Strengthening of Reinforced Concrete Beams with Fabric Reinforced Geopolymer Composite

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ABSTRACT: Proper strengthening and rehabilitation are essential to extend the lifespan of existing reinforced concrete (RC) structures. Fabric reinforced geopolymer composite (FRGC) is developed and adopted for strengthening of RC beams. The geopolymer matrix is prepared by using industrial by-products (e.g. slag and fly ash) and alkali activators (e.g. NaOH and Na_2SiO_3). Carbon fabrics are subsequently embedded in matrix to form the strengthening system. Flexural tests of RC beams with and without FRGC are conducted with a focus on the bonding behaviour between FRGC and concrete substrate. Test results indicate that externally bonding FRGC is able to enhance the cracking load, ultimate load and stiffness of RC beams. For instance, the cracking and ultimate loads are increased by 129.3% and 23.8% for the FRGC-strengthened beam, respectively. Installation of shear bolts and U-jacket are effective in preventing premature debonding of FRGC. U-jacket wrapping is recommended as it avoids introducing damage to beams.

1 INTRODUCTION

Many existing reinforced concrete (RC) buildings are facing the problem of insufficient structural capacity caused by the aging, the change of utilization purpose, and the post-fire damage (Jumaat et al. 2011). Comparing with demolition and reconstruction, proper strengthening and rehabilitation have been recognized as the sustainable and cost-effective solutions in construction industry. The strengthening technologies are immensely needed to extend the lifespan of existing RC structures.

Many studies have been devoted to developing various strengthening strategies for RC beams. One of the most common methods is to enlarge the cross section of RC beams. Diab (1998) enlarged beam section from 130 mm × 330 mm to 200 mm × 400 mm by using spraying fiber reinforced concrete. It was found that flexural strength and first cracking moment were greatly increased, while tensile stress in reinforcements was reduced. Embedding additional reinforcements to strengthen RC beams has also been widely investigated. Ha et al. (2007) revealed that both ductility and ultimate load capacity of beams can be enhanced by embedding CFRP trapezoidal bars to the tensile zone. Recently, externally bonding the reinforcing layer to the soffit of beam has gained the increasing popularity in construction industry, e.g. the use of steel plate and fibre reinforced polymer (FRP). Aykac et al. (2012) studied the performances of beams strengthened with steel plate. Test results showed that the loading capacity of beam can be enhanced by 35% to 85%, depending on the thickness of steel plate installed. Nonetheless, there are some intrinsic limitations in these methods, such as degradation at an elevated temperature, poor workability at a low temperature, lack of vapor permeability, and incompatibility between strengthening layer and beam (Menna et al. 2012, Raoof et al. 2012, Kouris and Triantafillou 2018). These are mainly attributed to the poor fire resistance and incompatibility of organic binder which is normally the polymeric epoxy.

Fabric reinforced cementitious matrix (FRCM) is a novel strengthening technology that overcomes the above defects as the matrix is inorganic. The approach is normally fulfilled by casting a cementitious matrix embedded with fabric to concrete surface. There are many existing studies investigating the properties and performances RC beams strengthened by FRCM. Du et al. (2018) investigated the flexural behaviour of basalt textile-reinforced concrete plates by considering effects of textile layer, fabric prestress, and volume content of chopped steel fibres. Larbi et al. (2010) applied textile reinforced concrete plate to strengthen short RC beams, and demonstrated that the shear capacity of beam can be enhanced by 17% - 68%. Raoof et al. (2017) revealed that both FRCM with FRP strengthening systems could substantially enhance the cracking and post-yielding stiffness of RC beams.

