Article

Experimental Investigation of the Behaviour of Self-Form Segmental Concrete Masonry Arches

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Abstract: This research aims to introduce a new technique, off-site and self-form segmental concrete masonry arches fabrication, without the need of construction formwork or centering. The innovative construction method in the current study encompasses two construction materials forms the self-form masonry arches, wedge-shape plain concrete voussoirs, and Carbon Fibers Reinforced Polymers (CFRP) composites. The employment of CFRP fabrics was for two main reasons; bond the voussoirs and forming the masonry arches. However, CFRP proved to be efficient for strengthening the extrados of the arch rings under service loadings. An experimental test conducted on four sophisticated masonry arch specimens. Research parameters were using thicker keystone as well as the partial strengthening of the self-form arch ring at the intrados. Major test finding was the use of thicker Keystone, alter the behavior of the self-form arch, considerably increased the load carrying capacity by 79%. Partial strengthening of the intrados with CFRP fabrics of typical arch ring Keystone resulted considerable increased the debonding load of fabrication CFRP sheets by 81%, increase the localized crushing load by 13%, and considerably increase voussoir sliding load by 107%.

Keywords: Masonry arches bridges; Self-form segmental arches technique; CFRP; Strengthening.

1. Introduction

One of the oldest conventional bridge forms is the masonry arches bridges. They are robust, durable, and additionally proved to be *maintenance free structures*. Rocks and clay bricks were the earliest masonry materials utilized in arches construction over 4000 years. The masonry arches are historically constructed within walls of the buildings and utilized for ventilation and the allowance of lighting through. The technology of masonry arch construction within the years improved for achieving large spans [1]. A straightforward identification of masonry arch bridge that which built from wedge-shaped blocks known as voussoirs and mortar. Furthermore, arches bridges are built on a temporary framework (commonly known as centering) as the masonry arch cannot stand-alone until the placement of the last voussoir at the apex, the keystone. Upon completion, the centering removed, and the arching force (thrust force) starts to act at the abutments. The complete construction process of a typical masonry arch bridge was shown in Figure 1.

Masonry arch bridges are almost million around the world. They are ancient, and many are carrying overestimated design loads, and they succeed to sustain hundreds of years. However, maintenance of masonry arches bridges still under consideration [2]. In most cases, deterioration in masonry arch bridges is due to water flowing throughout the structure and plant growth as a result of water existence [3]. Lack of maintenance of masonry heritage arches built from natural stone subjected to loading will lead to damage of the building stones at different levels [4].
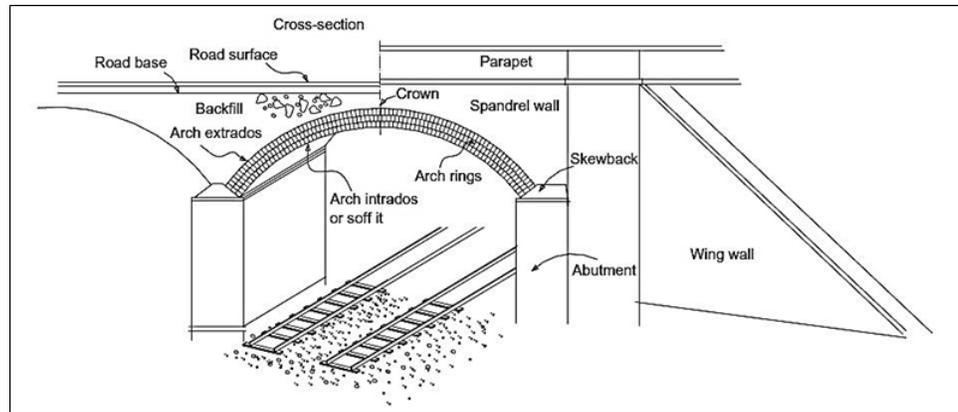
Figure 1. Typical masonry arch bridge construction (Source [2])

The classical problem which highlighted in 17th - 18th wondering how the masonry arches can carry loadings. Roberts Hook answered and reported his findings. Hook stated that: "As hangs the flexible chain, so – but inverted – will stand the rigid arch." The idea of Hook is attractive and straightforward if a hanging chain supports loads in tension when inverted, it will stand loads in compression [5-7].

Rocks, stones and clayey bricks are primary materials used in masonry construction, especially for bridges and have proved it sufficient durability. Most arch bridges constructed from such materials are survival and under service after hundreds of years. Contrarily, so many bridges built from modern materials since 20th century like steel and reinforced concrete requires repair and strengthening after being in service for a relatively small part of their life-span and so unable to confirm the requirements of the current regulations [8, 9].

Utilizing FRP composites in the strengthening of structures has particular attention and has been investigated in numerous experimental works [10, 11]. Several advantages from strengthening, gained by structures, using FRP composites in repair as well as upgrading structures to carry extra loads. Moreover, low weight, cost-effective, high strength/weight, and modulus/weight ratios compared with some metallic materials [12-15]. Numerous experimental tests were performed on strengthened masonry structures as well as masonry arches, shells; vaults concluded the efficiency of the strengthening system using FRP composites [16, 17].

In an economic aspect, it is not feasible to use a traditional technique for masonry arch construction due to several reasons like skilled labor cost for installing the framework and the manufacturing of voussoirs from natural stones. Therefore, it was a necessity for the cost-effective type of bridges with the decline in traditional masonry arches lead to the developed of FlexiArch bridges [18].

