FLEXURAL BEHAVIORS OF HIGH-PERFORMANCE TRM-RETROFITTED RC BEAMS UNDER CYCLIC LOADING

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ABSTRACT

Strengthening methods for reinforced concrete (RC) structural elements are of significant interest from researchers and engineers worldwide. This paper presents an experimental study on the flexural behavior of RC beams strengthened by a high-performance textile reinforced mortar (TRM) layer and examined for first time under cyclic loading. The cyclic loads were conducted referring to an on-site load method of existing RC structures as per ACI 437R-03. The main concerned parameters affecting the flexural behavior of TRM-strengthened RC beams were studied, including the loading type, the pre-cracking procedure, and the number of layers of fiber mesh. The failure modes and the deformation ability of the tested beams were analyzed in detail based on test observations and analysis results on deformation of the beams. The results verified the strengthening effectiveness of the TRM layer for RC beams under cyclic loading.

Keywords: Textile reinforced mortar, Flexural strengthening, Failure mode, Debonding failure, Deformation ability

1. INTRODUCTION

Reinforced concrete (RC) is considered as one of the widely-used materials for various civil and infrastructure structures. However, RC structures may deteriorate rapidly if their external load actions or surrounding environment conditions during lifetime overstep the considerations at the design stage. The structural deterioration may result in an unsatisfactory safety performance of RC structures which could be caused by the changes in their use or design criteria. For example, the requirements as per new design criteria exceed that of corresponding original design criteria when the RC structures are built. For this reason, many existing structures require an improvement of their structural behaviors by strengthening or repairing them totally or partly. From the literature, many researchers [1-3] experimentally and numerically investigated the structural behavior of strengthened RC beams with advanced composite materials such as fiber reinforced polymer (FRP) sheet.

Current methods to strengthen RC structures include (1) increasing the cross-section of elements, (2) strengthening with external bond materials such steel plates and (3) strengthening with external structural measures such as using steel structural elements. The first method usually increases the self-weight of original structures resulting in the reduction of usable spaces within the structure. The second one has attracted many concerns based on the literature which usually uses an external steel plate or other materials such as FRP sheet. Several researchers [4-6] have recently reported other innovative alternative solutions for strengthening RC structures with high-performance cementitious materials strengthening layers using innovative durable non-metal reinforcements. An attractive alternative is the textile reinforced concrete/mortar (TRC or TRM) strengthening method for its high structural performance and excellent durability [7-9]. TRC/TRM consists of multi-axial textile fabrics bonded to concrete surfaces with a fine-grained concrete/mortar. The effectiveness of TRC/TRM system under various loads was examined by other researchers such as Brückner et al. [7-9]. It was verified that TRC/TRM strengthening could be a solution with great potential and advantages comparing to existing strengthening materials and techniques.

However, existing studies mostly focused on the behavior of TRC/TRM-strengthened RC beams under static loads [10-12]. Up to now, quite limited studies have been reported on the cyclic behavior of such beams, although cyclic loads can make the performance deterioration of RC structures worse such as the fatigue cycling behavior of RC bridge girders. Based on ACI [13], cyclic load tests have been performed on existing structures as a diagnostic method to evaluate the performance of structural members in a short duration of time as compared with a standard load test. Therefore, this study mainly focuses on the critical cyclic behavior of TRM-strengthened RC beams. In addition, a pre-cracking methodology is usually used in laboratory testing on strengthened RC beams to simulate the damages in their initial stage such as initial cracks based on previous studies [14-16]. The methodology is in order

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to identify a critical load for the tested specimens on which the beams are damaged by the initial cracking. Then, the pre-cracked beams are repaired and imposed under cyclic loading. Therefore, the paper also concerns the effect of TRM strengthening layer on the structural-behaviors of the pre-cracked beams. In summary, the key objective of this paper is to provide a better understanding of the flexural performance of RC beams strengthened by high-performance TRM layer subjected to cyclic loads. The main concerned contents are the flexural strength, deformation, and failure modes of the strengthened beams.

