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Assessment of Flexural Performance of Reinforced Concrete Beams Strengthened with Internal and External AR-Glass Textile Systems

Rana A. Alhorani [1], Hesham S. Rabayah [1], Raed M. Abendeh [1,*] and Donia G. Salman [2]

[1] Department of Civil and Infrastructure Engineering, Al-Zaytoonah University of Jordan, Amman 11733, Jordan; r.alhourani@zuj.edu.jo (R.A.A.); h.rabayah@zuj.edu.jo (H.S.R.)
[2] Department of Civil Engineering, University of Mississippi, Oxford, MS 38677, USA; dgsalman@go.olemiss.edu
* Correspondence: r.abendeh@zuj.edu.jo

Abstract: This paper is an experimental study of the effectiveness of using internal and external alkali-resistant glass fabric textile (AR-GT) layers for flexural strengthening of reinforced concrete (RC) beams. The experimental work compares internal single and triple layers of AR-GT as supplemental flexural reinforcement with textile-reinforced mortar (TRM) in RC beams subjected to four-point bending loading. In addition, a control beam specimen is cast with no AR-GT fabric. Monitoring the load–deflection curves, crack patterns, and strengthening layer performance showed that using AR-GT for internal and external layers increased the load-carrying capacity of RC beams. The failure patterns of beams with one external AR-GT layer and three internal AR-GT layers showed a similar trend, with higher loading capacity and lower deflections than the other beams. Three internal textile AR-GT layers recorded higher flexural strength (52%) than one internal layer (6.3%), compared to the control beam specimen. Moreover, using one layer of external AR-GT fabric exhibited higher flexural strength than using one or three internal layers (56.8%).

Keywords: AR-glass textile; textile-reinforced mortar; load-carrying capacity; flexural strengthening; reinforced concrete beams; repair

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Citation: Alhorani, R.A.; Rabayah, H.S.; Abendeh, R.M.; Salman, D.G. Assessment of Flexural Performance of Reinforced Concrete Beams Strengthened with Internal and External AR-Glass Textile Systems. *Buildings* **2023**, *13*, 1135. https://doi.org/10.3390/buildings13051135

Academic Editor: Fabrizio Greco

Received: 26 March 2023
Revised: 9 April 2023
Accepted: 22 April 2023
Published: 24 April 2023

1. Introduction

Textile-reinforced concrete (TRC) is an innovative technique which may replace numerous traditional approaches of repairing or strengthening existing concrete structures (steel jackets, bonding of sheets of fiber-reinforced polymer (FRP), shotcrete, etc.). FRP is a popular method for rehabilitation or strengthening concrete elements due to its large ratio of strength to weight, ease of application, low thermal conductivity, and durability in a severe environment [1]. In addition, the use of FRP in damaged concrete elements is efficient, since it enhances the load-carrying capacity and ductility. It is worth mentioning that FRP composites have been used to reinforce RC beams against seismic [2–4] and impact loads [5–7]. Nevertheless, it is reported that FRP methods have some disadvantages, such as application cost, low performance at high temperatures, weak integration between the concrete surface and the binder, and adhesion on wet surfaces [8–10].

In order to overcome these disadvantages, attention towards the use of TRC has been growing as a reinforcing material for concrete elements in buildings, as another option for FRP techniques. TRC is usually made of fibers woven or stitched in two orthogonal orientations, producing an open mesh. TRC can enhance the mechanical strength, energy absorption, and ductility, as well as reduce application cost, weight, and emissions of carbon dioxide of concrete members [11,12]. TRC is made of high-strength materials such as carbon, AR-glass, or basalt fibers embedded in inorganic materials, e.g., cement-based mortars, when it is used as an external layer on a concrete surface, and it is known as textile-reinforced mortar (TRM) or fabric-reinforced cementitious matrix (FRCM).

Many researchers have compared TRC and FRP techniques for external strengthening of flexural or shear capacities of concrete members. In general, the limitations of some composite materials, such as their incompatibility with sustainable environmental requirements, their brittleness, and their low fire resistance, have slowed their development and use for strengthening/repairing purposes. Furthermore, the literature has highlighted that the performance of hybrid TRC solutions is similar to that of CFRP under service limit states, but using TRC alone to strengthen RC beams revealed lower capacity gain performance under strength limit states. In particular, as noted by Larbi et al. [13], beams strengthened with TRC exhibited crack kinematics similar to that of undamaged RC beams, while no effect of TRC composite strengthening on the qualitative development of crack opening was observed. Verbruggen et al. [14] studied the effect of using external CFRP and TRC systems to test small-scale reinforced concrete beams that were strengthened for flexure. The results showed that both external systems cause the concrete beams to maintain high initial stiffness despite crack initiation. This is until reaching the cracking loads, which were found to be in excess of the calculated loads. The experiment showed that the number of cracks is independent of the type of external strengthening systems, but more than twice that of the reference beams. The researchers concluded that using CFRP or TRC for the external reinforcing layers of RC beams has a beneficial effect on the crack width, which was smaller, thus protecting the reinforcing bars by reducing moisture penetration. The crack widths were comparable to TRC- and CFRP-reinforced beams, up to 75% of the failure loads. Finally, the authors concluded that the pre-cracking of RC beams does not affect failure mode, ultimate load, crack number, and crack width compared to the performance of uncracked beams. The difference was the loss of the initial stiffness of the beams due to the opening of the existing cracks.

The flexural strengthening of beams using TRC has been conducted in different studies to investigate various parameters such as the material of the textile fiber, including carbon fiber textile [15–17], polyparaphenylene benzobisoxazole (PBO) fiber textile [16–18], and basalt fiber textile [19], the number of textile fiber layers used [16–21], the strengthening configuration [16], and the compressive strength of concrete [20]. It was concluded that using various textile fiber for reinforced concrete beams improved their flexural capacity, and increasing the number of textile layers increased flexural capacity and changed the failure mode.