The FRCM, however, faces the problem of the installation. This is mainly associated to the use of cementitious binder. Unlike the organic polymer adhesive, which can be easily operated and takes short time to gain the strength, the ordinary Portland cement (OPC) binder needs longer curing before it reaches the target strength. As an alternative binder, geopolymer has a shorter setting time. Comparing to the OPC, the geopolymer is also known for the better fire resistance, higher durability, lower cost and higher sustainability (Davidovits 1994). However, there are limited studies focusing the effectiveness of fabric reinforced geopolymer composite (FRGC) on strengthening of RC beams. Menna et al. (2012) adopted FRGC to strengthen the beams, and pointed out that flexural capacity of beams can be significantly enhanced by around 110%. Shaikh and Patel (2018) found that both AR glass FRGC and FRCM exhibited similar flexural stress and deflection behaviours.

Debonding of strengthening layer from concrete substrate is one of the challenges in the flexure-strengthened RC beams, especially for those with multiple strengthening layers (Irshidat and Al-Shannaq 2018). Therefore, different anchorage methods have been put forward to improve their bonding behaviour. Lamanna et al. (2004) fastened the FRP strips to concrete surface by nails, and observed that the yielding and ultimate moments of beams can be improved by 21.6% and 20.1%, respectively. Ebead (2011) combined grout bonding with bolts fastening to install FRP strips, and found that the strengthened beam with anchorage showed superior enhancement in terms of ultimate loading capacity and flexural stiffness, as compared to those without epoxy strip/fastener anchorage. Zhou et al. (2013) attempted friction hybrid bonded FRP technique, and found that the ultimate loading capacity of the strengthened beam was 2.13 times of that with ordinary bond technique. Currently, most of anchorage methods are mainly developed for the FRP-strengthened beams. There are limited studies focusing on the anchorage methods for FRCM or FRGC. Raoof et al. (2017) proposed the U-shaped jacket to prevent the end-debonding failure for the FRCM strengthening method. The effectiveness of this anchorage method for the FRGC needs further investigation as the properties of geopolymer are different from those of OPC.

In this study, flexural performance of RC beams strengthened with FRGC is evaluated. Two anchorage methods, including shear bolts and U-jacket, are adopted to enhance the interfacial bond between FRGC and concrete substrate. Four RC beams with and without strengthening were tested under monotonic load. Parameters include the layers of fabric, mesh size of fabric and use of anchorage system. Failure mode, load-deflection relationship, loading capacity and flexural stiffness of RC beams are analysed and discussed.

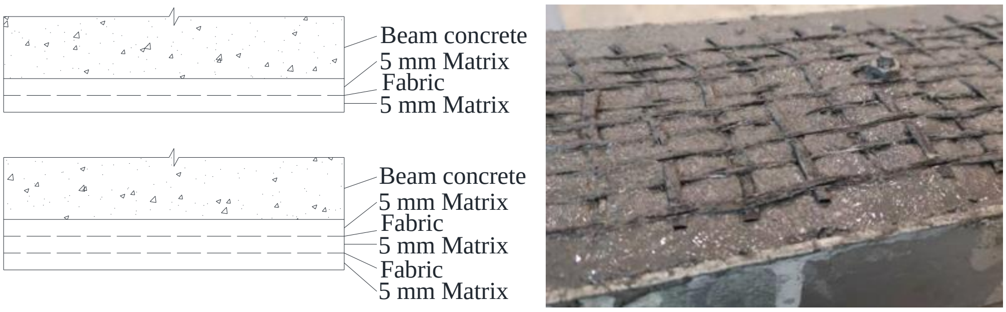

Figure 1. FRGC strengthening schemes for RC beam

2 EXPERIMENTAL PROGRAM

2.1 Materials

2.1.1 Fabric reinforced geopolymer composite

Flexural strengthening of RC beams was fulfilled by attaching a FRGC layer on the soffit of beam. The strengthening layer consists of geopolymer matrix and embedded fabrics. Each geopolymer matrix has a thickness of 5 mm. Figure 1 shows two strengthening schemes with one and two layers of fabric and the carbon fabric being embedded into the geopolymer matrix.

