J. Build. Mater. Struct. (2017) 4: 84-92 *Original Article*
DOI : 10.5281/zenodo.1173379

Repair of reinforced concrete beams in shear using composite materials PRFG subjected to cyclic loading

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Abstract. Nowadays, finding new approaches to attenuate the effects of the catastrophic shear failure mode for reinforced concrete beams is a major challenge. Generally the bending failure is ductile. It allows a redistribution of the stresses providing an early warning, whereas the rupture by shear is fragile and sudden which can lead to detrimental consequences for the structures. This research focuses on the repair of deep beams in reinforced concrete shear subjected to 4-point bending. After being preloaded at different levels of their ultimate loads, the beams are repaired by bonding a composite material made of an epoxy resin reinforced by glass fibers. The main objective of this study is to contribute to the mastery of a new method developed by the authors that consists by banding the cracks in critical zones in order to avoid fragile ruptures due to the shear force. This new technique led to better results in terms of mechanical properties when compared to conventional methods, notably the absence of the debonding of the composite found in the case of the repairs of the beams by bands or U-shaped composites. The feasibility, the performances and the behavior of the beams have been examined. The experimental approach adopted using this new technique has shown the influence of the type of loading on the fatigue behavior. In addition, the repair performed led to a considerable improvement in the fatigue durability of the preloaded beam.

Key words: Deep beam, Shear failure, Preloading, Composite, Repair.

1. Introduction

During their lifetime, concrete structures can be subjected to different types of loading and environmental conditions. Cracks produced and preload conditions are initial damage that can affect long-term structural behavior. These initial cracks and damage propagate and increase over time as a result of cyclic loading. In the case of deep bridge beams, for example, the structural elements are subjected in service to maximum values stresses of generally known but time-varying, most of which result from cyclic variations in stresses.

Generally a bridge is designed for a century, even in a regulatory way, their operating conditions turns out to change following the development not only of the size and load of vehicles but also road traffic. This leads to a reduction in their initial lifetime, sometimes causing catastrophic ruptures even when they are subjected to cyclic of modest maximum value stresses. The phenomenon involved in this is fatigue damage. It is characterized by irreversible deformations in the form of cracks that develop slowly over time without macroscopic signs. By accumulating, these can lead to a catastrophic rupture.

Indeed, the literature review shows clearly that experimental research and analytical studies on the fatigue behavior of reinforced concrete (RC) beams reinforced or repaired with FRP are very limited. The majority of these studies relate to flexural reinforcement, while very few studies have been carried out on shear reinforcement (deep beams).

Meier et al. (1992) tested two RC beams reinforced with a hybrid glass/carbon composite. Bames and Mays (1999) conducted an experimental program to study the flexural behavior of reinforced RC beams using FRP under fatigue stress. The reinforcement used is a unidirectional composite fabric based on carbon fibers (CFRP) bonded to the underside of the beam (tensile zone), which leads to the conclusion that the internal reinforcement rate affects the failure mode. Shahawy and Beitelman (1999) tested six beams of T shape under cyclic fatigue with a loading level between 0 to 25% of the ultimate load.

Papakonstantinou et al. (2001) also conducted fatigue tests in 4-point bending at a frequency of 2 or 3 Hz on 14 reinforced RC, eight reinforced with glass fiber (GFRP), and six non-reinforced with different fatigue loading levels. On the one hand, they found that the fatigue failure of the reinforced beams is caused by the fatigue failure of the tensile steel armature reinforcements after their plastification and, on the other hand, the use of the FRP increases the lifetime of the beams loaded at cyclic loading.

Masoud et al. (2001) also performed fatigue tests under 4-point bending with a frequency of 3 Hz on RC beams, whose tensile steel armature are corroded, reinforced with a carbon fabric. The loading level is between 10% and 80% of the ultimate strength of unreinforced RC beams. The fatigue failure of reinforced beams is caused by the fatigue of the tensile armatures similarly to Shahawy and Beitelman (1999).

In addition, some studies have also investigated a structural elements preloaded, reinforcement with composite materials in particular (Arduini, 1997; Choi et al.; De Lorenzis and Teng, 2007; Boussaha, 2008; Kreit, 2011; Dong, 2013 and Teo, 2017). The problems of premature failure associated with the complexity and incomprehension of the shear behavior of RC beams, under cyclic fatigue loading (loading/unloading) were the aim of this study.