Masonry arch bridges proved over the year its strength and durability in addition to the aesthetics view, which enhances the surroundings. Therefore, the insight brings us to develop a new form of masonry arch bridges after a receding in the construction of such type of bridges for many years. Extensive experimental test program for the develop masonry arch bridges illustrated in this article.

2. The Significance of the Present Investigation

The important of the present research is to study the behaviour of a new method for constructing masonry arch bridge system. The self-form segmental concrete masonry arches system manufactured from plain concrete wedge-blocks and Carbon Fiber Reinforced Polymers (CFRP)

fabrics without any mortar and centering. Furthermore, studying the contribution of using enlarge Keystone size on the load carrying capacity of the self-form segmental concrete masonry arches. Moreover, investigate the effect of upgrading the self-form segmental concrete masonry arches bridges by CFRP fabrics in the local portion of the arch ring intrados. This study is also believed to assist in introducing a technique; one of its achievements is the featured speed of construction.

3. The Experimental Program

3.1 Description of Test Specimens

The test specimens comprised four experimental models of self-form segmental concrete masonry arches rings of 2m span and 0.8m rise. Figure 2 shows the arch designation system, which considers the arch ring number, thickness of the arch ring, thickness of Keystone, and the strengthening index.
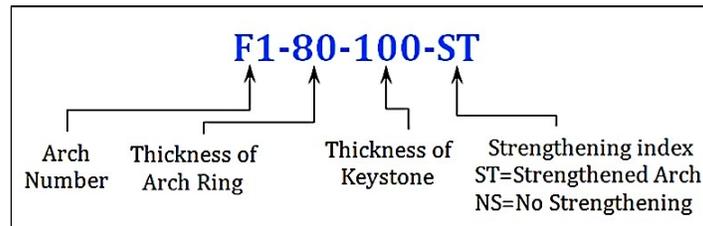

Figure 2. Designation system for self-form segmental concrete masonry arches

3.2 Fabrication of Self-Form Segmental Concrete Masonry Arches

Four experimental models of self-form masonry arches of 2m span and 0.8m rise fabricated as shown in Figure 3. The geometry of the wedge-type voussoirs carefully calculated from the arch above ring dimensions for a segment of a circular arch profile. Each arch ring consisted of 23 wedge-shaped voussoirs; the end voussoirs were slightly different in dimensions for final arch ring installation purposes, as shown in Figure 4.
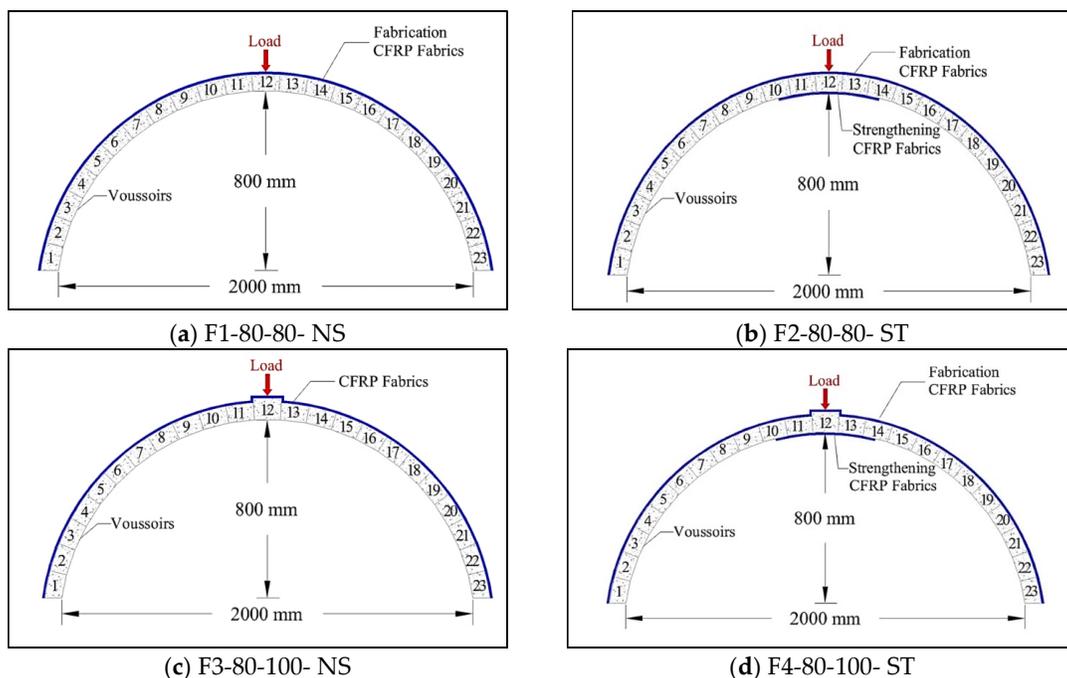