2.1.2 Geopolymer matrix

Class F fly ash (FA) and ground granular blast-furnace slag (GGBS) were used to prepare geopolymer matrix. The alkaline activator solution with 4.0% Na_2O (by weight of binder) and 1.5 silicate modulus was prepared using the mixture of water glass and sodium hydrate pellets. The silicate modulus (Ms) of the industry-grade water glass consists of 26.83% SiO_2, 8.32% Na_2O, and 64.85% H_2O by mass, and sodium hydrate is laboratory-grade with purity≥ 98%. The river sand with the maximum particle size of 2.5 mm was used as fine aggregates in the geopolymer matrix. The geopolymer binder composes of 70% GGBS and 30% FA, and has a fixed water-to-binder ratio of 0.33. The sand-to-binder ratio is kept constant at 1.25. In addition, 1.0% polypropylene (PP) fibre (by volume of matrix) was added into the matrix to avoid the occurrence of cracks caused by the large shrinkage of geopolymer matrix.

2.1.3 Carbon fabric

The carbon fabric used in this test was provided by a commercial supplier. Fabric mesh has an opening of 20 mm in both longitudinal and transverse directions. It was also modified to obtain a mesh size of 10 mm in longitudinal direction and 20 mm in transverse direction as shown in Figure 1. Mechanical properties of carbon fabric are described as follows: tensile strength 4,620 MPa, rupture elongation rate 2.0%, elastic modulus 243 GPa. Equivalent thickness of the 20 mm fabric is 0.047 mm, which is doubled for the 10 mm fabric.

2.1.4 Reinforced concrete beams

Four RC beams with the same reinforcing detailing were prepared. The beam has a cross-section of 102 mm×203 mm and has a span of 1,675 mm, as shown in Figure 2. C30 concrete was used to cast beams. Bottom and top longitudinal reinforcements are 2D10 and 2D8 HRB400 deformed bars, respectively. D6 HPB300 plain steel bars were adopted as the stirrups with a spacing of 100 mm.

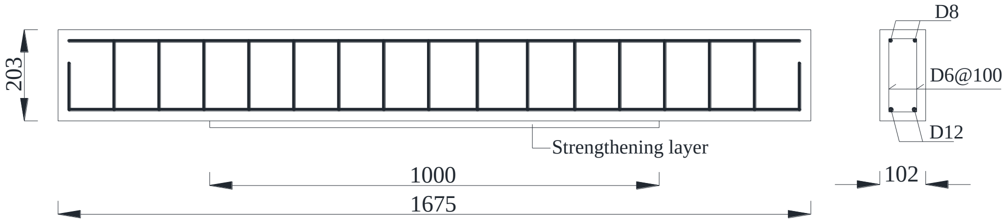

Figure 2. Dimension and reinforcement details of RC beam.

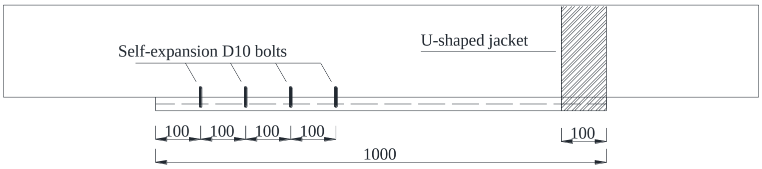

Figure 3. Two anchorage systems for the FRGC.

In the strengthening scheme, the layer of fabric, mesh size of fabric and anchorage methods are varied as the parameters. Terminology of the beams starts with a B, followed by the layer of fabric and mesh size in sequence. If anchorage method was applied, the specimen name ends with an A. For example, B-1-20 is the beam strengthened with one layer of fabric having 20 mm mesh size. Table 1 summaries the details of four RC beam specimens.

2.2 Strengthening procedure

General procedure for strengthening RC beams is described as following:
- rough concrete surface and clean;
- cast the first layer of geopolymer matrix;
- embed the first layer of carbon fabric;
- cast the second layer of geopolymer matrix;
- embed the second layer of carbon fabric if have;
- cast the third layer of geopolymer matrix if have;
- cover the FRGC for curing.

