Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 691.328.43

DOI: 10.34910/MCE.122.2

Structural behavior of concrete arches reinforced with glass textiles

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Keywords: textile-reinforced concrete, arch structures, thin-walled structures, flexural test, strength

Abstract. Thin-walled concrete structures with textile reinforcement have a number of advantages over conventional reinforced concrete. This article discusses the manufacturing method and investigates the structural behavior of the arch made of textile-reinforced concrete (TRC). The possibility of manufacturing an experimental arched structure with textile reinforcement is demonstrated. This study includes the arch design, mold preparation and loading test. With the use of a 3D printer, the mold of the arched structure was printed, which made it possible to implement a distributed loading scheme. Three concrete arches including a reference non-reinforced arch and two concrete arches reinforced with glass textiles were designed and tested. The test results showed a slight increase in the strength of the reinforced arch compared to the control non-reinforced arch. The effectiveness of the reinforcement of the arch structure amounts to about 10 % increase in contrast to arches with external reinforcement, where the increase in strength reaches 40–85 %. However, the main advantage of such reinforcement is the significant residual strength of the arch structure, which prevents catastrophic collapse of it. The textile reinforcement continued to hold the failed concrete matrix in contrast to the external reinforcement, where the loss of cohesion leading to delamination could cause the fracture of parts of the concrete.

Citation: Stolyarov, O.N., Dontsova, A.E., Kozinetc, G.L. Structural behavior of concrete arches reinforced with glass textiles. Magazine of Civil Engineering. 2023. 122(6). Article no. 12202. DOI: 10.34910/MCE.122.2

1. Introduction

An increasing interest in fibrous concrete reinforcement is dictated by the need to design lightweight concrete structures. To date, a large number of lightweight arch structures are manufactured using polycarbonate. Along with several advantages, such as light weight, low cost, etc., there is also a number of disadvantages associated primarily with the service life of such plastic structures. Weather conditions periodically cause a situation in which the snow load on the extrados can increase significantly, for example due to melting of snow and subsequent formation of ice when the temperature drops. In practice, this leads to the destruction of brittle structures made of polycarbonate. At the same time, these structures are practically non-repairable and are subject to disposal. Thus, for example, in St. Petersburg every spring there is a large amount of polycarbonate structures waste. In turn, this causes an environmental problem associated with both the growing production of plastics and the difficulties of their recycling. An alternative to polycarbonate arch structures are thin-walled concrete structures. These designs can be produced with a thickness of 15–20 mm. Of course, the cost of such structures is somewhat higher than the cost of plastic structures, but the main advantage is their significant durability compared to polycarbonate structures. Durability of such structures is primarily due to two main factors. Firstly, the concrete structure is less susceptible to mechanical stress and local damages, for example, due to the formation of ice. Secondly, concrete is less exposed to sun and weather. Thus, due to exposure to ultraviolet radiation, plastics undergo significant degradation, leading both to a deterioration in mechanical properties and to loss of their original appearance due to tarnishing. At the same time, the fine-grained concrete used for the production of TRC has an excellent smooth surface and can be used without additional finishing materials. The higher cost of such arches can easily be offset by their service life. According to the observations of the authors of this work, single pilot projects on lightweight TRC arch are used as shelters for parking bicycles, small pavilions for at least 10 years without visible surface damages, and in structures with polycarbonate arches, there is a periodical replacement of some damaged sections after the winter period.

Arch structures are the object of this research. Arch structures find increasing use in various structures including bridges, tunnels, domes, etc. Arch structures are widely used due to load bearing capacity and ability to bridge between large spans without any need for columns [1]. Arches are both made of masonry and concrete. Research fields in arched structures using composite materials can be divided into two major groups. The first involves strengthening existing arch structures, both brick [2–7] and concrete [8–11]. The second group involves the development of lightweight floor structures [12, 13]. In each of these fields, the main role is played by high-strength fiber composites. Their main advantages are high load-bearing capacity, corrosion resistance and ease of installation.