Some studies have made numerical simulations of RC beams in order to assess the load-carrying capacity and crack resistance. Maio et al. [22] used an integrated numerical fracture model to model the damage phenomena of FRP-strengthened RC beams. Rimkus et al. [23] simulated concrete cracking of RC beams by using a smeared crack approach. The numerical analysis included the influence of the bond, fracture energy, and mesh of finite elements.

Ohno and Hannant and Peled et al. [24,25] initiated research to classify TRC composite structures according to their tensile strength properties. Then, Triantafillou and Papanicolaou [26] and Brückner et al. [27] initiated studies focusing on using TRC to strengthen and repair concrete elements. Thus, several experimental and numerical studies have been performed to evaluate the technical feasibility of TRC to determine the mechanical performance of composite structures compared to conventional solutions incorporating CFRP [28]. Elsanadedy et al. [19] conducted experimental and numerical investigations concerning textile-reinforced mortar (TRMs) effectiveness in the enhancement of the flexural capacity of RC beams. Basalt-based textiles were used to study variables including mortar types, number of TRM layers, and TRM types versus CFRP composites. The researchers concluded that the TRM strengthening system was less effective as it increased the tested beams' flexural strengths by 7.2% only but provided 61% higher ductility than FRP systems. The experimental tests in their study showed that using polymer-modified cementitious mortar to install TRM layers on concrete provides better bonds in the composite structure than using cementitious mortar. Additionally, reinforcing the concrete beams with layers of basalt-reinforced mortar resulted in a significant increase in the flexural strength ranging from 39% to 91%.

AR-glass textile fabric is a high-strength reinforced structural fabric made from alkali-resistant glass fibers with a special reactive coating. The general characteristics of AR-GT include its bidirectional configuration, high tensile strength, high ductility, and durability. It is removable without damaging the structure, easy to use, resists the alkaline environment of mortars due to its ZrO_2 content, and is fully compatible with mortars based on hydraulic cement or lime. Furthermore, it has high adhesion properties with a special reactive coating, and is available in different weight and mesh size options. Structural applications of AR-GT fabric include repairing and strengthening of concrete structures.

Experiments by Giese et al. [29] were carried out to study the flexural strengthening of RC beams using AR-glass textiles (two, three, and four layers) with variable TRM ages (3, 7, and 28 days) for different pre-cracking levels (no pre-cracking, 50%, and 100% of yielding loads obtained from the corresponding control specimens). The study concluded that all TRM beams showed increasing ultimate loads within the service limit state. The beams' cracking and yielding loads were affected by different TRM ages (increased by 49% for 28-day TRMs) and pre-cracking levels (from 35% to 72% for the uncracked beams compared to the control beams). Nevertheless, the same had no significant effect on the ultimate loads. However, the TRM strengthening systems significantly improved the beams' ultimate loads when increasing the number of layers, by 31%, 54%, and 72% for using two-, three-, and four-layer glass fabrics, respectively. It was observed that the beams with a pre-crack level of 50% exhibited a decrease of 10.9%, while there was a decrease of 41.4% for pre-cracked beams with a level of 100%. However, the TRM external strengthening of beams enhanced their behavior in the second stage of the load–deflection curves to record yielding loads equivalent to those of the uncracked beams, but reduced their ductility, as the average ductility ratio was 2.45–3.25 for the strengthened beams versus 4.02 for the control beams.

A few studies have investigated the embedded fabric textile in reinforced concrete members to strengthen flexural capacity. Limited researchers have studied the use of internal layers of AR-GT in concrete prisms and slabs. They reported that the inclusion of bidirectional glass grids could improve the flexural capacity of reinforced foam concrete prisms under a three-point bending test [30]. Furthermore, using lateral reinforcements of AR-GT grids under the four-point loading test improved the shear resistance of the polypropylene fiber-reinforced foam concrete beams [31]. Applying glass fiber grids and polypropylene grids for concrete slabs improved the punching capacity, and better behavior was observed at the interface between concrete and glass fiber grids compared to the glued fiber-reinforced polymer plates on the surface of the slab [32].

Accordingly, it is clear that study of the feasibility of using internal fabric textile layers for flexural strengthening of RC beams has not been performed. This article aims to conduct and evaluate the mechanical characteristics of solutions based on AR-GT fabric. In comparison to the conventional external AR-GT application, this paper investigates the qualitative and quantitative effectiveness of enhancing the flexural strength and ductility of reinforced concrete beams by applying internal layers of AR-GT fabric. Thus, the RC beam specimens prepared with one internal layer and three internal layers of AR-GT fabric were tested. Furthermore, one strengthened beam specimen was prepared with one external layer of AR-GT fabric using the TRM technique. Four RC beams were inspected by four-point flexural loading to monitor load-bearing capacity, load–deflection curves, crack propagation, ductility index, and failure pattern.

2. Experiment Work

2.1. Materials

2.1.1. Concrete and Steel

The beams were prepared using ready-mix concrete, which has been tested according to ASTM standards. Three cubes with side dimensions of 150 mm were tested for compressive strength of concrete and obtained an average value of 50 MPa. The tensile strength of concrete splitting was determined based on the test of two cylinders with a diameter of 150 mm and a height of 300 mm, with an average value of 4.5 MPa. The measured yield strengths of the main and shear reinforcement were 517 MPa and 280 MPa, respectively.

