# Effect of Fabric Reinforced Cementitious Mortar (FRCM) on the Strength of Shear-Damaged Reinforced Concrete Beams

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**Abstract.** This paper discusses an experimental study on the shear strengthening of damaged reinforced concrete beams using fabric reinforced cementitious mortar (FRCM). The key parameters studied were: 1) level of damage, namely presence of the first shear crack and 70% of the ultimate theoretical load and 2) the wrapping scheme used (continuously wrapped and intermittent strips). In total six 2 m long rectangular beams were constructed, one of the beams was left unstrengthened to act as control specimen, while all of the remaining beams were wrapped using a U-shaped wrapping scheme. Two beams were strengthened prior to any loading and the remaining three beams were repaired after sustaining the specified damage. When comparing the two wrapping schemes, it was found that, while both were able to increase the load-carrying capacity of the beams, specimens with intermittent wrapping had about 88% of the capacity compared to fully wrapped beams. It was also found that both wrapping schemes were fully effective in restoring the beams' strength for the lower level of damage. However, as the damage increased the strengthening became less effective.

**Keywords:** Concrete repair and strengthening · Shear · Damage · Fabric reinforced cementitious mortar · Textile reinforced mortar

## 1 Introduction

In the past decades, the issue of deteriorating infrastructure has come to the forefront of civil engineering. When most existing infrastructure was first built, there was no long-term plan in place to maintain it, allowing it to fall into disrepair. While this problem has since been recognized, there is still the issue of the difference between existing funds and the amount required to upgrade/replace these structures, called the infrastructure gap (Mackenzie 2013). To combat the infrastructure gap, innovative repair techniques are required. One promising new repair technique is the use of fabric reinforce cementitious mortar (FRCM). This repair technique is similar to hand layup fibre reinforce polymer (FRP) sheets, however the polymer based resin used in FRP is replaced with cementitious mortar. The mortar offers several benefits over the polymer resin including reduced cost, improved fire resistance, improved worker safety (no toxic fumes), and the ability to be applied to cold, wet, or rough surfaces. Initial studies (Bournas and Triantafillou 2011;

Aljazaeri and Myers 2016) have indicated that FRCM shows potential for an array of reinforced concrete (RC) strengthening applications.

One of the most critical areas of structural concrete repair and rehabilitation is shear strengthening. If a structure is not adequately reinforced in shear, a sudden and catastrophic failure may occur, presenting a major hazard to public safety. Shear deficiency can be introduced in several ways including construction errors, lower than specified concrete strength, corrosion of existing shear reinforcement, increased loading conditions, and updated code requirements. There have been many studies dealing with the shear strengthening of undamaged RC members using FRCM (Aljazaeri and Myers 2016; Awani et al. 2016; Younis et al. 2017; Tetta et al. 2018). However, in field conditions structural deficiency may not be detected until the structure has endured some level of damage. Based on research into the repair of damaged shear deficient RC beams using FRP jacketing (Chalioris et al. 2019), it was thought that FRCM could be used for the same applications.

In this study, to simulate real world rehabilitation conditions, RC beams were damaged in shear before they were strengthened. To strengthen the beams, several different FRCM wrapping schemes were used. The beams were then tested to evaluate the effectiveness of the FRCM systems.

## 2 Experimental Program

### 2.1 Study Parameters and Test Specimens

In this paper two key parameters were studied: a) The effect of different wrapping schemes (continuously wrapped and intermittent strips with half the fabric area of the full wrap) and b) the impact of different levels of shear damage (no damage, first visible shear crack, and 70% of the maximum theoretical load). In order to investigate the effects of these parameters six beams were tested (Table 1). The naming system for the beams is X-DY, with X denoting wrapping scheme used (I for intermittent strips and F for full wrap). The level of damage is indicated by the DY term (D0 for no damage, D1 for first shear crack, and D2 for 70% of maximum theoretical load).