The main objective of this study is to elucidate, using an experimental investigations, the fatigue behavior of deep beams repaired by FRP using a new technique. This technique was developed recently by the authors Boumaaza et al. (2017) for static tests (non-cyclic). The deep beam, used in the present work, is tested under 4-point bending assuming that the shear failure mode is predominant, with cyclic loading. For this purpose, a beam is preloaded at 80% of its ultimate load and then it has repaired by composite materials using the new technique SCR. After at list 15 days, resin polymerization time, the beam is cycled 19 times at 65 % of its ultimate load.

2. Experimental protocol

The aim of the experimental part is to investigate the fatigue behavior of the RC deep beams under cyclic loading (load/unload), repaired by glass fiber composites (GFRP) using the SCR technique. The concrete beams were designed in accordance with ASTM C78-00, armed with two HA8 in tensile zone and two HA6 in compressed zone, and 6 frames used as transverse reinforcements spaced of 110 mm. Fig. 1 shows the detail of the reinforcement in steel armatures of the beams. After at least 28 days, the manufactured beam is preloaded at 60% of its ultimate load.

The beam is repaired using the SCR technique which requires the preliminary work as follows:

- Drilling the beam on each side at the vicinity of the diagonal cracks of the concrete by passing through it (Figure 2a);
- Before the glass fabric was inserted, a repair was carried out using the mortar Fig. 2(b);
- The positions of the grooves, having 25 mm wide and 3 mm depth, were traced on the surface of the beam (Figure 2c). Then the grooves are subsequently cleaned of dust and concrete debris;

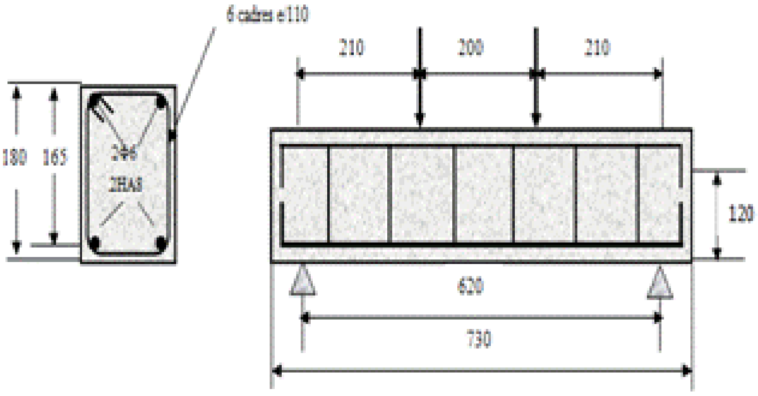

Fig 1. Schematic layout of the specimen and steel reinforcement in accordance with ASTM 78-00.

- The unidirectional of 600 g/m^2 surface density fabric is cut in pieces having a size of 1500x25mm and 1000x25mm. Then the fabric, previously impregnated with the epoxy resin, is inserted into the grooves.

SCR repair involves introducing composite bands into holes in the shear zone in order to band the diagonal cracks (Figure 2d).