2.1.2. AR-Glass Textile and Mortar Matrix

The general characteristics of the AR-glass fabric listed on the manufacturer's data sheet show 81% fiberglass content with a 19% alkali-resistant treatment. The web width (warp) was shown to be 4.15 mm ± 5%, and the web width (weft) was 3.8 mm ± 5%. The mechanical properties of the glass fabric demonstrate a tensile strength (warp and weft) of more than 35 N/mm, with an elongation of 5%. Details of AR-glass fabric textiles are shown in Figure 1.

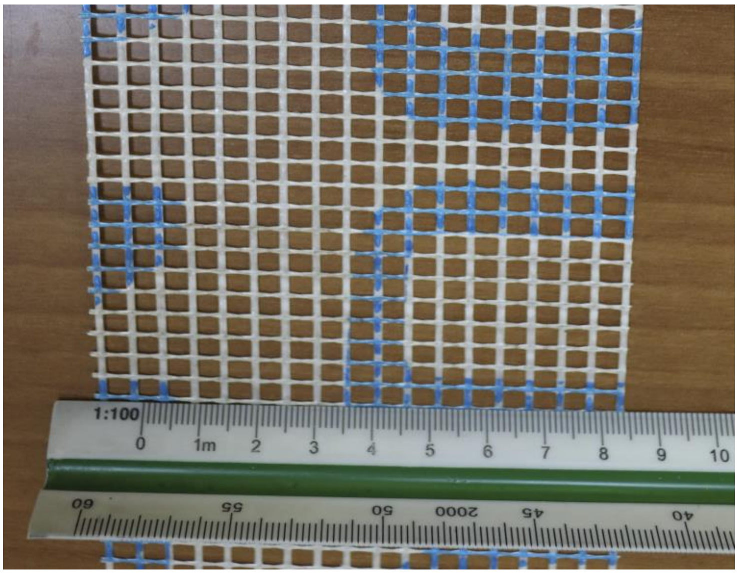


Figure 1. AR-glass fabric textile.

A hydraulic cement-based mortar was used to install the GT layers. It consists of a cementitious powder with a density of 1.6 kg/L which has a high polymer content, specific silicon/quartz mineral charges, and additives. The mortar mixture has an initial bond strength of 2.1 MPa and can be used up to 15 mm in thickness.

2.2. Preparation of Beams

The mortar mixture was prepared by mixing 1 kg of mortar and 0.483 L of water using an electric mixer and then left for 5–10 min before re-mixing to bed in the layers of the GT fabrics. The stages of fixing the external glass fabric involved firstly spreading a 3 mm thick layer of mortar using a trowel at the bottom of the beams to gradually lay the GT fabric over the mortar, then covering the fabric with a 2–3 mm layer of mortar. Figure 2 illustrates applying the external AR-GT fabric on a reinforced concrete beam.

To install the internal textiles, the glass fabric was placed directly under the stirrups of the specimens. For the three-layer strengthening beams, the first and second layers were placed on top of each other below the stirrups. The third layer of fabric was installed directly on top of a 30 mm layer of concrete above the main reinforcing bars, with a distance of 18 mm between the first two layers and the third layer. Figure 3 depicts the installation technique of one layer of internal GT fabric in reinforced concrete beams.

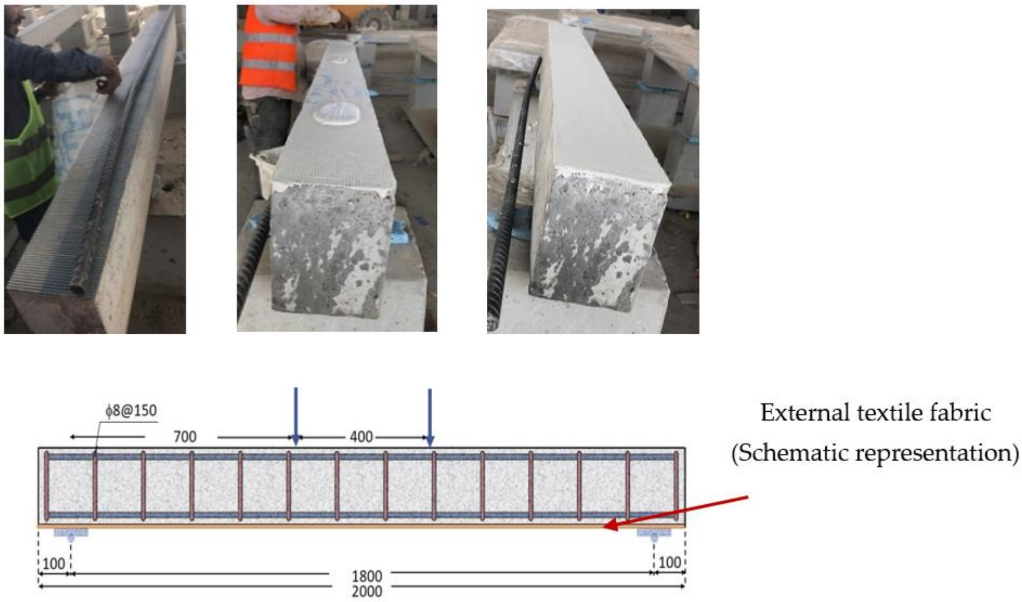


Figure 2. Application of external AR-GT fabric.