**Table 1.** Test matrix

| Group | Specimen ID | Wrapping scheme | Fabric area (mm$^2$/m) | Damage |
|---|---|---|---|---|
| Control | N-D0 | None | None | None |
| Continuous | F-D0 | Continuous | 314 | None |
|  | F-D1 | Continuous |  | 1$^{st}$ shear crack |
|  | F-D2 | Continuous |  | 70% of theoretical capacity |
| Intermittent | I-D0 | Intermittent | 157 | None |
|  | I-D1 | Intermittent |  | 1$^{st}$ shear crack |

The control specimen, N-D0, received no strengthening and was not damaged. Two beams were strengthened prior to testing using the two wrapping schemes (Beams F-D0 and I-D0), while the final three beams were damaged prior to the application of the FRCM wrap (Beams F-D1, F-D2 and I-D1). It should be noted that the intermittent wrapping scheme was only tested on the lower level of damage.

To test the beams, an asymmetric three-point loading setup was used. The total specimen length was 2000 mm. The distance between the supports was 1500 mm and the shear critical section had a length of 500 mm resulting in an a/d ratio of 2.3 (Fig. 1). The beams cross-section was 265 mm × 200 mm (Fig. 1). The concrete cover was 19 mm on the beams sides, and 25 mm on the top and the bottom of the cross-section. As shear capacity was the area of interest for this study, the beams were heavily reinforced in flexure with 2-25M bars, to prevent flexural failure. Smooth bars, 6 mm in diameter, were used as shear stirrups. To ensure shear failure, a stirrup spacing of 150 mm was used in the shear critical section of the beam. This spacing is larger than the maximum allowed by CSA A23.3-14. To prevent shear failure elsewhere in the beam, a stirrup spacing of 100 mm was used.

## 2.2   Material Properties

The concrete was supplied by a local ready-mix plant and had a strength of 45 MPa at the time of the beams' testing. The steel mill certificate indicated that the 25M rebar had a yield strength of 471.6 MPa, while the 6 mm rods had a yield strength of 340 MPa.
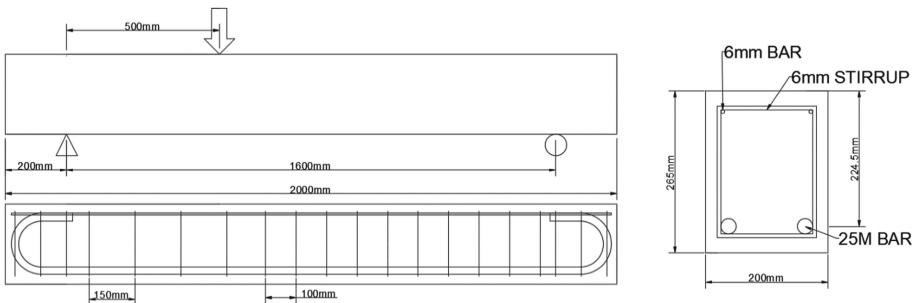


**Fig. 1.**  Longitudinal and cross-section details of the test specimens

To strengthen and repair the beams, an FRCM wrap was utilized. The wrap was composed of two materials, unidirectional carbon fabric grid and cementitious mortar. The unidirectional fabric grid was composed of carbon fibres with an area of 157 $mm^2$/m. The fibre bundles had a centre-centre spacing of 15.5 mm. The tensile strength of the fabric was 450 kN/m and the ultimate tensile strain was 1.5%, as reported by the manufacturer. The cementitious mortar was reported by the manufacturer to have a 28 days tensile strength of 4.8 MPa and compressive strength of 52 MPa. The FRCM composite was reported by the manufacturer to have a tensile modulus of 49 GPa, a tensile strength of 885 MPa, and an ultimate strain of 1.1%.

## 2.3 Damage

In order to replicate an in-field beam damaged in overload conditions before rehabilitation three of the Beams (I-D1, F-D1, F-D2) were loaded in asymmetric three-point bending. The first level of damage, D1 corresponded to the first shear crack visible by visual inspection. In all the specimens, the first shear crack was observed at approximately 115 kN. The second level of damage was 70% of the maximum theoretical load, as predicted by the combined strut and tie model of Garay-Moran and Lubell (2008), which corresponded to a value of 147 kN. This level of damage was verified experimentally by testing the control beam (Beam N-D0). Once the beams had been damaged, they were removed from the testing frame and the FRCM was applied. The beams were then tested until failure.