Currently, there is a trend towards the manufacture of economically efficient and durable building structures. One of the promising materials used for reinforcing concrete is textile reinforcement. Advanced composite materials based on it include TRC that has already proved itself in various fields of application in construction [14, 15]. Examples of the implementation of TRC include wall panels, light ceilings, bridges, etc. A certain amount of material has been accumulated on the properties of textile reinforcement and textile-based composites. To a lesser extent, the elements of finished building structures made of TRC have been studied. There are only limited examples of research on, for instance, arched structures made of TRC. The researchers mainly concern the application of external reinforcement for masonry vaults [16] and reinforced concrete structures [17]. And here the main task is to analyze the interaction at the interface between the concrete matrix and the reinforcing fiber since significant stress concentration can lead to delamination of fiber reinforcement [17]. A full-scale pavilion entirely in TRC was designed and erected by P. Valeri, P. Guaita et al. [13]. D.L.N.D.F. Amorim et al. [18] developed a simplified model of cracking and damage in reinforced concrete arches for their structural assessment. A. Khaloo, H. Moradi et al. [19] have studied the behavior of arches reinforced with steel rebars and unidirectional glass fabric composites. It was shown that extrados strengthening is more effective (up to 200%) than intrados strengthening. However, the use of excessive glass fabric layers may lead to brittle collapse in shear failure mode. T. Martin, S. Taylor et al. [20] have used basalt and carbon fiber reinforced polymers while strengthening of concrete floor slabs to enhance slab capacity. In [21] carbon fiber reinforced polymers (CFRP) were applied to repair the damaged buried arch structure subjected to underground explosions. Z. Tang, Y. Zhou et al. [22] used basalt fiber reinforced polymer (BFRP) bars to build concrete arches. It was shown that the BFRP bars reinforced arch has comparable or even better blast resistance than the steel bars reinforced arch. In [23], glass fiber reinforced polymer (GFRP) was applied to strengthen the laminated bamboo arches. It is found that the GFRPS effectively restrains the delamination and greatly enhances the load carrying capacity. Z. Qiu, M. Yan et al. [24] used CFRP for strengthening of laminated bamboo arches. In [25], Ultra-high Performance Concrete was used for strengthening pre-damaged reinforced concrete arches. It was found that the bearing capacity of arch intrados strengthened with UHPC increased by 85 %. In [26], the possibility of using fiber reinforced concrete FRC precast tunnel segments was demonstrated. Full-scale tests on both traditional reinforced concrete and FRC elements have been performed. The tests results showed the fiber reinforced concrete can substitute the traditional reinforcement. H.J. Dagher, D.J. Bannon et al. [8] investigated the concrete-filled fiber-reinforced polymer (FRP) tubes for buried arch bridge structures. The tubes were fabricated from braided E-glass and carbon fiber infused with resin. In [27], failure mechanisms of carbon fiber reinforced polymer (CFRP) wrapped arches under static and blast loadings were investigated. Load carrying ability of CFRP arches achieves the level of steel bar reinforced concrete (RC) arch in the static loading experiment. Subjected to explosive loading, CFRP plays an important blast protective role in arch. In [11] different techniques including bonding and bonding/wrapping with carbon fiber reinforced polymers were applied to improve the strength of reinforced concrete arches. It is shown that bonding/wrapping technique is much more effective than bonding method. Also, in general, loading occurs through one point in the center. RC arches are usually tested under centrally concentrated point load. At the same time, the distributed load more realistically reveals the structural properties of arched structures. In this paper, an attempt was made to develop an arched canopy made of textile-reinforced concrete. A distinctive feature of this work is the proposed approach to the design of mold for the implementation of a distributed loading scheme, the manufacture of an arched structure and mechanical testing.

Relevance of this study includes manufacturing method, analysis of the structure and flexural properties of textile-reinforcing concrete arches.

The aim of this work is to develop arch structures made of TRC and investigate their structural characteristics and flexural behavior.

The objectives of this work are:

- experimental studies of manufacturing process to produce TRC arch with tailored properties;
- optimization of 3D printing for manufacturing of mold for casting of the arch structures;
- study the flexural behavior of TRC arch structures and to develop a technical approach that facilitates the measurement of the deformations.