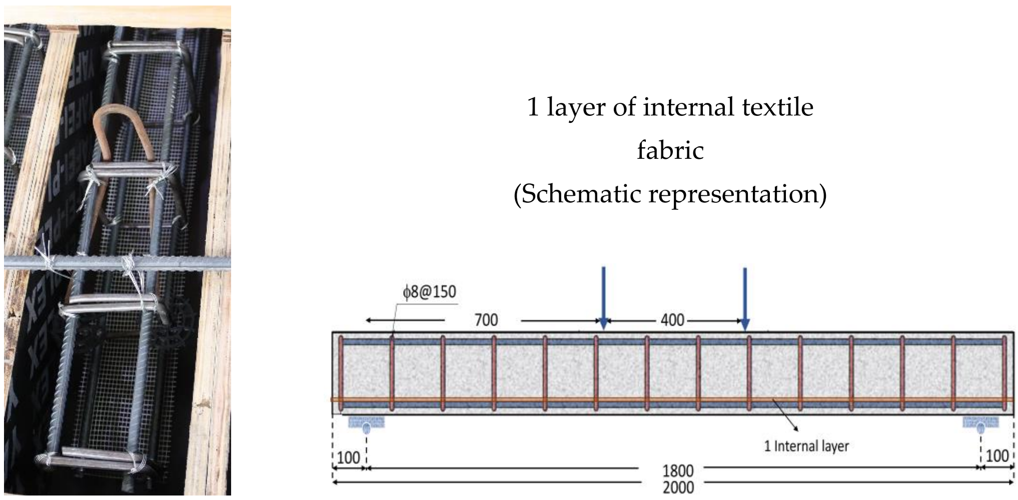


Figure 3. Installation of internal AR-GT fabric.

2.3. The Experiment Setup and Specimen Details

The study was completed based on the test of four RC beams 150 mm wide, 200 mm deep, and 2000 mm long under four-point loading. Details of the reinforcement of the beams are shown in Figure 4. The experimental program included the preparation of a control beam specimen (CTRL), and three strengthened beams as follows: two beams with one layer and three inner GT fabric layers marked with (INT1L) and (INT3L), respectively, and a single beam with one outer GT textile layer (EXT1L).

The beam specimens were simply supported on solid concrete blocks with a center-to-center supported distance of 1800 mm. Deflection measurements were taken every 5 kN incremental loading using a linear variable differential transducer (LVDT) positioned at the center of the supported specimen length.

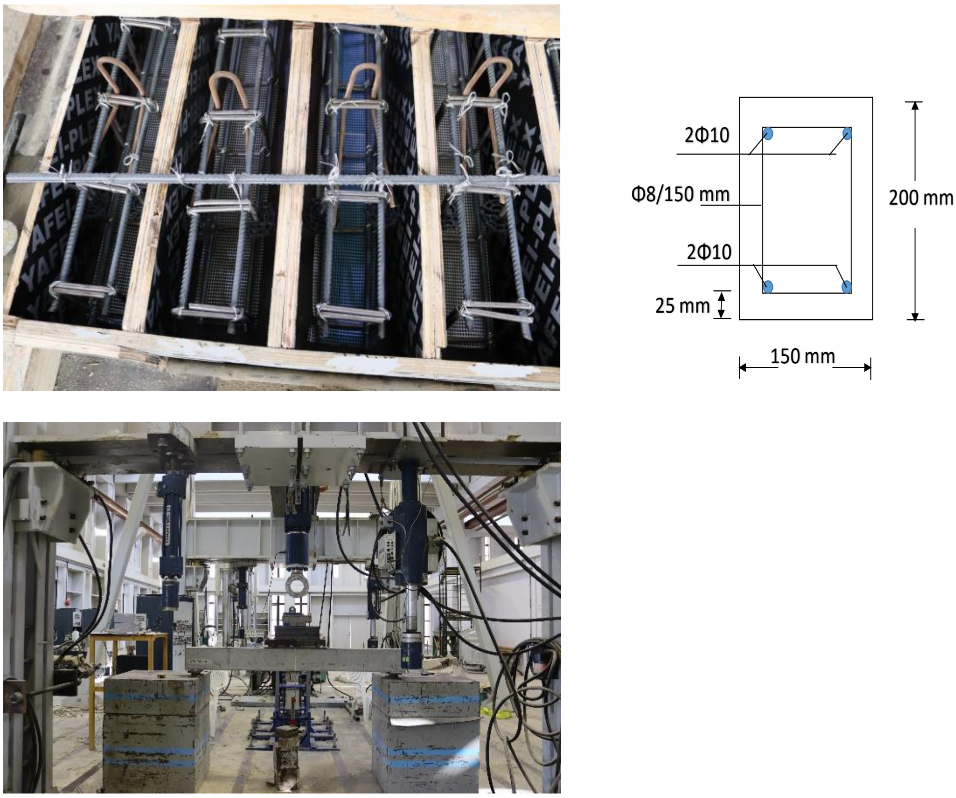


Figure 4. The test setup and beam reinforcement details.

2.4. Setup of Beams

The beam specimens were placed for testing as shown in Figure 5. The supports were placed 100 mm from the edge of the beams; thus, the centers of supports were distanced at 1800 mm. The supports were placed on rigid concrete blocks at the two edges. The load was applied gradually through a heavy-duty load cell, and deflection values were recorded every 5 kN increment. The deflection measurements were taken with a linear variable differential transformer (LVDT) placed beneath the center of the beams. Figure 6 shows schematic representations of the experimental setup of the four tested beams.

Figure 5. Experimental setup of RC beam specimen.