To prevent premature debonding failure and better utilize the reinforcing layers, two anchorage systems were attempted, namely shear bolts method and U-jacket method. Due to the limited number of specimens, the two anchorage methods were exerted on one beam. To install shear bolts, holes with a diameter of 10 mm were first drilled at bottom of the beam. Subsequently, D10 expansive bolts were installed before casting the strengthening layer. To apply U-jacket method, a transverse sheet of fabric was embedded when applying the final layer of carbon fabric. The transverse fabric was also cast at the both sides of beam. The details of the two anchorage methods for the RC beam are shown in Figure 3.

Table 1. Allocation of RC beams with and without strengthening.

Specimen	Bottom reinforcement	Top reinforcement	Reinforcing layers	Fabric mesh size	Anchorage
B-0	2D10	2D8	N/A	N/A	N/A
B-1-20			1	20 mm	N/A
B-2-10			2	10 mm	N/A
B-2-10-A			2	10 mm	Bolts & U-jacket

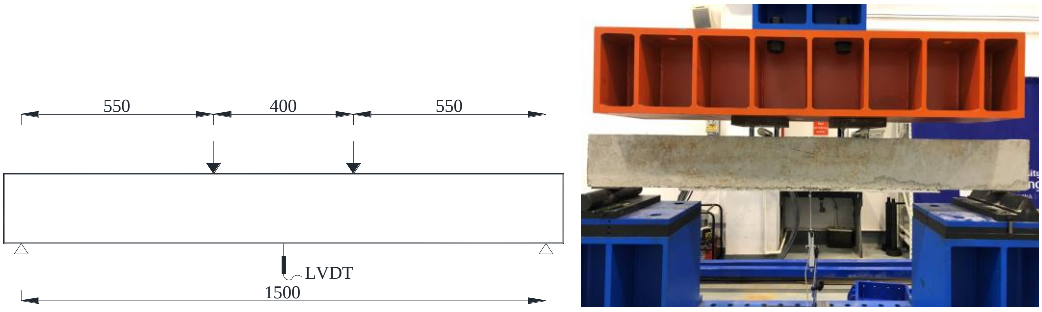

Figure 4. Test setup for RC beam.

2.3 Loading scheme

Beams were subjected to 4-point loads as illustrated in Figure 4. Vertical load was applied monotonically by a servo-hydraulic actuator with loading capacity of 1000 kN. A LVDT with range of 100 mm was installed to monitor the mid-span deflection. Loading rate was fixed at 2 mm/min. Applied force and monitored deflection were recorded automatically by a data logger. Test was terminated by beam failure or beam deflection over the capacity of the LVDT.

3 EXPERIMENTAL RESULTS

3.1 General behaviour & failure modes

The first crack in specimen B-0 appeared in the pure-bending zone when the vertical load reached 5.8 kN. The cracks developed in quantity and width as the applied load increased. The beam initially deflected under the increasing load, and was then subjected to increasing deflection but without further increase of load. The latter was identified as a typical yielding stage. The beam reached the loading capacity of 36.5 kN at the deflection of 27 mm. Finally, concrete in the compression zone of beam crushed, and the beam lost its loading capacity quickly. Specimen B-0 showed a typical ductile flexural failure.

Similar to specimen B-0, specimen B-1-20 firstly deflected with ascending applied load. The first crack was observed in the strengthening matrix when the applied load reached 9.1 kN. It indicates that the FRGC is effective in delaying the occurrence of cracks, and hence increases the cracking load of RC beam. As the applied load increased, more and more cracks were observed and propagated. With the load further increased, the beam entered the yielding stage. Specimen B-1-20 achieved a loading capacity of 33.8 kN at the deflection of 21 mm. Afterwards, cracks in the strengthening layer kept widening followed with the rupture of fabric at the deflection of 36 mm. Specimen B-1-20 failed in the ductile flexural mode with the rupture of FRGC strengthening layer.