(**a**) F1-80-80- NS

(**b**) F2-80-80- ST

(**c**) F3-80-100- NS

(**d**) F4-80-100- ST

Figure 3. Experimental models of self-form segmental concrete masonry arches
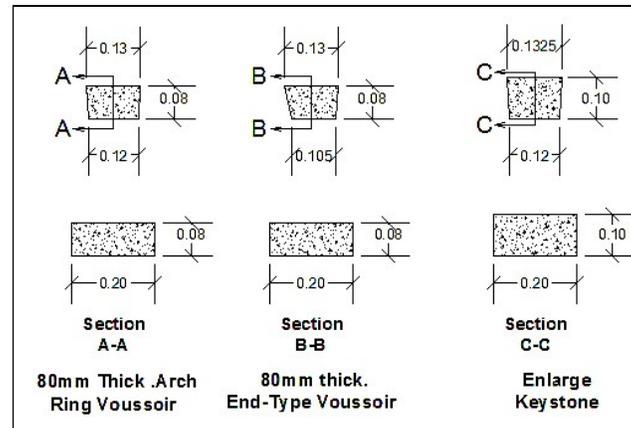
Figure 4. Wedge-shape voussoirs geometry

Normal strength concrete with specifying compressive strength of 30MPa at 28-days designed for casting concrete voussoirs. Steel molds were fabricated very precisely for casting concrete voussoirs.

Upon completion of curing the wedge-shaped voussoirs, the fabrication stage of the self-form arch started as shown in Figure 5. The voussoirs were laid contiguously on the flat rigid bed, and the surfaces of the voussoirs were grinded utilizing an electrical grinder. Furthermore, the voussoirs were restrained temporarily by thick two wood panels and five F-clamps distributed evenly. Soon after, the epoxy resin components were mixed mechanically and applied on the top surface of voussoirs. The fabrication accomplished by bonding CFRP fabrics on the epoxy coated area and left for curing. Figures 6 illustrate the fabrication stages for the self-form segmental concrete masonry arch.
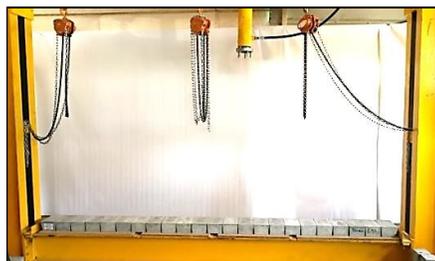
(**a**) Placing voussoirs on the rigid bed

(**b**) Grinding of voussoirs surfaces
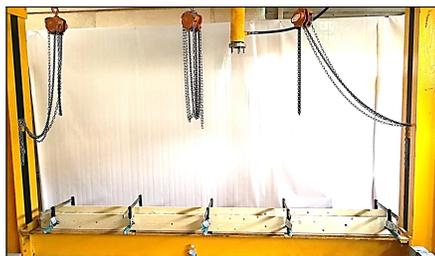
(**c**) Temperately restraining voussoirs by wood panels and five F-clamps

(**d**) Mixing and applications tools of epoxy resin

(**e**) Bonding CFRP fabrics by epoxy resin   (**f**) Accomplished fabrication of self-form arches

Figure 5. Fabrication of self-form segmental concrete masonry arches

3.3 Lifting Self-Form Segmental Concrete Masonry Arches

The self-form arch initially fabricated on rigid steel bed in a flat shape. Lifting of self-form arch was done from three positions exactly on third-span, as shown in Figure 6. The self-form arch lifted, in the beginning, from the keystone (L2) till the other two other lifting locations released from the resting bed. Lifting process continued simultaneously from three points, the wedge-shaped voussoirs will rotate, and the gap in-between closed. The self-form arch was formed, as a segment of a circle, upon completion of the lifting process as shown in Figure 7.
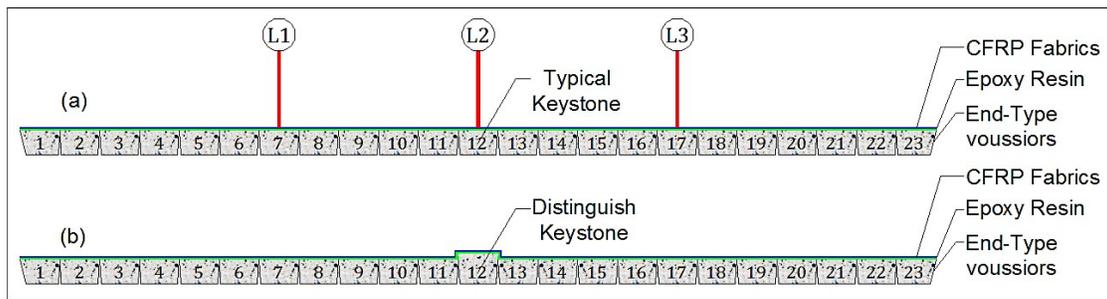
Figure 6. The self-form arch ready for forming.
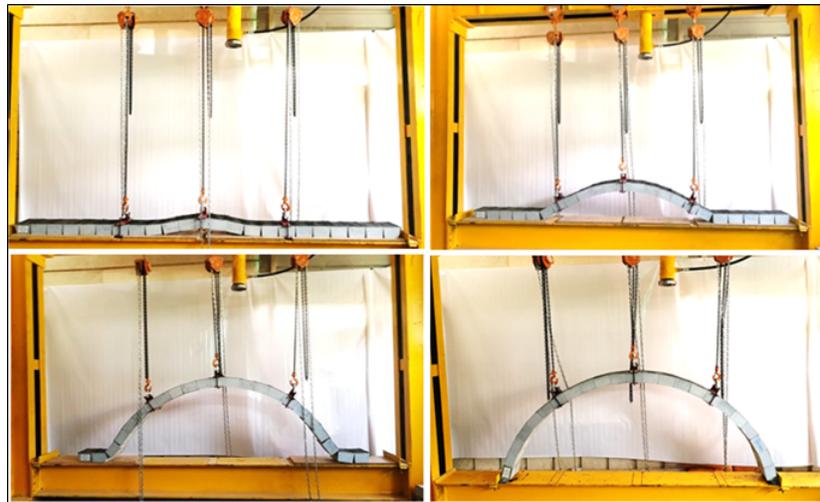
Figure 7. Formation of self-form segmental concrete masonry arches.