## 2.4 Strengthening

To assess the ability of the different FRCM wrapping schemes to increase the shear capacity of the RC specimens, only the shear critical section of the beams was wrapped. For all the wrapping schemes a U-shaped cross-sectional scheme was utilized (Fig. 2). The first step of the strengthening process was to roughen the beam's surface. This was accomplished using a concrete shot-blasting unit, which yielded a concrete surface profile (CSP) roughness of 5–6, based on the International Concrete Repair Institute (ICRI) scale. To achieve this roughness level, two passes were made over the shear critical section on both sides and the tension face of the beam. Once the surface was roughened, it was scrubbed with a steel wire brush and blown clean with compressed air to remove any debris. The surface was soaked with water overnight so that it would be at saturated surface dry (SSD) condition when the strengthening was applied. The mortar was mixed at the proportions recommended by the manufacturer. A 5 mm layer of mortar was applied to the beam's surface, followed by the carbon fabric grid, then a second 5 mm layer of mortar was applied. Once the wrap had been applied, it was allowed to cure under wet burlap for 7 days, followed by at least 21 days of curing in open air.

The dimensions of the two different wrapping schemes are shown schematically in Fig. 2. The continuously wrapped beams were wrapped across the entire shear critical section. The intermittently wrapped beams incorporated 75 mm wide strips at a centre to centre spacing of 150 mm. The spacing was chosen so that the strips would be placed in between the stirrups in order to maximize the effect of the strengthening system. The width of the strips was chosen as 75 mm so that the intermittently wrapped beams would have half the area of fabric per metre of the continuously wrapped beams. The first strip was placed 150 mm from the support in the shear critical section.
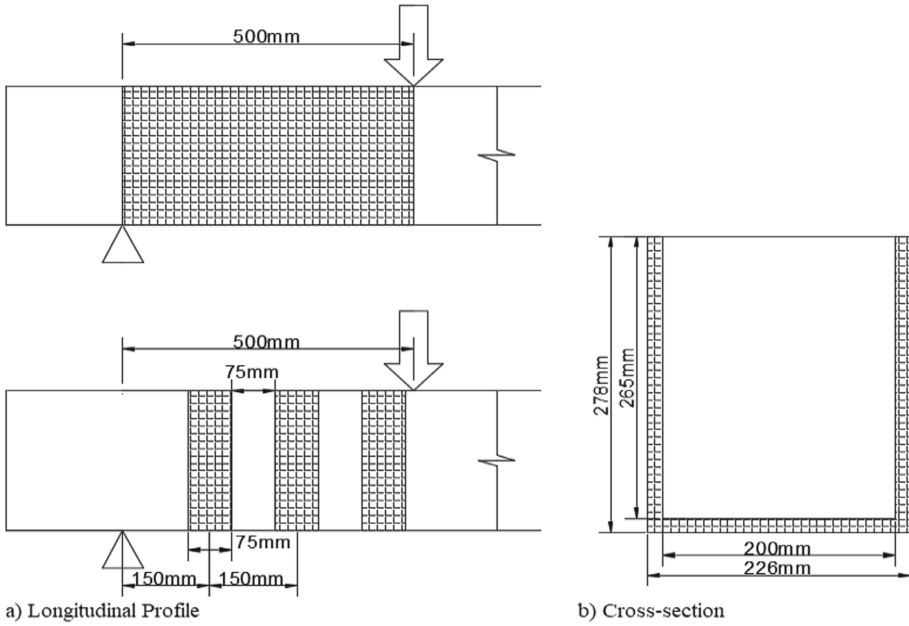
**Fig. 2.** Strengthening schemes