2. Materials and Methods

2.1. Test samples

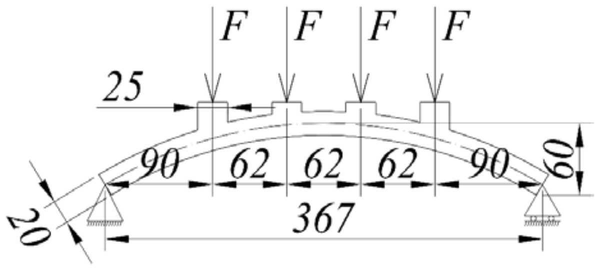
Three arch samples with a cross section of 20×260 mm were designed and manufactured. Two of them (Type I) were reference (non-reinforced) and reinforced with glass fiber warp-knitted fabric. These arches have span length of 367 mm and span-to-rise ratio of 6.1. The third arch (Type II) has span length of 1068 mm and span-to-rise ratio of 6.7. The reinforcing fabric was placed in the tension area at a distance of 5 mm from the intrados. Geometric properties of specimens are presented in Fig. 1. Two molds of polylactic acid (PLA) plastic were fabricated using 3D printer Raise 3D (Model Pro2 Plus). All samples were cast using concrete mix listed in Table 1. Mechanical properties of the reinforcing fabric and concrete are listed in Table 2.

Table 1. The constituents of fine-grained concrete (kg/m^3).

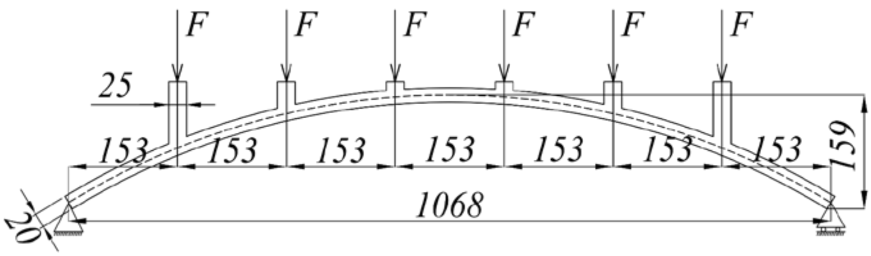
Portland cement	750
Sand (0–0.63 mm)	1365
Plasticizer	8
Water	275

Table 2. Mechanical characteristics of the reinforcing textiles.

	Units	Fabric	Concrete
Tensile strength		900	-
Compression strength	MPa	-	40
Flexural strength		-	4.8
Young Modulus	GPa	47.2	32.0



(a)



(b)

Figure 1. Geometry and supporting conditions of the TRC arch under a uniformly distributed load (units: mm).

2.2. Manufacturing of 3D printed mold for concrete casting

One of the most difficult tasks in the manufacture of test specimens is the manufacture of a mold. In contrast to a realistic structure, in the manufacture of mold, it becomes necessary to provide a uniformly distributed load in order to realistically reflect the service conditions of the structure. When analyzing the literature, it was revealed that basically there is a single point loading. Only in [12] the mold was made in the form of an arch with additional columns at the top through which a distributed load was transmitted.

Molds for arched structures are mainly made of wood. This is due to the simplicity and low cost of the raw material. However, the use of wooden mold limits the possibilities of applying the distributed loading scheme, and, as a result, the presence of only mold with concentrated loading indicates the difficulties encountered by the research. The difficulty lies in designing several points (usually 5 or 6) of load application due to the formation of a profile with columns having different heights, increasing with distance from the center of the arch. Joining of numerous parts of a wooden panel leads to the need to seal the joints to prevent leakage of the fine-grained concrete mix. Alternatively, plastic extrusion on a 3D printer can be used. The devices have proven themselves in the printing of various parts and products. There are also many individual examples of using 3D printing for the manufacture of mold for small concrete products. The main advantage of 3D printing is the seamlessness of the technology, i.e., the mold is made entirely and is completely suitable for concrete casting.