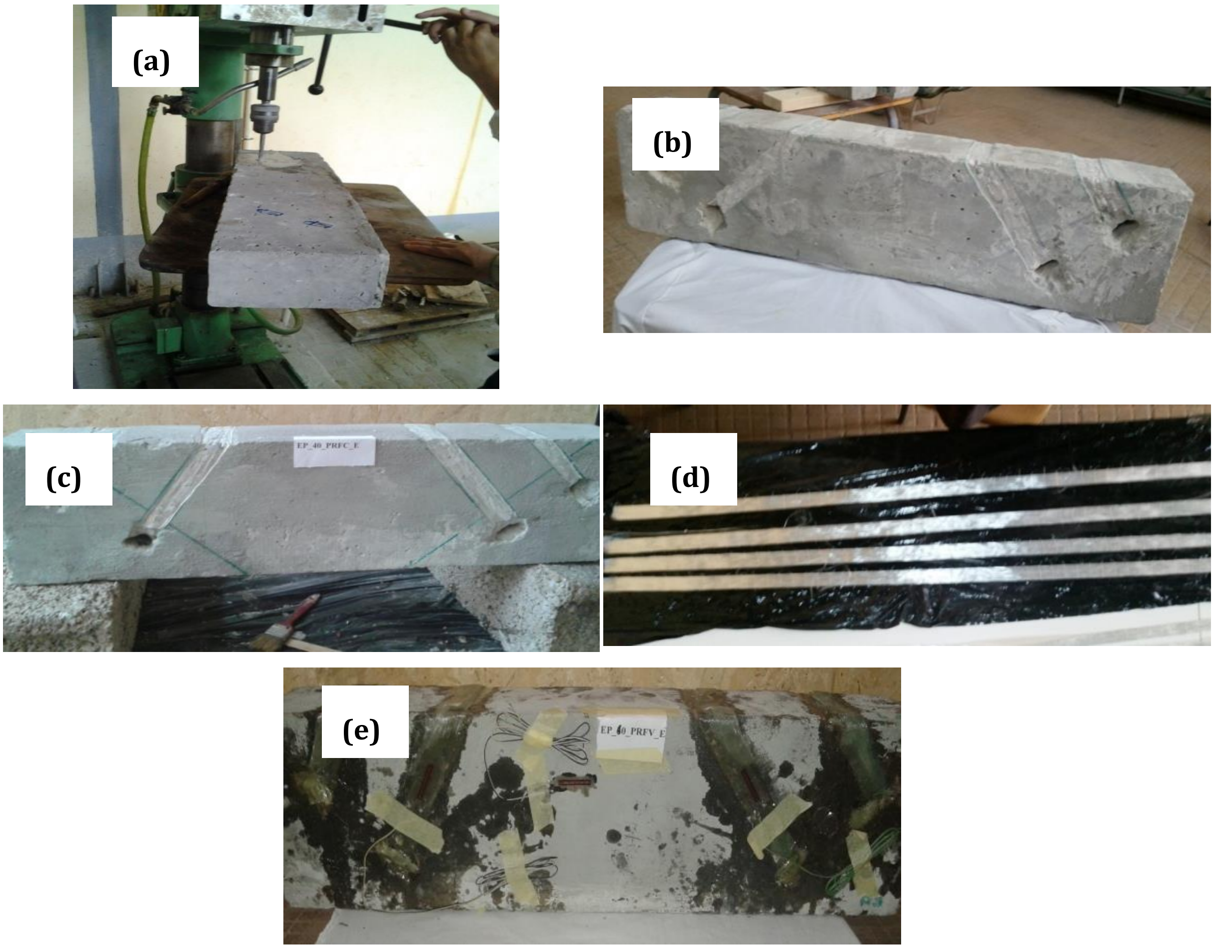

Fig 2. Repair of the beam (a) drilling of the holes (b) grooving (c) mortar reparation (d) cut of the unidirectional fabric (e) repair of the beam using SCR technique.

The tests were carried out in a bending machine (Controls) in the architecture laboratory of the University of Guelma. The frame of this machine is equipped with a load cell of 100 kN (Figure 3). The vertical displacement was measured, in the middle section, using an LVDT sensor with a maximum stroke of 100 mm. The strains were measured using 3 strain gauges, where two are glued at the external surface of the composite bands and the third one in the tensile face in the middle of the beam (Figure 2e).

Fig 3. Machine test.

3. Results and discussion

3.1. Global behavior

The stress/displacement curves versus the loading, of the control beam and the beam preloaded at 65% and then repaired by the GFRP composite using SCR technique are represented in Figure 4. The curves obtained show that, after the discharges (at zero loads), the presence of a permanent displacement due to inelastic behavior and therefore the existence of residual arrows which can be interpreted as an irreversibility due to the cracking of the concrete. These results are in agreement with the ones obtained by (Boussaha, 2008) and (Kreit, 2011).

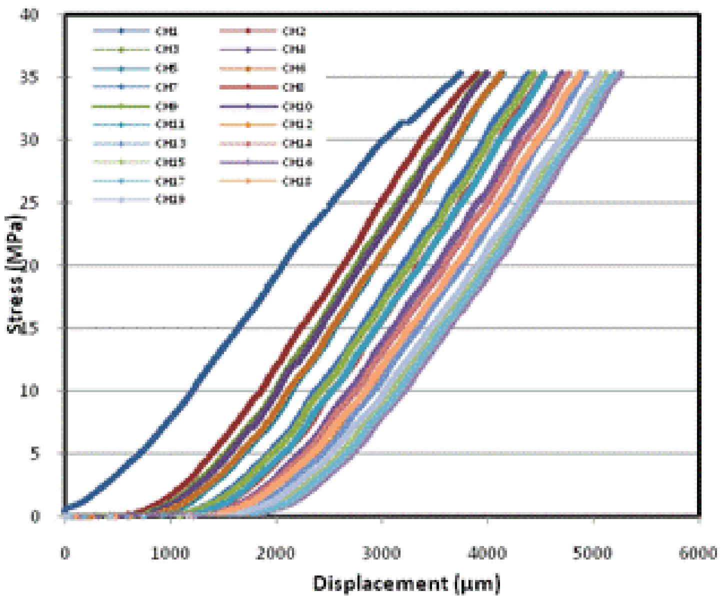

Fig 4. Stress/displacement of the beam EP_65% _PRFV_E of the 19 cycles load/unload.