The first crack in specimen B-2-10 appeared at the load of 13.3 kN. Extensive flexural cracks initialized in the tensile zone of beam and spread upwards as the load increased. As seen in Figure 5, the FRGC strengthening layer suddenly debonded from the concrete surface as the load further increased. Detachment effect creeped towards mid-span and converged with vertical flexural cracks. Test was terminated when debonding of FRGC dominated the failure mode of RC beam. Specimen B-2-10 achieved a loading capacity of 45.2 kN at the deflection of 13 mm. Premature debonding of FRGC dominated the loading capacity of the strengthened beam.

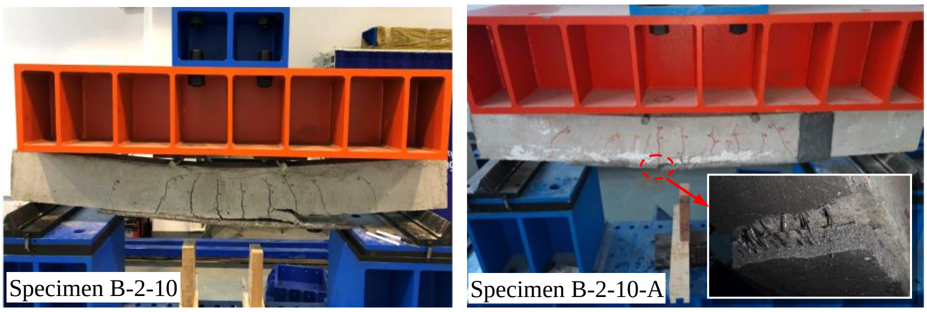

Figure 5. Failure modes of strengthened beams.

Specimen B-2-10-A deflected with increased applied load as other specimens. The first crack was found at load of 14.1 kN in the strengthening layer and propagated to the beam. Meanwhile, more vertical cracks showed up in the pure-bending zone. As the load increased, specimen B-2-10-A reached the yielding stage as the load remained the same level with increasing deflection. Subsequently, both layers of fabric ruptured as the deflection increased. Unlike specimen B-2-10, end debonding of FRGC was not observed in specimen B-2-10-A. This is mainly attracted to the two anchorage methods. The loading capacity of specimen B-2-10-A was attained at 42.4 kN at the deflection of 9 mm. Failure mode of specimen B-2-10-A was shifted from FRGC debonding to flexural failure due to adoption of anchorage systems, as shown in Figure 5. It indicates that both shear bolts and U-jacket wrapping are effective in prevent the debonding of FRGC strengthening lay from concrete substrate.

3.2 Load-deflection relationships

Figure 6 shows the load-deflection curves for the four RC beams tested. Generally, all four beams behaved an ascending trend followed by a plateau phase before failure. At the initial stage of loading, four specimens exhibit the similar stiffness before the occurrence of first cracks. Afterwards, three strengthened beams show the higher flexural stiffness than the control specimen. The FRGC strengthening method enhanced the initial flexural stiffness of RC beams. As the mid-span deflection increases, the beam strengthened with one layer of fabric (i.e. specimen B-2-10) exhibits the lower flexural stiffness than those with two layers of fabric (i.e. specimens B-2-10 and B-2-10-A). The RC beams strengthened with two layers of fabric also possess higher load than those with one layer of fabric at the same deflection level. It indicates that two layers of carbon fabric or equivalent fabric volume are the minimum requirement for enhancing the flexural behaviour of RC beams. The beam strengthened with one layer of fabric (specimen B-1-20) shows the obvious load degradation. The slight difference in load for specimens B0 and B-1-20 is probably attributed to the concrete quality as the four beams were not casted in the same batch. After the yielding of steel bars and fabric, the neutral axis moved upward and the flexural strength highly depends on concrete properties.