2. TEST PROGRAMS

In this research, six simply supported rectangular RC beams were tested, with a span length of 3000mm, a width of 150mm and a depth of 250mm. As per current Eurocode 2 [17], all RC beams were designed with a potential flexural failure mode. In each beam, three 12mm diameter deformed steel rebars (D12) were used at the tensile zone of beams as longitudinal reinforcing steel bars while two 10mm steel bars (D10) were applied at compression zone. Seventeen steel stirrups of 8mm diameter (R8) were set in each beam with a spacing of 170mm. The thickness of concrete cover was 20mm. The details of the specimens are listed in Table 1 and plotted in Fig.1. Beams CB1 and CB2 were studied as control beams and the TB series of beams (TB1 and TB2) were directly strengthened by TRM layer. The strengthened beams PTB1 and PTB2 were first loaded for a pre-cracking in the 40% of the total capacity of the beams and then strengthened by TRM layer. Under this level of flexural 4-point load, the deflection of the beam was considered to reach a level of $l/250$, which is considered as the maximum allowed deflection for serviceability limit states according to the Eurocode [17], where l is the span length of RC beams. It should be noticed that the aging of steel rebars in the beam was not considered in this study for all tests was finished within three months.

Table 1 Details of test specimens

Specimens	bxD (mm)	Pc (%)	A_s (mm^2)	F_c/F_m (MPa)	Loading type	N
CB1	150x 250	0	339.29	39.40/-	M	0
CB2		0		39.40/-	C	0
TB1		0		35.96/75.6	C	1
TB2		0		35.96/79.10	C	1
PTB1		40		41.09/62.52	C	1
PTB2		40		41.09/54.96	C	2

b: the width of beam; D: the gross depth of beam; F_c: the compressive strength of cylinder concrete; F_m: the compressive strength of the mortar of TRM; P_c: the percent of pre-carking load (% of total capacity); M/C: monotonic/cyclic loads; A_s: the total cross-section area of all longitudinal tensile reinforcing rebars in beam section; N: the number of layers of fabric mesh in TRM layer.

2.1 Materials

(1) Reinforcements

12mm and 10mm nominal diameter S500 steel rebars (D12 and D10) (EU standard) were used as the longitudinal steel rebars for all the beams of this study. The yield strengths of two rebars both were 570MPa.

(2) Concrete

Normal strength concrete (C40 level) was used for all tested RC beams in the study. The water/cement ratio of the concrete was 0.54. The density and elasticity modulus of the concrete were 2307kg/m^3 and 34.26GPa, respectively, which were obtained through standard tests of three standard cylinder specimens (150mm diameter and 300mm height) cured in a standard concrete curing room (relative humidity of 95%, temperature of 18-22^{o}C). The actual compressive strengths of the concretes are listed in Table 1.

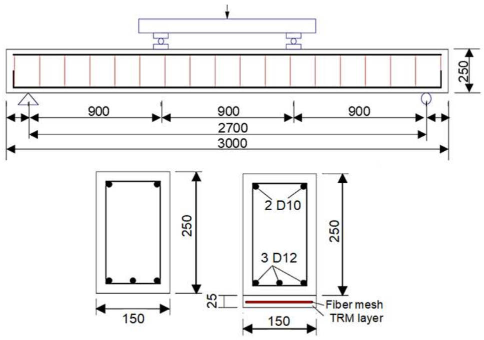

Fig.1 Details of tested specimens (in mm)

(3) Strengthening materials

The used high-performance textile reinforced mortar (TRM) strengthening layer consisted of a high-performance fabric mesh and a high strength mortar which was made of CEM I 52.5 cement, fly ash, micro silica and fine-grained sands (0.2-0.6mm), respectively. The actual compressive strengths of the mortars are listed in Table 1. For the strengthening procedure, as shown in Fig.2, the tensile side of the beams was wetted firstly. The first layer of the mortar was sprayed to the surface of the beams for having a better bond between concrete surface and TRM layer. Then, the textile fabric mesh was attached on the surface of the mortar, which was then covered with the rest layer of mortar. The TRM layer was in total 25mm in thickness and was considered as one layer of TRM strengthening layer. The used carbon fabric mesh (named as XCIM 180) provided by a local manufacturer. It was made of carbon in four layers of roving oriented in four directions (0/-45/90/+45 degree), has a fabric weight of 150g/m^2(+/-5%). The tensile strength and Young's modulus of the used fabric mesh layers were 4000MPa and 235GPa, respectively.