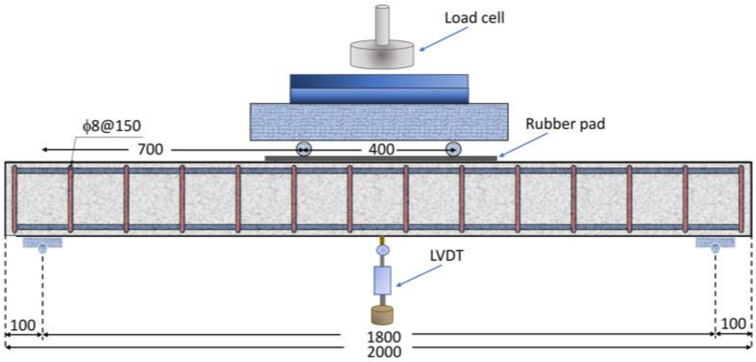


Figure 6. Schematic representations of the experimental setup of RC beams.

3. Experiment Results and Discussion

Figure 7 displays the load–deflection curves for the four beams (CTRL, INT1L, INT3L, and EXT1L) along with the ultimate flexural loads (kN) and the associated deflections (mm). Table 1 lists the experimental results for the cracking load (Pcr) and deflection (Δcr), the yield load (Py) and deflection (Δy), the ultimate load (Pu) and deflection (Δu), the failure load (Pf) and deflection (Δf), the ductility indices, and the strengthening ratios. The failure modes are presented in Figure 8, where cracks and loading are recorded for visual inspection.

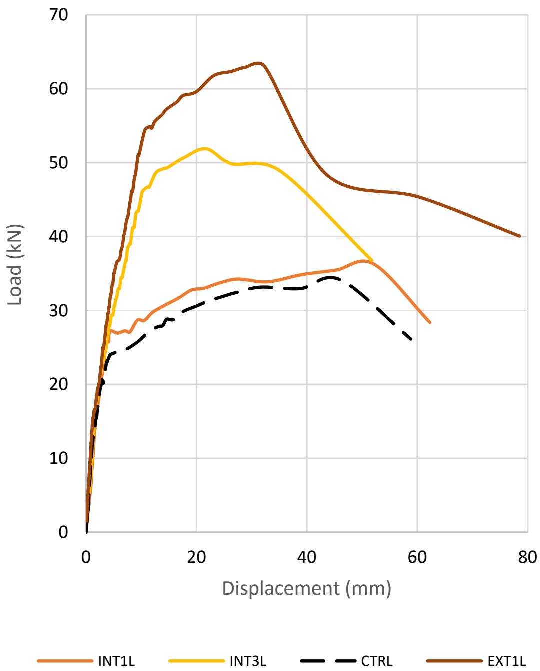


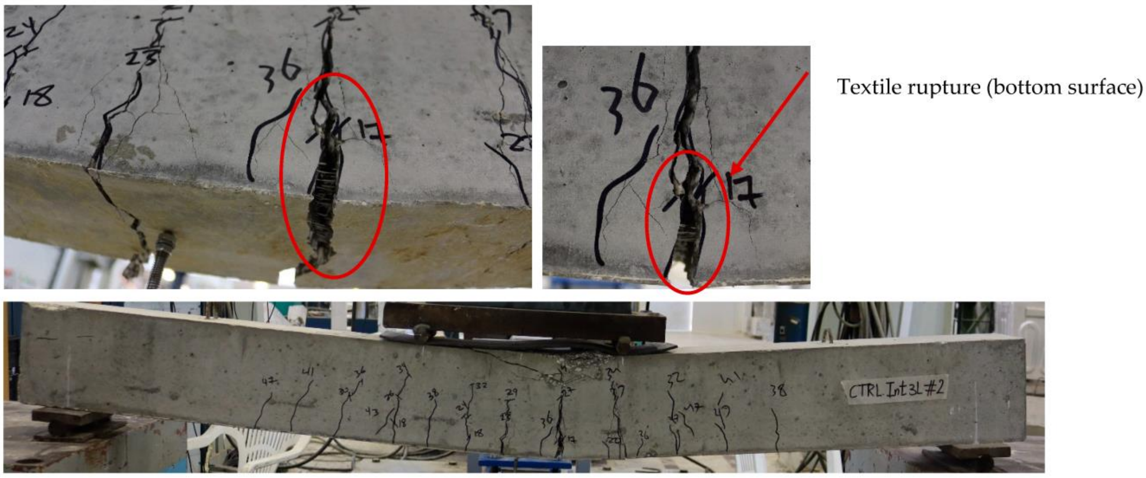
Figure 7. Load–deflection curves for four RC beam specimens.

Table 1. The experimental results.

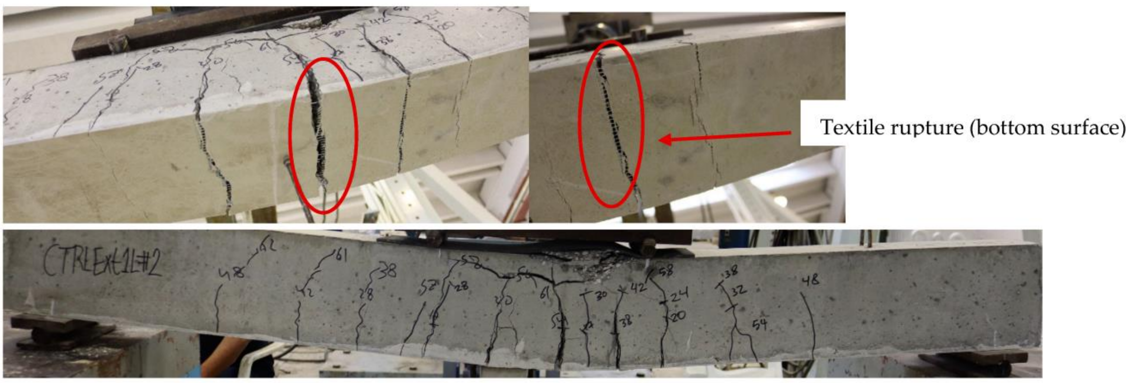
Specimen	Pcr (kN)	Δcr (mm)	Py (kN)	Δy (mm)	Pu (kN)	Δu (mm)	Pf (kN)	Δf (mm)	Ductility Index (Δu/Δy)	Strengthening Ratio for (Pu, Δu) (%)
CTRL	17.71	2.24	23.06	3.71	34.13	46.13	26.13	58.84	12.43	-
INT1L	16.84	2.05	27.23	4.32	36.28	52.14	28.39	62.28	12.07	(6.3, -)
INT3L	17.99	2.02	43.45	9.34	51.87	21.78	36.77	51.77	2.33	(52.0, 52.8)
EXT1L	17.89	1.82	54.87	11.55	63.01	32.36	40.06	78.53	2.80	(84.62, 29.9)