3.4 Strengthening of Self-Form Segmental Concrete Masonry Arches

Strengthening of self-form masonry arches by CFRP textile was investigated in order to discover the contributions of CFRP composites on the load carrying capacity of the self-form

masonry arches. After lifting, forming and installing the self-form masonry arch, the intrados of two sound arches were partially strengthened in local region of the Keystone as shown in Figure 8.
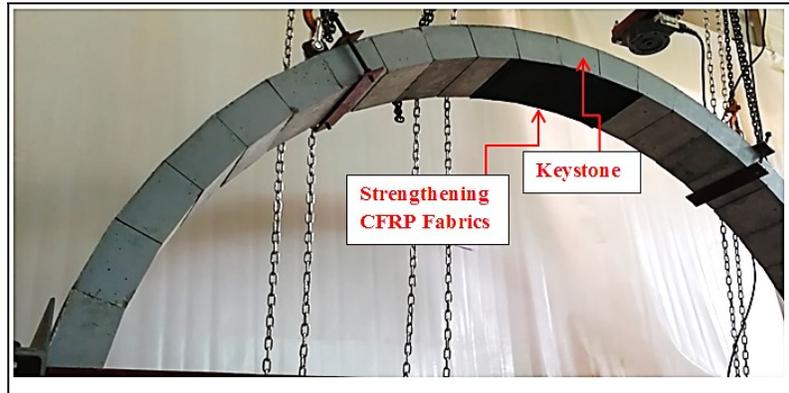

Figure 8. Strengthened self-form masonry arch F2-80-80- ST

4. Instrumentation and Testing

Four self-form arches were fabricated. The arches rings were positioned in the loading frame and restrained against translation displacements in both horizontal and vertical directions. The load applied at the apex of the self-form arches on the Keystone employing the hydraulic actuator as displayed in the schematic diagram of test setup Figure 9. Four digital indicators were used to measure arch translations; two were used to measure outward horizontal displacement at the abutments while two more were utilized to record the outward inclined translations at the third-spans. Furthermore, two precisely calibrated linear variable differential transducers (LVDT's) also used for measuring the vertical displacements of the self-form masonry arches at the Keystone.

Compressions, as well as tensile stains at both of the extrados and intrados of the arches, also measured. Two types of single element wire strain gauges, namely PL-60-11-3L and BFLA-5, were used for recording strains in both concrete voussoirs and EBR-CFRP fabrics; respectively. Technical specifications for both types of strain gauges were shown in Table 1. Four strain gauges were located at the third span and near the supports. Two strain gauges were used for measurement tensile strains in EBR-CFRP fabrics while the other two gauges used for measurements compression strain in concrete voussoirs. Data logger type CR-1000 from Campbell Scientific (USA made) was used for recording the strains, loadings from the load cell, and the LVDT's readings.
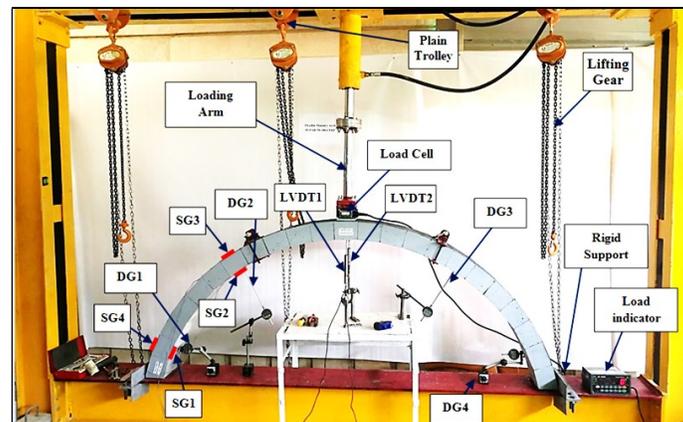

Figure 9. Test setup of self-form segmental concrete masonry arches

Table 1. Technical specifications of TML strain gauges

Model	Gauge size, mm		Backing size, mm		Gauge materials	Backing material	Resistance Ω	Application
	Length	Width	Length	Width				
PL-60-11-3L	60	1	74	8	Wire SG*	Transparent plastic	120	Concrete
BFLA-5	5	1.5	12.3	3.3	Foil SG*	Foil	120	Carbon and Composite material

*SG = Strain Gauge

5. Results and Discussion

Four self-form segmental concrete masonry arches as detailed in subsection 3.2 were tested under static loads considering the study of selected parameters. Two of those arches were upgraded by strengthening the intrados by CFRP fabrics on limited mid-span region. Test results, as well as the contribution of strengthening by CFRP fabrics on the loading capacity of self-form masonry arches masonry arches, are summarized in Table 2.