Fig.2 Preparation of TRM strengthening layer

2.2 Loading and Pre-cracking Method

All tested specimens were subjected to a four-point cyclic bending load conducted in the Structures Heavy Laboratory at the University of Leeds, UK. The loads were controlled by the mid-span deflection of the beams and the applied loading rate was set as 5kN/min. Several Linear Variable Differential Transformers (LVDTs) were used to measure the deformation and displacements of the beams, which were placed at the mid-span of the beam, at the right and left of the middle in a distance of 150mm. Two LVDTs were placed in the ends of the tested beams in order to monitor the potential movement of the beams during the tests in its axis direction. Meanwhile, two strain gauges were placed at the longitudinal tensile reinforcements and five strain gauges were placed on between the old concrete surface and TRM strengthening layer.

Considering that the practical strengthening process of RC elements usually is conducted after the elements have been subjected to external loads which usually caused cracks in original RC beams. For this, the study performed a pre-cracking procedure for two of the beams to analyze its effect on the structural behavior of strengthened beams. For pre-cracked RC beams (PTB1 and PTB2), the pre-loading procedure was stopped when the mid-span deflection of the beams reached 6mm. This level of deflection is estimated about the 50% of the deflection corresponding to *l*/250 of the beams, which is the maximum allowed deflection for the serviceability limit state (SLS) according to the Eurocode [17], where *l* is the span length of the beams. Therefore, according to the stop criterion, the maximum load applied for the pre-cracking tests of both beams was 33.2kN.

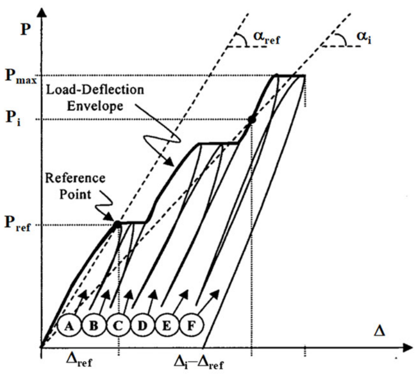

Fig.3 Applied cyclic loading method as per ACI[13]

In order to evaluate the cyclic performance of RC structural members strengthened with the TRM layer and confirm its strengthening effectiveness, a cyclic load test based on ACI 437R-03 [13] focusing on the evaluation of existing RC buildings was conducted in this study. According to the ACI code, a test called as the closed-loop test was used to simulate the cyclic loading in the laboratory, which was based on concentrated loads in a quasi-static method by producing at least six loading/unloading cycles. The entire process of loading-unloading described is shown in Fig.3, where the first two cycles (cycle A and B) applied for 10kN (1st P_{ref}) and cycle C and D applied for 20 kN (2nd P_{ref}). The increment rate of the reference load P_{ref} was set as 10kN in this study. The load process was continued, up to the ultimate failure of the beams with a severe concrete crushing in the compressive zone of the beams, or with a fracture of reinforcements or of TRM strengthening layer.

3. TEST RESULTS

(1) General observations

Fig.4 shows the ultimate damage situation of a representative specimen (TB1). As shown in the figure, all tested RC beams with and without strengthening demonstrate a typical flexural failure mode with a sufficient cracking evolution. The flexural cracks pass through the TRM layer of the strengthened RC beams. The main damage characteristics of the strengthened RC beams were divided into three aspects: (a) the de-bonding damage of the TRM strengthening layer from the RC beam, (b) the concrete crushing in compression zone at large deformation stage and (c) the ultimate fracture of the TRM layer at ultimate limit state of the beam starting from concrete fracture to textile fiber mesh fracture. However, before the fracture of the TRM strengthening layers, the cracking of the TRM layers got a sufficient evolution which confirms the flexural failure mode of the beams.

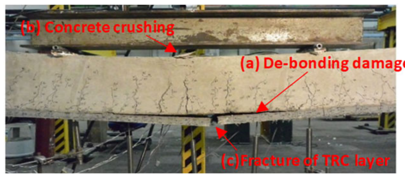

Fig.4 Damage characteristics of RC beam TB1 at ultimate state (Beam CB2 is similar)

