Abstract: Textile-reinforced mortar (TRM) is used to strengthen reinforced concrete (RC) structures using a textile and inorganic matrix. TRM is a part of textile-based composites; the basic structural behaviors, application methods, and methodologies for the extension of actual structures in TRM were studied. However, structural behavior and performance verification which depict the long-term service situation and fatigue is limited. Therefore, this study, verified the flexural behavior of TRM-strengthened beams and their fatigue performances using carbon- and alkali-resistant (AR) glass textiles through 200,000 load cycles. TRM-strengthened beams were applied to an optimization strengthening method which consisted of whether the textile was straightened. According to the test results, the strengthening efficiency of TRM-strengthened beams when subjected to cyclic loading was lower than that of the monotonic loading, except for the straightened carbon textile specimen. The average efficiency of the AR-glass textile (straightened and non-straightened) and carbon (non-straightened) was 0.86 compared to the TRM-strengthened beam subjected to monotonic loading in terms of flexural strength. In the case of deflection, the average efficiency of the AR-glass textile type was similar to the monotonic loading test results, while that of the non-straightened carbon textile was improved. The Ca-S specimen that was used to straighten the carbon textile showed a reliable structural performance with a strength efficiency of 0.99 and a deflection efficiency of 0.97 compared to the monotonic load test. Therefore, TRM strengthening using a straightened carbon textile is expected to be sufficient for the fatigue design of TRM-strengthened beams.

Keywords: TRM; flexural behavior; fatigue performance; straightened textile; carbon

1. Introduction

The textile-reinforced mortar (TRM) is part of textile-based composites, such as textile-reinforced concrete (TRC) and the fiber-reinforced cementitious matrix (FRCM). Textile-based composite studies were conducted in 2002 at RILEM on TRC and continued through collaboration with the ACI 549 Committee [1,2]. TRM is expected to solve problems caused by organic adhesives while maintaining the advantages of fiber-reinforced polymer (FRP) reinforcements, and various studies were conducted and summarized on tensile behavior, the bond between TRM and concrete substrates, the effect of flexural and shear strengthening, and seismic behavior within the column [3,4].

Banholzer [5] and Schorn [6] suggested a basic model of bond behavior between the textile and matrix. Colombo et al. [7] verified the design parameters on the TRC coupon through a tensile test. Kamani et al. [8] conducted a flexural behavior test of TRC using fabric with a different textile geometry and quantified the efficiency of flexural performance as a fiber performance index. Bulter et al. [9] investigated the durability of aged TRCs and described the appearance of the interface between the fiber and matrix...
using a scanning electron microscope. Studies have also been conducted to verify mechanical performance by considering various application methods with pre-tensioning [10,11], externally bonded strengthening [12–14], the types of structure members [15–17], the types of material [18–20], and so on.

Recently, various methodologies have been established to present the extension and applicability of textile-based composites to actual structures. Scheerer et al. [21] introduced various TRC shell structures and described the manufacturing method for each structure, and Cauberg et al. [22] suggested using TRC as a formwork for shell members. Valeri et al. [23] explained the structural points of various fibers and described the structural members and fabrication techniques that can be used as TRC. Nguyen et al. [24] introduced the characteristics of TRM and presented an overview of fire resistance. Simonsson [25] studied the strengthening, design, and fabrication methods for various types of geometric TRC members to utilize three concepts (thin, formable, and strong) in TRC. Hawkins [26] proposed a new architectural structure system using TRC and suggested a design methodology from theoretical work to complete actual projects. Pino et al. [27] performed experimental and analytical studies on damaged precast PC girders to measure the strength efficiencies of FRP and FRCM. The target was a girder that had been used for 55 years and had suffered some damage. Compared with FRP reinforcement, when considering predicted strength, FRCM showed lower a performance due to premature failure.