In this work, 3D printing of polyactide (PLA) plastic, which is a biodegradable thermoplastic aliphatic polyester, was used to manufacture the mold for the arch sample. This material is one of the most popular in 3D printing. Since it was planned to produce two standard sizes of arches, then, accordingly, two types of molds were designed. Fig. 2 shows the main steps in the manufacture of mold for an arch type I with four columns. Fig. 2a shows the beginning of the PLA printer printing with plastic. The speed of 3D printing is relatively low. Time for mold printing with a height of 260 mm takes approximately 45–50 hours. Fig. 2b shows the final stage of mold printing. The resulting mold, in principle, can be reusable. However, it is difficult to extract an arch sample without damaging the columns from above, so the decision was made to print a single use mold with the smallest possible thickness to ensure strength and stability. Finished molds are shown in Fig. 2c. Mold for arch Type II was made in a similar way but consisted of three parts due to limitations in the size of the 3D printer table. In this case, the number of columns was increased to 6. It was designed with appropriate tolerances for a smooth assembly.

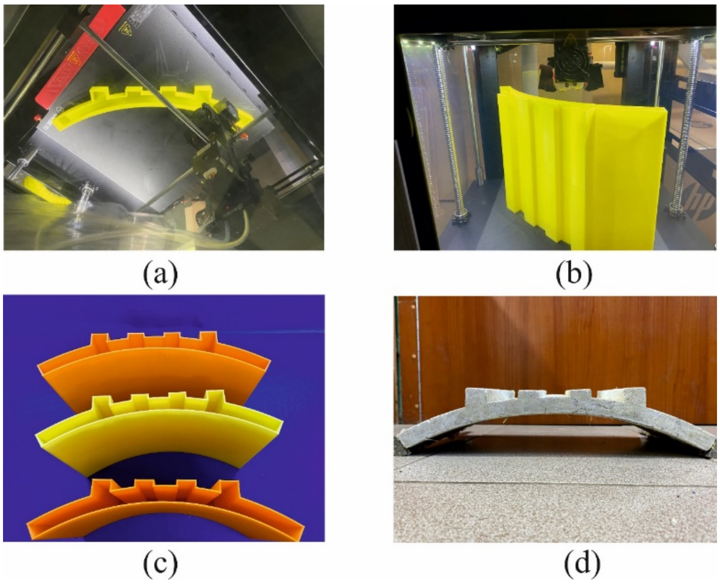


Figure 2. 3D printed mold for concrete casting:
(a) and (b) printing the mold; (c) printed molds; (d) cast arch Type I.

2.3. Concrete casting

Concrete mix was prepared according to the constituents listed in Table 1. The mold was filled with concrete mix. After casting, it was left to dry and then the mold was carefully disassembled. Abrasive paper was used to repair imperfections. Prior to testing, the test samples were stored for 60 days at 22 °C and 95 % RH. The reinforced arch type II is shown in Fig. 2d. Fig. 3 shows cast arch Type II.

Figure 3. Cast arch Type II.

2.4. Test setup

The mechanical behavior of the cast arches was investigated by using an Instron universal testing machine (model 5965). The test setup is shown in Fig. 4. The supported arch specimens were loaded by a uniformly distributed load. Load was applied with a rate of 1 mm/min. Monitoring devices include load cell at the crosshead of the testing machine and dial gauges at the arch columns. The load was applied simultaneously at four and six columns for the arch Type I and Type II, respectively.

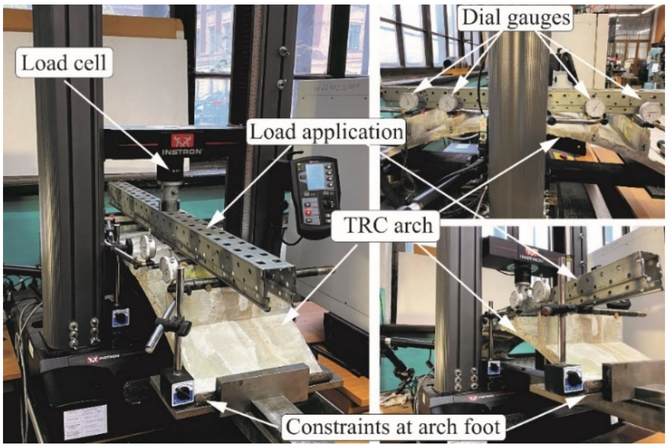


Figure 4. TRC arch (Type II) under testing.