## 2.5 Experimental Setup and Testing Procedure

A hydraulic linear actuator, with a capacity of 500 kN, was used to monotonically apply the load at a rate of 2 mm/minute. The actuator was positioned horizontally at a distance of 500 mm from the support at the shear critical end of the specimen (Fig. 3). A linear
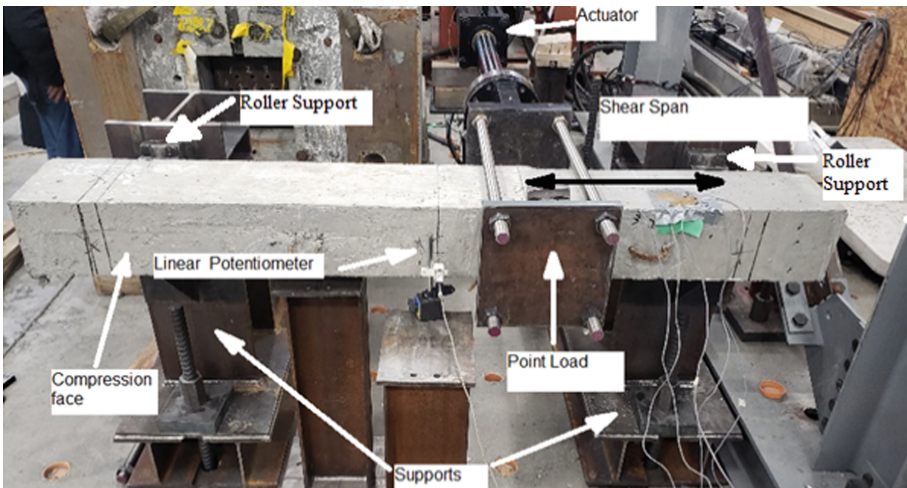


**Fig. 3.** Test setup

potentiometer, positioned at mid-span of the beam (Fig. 3), was used to record deflection. A computer program was used for data collection. A specimen was considered to fail when the load dropped by at least 20%.

## 3   Results and Discussion

The key results gathered during this study included failure mode and the peak load. These key results are summarized in Table 2. Figure 5 shows the shear critical section of the beams at failure, while the load-deflection curves of the full and intermittent wrap groups are presented in Fig. 6.

**Table 2.**  Results summary

| Group | Specimen ID | Failure mode | Peak load (kN) |
|-------|-------------|--------------|----------------|
| Control | N-D0 | Diagonal tension | 217.1 |
| Continuous | F-D0 | Premature debonding of side 1 Fabric slip of side 2 | 304 |
| | F-D1 | Debonding followed by diagonal tension | 311.2 |
| | F-D2 | Debonding followed by diagonal tension | 273.7 |
| Intermittent | I-D0 | Debonding followed by diagonal tension | 254.9 |
| | I-D1 | Debonding followed by diagonal tension | 285.5 |

### 3.1   Failure Modes

In Beam N-D0, which acted as the control beam, a large diagonal crack opened from the point load to the support, across the shear critical section, at a load of 115 kN. The crack continued to widen as the load increased until the beam lost its load bearing capacity (Fig. 4). The beam failed in shear induced diagonal tension at a peak load of 217 kN. Beam N-D0 after testing is shown in Fig. 5.