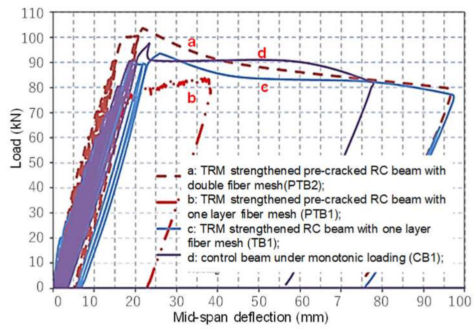

Fig.5 Load-midspan deflection of tested beams

(2) Load-deflection relationship

Fig.5 shows the load-midspan deflection curves of four representative specimens. The initial deformation of the beams shows a high level of similarity, however, strengthening of TRM improved the initial stiffness of the RC beams. The load-carrying capacities of TRM-strengthened RC beams (TB1, PTB1, PTB2) were 1.12, 1.16, 1.24 times the one of control beam, respectively. The strengthening effectiveness of TRM layer on the flexural behavior of RC beams was presented, however, beyond 40mm of mid-span deflection, the beams strengthened by TRM layer showed a similar load capacity reduction rate before the fracture of TRM layer. But the TRM layer in the strengthened beam using one-layer fiber mesh without the pre-cracking first fractured, as shown in Fig.5. The pre-cracking procedure has little influence on the load-carrying capacity of the RC beam strengthened by one-layer fiber mesh of TRM layer, as Curves b and c shown in the figure.

(3) Effects of main parameters on load-mid-span

deflection relationship

Effect of load type

As shown in Fig.6, although the initial stiffness of the control beam is affected due to the influence of the loading type, the load-deflection behaviour of the control beam presents a high similarity. This can be explained by the fact that the unloading process of concrete at the early stage of cycling load reduces the flexural deformation and damage accumulation of the beam. However, the unloading/reloading process at the later stage of cycling load accumulates the failure damage of the beam, which was verified by the fact that the ultimate deformation of the beam under cycling load is larger than that of the control beam under monotonic load, as shown in the figure. Besides, the unloading/reloading path of the cyclic loading was similar to that of the monotonic load in terms of load-deflection response up to the yielding point of the RC beams which was similar to the case of the FRP-confined concrete reported by Lam et al. [18]. However, after the beams reach their yielding point, it was remarkable that the failure of the control beam under cyclic loading happened earlier than that of the control RC beam under monotonic loading. Meanwhile, the cyclic loading curve reached the maximum load of 80kN at a maximum mid-span deflection of 35mm and the monotonic curve reached its maximum load of 84kN corresponding mid-span deflection of 38mm. Therefore, it is concluded that cyclic load expedites the ultimate failure of the RC beam but only have a small influence on the load-carrying capacity of beams, comparing with the case of a monotonic load.

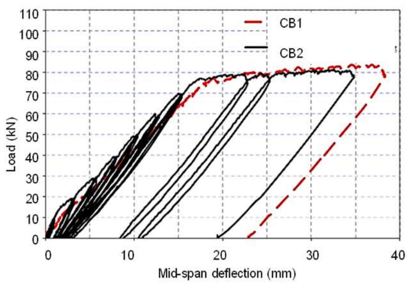

Fig.6 Load-midspan deflection of tested beams under different loads

Effect of pre-cracking procedure of RC beams

Fig.7 compares the load-deflection behaviour of beams strengthened by TRM with and without pre-cracking process under cyclic loads, respectively. Regardless of the use of the pre-cracking, the strengthening effects of the TRM layer in both beams was verified in terms of ultimate flexural strength and deformation ability. The improvement in the maximum flexural strength of the beam with the pre-cracking procedure is slightly higher than that of the beam without pre-cracking. A better interface bond behavior between original concrete surface and TRM strengthening layer may contribute to the enhancement in flexural strength increasing, which was caused by the small surface damage and cracking at the tensile side of the beam during the pre-cracking process. In addition, according to Fig.7, it can be seen that the TRM layer improves the sectional stiffness of the beams at the early stage regardless of the use of the pre-cracking procedure. The larger sectional depth and the flexural resistance of the TRM layer contributed to the increase of the lateral stiffness of the beams. On the other hand, as shown in Fig.7, the ultimate deformation-ability of both strengthened beams is significantly higher than the control beam CB2, especially for the beam without the pre-cracking procedure. For PTB1, the ultimate mid-span deflection reached 77.65mm which was 2.26 times higher than that of the control beam, while TB1 beam reached 97.02mm, which is 2.83 times more than that of the beam CB1. The reason why the beam TB1 has a higher ultimate min-span deflection comparing with that of beam PTB1 may be attributed to the fact that the deformation and cracking in PTB beam during the pre-cracking procedure are easier to be developed at subsequent cyclic loading procedure.