A study was conducted to verify the fatigue behavior of the textile-based composite. D’Antino et al. [28] analyzed factors that influenced the slip, energy dissipation, and stiffness degradation through fatigue load tests targeting the single-lap direct shear tests of FRCM-concrete joints and proposed a fracture mechanism approach. Dalabashi et al. [29] performed a cyclic loading pull-out experiment to understand the bond behavior of textiles and mortar. Mesticou et al. [30] analyzed textile properties under tensile loads by the cyclic load testing of TRC tensile members. In particular, the performance verification of the reinforced RC beam with TRM also performed under fatigue loading. Pino et al. [31] conducted a study on the parameters that affect the fatigue performance of poly(paraphenylene benzobisoxazole (PBO) FRCM and proposed a stress ratio versus the number of cycles (S–N) curve of FRCM-strengthened RC beams. Akbari and Nanni [32] applied a cyclic load to an RC beam reinforced with a glass FRCM to determine the ultimate strength, crack pattern, failure mode, bond performance, and fatigue threshold. Aljazaeri and Myers [33] examined the change in stiffness, crack and failure modes, and the energy absorption rate according to the curing conditions, and the sustained load and fatigue load conditions of RC beams when strengthened with FRCM. Aljazaeri and Myers [34] studied the change in stiffness through environmental exposure and fatigue frequency to a bridge exposed to various environments and verified that the resilience of FRCM was high even in the case of severe environmental exposure. Ngo et al. [35] investigated the effectiveness of carbon textiles in the shear strengthening of corroded RC beams subjected to monotonic and repeated loading. Calabrese et al. [36] studied the bond behavior between FRCM and concrete substrates, including shear and normal, using a modified beam test setup. Munck et al. [37] analyzed the strain, deflection, cracking, and the stiffness changes in the cyclic load testing on TRC tensile and sandwich elements.

Various studies on the essential characteristics of textile-based composites, such as TRC, TRM, and FRCM, and technical methodologies for their actual application to structures have been actively undertaken for approximately 20 years. However, studies of TRM-strengthened structures subjected to fatigue loading are still limited, despite the fact that verifying structural stability in a long-term service environment is important for actual application. Therefore, the flexural behavior of TRM-strengthened beams (TRM beams) subjected to cyclic loading are verified by comparing the identically designed TRM beams when subjected to monotonic loading performed by the author [38]. TRM beams in this study were applied to an optimized strengthening method which mainly consisted of whether the textile was straightened. In the case of the monotonic loading
Buildings 2022, 12, 1738

of test, the TRM beams with a straightened textile under a certain amount of load were improved in their load-bearing capacity and flexural stiffness. This study aims to verify whether the proposed strengthening methods show the same efficiency as in the monotonic loading, even under cyclic loading.

2. Materials and Methods

Five prepared specimens will load for a cyclic test. An RC beam without TRM strengthens was fabricated as a reference specimen; four TRM beams were fabricated; the TRM variables are carbon- and alkali-resistant (AR) glass textiles, straightened and non-straightened.

2.1. Material

Table 1 lists the used AR-glass and carbon textiles detailed specifications and properties. Ready-mixed concrete with a specified compressive strength of 35 MPa and polymer mortar with a specified compressive strength of 45 MPa were used for RC and TRM, respectively. The flexural strength of the polymer mortar was 8 MPa, and the bond strength was 1.8 MPa, which was increased by 20% using a primer from 1.5MPa. The yield strength of the steel reinforcement was 400 MPa, and the modulus of elasticity was 200 GPa. The properties of the strengthening material were provided from a manufacturer, and a more detailed description of the material was provided in a previous study [38,39].

Table 1. The detailed specification of the AR-glass and carbon textiles.

<table>
<thead>
<tr>
<th>Properties and Geometric Parameters</th>
<th>AR-Glass Textile</th>
<th>Carbon Textile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength of filament (MPa)</td>
<td>1789</td>
<td>4900</td>
</tr>
<tr>
<td>Modulus of elasticity of filament (GPa)</td>
<td>68</td>
<td>230</td>
</tr>
<tr>
<td>Elongation of filament</td>
<td>0.0262</td>
<td>0.022</td>
</tr>
<tr>
<td>Number of filaments per roving</td>
<td>1600</td>
<td>12,000</td>
</tr>
<tr>
<td>Area per one layer or textile (mm²)</td>
<td>2.952</td>
<td>2.772</td>
</tr>
<tr>
<td>Mesh size</td>
<td>8 mm × 8 mm</td>
<td>10 mm × 10 mm</td>
</tr>
</tbody>
</table>