In all the other beams, except for beam F-D0, the cracking pattern on both sides of the beam was the same, therefore only one image of the failed beams was included in Fig. 5. In the intermittently wrapped beams, a diagonal crack opened across the shear critical section at a load between 120 kN and 140 kN, for I-D0 and I-D1 respectively, similar to the control specimen. This was the only shear crack visible on Beam I-D0, however at 201 kN a second shear crack opened in Beam I-D1. In both beams, the middle strip of FRCM wrap was the first to debond. The middle strip debonded at a load between 255 kN for Beam I-D0 and 270 kN for Beam I-D1. This debonding caused diagonal tension failure to immediately occur in Beam I-D0. For Beam I-D1, despite debonding of the middle strip, the beam did not lose its load-bearing capacity, instead, the forces were redistributed, and the load increased slightly to 286 kN before the strip closest to the support debonded causing a diagonal tension failure. The tested intermittently wrapped beams are shown in Fig. 5.
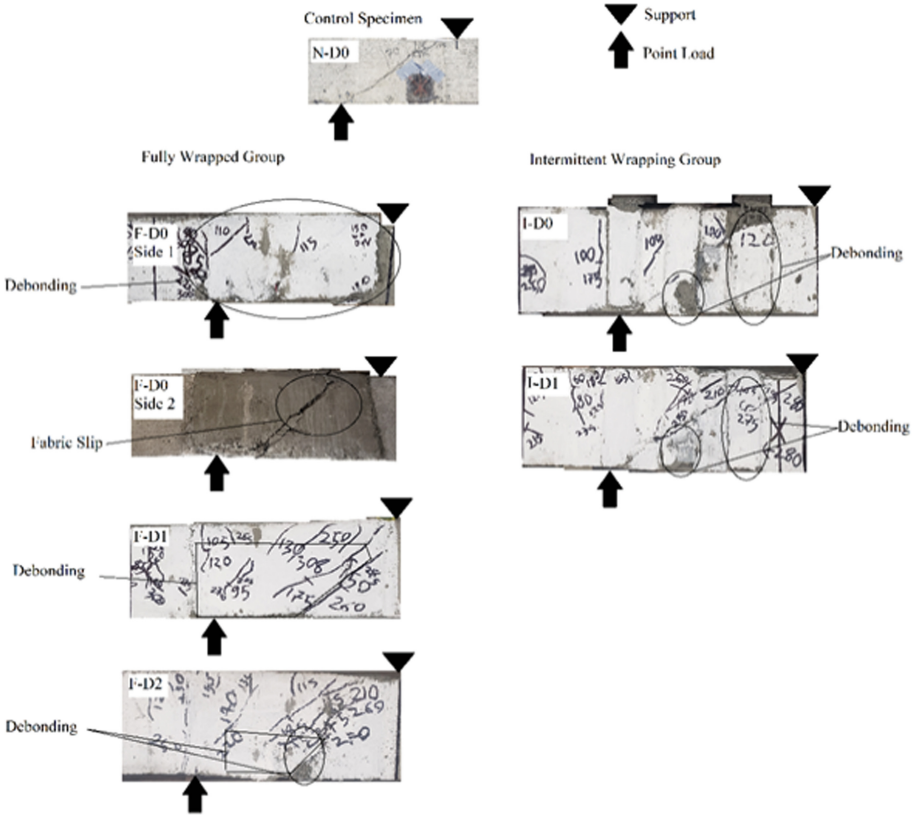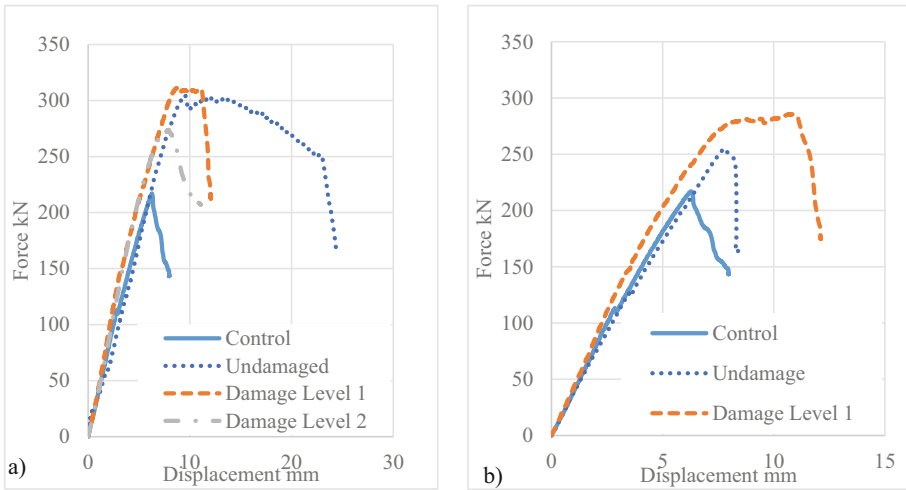
**Fig. 4.** Critical section of failed beams