Table 2. Test results of self-form segmental concrete masonry arches

Arch Designation	Keystone Joints Opening Load, N	Initial Localized Crushing Load, N	EBR-CFRP Debonding Load, N	Voussoirs Sliding Load, N	Ultimate Load, N	Failure Mode
F1-80-80-NS	570	3210	3490	3700	5590	Partially crushed
F2-80-80-ST	-	-	6540	7260	7570	No crushing
F3-80-100-NS	3150	3640	6310	7680	10010	Partially crushed
F4-80-100-ST	-	6580	5880	6770	8020	Partially crushed

5.1 Observed Behavior and Failure Mode

The behavior of self-form masonry arches under loading monitored at different loading stages. Five distinguished loading stage observed and considered as illustrated herein;

1. Load cause joints opening of the Keystone; which occurs at an early stage of loading of self-form masonry arch ring. When the load applied on the Keystone (V12), the joints V11-V12 and V12-V13 were opened accordingly.
2. Initial localized crushing load; most of the self-form masonry arch intrados (inner curve of the arch ring) under compression, except under the Keystone. In accordance with, high stress concentration being on the corner of the wedge-shape concrete blocks which caused localized or partial crushing.
3. Debonding of CFRP fabrics load; this was recorded as a critical loading stage. The debonding of fabrication CFRP fabrics was specifically in the top surface of the Keystone, as a result, the Keystone was released and freely to slide.
4. Voussoir initial sliding load; debonding of fabrication CFRP fabrics was followed by sliding of the Keystone. However, the friction forces as well as the thrust compression force tend to prevent Keystone sliding.
5. Ultimate loading; the loading which was recognized by progressive sliding of the Keystone.

The behavior of the self-form masonry arches subjected to loading at the apex started with the opening of the joints of the Keystone voussoir V12. The joints V11-V12 and V12-V13 opened at an early loading stage followed by localized crushing of some voussoirs (in the corners) along the intrados of the arch ring with a further increment of the applied loading. This is due to the concentration of the compression stresses over a small part over the section of the voussoirs. Under further loading, partial debonding of the fabrication CFRP fabrics observed along the Keystone. Debonding of CFRP fabrics was followed by sliding of the Keystone until it almost entirely released from CFRP fabrics and the arch ring tend to split out into two segments, which are considered the ultimate loading. Figure 10 shows the loading stages of self-form masonry arches.
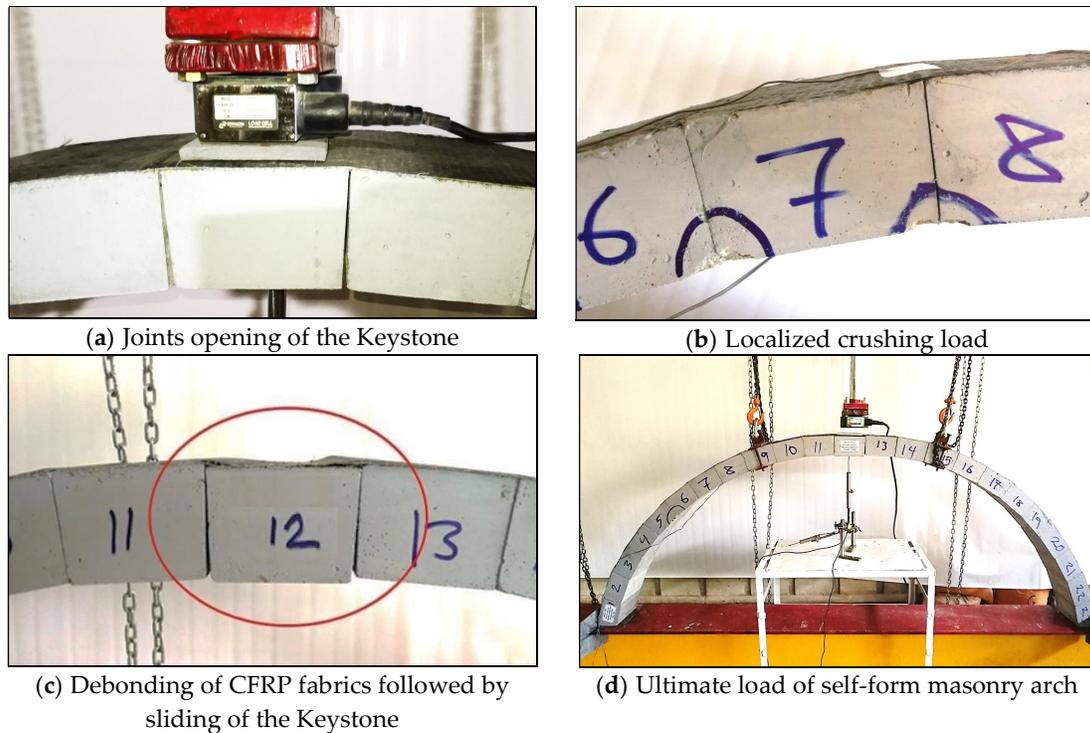

(**a**) Joints opening of the Keystone

(**b**) Localized crushing load

(**c**) Debonding of CFRP fabrics followed by sliding of the Keystone

(**d**) Ultimate load of self-form masonry arch

Figure 10. Loading stages of self-form segmental concrete masonry arches

5.2 Displacements of self-form masonry arches at the Keystone

The tested specimens of self-form masonry arch rings have no mortar as well as no backfilling, owing to that, the arch rings were not fully restrained against displacements when subjected to loading at any level except at support. Furthermore, the behaviors of self-form masonry arches were almost similar to traditional arches when loaded at the Keystone. The apex voussoir deflected downward, yet both of the quarter-to-third and supports segments of the arch ring were displaced outward. However, the existence of CFRP fabrics in the extrados tends to limit or prevent arch displacement. Upgrading of self-form masonry arches by CFRP even at the local region in the intrados reduced those displacements.