2.2. Experiment Setup

The TRM specimen used a textile corresponding to 20% of the balance reinforcement ratio calculated according to ACI549.4R-13 [2]. As fiber types, the straightened and non-straightened states of the AR-glass and carbon textiles were set as the main variables. A straightening force equal to tensile strengths of 5% were introduced for each fiber. Table 2 lists the detailed specifications of the specimens, including the textile configuration. AR and Ca indicate AR-glass textile and carbon textiles, respectively, and S indicates textile straightening. The same design process was performed for each specimen so that it could be compared with the monotonic test results performed by the author [38].

Table 2. The detailed specification of the study specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Textile Configuration and Strengthening Amount</th>
<th>Straightening Force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lamination</td>
<td>Layer</td>
</tr>
<tr>
<td>RC</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AR</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>AR-S</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Ca</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ca-S</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

The specimen and test setup specifications are shown in Figure 1. Diameters of 9.53 and 6.35 mm were used for the steel rebar and stirrup, respectively. In order to increase
the effect of TRM in RC beams, a rebar with the smallest diameter among those available was used. The length of the specimen was 1500 mm, the span was 1300 mm, and the length of the section where the TRM reinforcement was bonded was 1220 mm, excluding the support points. In the case of the specimen with textile straightening, the textile was fixed by using a steel plate and wedge anchor.

**Figure 1.** Schematic of specimen and test setup.

A cyclic load was applied for 200,000 cycles at 3 Hz with a stress ratio of 0.1 using a four-point loading test, and the maximum load was about 60% of the maximum yield load of the previous monotonic load test result, which was performed by [38]. In fact, it was loaded differently from the design, which was a result of considering the mechanical error caused by using a 100 kN class actuator; therefore, the maximum load of the TRM specimen was 24 kN, and that of the RC specimen was 18 kN, and the minimum load was determined to be 3 kN. To attach a crack gauge at an initial crack in the concrete and TRM, the test was stopped after the first cycle loading, and then the test was restarted. When the crack gauge had fallen out as the crack progressed, the reattachment of the gauge was omitted. Two steel strain gauges were attached to the center of the rebar, and three concrete strain gauges were attached to the center of the specimen. After the cyclic loading, a monotonic load was applied until a failure occurred. Figure 2 shows the loading process and how to compare with monotonic loading test results.

**Figure 2.** Process of experiment: (a) Cyclic loading test in this study; (b) Monotonic loading test in previous study [38].
3. Experimental Results

3.1. Failure Mode

Figure 3 shows the state of each of the TRM beams subjected to monotonic loading until post-cyclic failure. In the AR specimen, the debonding of TRM occurred in the 20 cm section of the right end when the first loading was applied. Subsequently, as the load repeated, debonding developed up to the loading point. The AR-S, Ca, and Ca-S specimens did not show any additional damage except for flexural cracks that occurred during first loading; some specimens had a small debonding of TRM when the failure occurred. The main failure modes of all specimens were textile rupture and concrete crushing in the compression section.

Figure 3. The failure mode of TRM strengthened RC beam.

3.2. Cyclic Loading

Figure 4 shows the specimens flexural stiffness (hereafter, stiffness) under cyclic loading. Each stiffness of the specimen was calculated using the test results. The legend indicated as “Designed” in Figure 4 is the average stiffness value of the TRM specimen using the same type of textile. The stiffness can be expressed as shown in the equation:

\[ \kappa = \kappa_{cr} + (M - M_{cr})(\kappa_y - \kappa_{cr})/(M_y - M_{cr}) \]  

\[ M_{cr} = \left( f_r + \frac{P_f e_f}{l_g y_b} \right) l_g \]  

\[ M_y = A_s f_s (d - \beta c) + A_f f_f (d_f - \beta c) \]  

\[ \kappa_{cr} = M_{cr}/(E I_g) \]  

\[ \kappa_y = \varepsilon_y/(d - c_y) \]  

\[ EI = M/\kappa \]  