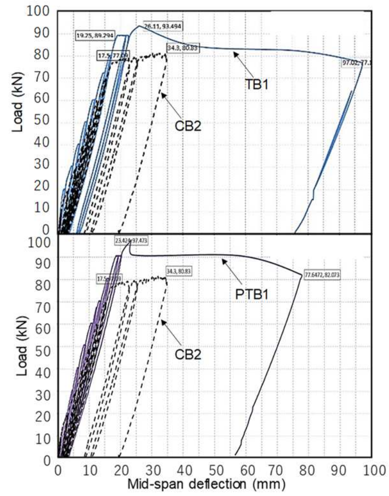

Fig.7 Effect of pre-cracking procedure

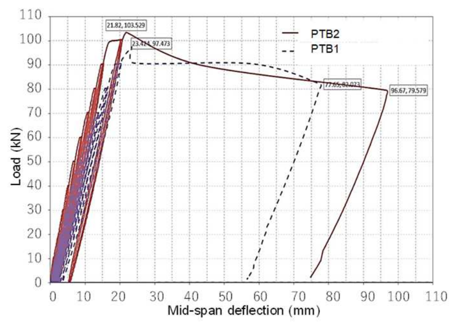

Fig.8 Effect of the layer number of fiber mesh

Effect of the number of fabric mesh in the TRM layer

Fig.8 shows the effect of the number of layers of fabric mesh in the TRM layer on the cyclic flexural behavior of the beams with a pre-cracking. The results plotted in Fig.8 show that the TRM layer with two layers of fiber mesh presents better strengthening from the view of flexural strength and deformation of the beams. The maximum flexural strength and ultimate mid-span deflection of the beam with two layers of fiber mesh reached 103.5kN and 96.67mm, which were 1.06 and 1.24 times that of the beam with one layer of fiber mesh, respectively.

As shown in Fig.8, although the mortar of TRM layer has a little smaller compressive strength in the beam PTB2, the flexural strength of the beam was still higher than the beam PTB1 strengthened by TRM with one layer of fiber mesh. This indicated that the main design consideration of TRM strengthening layer to improve the flexural behavior of RC beams should be the textile fabric mesh inside, i.e., the reinforcements of the TRM layer. In the beam PTB2, the improvement effect of TRM strengthening layer on the flexural strength, ultimate deformation, and stiffness of RC beams was similar to that at PTB1 having only one layer of fiber mesh. The beam with double layers of mesh had a higher ultimate mid-span deflection comparing with the beam with one layer of mesh, which can be attributed to that the TRM layer with double layers of fiber mesh provided a higher level of flexural resistance at the later stage of cyclic loading for the larger total tensile strength that the fabric mesh could provide.

3. DISCUSSIONS

(1) Flexural behavior and failure modes of beams

According to the test observations reported above, the flexural behavior and failure modes of TRM strengthened RC beams were significantly affected by the composition of TRM layer, i.e., concrete/mortar basis and textile fiber mesh layer. Fig.9 shows a simple description of the characteristics of load-deflection curves of TRM strengthened RC beams and their potential failure modes. The details of the different cases are discussed as follows,

Case (a)—strengthened by an ideal bonded and well-reinforced TRM layer

In this case, the TRM strengthening layer has an ideal bonding behavior with the surface of the original beam, in which the layer is usually reinforced by reinforcement (textile fabric mesh) strongly with a great co-working and deformation state.

Case (b)—strengthened by an ideal bonded and weakly-reinforced TRM layer

According to Case (a), when TRM layer has relative weak textile fabric reinforcements, the whole strengthening layer usually fractures at the early stage of large deflection such as Point *B*, which makes the load-carrying capacity of RC beam decrease sharply and the strengthened beam presents a similar behavior to that of un-strengthened beams. This steep reduction of the load-carrying capacity adversely affects the subsequent behavior of the beam making the load-resistance of the beam worse than the original beam.

Case (c)—strengthened/ by a well bonded and weakly-reinforced TRM layer

In this case, the load-carrying capacity of strengthened beams may reduce earlier (Point *A*) for other reasons, such as the deterioration of reinforcement or concrete cover due to external environment effect.

Case (d)—strengthened by a weakly bonded and weakly-reinforced TRM layer

The strengthening effectiveness of TRM layer is limited caused by a largely debonding damage of the external bonded TRM layer and fracture of the reinforcements in the layer, which both can result in the strengthened beam present a similar flexural behavior to that of non-strengthened beams. This means that the strengthening layer of the beam does not reach its target for the strengthening does not increase significantly the load-carrying capacity of the beam, on the contrary, the TRM layer increases the self-weight of the element.