Figure 11 shows the load-displacement behavior of the self-form masonry arches at the Keystone. A considerable increase in the load carrying capacity of the self-form arch F3-80-100-NS with 25% thicker Keystone compared to the self-form masonry arch F1-80-80-NS was 79%, although the displacements for both arches was almost the same at ultimate loading. This behavior was due to the contribution of the used thicker Keystone in resisting the loads that cause debonding, sliding and crushing as well as the ultimate loading. The outward displacement of the arch specimens at the third span as well as the supports were shown in Figure 12. It is clear that the arch F3-80-100-NS displaced much more than the arch F1-80-80-NS by (20-226) %. This behavior was probably due to

the thicker Keystone of the former arch ring, where the Keystone prevented from sliding due to its large dimension in addition to the high thrust force until loading reached twice the load that causes sliding of the Keystone of arch F1-80-80-NS.
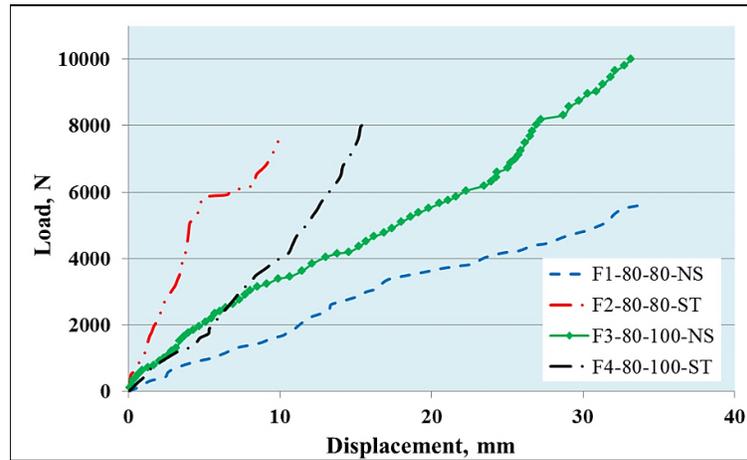

Figure 11. Load vs. vertical downward displacements of self-form arches at the Keystone.

(**a**) Outward horizontal displacement at the left support

(**b**) Outward horizontal displacement at the right support

(**c**) Outward vectored displacement at block 07

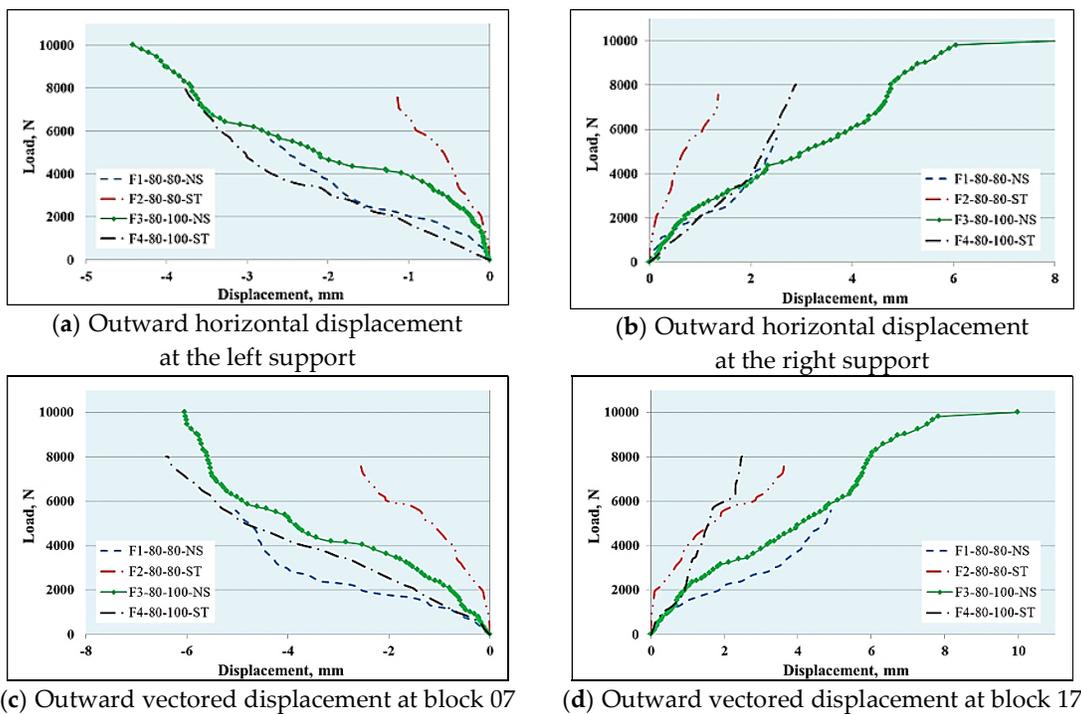(**d**) Outward vectored displacement at block 17

Figure 12. Load vs. outward displacements of self-form masonry arches.