**Fig. 5.** Force displacement behaviour a) Continuous group b) Intermittent group

In the continuously wrapped group, shear cracking was observed in the shear critical section at loads between 95 kN and 115 kN, which is comparable to the control specimen. Due to the bond between the FRCM and substrate concrete, it was assumed that cracking occurred simultaneously in both materials. In Beam F-D0, the initial shear cracking caused one side of the FRCM wrap to partially debond from the face of the concrete, however this did not compromise the load bearing capacity. This would be the only shear crack to form in the beam. Once Beam F-D0 reached its peak load, there was a period of approximately constant, and then slightly decreasing load as the fabric gradually slipped through the mortar on side 2 of the beam. In this beam, the fabric slipped from the upper region of the U wrap, towards the base as shown in Fig. 7, until the load dropped by more than 20% and failure was considered to have occurred (Fig. 5). In Beams F-D1 and F-D2, as the load increased, several shear cracks opened in the shear critical section, typically three or more cracks were observed. In Beam F-D1, the load reached 311 kN before the wrap began to gradually debond. This caused the load to slowly decrease before the wrap completely debonded, causing diagonal tension failure (Fig. 5). Beam F-D2 failed suddenly due to debonding of the upper layer of mortar from the fabric at a load 273 kN (Fig. 6). Post failure investigation of the beam revealed that a portion of the FRCM wrap had also debonded from the face of the concrete.
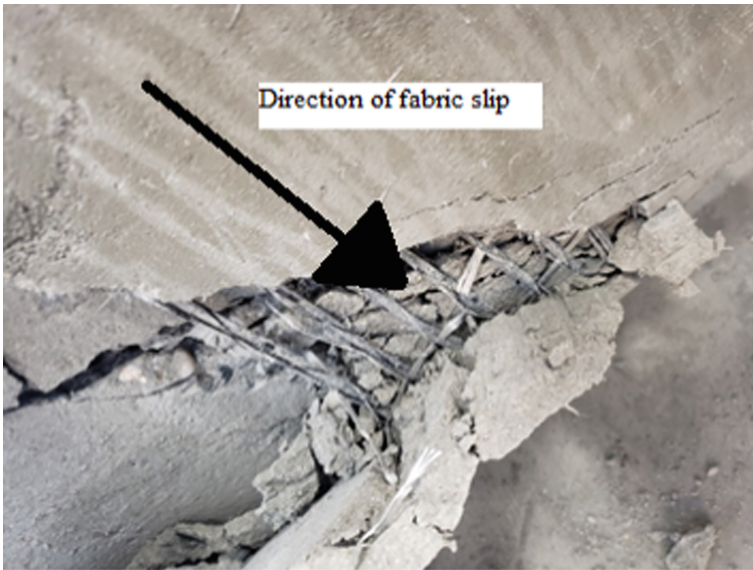


**Fig. 6.** Fabric slip in Beam F-D0 on side 2

## 3.2 Peak Loads

Two factors which are known to impact peak load are reinforcement quantity and bond strength between the reinforcement and underlying material. The effect of reinforcement

quantity is a variable of this study, as discussed above. Bond strength can have a major impact on strengthening effectiveness and is affected by the quality of workmanship. In order to minimize the effect of bond strength variations in this study, all FRCM applications were undertaken in the same environment, following the same application techniques. Both beams which were intermittently wrapped, I-D0 and I-D1, showed a strength increase of 17% and 32% over the control specimen, respectively. The level of strength gain correlated with gradual or sudden debonding failure. Specimen I-D0, which failed suddenly due to debonding at a peak load of 255 kN, had a lower strength increase than I-D1. Beam I-D1, experienced a load plateau before failure with a peak capacity of 286 kN. All of the continuously wrapped beams exhibited a substantial strength increase compared to the control specimen (26% to 43%). A similar trend regarding gradual or sudden failure was observed in the continuously wrapped group. Beam F-D2, which showed the lowest increase in strength, failed suddenly at 274 kN. Whereas beams F-D0 and F-D1 both failed at over 300 kN, with failure occurring gradually.