where \( \kappa, \kappa_{cr}, \kappa_y \) are the curvature of arbitrary, cracking, and yielding, respectively; \( M, M_{cr}, M_y \) are the moment of arbitrary, cracking, and yielding, respectively; \( f_r \) is the tensile strength of concrete \((= 0.3 (f_{cm})^{2/3})\); \( P_f \) is the tensile force for textile straightening; \( e_f \) is the eccentricity distance of the textile, \( A_g \) and \( l_g \) are the total area and gross moment of the inertia of the TRM beam, respectively; \( y_b \) is the distance from the neutral axis to the bottom of the TRM beam; \( A_s \) and \( A_f \) are the area of the steel rebar and textile reinforcements, respectively; \( f_s \) and \( f_f \) are the stresses of the steel rebar and textile
Buildings 2022, 12, 1738

reinforcement, respectively; \( c \) is the neutral axis depth; \( d \) and \( d_f \) are the effective depths of the steel rebar, and textile, respectively; \( \beta \) is the concrete stress block factor; \( E_c \) is the concrete elasticity modulus; \( EI \) is the flexural stiffness; and \( f_{cm} \) is the mean compressive strength of the concrete (= \( f_{ck} + \Delta f \)).

All specimens except the AR specimen showed an initial stiffness higher than the design value. In the case of the AR specimen, the initial stiffness was 99% of the design value because part of the TRM experienced debonding at first loading. The stiffness continued to decrease as the load cycle increased and decreased by 16% compared to the design value at 200,000 cycles. The stiffness of the AR-S specimen was 48% higher than the design value in the first cycle, as the stiffness matched the design value in 100,000 cycles. At 200,000 cycles, the stiffness of AR-S decreased by 1% compared to the design value. The stiffness of the Ca specimen was 41% higher than the stiffness of the design. Although it continued to decrease as the test progressed to 200,000 loading cycles, the stiffness was 6% higher than the design. The stiffness of the Ca-S specimen was 37% higher than the design value but was the same as the design value at 50,000 cycles and then gradually decreased to 3% lower than the design value at 150,000 cycles. However, the final stiffness at 200,000 cycles increased by 5% compared to the design value.

Figure 4. Flexural stiffness comparison: (a) AR-glass textile; (b) Carbon textile.

Figure 5 shows the TRM crack widths for the maximum and minimum loads. Both AR-S and Ca-S straightened textile specimens had crack widths smaller than those of the AR and Ca specimens. In the case of the AR specimen, the crack width increased rapidly after 1000 cycles at a load of 24 kN, and the crack width increased after 150,000 cycles at a load of 3 kN. The crack width of the AR-S specimen was an average of 60% at 24 kN and an average of 68% at 3 kN compared to the AR specimen. While the crack width in the Ca specimen steadily increased, the crack gauge in the Ca-S specimen detached at 100 cycles. The crack width of the Ca-S specimen, up to 100 cycles, was an average of 80% at 24 kN and an average of 58% at 3 kN compared to the Ca specimen. The crack width of the concrete in the samples was smaller than or similar to the width of the crack that occurred in the TRM reinforcement and showed a tendency to increase steadily as the loading cycle increased.
Figure 5. Crack width of the TRM under cyclic loading: (a) AR-glass TRM; (b) Carbon TRM.

Figure 6 and Table 3 show the load-deflection curves and detailed results by monotonic loading after 200,000 loading cycles, respectively. A load of all specimens decreased and fluctuated after yielding. This result is a characteristic of a series of studies conducted by the author that implemented the same type of TRM specimens [38,40]. The yield load in the AR, AR-S, Ca, and Ca-S cases increased by 3%, 11%, 8%, and 15%, respectively, compared to the RC specimen. The ultimate load for the AR specimen was 1% lower than that of the RC specimen, and the ultimate load for AR-S, Ca, and Ca-S increased by 12%, 4%, and 12%, respectively, compared to the RC specimen. Therefore, it confirms that the TRM strengthening had a higher stability at the yield load.

Figure 6. Load and deflection curves until failure: (a) AR-glass TRM beam; (b) Carbon TRM beam.