5.3 Strains in the self-form segmental concrete masonry arches

Load vs. compression strain in the concrete voussoirs V2 and V7 in the intrados of the tested self-form masonry arches were shown in Figure 13. As aforementioned, arch F3-80-100-NS sustained higher ultimate load than arch F1-80-80-NS by 79%. Moreover, the compression strain developed in voussoirs V2 and V7 of arch F3-80-100-NS were 38% and 29%; respectively than that developed in arch F1-80-80-NS. The increment in strains was probably due to the effect of using thicker as well as broader Keystone in arch F3-80-100-NS which produces higher localized thrust forces and hence higher compression strain.
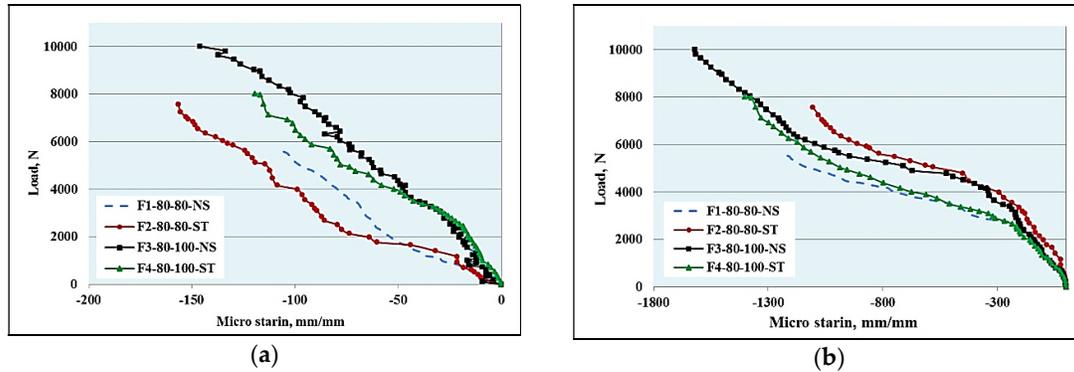
Figure 13. Load vs. compression strain in the concrete voussoir.

Figure 14 shows the load vs. tensile strain generated in the fabrication CFRP sheets read by the strain gauges adhered on the extrados of the self-form masonry arch ring at voussoirs V2 and V7. The tensile strain developed in voussoirs V2 and V7 of arch F3-80-100-NS were 31% and 81% than arch F1-80-80-NS; respectively. The resulted in higher strain in arch F3-80-100-NS was expected as the thrust force developed in arch F3-80-100-NS was almost twice than that in arch F1-80-80-NS. Furthermore, the thrust force was probably being tangent or close to the intrados of arch F3-80-100-NS at V7 which produces higher tensile stress in limited depth of voussoir V7 which was carried mostly by CFRP fabrics and hence producer higher tensile strain.
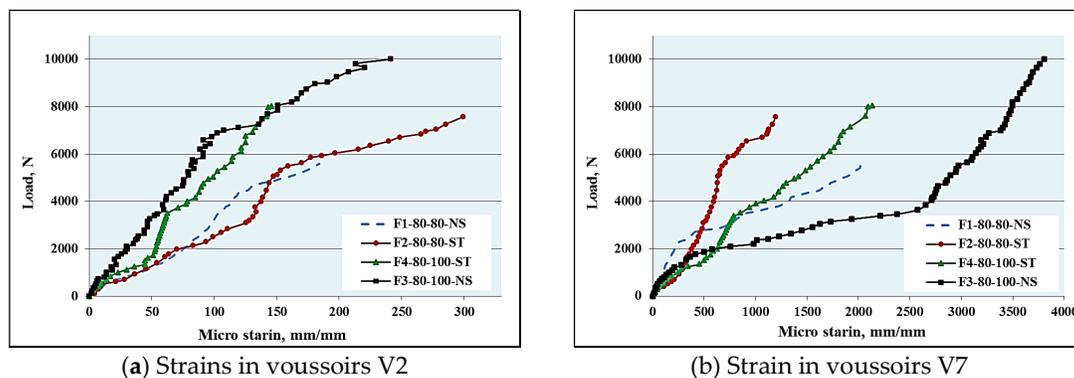

(**a**) Strains in voussoirs V2   (**b**) Strain in voussoirs V7

Figure 14. Load vs. tensile strain in fabrication CFRP

5.4 Contribution of strengthening CFRP fabrics

Strengthening of the self-form masonry arches were done partially and limited to the mid-loading zone. Considering arches F1-80-80-NS and F2-80-80-ST, which are typical except the later, were strengthened by CFRP fabrics as shown previously in Figure 3(b). The strengthening enhanced the load carrying capacity of arch F2-80-80-ST by 35% and considerably reduced the vertical displacement at the Keystone by 70% concerning arch F1-80-80-NS. The failure mode of a strengthened arch was different, joint opening, as well as sliding of the Keystone, was prevented by the strengthening CFRP fabrics from sliding. Moreover, the strengthening CFRP fabrics limited the thrust force within the middle of the depth of the arch ring and hence prevented the generation of localized stresses as well as the crushing of the voussoirs. Furthermore, partial strengthening by CFRP fabrics for voussoirs V11 to V13 makes these mid-three voussoirs behave as a rigid segment and slide over the unstrengthened closest voussoir V15, as shown in Figure 15(a).