(a) CTRL

(b) INT1L



(c) INT3L



(d) EXT1L

Figure 8. Failure patterns of specimens.

3.1. Failure Patterns

Overall, there is a relationship between the developed cracking pattern and failure and the configuration of AR-GT fabric applied to strengthen the flexural capacity of the beams (Figure 8 and Table 1). Schematic representations of the recorded failure patterns are also displayed in Figure 9. All the strengthened beams (INT1L, INT3L, and EXT1L) exhibited a flexural crack pattern similar to the un-strengthened specimen (CTRL). The loss of strengthening action occurred due to AR-GT fabric rupture prior to the beams' failure by concrete crushing in the compression zone.

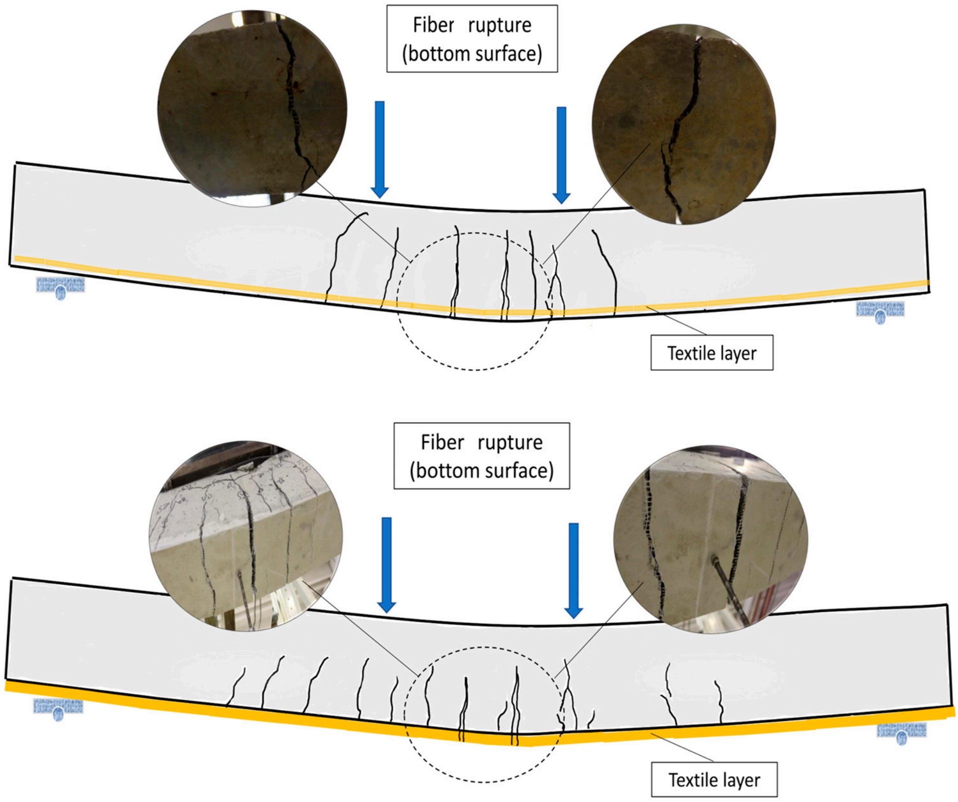


Figure 9. Schematic failure modes of specimens.

The control beam (CTRL) failed in flexure after the formation of flexural cracks in the constant moment span. The failure was due to the post-yielding response and rupture of the tensile reinforcement bars (Figure 8a). This type of failure mode is typical for under-reinforced beams. This type of failure was consistent with the results obtained by Giese et al. and Sen and Reddy [29,33]. Sen and Reddy [33] tested two control beams and observed major vertical cracks developed at the mid-span in the lower face of the RC beams and extended towards the top face.

All AR-GT-strengthened beams also failed in flexure at loads substantially higher than the control beam (Table 1). Thus, the contribution of AR-GT strengthening fabrics in increasing the flexural capacity was 6.3%, 52.0%, and 84.62%, for INT1L, INT3L, and EXT1L, respectively. Similar behavior was observed in the literature [19,21,34]. Raoof et al. [21] reported that all FRP-strengthened beams failed in flexure and rupture of the fibers and had an ultimate load higher than the control beam. The RC beam strengthened with TRM recorded an ultimate load of 43.2 kN, whereas the control beam recorded 34.6 kN. The main failure mode for INT1L, INT3L, and EXT1L specimens was a textile rupture, in which textiles are damaged because cracks on the extreme concrete surface open while increasing load. Flexural cracks occurred until the yielding load was reached. This increases the beam deflection and causes the concrete to crush in the compression zone at the ultimate loads.

Figure 10 presents the total number of visible cracks in the beam specimens and change percentage in the number of cracks relative to the CTRL beam. In all specimens, approximately 50% of the total visible cracks occurred in the constant moment span. A similar behavior trend was observed in previous studies [35–37]. Park et al. [35] found that the number of cracks in the pure moment zone of the TRM beam appeared more than in the control beam. This result indicates that AR-GT textile fabric is beneficial for the uniform distribution of cracks and effectively enhances flexural capacity.