Table 3. Post-cyclic monotonic loading results.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Yield</th>
<th>Ultimate</th>
<th>Designed</th>
<th>( P_{dy}/P_{dy} )</th>
<th>( \delta_{dy}/\delta_{dy} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen</td>
<td>( P_y ) (kN)</td>
<td>( \delta_y ) (mm)</td>
<td>( P_u ) (kN)</td>
<td>( \delta_u ) (mm)</td>
<td>Yield Strength, ( P_{dy} )</td>
</tr>
<tr>
<td>RC</td>
<td>35.39</td>
<td>5.37</td>
<td>37.22</td>
<td>29.37</td>
<td>33.6</td>
</tr>
<tr>
<td>AR</td>
<td>36.28</td>
<td>6.47</td>
<td>36.82</td>
<td>18.19</td>
<td>40.13</td>
</tr>
<tr>
<td>AR-S</td>
<td>39.13</td>
<td>5.57</td>
<td>41.67</td>
<td>16.11</td>
<td>40.58</td>
</tr>
<tr>
<td>Ca</td>
<td>38.2</td>
<td>5.42</td>
<td>38.89</td>
<td>7.33</td>
<td>40.22</td>
</tr>
<tr>
<td>Ca-S</td>
<td>40.59</td>
<td>5.82</td>
<td>41.66</td>
<td>8.32</td>
<td>40.62</td>
</tr>
</tbody>
</table>

The designed yield strength in Table 3 was calculated as shown in the representative equation (7).

\[
P_{dy} = \frac{2M_y}{a}
\]  

(7)

where \( a \) is the distance from the support to the loading point.
The yield load of the RC specimen was 5% higher than the design value, but that of the AR was 10%, AR-S was 4%, and Ca was 5% lower than the design value. In the case of Ca-S, the yield load showed almost the same value as the design value. Therefore, a sufficient strengthening efficiency was confirmed using a straightened textile in terms of flexural strength. The ductility of the RC, AR, and AR-S specimens was greater than 2, which ensured sufficient ductility for practical structural applications [41,42]. However, the ductility of the Ca specimen was 1.35, and that of the Ca-S specimen was 1.43, lower by an average of 51% than that of the AR-glass specimens.

4. Discussion

4.1. Results of Cyclic Load

Except for the AR specimen, the TRM beams maintained a stiffness similar to the designed stiffness, even at 200,000 loading cycles. In the case of the AR-glass textile specimen group, the initial stiffness of the AR-S specimen was excellent, but the decrease in stiffness was steeper than that of the AR specimen. Assuming that the debonding of the AR specimen did not occur at first loading, the AR-glass textile's straightening had no additional strengthening effect in terms of flexural stiffness. In the case of the carbon textile specimen group, the initial stiffness of the Ca-S specimen was 3% lower than that of the Ca specimen; the stiffness thereafter was maintained at an average of 8% lower than that of the Ca specimen because of the bond strength which weakened the matrix due to the smooth surface properties of carbon fiber [43]. The decrease in stiffness with an increase in the loading cycle in the carbon textile group was similar. Therefore, the straightening of the carbon textile did not have any additional strengthening effect on the stiffness. However, considering that the stiffness of the AR-S specimen was lower than the designed stiffness after 200,000 cycles, the specimen using the carbon textile maintained a stiffness higher than the designed stiffness. The average stiffness of the carbon TRM specimen was 292 kN·m², 10% higher than that of the AR-glass TRM of 265 kN·m²; from this, it can be concluded that the carbon textile is more advantageous in securing stiffness.

In terms of the concrete crack width, the maximum value of 200,000 cycles was 0.4 mm, 0.23 mm, and 0.25 mm for the AR, AR-S, and Ca specimens. The crack gauge of Ca-S had fallen out before 200,000 cycles. According to the ‘detailed guidelines for the safety and maintenance of facilities—Bridges (2019)’ in Korea [44], a level of 0.3-0.5 mm represents three of five levels, one grade higher than the fourth level, which represent severe damage to the structure. Therefore, the performance of TRM beams in terms of crack width is also satisfactory in maintaining structural performance. In particular, the specimens using straightened textiles performed better than those using non-straightened textiles. Furthermore, in terms of material, the maximum crack width of the Ca specimen was 63% compared to that of the AR specimen, indicating excellent carbon performance in the crack width control.