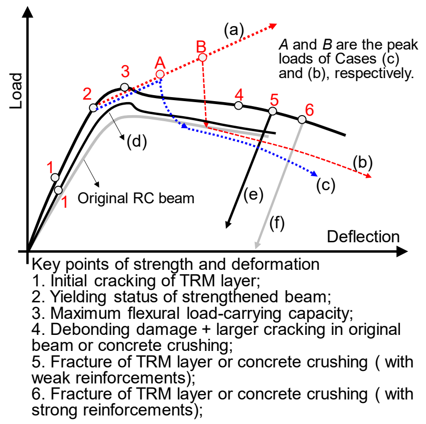

Fig.9 Failure modes and characteristics of load-deflection curves

Case (e, f)—strengthened by a well-designed TRM layer with appropriate bonding and reinforcements

When TRM layer has an appropriate bonding behavior and reinforcements, the strengthened beams can present a well-improved flexural behavior shown as Cases (e) and (f). Fig.9 depicts the key points on load-deflection curves of strengthened RC beams. The beams usually show a perfect flexural behavior including elastic deflection, yield load, peak load, and ductile post-peak behavior. The reasons leading to the failure of such beams are still the large debonding damage or fracture of fiber mesh in the TRM layer which happens at almost the same moment of the fracture of the whole strengthening layer. Generally, the debonding damage occurs before the fracture of fiber mech layer. The difference between Case (e) and (f) mainly is from the layer number of the fiber mesh in the TRM strengthening layer. However, it should be noticed that the increase from Point (5) to Point (6) at large deflection stage is limited under the same condition of TRM layer.

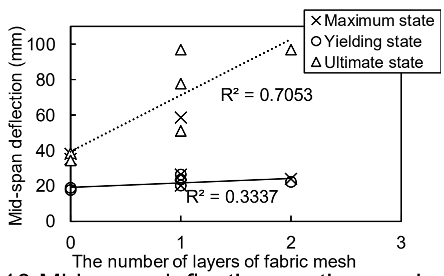

Fig.10 Mid-span deflection vs. the number of layers of fabric mesh

(2) A simple discussion on deformation-ability of RC beams

The deformation-ability of RC elements has a significant influence on the whole structural stability of RC structures. As shown in Fig.10, the mid-span deflections of the tested beams at ultimate limit state increase as the number of layers of fabric mesh in the TRM layer. As explained earlier, TRM with more layers of fabric mesh can improve the deformation-ability of RC beams at the latter stage of loading for the high strength TRM layer usually present a higher tensile behavior.

However, the number of layers of fabric mesh did not affect so much the yield deflection at midspan, as shown in Fig.10. This can be attributed to the increase of fiber mesh in TRM layer does not change the resistance mechanism of the layer at the early stage of deformation, and it is dependent on the bond between beam surface and TRM layer. This may support an assumption for the future structural simulation of such strengthened RC beams: the yield state of the strengthened RC beams is still dependent on the main reinforcement ratio of original beam, for the strengthening effect of the TRM layer is not released at that time, a relative low deflection (yield state) and main deflection resistance of the beams are from the co-working of concrete and main reinforcements at the stage.

4. CONCLUDING REMARKS

This paper studied experimentally the cyclic flexural behavior of high-performance TRM-strengthened RC beams. The main conclusions are drawn as follows:

(1) The results reported in the study confirmed the strengthening effectiveness of the TRM layer to RC beams under cyclic loads.

(2) The main design factors, related to the TRM layer, for strengthening a flexural-dominant RC beam are the interface bond and textile fabric reinforcement inside the layer.

(3) The cyclic load has little influence on the flexural capacity of RC beams, while it decreases the ultimate deformation-ability.

(4) The initial damage of the RC beam, such as cracking, did not affect significantly the strengthening effect of the TRM layer in the ultimate capacity of the RC beam, while the beam without pre-cracking presented a higher ultimate midspan deflection. The number of the layers of fiber mesh in presented a significant influence on the strengthening of RC beams. It is worth noting that the mortar in TRM used in the current study is of high compressive strength. The results may not be applicable when the TRM layer is made of low strength, meaning further studies are expected.

(5) Detailed analysis of failure modes of beams and a discussion on the deformation-ability of TRM strengthened beams have been provided. The results indicated that a well-designed TRM layer is critical to ensure the ideal cyclic flexural behavior of the beams, consisting of appropriate reinforcements and mortar with good interface bond properties.

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