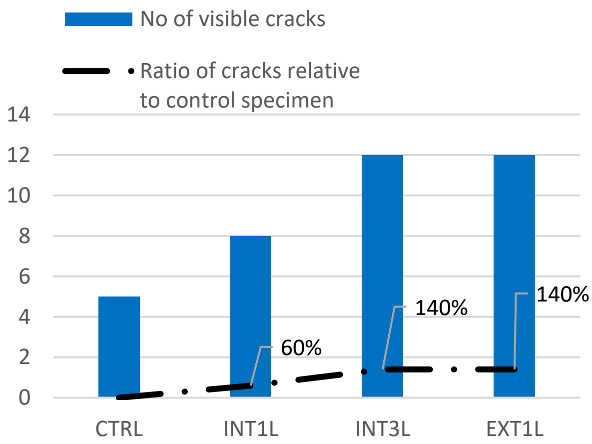


Figure 10. Visible crack numbers and percentage change in crack number relative to CTRL.

The following sections discussed the flexural capacity, ductility, and comparisons of the load–deflection behavior developed by beam specimens strengthened with different configurations (internal or external) and numbers of AR-GT fabrics.

3.2. Flexural Strengthening and Load–Deflection Relationship

In the literature, load–deflection curves obtained by beam flexural tests have been simplified to illustrate the effect of strengthening systems used. Three linear branches up to the ultimate load describe the flexural behavior of the tested beams in three phases [26], namely, the uncracking phase up to the first cracking of the concrete, the cracking phase up to steel yielding, and the plastic hinge phase in the case of un-strengthened elements or the full activation phase of the fabric until the ultimate load in the case of strengthened specimens.

The slope of the straight branch of the load–deflection curves in Figure 7 describes the flexural stiffness of the uncracked beams in the flexural tests. The AR-GT-reinforced beams showed stiffness behavior almost the same as the control beam specimen. In this loading stage, with uncracked beam sections, the deflection is slight because of the full section stiffness capacity of the beams. Figure 7 indicates that crack loads for all specimens occurred at approximately the same load level (17–18 kN), indicating that the AR-GT fabrics in the tensile zone were not activated prior to concrete cracking [38].

The second branch of the load–deflection curves in Figure 7 reveals the behavior of cracked concrete beams with decreasing stiffness and, thus, increasing deflection. The load–deflection curves differ due to applying different strengthening configurations of the AR-GT. In this stage, multiple crack modes of concrete resulted in AR-GT fabric layer activation. Therefore, relatively, a stiffer flexural behavior compared to the control specimen was observed in INT3L and EXT1L beams, along with increased loads at the yielding stage. Therefore, from the steel yielding point and beyond, the contribution of AR-GT fabrics to the beam flexural resistance has become significant. Any additional load after that point is expected to be carried almost solely by the AR-GT layers until failure occurs and the ultimate deflection is reached.

As shown in Figure 7 and presented in Table 1, the control beam (CTRL) supported an ultimate load of 34.13 kN, causing a deflection of 46.13 mm. The specimen failed at 26.13 kN and deflection capacity of 58.84 mm.

The AR-GT-reinforced beams INT1L and INT3L exhibited approximately the same shape of load–deflection curves as the control beam. The beam strengthened with a single internal layer of GT fabric had an ultimate load of 36.28 kN, with a slight increase in its flexural load (6.3%), indicating a negligible effect of the AR-GT fabric layer. However, using a single internal GT fabric slightly enhanced the beam deflection capacity by increasing its ultimate deflection (Figure 7 and Table 1) and increasing the number and spread of flexural cracks (Figures 8 and 10).

When three internal layers of AR-GT fabric (INT3L) were used, the load–deflection curve in Figure 7 shows that the ultimate load increased to 51.87 kN, resulting in a 52% increase in the flexural load capacity compared to the control beam. Additionally, the beam exhibited a significant decrease in its mid-span deflection caused by the ultimate load. This was associated with an increase in the width of the cracks. This behavior can be attributed to the increased yield loads, approximately from 23.06 kN for CTRL to 27.23 kN and 43.45 kN for INT1L and INT3L, respectively. A textile rupture at the failure stage was observed in INT1L and INT3L. Therefore, it can be expected that the number of internal GT layers to three layers can positively enhance the flexural load capacity of a strengthened beam with a decrease in its ultimate deflection, 52.0% and 52.8%, respectively.

The highest flexural capacity was found for the RC beam with TRM of a single external layer of AR-GT fabric (EXT1L), which was 63.01 kN with 84.62% flexural strengthening for this beam compared to the control beam. Furthermore, the yield load for EXT1L was 54.87 kN, resulting in a 138% enhancement compared to the control beam. These findings were similar to the studies by D'Ambrisi and Focacci and Raoof et al. [16,21], with a few exceptions. Raoof et al. [21] used TRM with seven layers of glass-fiber reinforcement to strengthen RC beams. They found that the RC beams failed in flexure due to rupture of fibers at the constant moment region at loads higher than the reference beams with increasing in flexural capacity of 39.3%. The failure of specimens is attributed to the loss of the strengthening action, which can be either progressive or abrupt in the mode of concrete crushing cases or shear failure. After a significant loss of strength, the residual flexural capacity of the strengthened specimens approaches the plastic moment capacity of the control specimen. The combination of concrete crushing in the compression zone and shear cracks can be seen from the failure pattern of EXT1L in Figure 8d as well as from the load–deflection curve in Figure 7. Furthermore, rupture of the external AR-GT fabric layer was observed with no separation occurring at the interfaces between the fabric, concrete, and mortar. In EXT1L, with the layer positioned at the extreme face of the beam section, textile fibers in the region of the maximum moment are expected to reach high tension stresses that exceed their tensile capacity. This mechanism is brittle, resulting in a sudden drop in the beam load capacity [19–21].