Relating to self-form masonry arches F3-80-100-NS and F4-80-100-ST, both of those arches have distinguished thicker Keystone, and the same arch barrel except the later was strengthened by CFRP fabrics as shown in Figure 3(d). Despite the strengthening considerably decreased the vertical displacement of the arch F4-80-100-ST at the Keystone by 52%, the load carrying capacity was

reduced by 19% compared to arch F3-80-100-NS. This behavior due to the existence of partial strengthening of arch ring intrados from voussoirs V11 to V13 prevented the sliding of V12. Additionally, partial strengthening CFRP fabrics make these mid-three voussoirs behave as a rigid segment and slide over the least thickness of the ring (without strengthening) over the closest voussoir V14. Also, debonding of fabrication CFRP fabric and sliding of voussoir V14 over V15 was an additional reason, as shown in Figure 15(b).
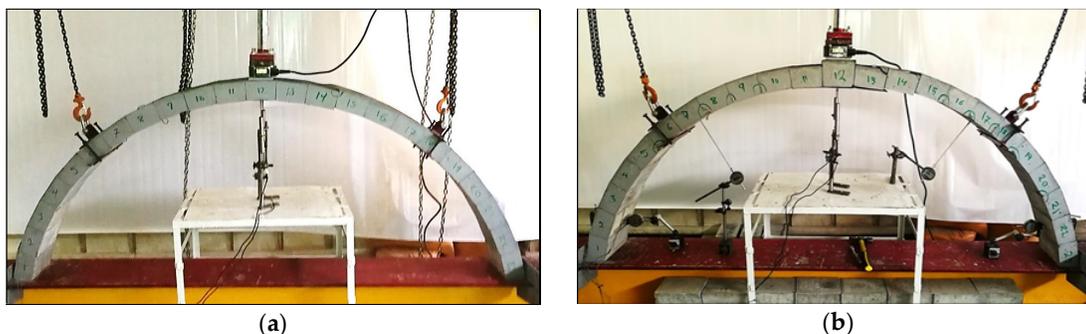

| (a) | (b) |

Figure 15. Failure of strengthened self-form masonry arch (a) F2-80-80-ST; (b) F4-80-100-ST

6. Conclusions

An experimental program comprised of four self-form segmental concrete masonry arches with a span of 2m and the rise of 0.8m was conducted to introduce the behaviour of novel method for fabrication masonry arches without any formwork as well as voussoirs binding mortar. The parametric study focused on the effect of using distinguished thicker Keystone by 25% among the typical arch ring voussoirs and the contribution of partial strengthening the intrados of the arch ring by CFRP fabrics in order to investigate the load carrying capacity of the self-form arches. Based on the results obtained from the experimental program, the following conclusions are presented.

- The self-form segmental concrete masonry arches are easy to fabricate, consisted of precise precast concrete voussoirs, and could install without the need of any construction framework.
- The use of thicker Keystone alters the behavior of the self-form masonry arch as well as considerably increased the load carrying capacity and reduced the vertical displacements. Furthermore, the existence of thicker Keystone in self-form masonry arch F3-80-100-NS delayed the joints opening to loading more than 5-times the load that causes the joint opening of self-form masonry arch F1-80-80-NS.
- The upgrading of self-form arch F2-80-80-ST, which not used thicker Keystone, by the partial strengthening of the intrados with CFRP fabrics was found effective. A considerable increase in the debonding load of fabrication CFRP fabrics by 81%, increase the localized crushing load by 13%, considerably increase voussoir sliding load by 107% as well as the ultimate load carrying capacity of the self-form masonry arch by 79% compared with unstrengthened arch F1-80-80-NS.
- The upgrading of distinguished thicker Keystone self-form arch F4-80-100-NS by the partial strengthening of the intrados with CFRP fabrics alter the behaviour and was found useful at an earlier stages of loading. The strengthening of the intrados considerably increases the localized crushing load by 80%. However, a decrease in all other loading stages was found by (7, 11, 19)% for CFRP fabrics debonding load, voussoir sliding load and ultimate load, respectively in relation to unstrengthened arch F3-80-100-NS.

7. Area of Future Studies

To summarize the recommendations for future work, the following points are highlighted:

- Investigation of the behavior of self-form masonry arches with backfilling.
- Formulating numerical model for analyzing self-form masonry arches.

- Studying the effectiveness of variable self-form masonry arches barrel thickness on the load carrying capacity.
- Considering more grades of concrete and discover the localized crushing stresses, if exists.

Author Contributions: conceptualization, A.A. and A.S.; methodology, A.A. and A.S.; validation, A.A. and A.S.; investigation, A.A.; resources, A.A.; data curation, A.A.; writing—original draft preparation, A.A.; writing—review and editing, A.A.; visualization, A.A. and A.S.; supervision, A.S.

Conflicts of Interest: The authors declare no conflict of interest.

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