3. Results and Discussion

3.1. Strength efficiency

The smaller type 1 arch was designed to test the performance of the reinforcement and the performance of the reinforced arch under load. The flexural test results for the reinforced and non-reinforced (control) arches are shown in Fig. 5 as load – vertical displacement curves. According to the obtained curves, a significant difference in the mechanical behavior of the two samples is observed. It can be seen that the load of the control sample increases dramatically and failure occurs at a value of about 3000 N. A crack is formed and the sample instantly breaks into two parts. Destruction occurs approximately in the middle at the location with the maximum bending moment. The reinforced arch sample (shown with red dashed line) exhibits a fundamentally different behavior. So, after reaching the strength at the first crack, a slight decrease in the load occurs and then a reinforcing fabric is switched to the work, which does not allow the sample to break into pieces. As a result, we have a sufficiently high residual strength on the sample of the reinforced arch. This behavior continues for quite a long time, turning into a horizontal displacement of the movable support. This is an indisputable advantage of such reinforcement, because there will be no sudden destruction of the entire structure. If we analyze both curves in terms of reinforcement efficiency, then insignificant differences between them are found. First, the strength of the reinforced arch is about 10 % higher than that of the control arch. This difference is insignificant, and even when using a carbon reinforcing fabric, one should not expect a significant increase, because textiles in a concrete matrix work mainly in tension. Secondly, there is an increase in vertical displacement without fatal destruction and debonding of textiles from the arch [12]. When analyzing the curves, one should also note the selection of slacks in the initial stage of loading, which is due to the tooling used.

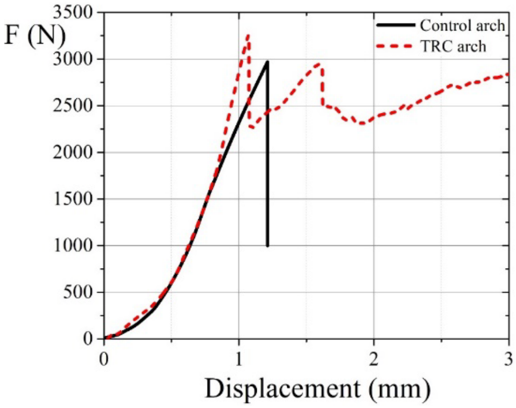


Figure 5. Load versus vertical displacement of the reinforced arch compared to control arch (Type I).

3.2. Load versus vertical displacement

Fig. 6 shows the test results for a reinforced arch type II. The mechanical behavior is similar to what we observed in the arch type I. Initially, the load increases sharply, and then there is a decrease after the formation of a crack, and further the reinforcement is put into operation. In this case, the initial section of the curve is fairly flat. There is no slack, like it was observed in the arch type I. This is due to the massiveness of the manufactured sample of the arched structure.

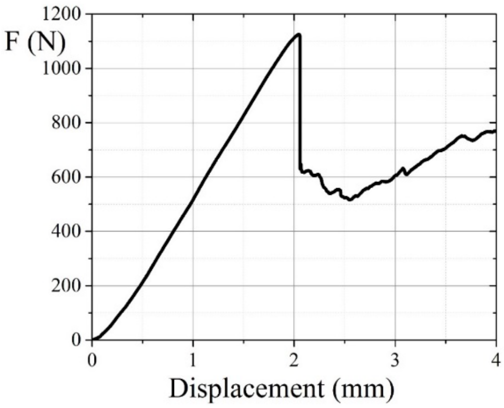


Figure 6. Load versus vertical displacement of the arch Type II.

When analyzing the mechanical behavior of a reinforced arch structure, it is of interest to determine the vertical displacements. For this, dial indicators were used, located on top of the columns as shown in Fig. 4. The measurement results are presented in Fig. 7. These diagrams are constructed in such a way as to show vertical displacement along the entire length of the arch. The ratio of the current coordinate to the entire length of the arch is plotted on the horizontal scale. According to the results obtained, it can be seen that with an increase in the load, approximately the same increment of displacement occurs on symmetrically installed indicators: s/L = 0.143 and s/L = 0.858; s/L = 0.286 and s/L = 0.715. At greater loads, there is a significant increase in vertical displacement on the indicator in the position s/L = 0.286. This may be due to the fact that a crack developed in this place. With the approach of loads to destructive vertical displacements increase significantly.

