c</sub>) mm | Ultimate Deflection 
(Δ<sub>u</sub>) mm |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| CS              | 36              | 80              | 3.2             | 11.8            |
| CSPT            | 148             | 385             | 2               | 9.9             |
The load-deflection curves showed a linear behavior up to the first cracking load. Cracking in CS specimen occurred when the load increased to about 36 kN, while the cracking load of CSPT specimen increased to about 311% higher than CS specimen. By the post-tensioning process, a state of compressive stress is created in the concrete section. No yielding of steel wires was observed in CS and PTCS specimens as a result of their high tensile strengths, while a pullout of steel fibers from the mortar structure occurred at the failure mode. The stage at which the specimen does not have enough capacity to carry further load is known as ultimate loading capacity [16]. The use of post-tension steel reinforcements has a major influence on the curved slab carrying load capacity. The ultimate load of the PTCS specimen increased to about 381% compared to the CS specimen. When the prestressing steel wires are released, compressive stresses are induced on the concrete. Such compressive stresses delay the concrete cracking. Thus, the load-bearing capacity of the curved slab member is increased. Both specimens failed at the region between the shell and the edge beam as shown in Figure 7. At the cracking stage, capillary cracks appear in the bottom surface at the center of the arch. By increasing the load, the cracks appear near the edge beams. Main transverse cracks as yield lines, at the top surface of the curved slab at the connection region with the edge beam, caused the ultimate failure by flexural-tensile stress in the RPC accompanied with pulling out of steel fibers from the mortar structure.

![Figure 7](image)

5. Conclusions

In this research program, a manual mechanical prestressing system was manufactured and tested for applying post-tension forces to high-tensile steel wires in thin shallow curved slab members. The main conclusions of this work can be summarized as follows:

1. The prestressing system was effective to apply and transfer the post-tension force from the steel wires to RPC curved slab members.
2. No cracks were observed during prestressing and releasing of steel wires.
3. Preventing a difference in the transverse stress in the curved slab by pulling all the steel wires together.
4. Pulling the prestressing force perpendicular to the curved slab cross-section prevented the generation of forces outside the plane of the shell that might overturn the curved slab member.
5. Applying the post-tension prestressing force in the curved slab member increased the cracking and ultimate loads to about 311% and 381% respectively compared to the non-prestress curved slab, whereas the failure mode is nearly the same for both shells.
6. The obvious improvement in the structural performance of the post-tensioned curved slab contributes greatly to the expansion of the use of these structural elements in bridges, canals, tunnels, roofs, etc.

6. References

[1] Hauso A. Analysis methods for thin concrete shells of revolution 2014:142.
[2] Kanta N. Design of a Thin Concrete Shell Roof 2015:111.
[3] Richard P and Cheyrezy M. Composition of reactive powder concretes. Cem Concr Res
1995;25:1501–11. https://doi.org/10.1016/0008-8846(95)00144-2.

[4] Cizmar D, Mestrovic D and Radic J. Arch bridge made of reactive powder concrete. *WIT Trans Built Environ* 2006;85:429–37. https://doi.org/10.2495/HPSM06042.

[5] Dallinger S and Kollegger J. Thin post-tensioned concrete shell structures. *Proc Int FIB Symp 2008 - Tailor Made Concr Struct New Solut Our Soc* 2008:158. https://doi.org/10.1201/9781439828410.ch114.

[6] Aravindhan J and Vijayakumar G. Studies on strength characteristics of reactive powder concrete. *Int J Chem Sci* 2016;14:149–54.

[7] C150/C150M A. Standard Specification for Portland Cement. Current 2020; *ASTM International*, West Conshohocken, PA, www.astm.org

[8] ASTM C1240. Standard Specification for Silica Fume Used in Cementitious Mixtures. 2020, *ASTM International*, West Conshohocken, PA, www.astm.org

[9] ASTM C494/C494M A. Standard Specification for Chemical Admixtures for Concrete. 2019, *ASTM International*, West Conshohocken, PA, www.astm.org

[10] ASTM A881M. Standard Specification for Steel Wire,Indented, Low-Relaxation for Prestressed Concrete. 2016, *ASTM International*, West Conshohocken, PA, www.astm.org

[11] ASTM C39. Compressive Strength of Cylindrical Concrete Specimens. 2015, *ASTM International*, West Conshohocken, PA, www.astm.org

[12] ASTM C496/C496M. Standard test method for splitting tensile strength of cylindrical concrete specimens1. 2017, *ASTM International*, West Conshohocken, PA, www.astm.org

[13] ASTM C78/C78M. Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) 1. 2010, *ASTM International*, West Conshohocken, PA, www.astm.org

[14] ASTM C469. Standard Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression. 2014, *ASTM International*, West Conshohocken, PA, www.astm.org

[15] ACI Committee 318. *Building Code Requirements for Concrete Thin Shells (ACI 318.2-19) and Commentary 2019*.

[16] Rashid MU, Qureshi LA and Tahir MF. Investigating flexural behavior of prestressed concrete girders cast by fiber-reinforced concrete. *Adv Civ Eng* 2019;2019. https://doi.org/10.1155/2019/1459314.

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