As seen in Figure 6, load-deflection relationship of specimen B-2-10 experiences fluctuation after the beam enters the yielding phase. After several cycles of load ascending and dropping, premature debonding of FRGC dominates its load-deflection response. Both anchorage methods help ameliorate the bonding between geopolymer matrix and concrete substrate. With the help of anchorage systems, the fluctuation of load-deflection curve is alleviated in specimen B-2-10-A. However, load of specimen with anchorage system is lower than that without anchorage system. Apart from the concrete quality, installation of shear bolts through drilling holes in concrete could introduce cracks to RC beam. Thus, the use of U-jacket wrapping is preferred to prevent the debonding of FRGC from concrete substrate.

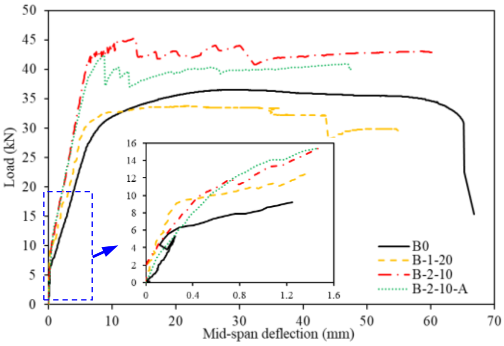

Figure 6. Force-deflection curves for beam specimens.

3.3 *Ultimate load and flexural stiffness*

Loading capacity and flexural stiffness of RC beams with and without strengthening are compared in Table 2. Here, the ultimate load is defined as the maximum load sustained by the beam. Elastic stiffness is defined as the slope of the line connecting origin to first cracking point, while cracking stiffness is defined as the inclination after cracking point (Truong et al. 2017). Generally, FRGC strengthening method is able to improve the cracking load, ultimate load, elastic stiffness and cracking stiffness of RC beams. Increasing the layer of fabric results in a higher enhancement for the cracking and ultimate loads of RC beams. For instance, the enhancement ratio on cracking load is increased from 56.9% for that with one layer fabric to 129.3% for that with two layers of fabric. Installation of anchorage system can further enhance the cracking load by 143%. However, installation of anchorage system slightly decreases the ultimate load and cracking stiffness.

Table 2. Characteristic loads and stiffness of specimens.

Specimen	Cracking load		Ultimate load		Elastic stiffness		Cracking stiffness	
	(kN)	(%)	(kN)	(%)	(kN/mm)	(%)	(kN/mm)	(%)
B0	5.8	N/A	36.5	N/A	20.8	N/A	3.7	N/A
B-1-20	9.1	156.9	33.8	92.6	29.6	142.3	4.0	108
B-2-10	13.3	229.3	45.2	123.8	26.3	126.4	5.4	146
B-2-10-A	14.1	243.1	42.4	116.2	13.9	66.9	5.1	138

4 CONCLUSIONS

This paper evaluated the effectiveness of FRGC for strengthening of RC beams. Two kinds of anchorage systems, namely shear bolts and U-jacket wrapping, were adopted to prevent the premature debonding of FRGC from concrete substrate. Based on the test results, the following conclusions can be drawn.

(1) The externally bonding FRGC at the soffit of beams is effective in improving their load capacity and flexural stiffness. The cracking load, ultimate load, elastic stiffness and cracking stiffness of RC beams can be increased by up to 129.3%, 23.8%, 26.3% and 46.0%, respectively.

(2) Increasing the layer of fabric increases the loading capacity but decreases the flexural stiffness of FRGC-strengthened beams. However, proper anchorage is required to prevent the debonding of FRGC from concrete substrate.

(3) Both the shear bolts and U-jacket wrapping methods are effective in preventing premature debonding of FRGC. Failure mode of FRGC-strengthened beam can be shifted from

debonding to fabric rupture. U-jacket wrapping method is preferred as it would not introduce damage to concrete.

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