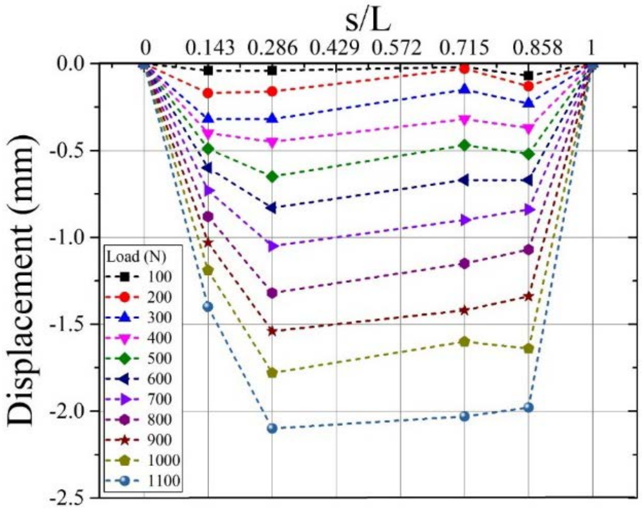


Figure 7. Experimental displacement in the arch Type II at different locations: s is a coordinate along the arch and L is the length of the arch).

Additionally, load-displacement diagrams were built for each dial indicator. These curves are shown in Fig. 8. The resulting curves more clearly characterize the mechanical behavior of such arch structures and can be used for further calculations.

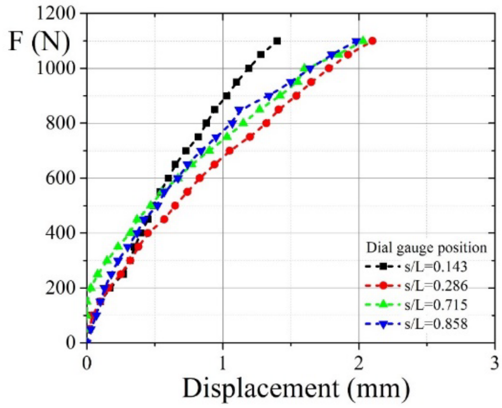


Figure 8. Load versus vertical displacement of the arch Type II at different locations.

One of the main tasks of this work is to focus on the reinforcement efficiency. The results showed a slight increase in strength characteristics. The main advantage, in fact, is a significant residual strength, which allows maintaining the integrity of the arched structure. Unfortunately, it is not possible to compare it with the works of other authors, because they studied the external reinforcement of arched structures, and the results they achieve are due to the work of fiberglass or carbon fiber on intrados or extrados of the arch. Therefore, sometimes strength was achieved with an increase in the intrados surface by 40 % [12] and even by 85 % [25]. All this is due to the work of directional reinforced plastics with high mechanical characteristics. In fact, this is an additional layer of composite material that forms a hybrid system held by good bonding. That is, we have an arch in the arch. The strength and rigidity of such a layer provide a desired effect on strength efficiency. Thus, an increase in this composite layer increases the strength of the entire structure. At the same time, A. Khaloo, H. Moradi et al. [19] note that the excessive increase in the layers of the glass sheet can lead to brittle fracture of the structure.

4. Conclusions

In this work, an experimental study was carried out on the possibility of reinforcing an arched structure made of textile-reinforced concrete using a textile fabric made of glass rovings. The study included the development of mold, its 3D printing, the production of samples of concrete arches and the study of their mechanical behavior. The results showed that

- the concrete casting method should include application of a distributed load using a printed plastic mold;
- samples of arch concrete structures reinforced with glass textiles are developed, the correlation between the reinforcement and flexural properties of concrete composite was established;

- effectiveness of the reinforcement of the arch structure is insignificant and amounts to about 10 % increase in contrast to arches with external reinforcement, where the increase in strength reaches 40–85 %;
- the main advantage of arches with internal reinforcement is their significant residual strength, which prevents catastrophic collapse of the structure. The textile reinforcement continues to hold the failed concrete matrix in contrast to the external reinforcement, where the loss of cohesion leading to delamination can cause parts of the concrete to fall out.

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Received 16.03.2023. Approved after reviewing 14.06.2023. Accepted 14.06.2023.