As a result of the post-cyclic test, the strength efficiency of the TRM with textile straightening was better than the non-straightening specimen, but the TRM beams showed a loss in their strengthening effect. A detail description is given in Section 4.2. The ductility of the AR-glass textile specimen was sufficient, but the carbon textile specimen was unstable. However, considering that the actual structure was used in the service load, ductility cannot be an absolute criterion for the design of TRM strengthening. The failure mode of the TRM beam did not cause a full debonding of the TRM member under cyclic loading but failed due to a minor debonding, textile rupture, and concrete crushing under the post-cyclic test. Therefore, the possibility of brittle failure in TRM beams is expected to be low.
4.2. Comparison Results with Monotonic Flexural Behavior

Table 4 compares the experimental results on the yield load and deflection between this study and the monotonic loading test performed by Park et al. [38]. The value in Table 4 is the ratio of the experimental result to each reference of the RC specimen. Escrig et al. [19] presented the TRM beam yield point as the TRM strengthening limit defined as the highest TRM strengthening efficiency. In this section, the result of the previous study can be seen as ‘monotonic’, and the experimental results of this study as ‘post-cyclic’.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Loading</th>
<th>Yield Load</th>
<th>Deflection</th>
<th>Specimen</th>
<th>Loading</th>
<th>Yield Load</th>
<th>Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARLo1</td>
<td>Monotonic</td>
<td>1.2</td>
<td>1.16</td>
<td>CaLo1</td>
<td>Monotonic</td>
<td>1.23</td>
<td>1.34</td>
</tr>
<tr>
<td>AR</td>
<td>Post-cyclic</td>
<td>1.03</td>
<td>1.2</td>
<td>Ca</td>
<td>Post-cyclic</td>
<td>1.08</td>
<td>1.01</td>
</tr>
<tr>
<td>Post-cyclic/Monotonic</td>
<td>0.86</td>
<td>1.03</td>
<td>Post-cyclic/Monotonic</td>
<td>0.88</td>
<td>0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARLo1P</td>
<td>Monotonic</td>
<td>1.3</td>
<td>0.98</td>
<td>CaLo1P</td>
<td>Monotonic</td>
<td>1.16</td>
<td>1.11</td>
</tr>
<tr>
<td>AR-S</td>
<td>Post-cyclic</td>
<td>1.11</td>
<td>1.04</td>
<td>Ca-S</td>
<td>Post-cyclic</td>
<td>1.15</td>
<td>1.08</td>
</tr>
<tr>
<td>Post-cyclic/Monotonic</td>
<td>0.85</td>
<td>1.06</td>
<td>Post-cyclic/Monotonic</td>
<td>0.99</td>
<td>0.97</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the post-cyclic AR-glass specimen group, the yield load and deflection ratio of AR and AR-S were decreased by 14–15%, and the deflection ratio was increased between 3 and 6% compared to the monotonic results. The strengthening efficiency after cyclic loading was decreased for both the load and deflection, but the difference in the deflection ratio was smaller than that of the load ratio. In the post-cyclic Ca specimen, the yield load ratio was decreased between 12% and 1%, and the deflection ratio was decreased between 25% and 3% compared to the monotonic results. The strengthening efficiency of Ca-S was better than Ca in both load and deflection. The Ca-S specimen showed the closest behavior to the monotonic load result.

In terms of failure mode, the debonding of the TRM occurred in most of the TRM specimens under monotonic loading. However, the TRM beam with cyclic loading was mainly damaged by textile rupture and concrete crushing, except for a minor debonding. Hence, the fatigue behavior of the TRM beam is expected to have a lower probability of brittle failure than monotonic loading.