### 3.3 Effect of Damage

To assess the effect of damage on the effectiveness of the FRCM wrapping, the peak loads, normalized to the control beam, were plotted and grouped by damage level (Fig. 7). The first level of damage, $1^{st}$ shear crack, did not appear to have any negative effect on the peak load attained by either wrapping scheme. However, it can be observed that for the continuously wrapped group the second level of damage, 70% of maximum theoretical load, the peak load was only 88% of that of the undamaged specimen. This indicates that FRCM is more effective for structures with lower levels of damage. When comparing the stiffness values of the specimens before and after FRCM application (Fig. 8), it was observed that the stiffness values are either unchanged or slightly higher. Therefore, the FRCM wrapping schemes used in this study were able to restore the beams' original stiffness.

### 3.4 Effect of Wrapping Scheme

From preliminary observations of the peak loads of both wrapping schemes (Fig. 7), the average strength gain of Beams I-D0 and I-D1 are only 88% of their continuously wrapped counterparts. Beam F-D2 was not included in this average as there was no intermittently wrapped beam that has level 2 damage. Based on these findings, the full wrapping scheme was more effective in increasing the load bearing capacity of the beams, when comparing the beams' stiffness normalized to the control beam (Fig. 8), it can be seen that the two wrapping schemes were comparable.
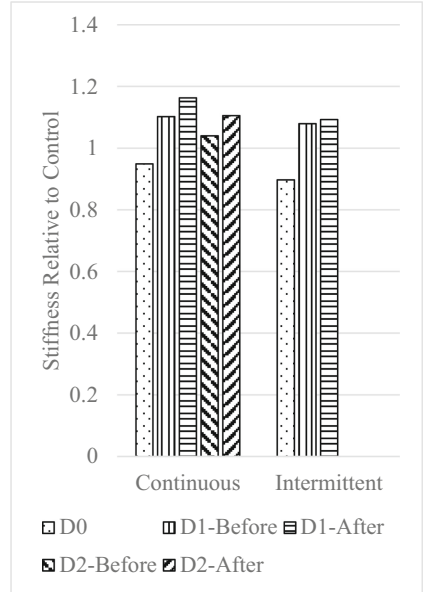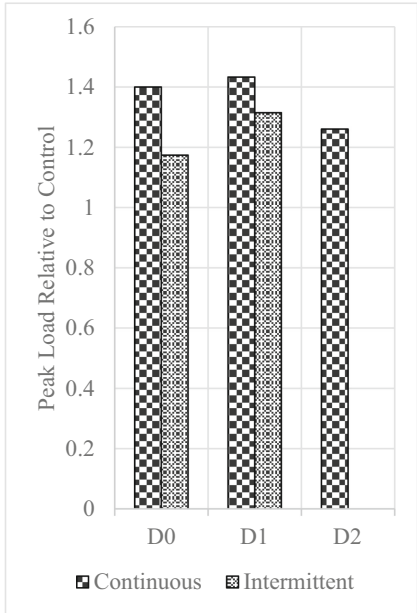
**Fig. 7.** Peak load normalized to control beam     **Fig. 8.** Stiffness normalized to control beam

## 4  Conclusions

In this study the effectiveness of various FRCM wrapping schemes on the repair of shear-damaged reinforced concrete beams was assessed. Based on the discussion of the results, the following conclusions were drawn:

- Both of the wrapping schemes were effective in repairing low levels of damage. As damage increased the continuous wrapping scheme was less effective (88% of the lower level)
- Both of the wrapping schemes were able to restore the damaged beams to the original level of stiffness
- The continuous wrapping scheme was able to provide more strengthening than the intermittent wrap (42% vs 24%)
- Both wrapping schemes had a comparable effect on the stiffness of the beams.

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