It should be noted that a higher deflection reading was obtained in EXT1L than in INT3L, comparatively. This flexural response can be attributed to the gradual decrease in the flexural stiffness of the beam with increasing crack spacing, as indicated by the failure pattern and the load–deflection curve of EXT1L in Figures 8d and 7, respectively.

3.3. Ductility Index

The ductility index is the ratio of ultimate deflection to the deflection at the yielding of the tensile reinforcement bar. Figure 11 shows that all of the strengthened specimens developed lower levels of ductility index than that in the control beam. This is consistent with the results from Ebead et al. [17]. The authors found that the strengthening led to a reduction in the ductility index compared to the control specimen. This can be explained by the fact that the deflection of the strengthened beams at yielding loads was generally higher than that of the control beam, while the control beam's ultimate deflection was higher than that of the beams strengthened with AR-GT fabrics, except for INT1L. This means that the use of AR-GT fabrics as a flexural strengthening reduced the increase in deflection that occurred when the applied load increased from the yield stage to the ultimate stage.

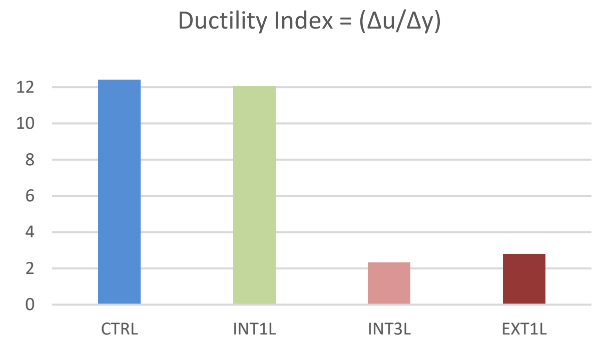


Figure 11. Ductility of the tested RC beam specimens.

Moreover, the results presented in Figure 11 indicate a correlation between the decrease in the ductility levels of the tested beams and the increase in the number of visible cracks relative to CTRL (Figure 10). The beam specimens that developed more cracks resulted in lower ductility than the CTRL specimen of 77.5–81.26%. Furthermore, strengthening the beam with a single external layer of AR-glass textile fabric showed a slightly higher level of ductility than strengthening the beam with three layers of internally fixed AR-glass fabric. This is due to the relatively high deflection (78.53 mm) at the ultimate load in the EXT1L beam specimen. The high deflection and the ultimate load recorded in the EXT1L beam can be attributed to its longer lever arm of the AR-GT layer compared with the lever arm of internal AR-GT layers.

4. Conclusions

This article experimentally studied the behavior of alkali-resistant glass textile fabric in the flexural strengthening of RC beams. Two main parameters were examined in four full-scale RC beams under the four-point flexural test: (a) internal and external GT fabric and (b) the number of GT layers. Based on the load–deflection curves, mode of failure, and strengthening layer behavior, the following conclusions can be drawn:

- Generally, using AR-glass textile fabric in reinforced concrete beams increased the load-bearing capacity.
- The embedded AR-GT as an internal supplementary reinforcement layer in RC beams enhanced not only the flexural strength but also substantially increased the cracking and post-yielding stiffness (up to 52%) compared to the un-strengthened beam.
- The flexural capacity is sensitive to the number of internal AR-GT fabric layers used. Using one internal layer of AR-GT fabric recorded a flexure capacity enhancement of only 6.3%, whereas using three layers of AR-GT resulted in an enhancement of 52% in load-bearing capacity.
- The use of textile concrete mortar systems increased the beam's flexural capacity. The strengthened RC beam with one external layer displayed an increase of 56.8% in flexural capacity with respect to the control specimen.
- The load–deflection response of the two beams made with internal AR-GT fabrics was similar to that of the control beam. This behavior may be due to the fact that AR-GT layers are embedded at almost the same level as the main steel reinforcement bars.
- When the textile fabric was used as external strengthening, the beam specimen exhibited a different load–deflection behavior than the control beam specimen because the AR-GT fabric worked as additional tensile resisting reinforcement with a larger lever arm.
- The failure patterns of RC beams strengthened with one external AR-GT fabric layer and three internal fabric layers showed a similar trend with higher load-bearing capacity and lower deflections compared to the other beams.
- Using many layers of internal AR-GT fabric can be used in strengthening RC beams and may efficiently replace using a TRM technique.

- All the strengthened RC beams exhibited lower levels of ductility index than that in the control beam. This means that the use of AR-GT fabrics as a flexural strengthening reduced the increase in deflection that occurred when the applied load increased from the yield stage to the ultimate stage.

The abovementioned conclusions were based on a limited number of RC beams. For future research, it is recommended to use RC beam specimens made with AR-GT by considering different parameters such as different concrete strengths, different AR-GT fabric configurations, and subjecting the specimens to harsh environments or a wide range of high temperatures.

Author Contributions: Methodology, R.A.A.; Resources, D.G.S.; Data curation, H.S.R.; Writing—original draft, R.M.A. and R.A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Al-Zaytoonah University of Jordan, Amman, Jordan. Grant No. 08/23/2019-2020.

Acknowledgments: The authors thank the Deanship of Scientific Research at Al-Zaytoonah University of Jordan, Amman-Jordan, for funding this research under Grant No. 08/23/2019–2020.

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

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