The analysis of Figure 5 shows that the evolution of the stress/displacement of the control beam is very close to that obtained at the first cycle (1st cycle), whereas the curve of the 19^{th} cycle is distant from the previous one by approximately 1.64 mm (residual arrow) due to the plastification of the steel armature reinforcements of the tensile zone of the beam.

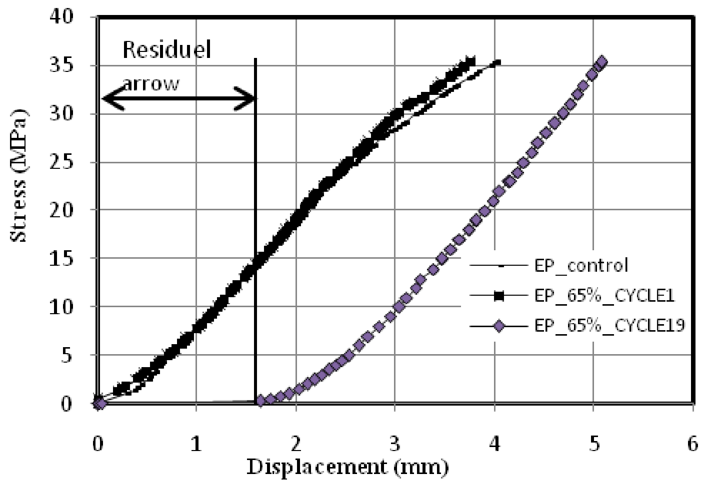

Fig 5. Evolution of the stress versus displacement of the control beam and EP_GFRP_65%_Test 1 and Test 19.

The results obtained, under fatigue loading, show generally that the displacements versus the cycling (load/de-load) number of the repaired beam are higher compared to the control one. However, the maximum displacements reached during the first three cycles of the repaired beam are lower than that obtained for the control beam (Figure 6) and Table 1.

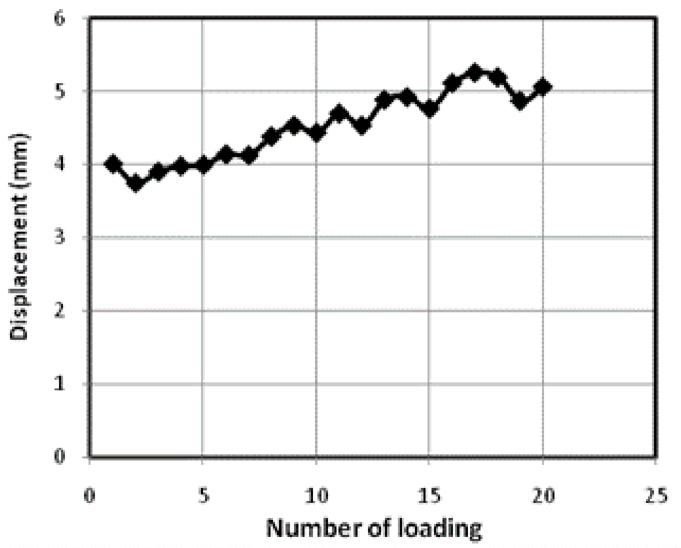

Fig 6. Evolution of the displacements versus the loading cycle numbers.

3.2. Influence of the repair on the stiffness of the beams

For the beam, preloaded and then repaired, bending stiffness was determined experimentally, which represents the slope of the linear part of the stress-displacement curve. The experimental results of the rigidities of the beams tested before and after the repair are presented in Figure 7.

A decrease of approximately 14.1% in the rigidity of the beam repaired with the GFRP is noticed for the 1st loading cycle compared to the control beam. However, in the second cycle, the stiffness increased by about 17% and then slow decrease is observed while remaining greater than the rigidity of the control beam even for the 19th cycle. These results are in good agreement with the work of Shahawy and Beitelman (1999).