Table 5 shows a comparison between the stiffness of the monotonic and post-cyclic tests with each reference RC specimen based on a load of 30 kN, which is higher than the maximum cyclic load. In the monotonic loading test, except for the CaLo1 specimen, the stiffness was higher than that of the reference specimen, and the CaLo1 specimen decreased only by 2%. In the case of the post-cyclic test, the carbon textile specimens showed a stiffness higher than that of the reference specimen, but AR-glass specimens showed a stiffness lower than that of the reference specimen. The stiffness of AR-S was similar to that of the reference specimen with a value lower than 2%; the AR specimen significantly affected the initial debonding of TRM.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Loading</th>
<th>Specimen/RC</th>
<th>Specimen</th>
<th>Loading</th>
<th>Specimen/RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARLo1</td>
<td>Monotonic</td>
<td>1.07</td>
<td>AR</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>ARLo1P</td>
<td>Monotonic</td>
<td>1.44</td>
<td>AR-S</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>CaLo1</td>
<td>Monotonic</td>
<td>0.98</td>
<td>Ca</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>CaLo1P</td>
<td>Monotonic</td>
<td>1.04</td>
<td>Ca-S</td>
<td>1.01</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7 compares the number of cracks that appeared when the TRM beam failed in the monotonic and post-cyclic tests. Except for Ca-S, the number of cracks in all the post-
cyclic specimens was lower than in the monotonic loading specimens. The reason for this is that the stress caused by the cyclic loading continuously concentrated in the cracks that occurred at the first loading; any additional cracks that were formed were limited.

Figure 7. Number of cracks on monotonic and cyclic loading specimens in the RC section.

5. Conclusions

In this study, the flexural behaviors of TRM-strengthened beams were analyzed through cyclic loading, and their performance was verified by comparison with a monotonic loading test. As a result, it was found that the fatigue performance of the TRM-strengthened beam, when subjected to cyclic loading, had sufficient structural safety but the strength efficiency was lower than that of the monotonic test. Detailed results are as follows:

In terms of serviceability, the flexural stiffness of the AR-S, Ca, and Ca-S was 99%, 106%, and 97-105% of the designed stiffness when subjected to loads of 200,000 cycles, except for AR, which occurred alongside TRM debonding at first loading. The average stiffness of the carbon TRM specimen was 10% higher than that of the AR-glass TRM specimen, therefore proving that the carbon textile was more advantageous in securing flexural stiffness. The crack width of RC ranged from 0.3 mm to 0.5 mm, so that the crack control of the TRM for the RC beam was satisfactory to maintain durability, especially when the straightened textile showed a better performance compared to the nonstraightened textiles.

In terms of flexural behavior, the flexural strength of the TRM beam during the post-cyclic period was higher than that of RC, especially for the Ca-S specimen (as high as 15%). The structural stability in the cyclic loading was secured because the possibility of brittle failure was low; the main failure modes were textile rupture and concrete crushing, not TRM debonding. The AR-glass specimen was more advantageous than the carbon textile in securing the ductility of the structure.

When comparing with monotonic test, the strengthening efficiency of the TRM specimen when subjected to cyclic loading was lower than that subjected to monotonic loading. However, only Ca-S showed a reliable structural performance and stability in terms of flexural strength and stiffness, crack occurrence and width, and a low potential of brittle failure, excluding ductility performance. If the scope of the structural design was limited based on the TRM strengthening limit (yield point), TRM strengthening using a straightened carbon textile is expected to be sufficient for fatigue performance.

In this study, the characteristics of the flexural behavior of the TRM beam were verified only for limited loading cycles. Therefore, an additional performance verification is required for the cyclic loading of more than 200,000 cycles, sustained loading, and impact loading.
Author Contributions: Conceptualization, methodology, investigation, writing-original draft, and writing-review and editing, J.P.; methodology and investigation, J.Y.; project administration and supervision, S.K.P.; conceptualization and writing-review and editing, S.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded National Research Foundation of Korea (NRF) with a grant funded by the Korea government (MSIP) (No. NRF-2017R1A2B2012535).

Data Availability Statement: Data are contained within the article or the data presented in this study are openly available in [Materials] at [10.3390/ma13051137 (4 March 2020); 10.3390/ma14216473 (28 October 2021)], reference number [38,39].

Acknowledgments: This work was supported by the National Research Foundation of Korea (NRF) with a grant funded by the Korea government (MSIP) (No. NRF-2017R1A2B2012535).

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

References