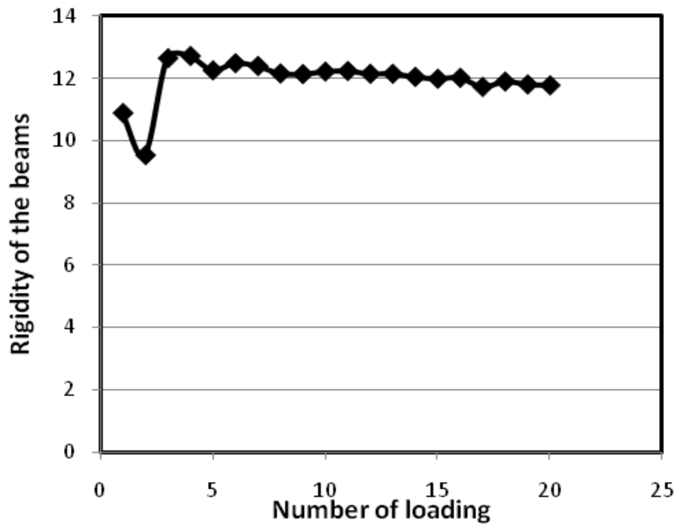

Fig 7. Stiffness of the beams during the cyclic fatigue tests.

3.3. Local behavior

The stress/strain curves for the first loading cycle, plotted using the strain gauges (g1, g3 and g4), which their locations are illustrated in Figure 10a, are shown in (Figures. 8 and 9). The strains are measured in the middle of the tensile zone of the concrete beam using g1, while g3 and g4 at the cracks. Table 1 recapitulates the obtained results of the strains gauges obtained by (g1, g3 and g4), displacements and rigidities of the control beam and the repaired one for the 19^{th} tests.

Table 1. Obtained strains using strain gauges (g1, g2 and g3), displacements and rigidities of the control beam and the repaired one for the 19^{th} tests.

N° of loading	Strains g1 (µm)	Strains g3 (µm)	Strains g4(µm)	Displacements (mm)	Rigidity
Control beam	385	3566	132	4.01	10,9
Cycle 1	271	2553	2195	3.75	9,55
Cycle 2	353	2412	2742	3.91	12,66
Cycle 3	676	2303	1786	3.98	12,73
Cycle 4	736	2268	1792	4.00	12,27
Cycle 5	798	2228	1785	4.15	12,5
Cycle 6	823	2210	1802	4.13	12,41
Cycle 7	840	2156	1809	4.39	12,17
Cycle 8	865	2122	1812	4.54	12,15
Cycle 9	854	2119	1896	4.44	12,23
Cycle 10	888	---	---	4.71	12,25
Cycle 11	884	2107	1828	4.54	12,16
Cycle 12	863	2074	1813	4.89	12,16
Cycle 13	896	2092	1798	4.93	12,06
Cycle 14	891	2118	181	4.77	12
Cycle 15	893	2117	1790	5.12	12,03
Cycle 16	882	2119	1781	5.27	11,74
Cycle 17	866	2091	1784	5.2	11,91
Cycle 18	862	2134	1796	4.88	11,82
Cycle 19	864	2135	1766	5.07	11,79

Figure 8 and Table 1 show the strains increases for the strain gauge (g1) from the 3rd cycle compared to the control beam, ie an increase of 1237% for the 19th cycle.

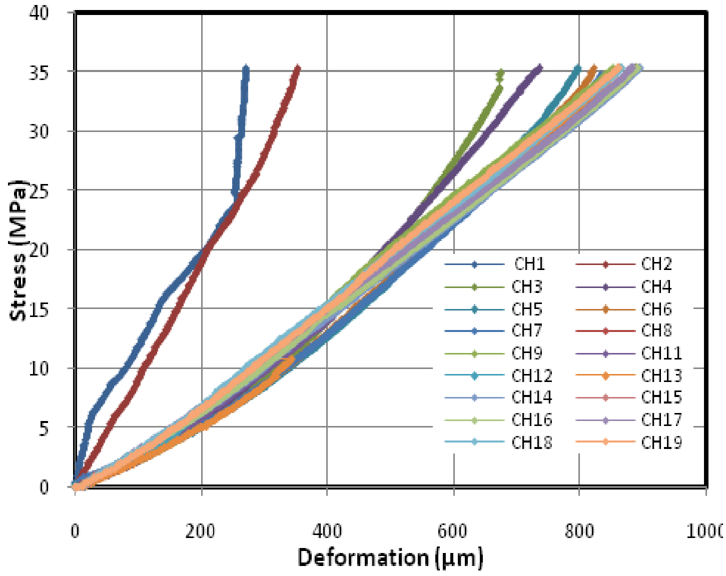

Fig 8. Stress/Strains obtained by strain gauge (g1) versus the cyclic loadings.

It should also be noted that the recorded strains of the composite with the strain gauge g3 for the repaired beam have decreased for all cycles. The strains obtained for the control beam and the repaired one after the 19th cycle are respectively 3566 and 2135 µm, i.e. a decrease of 67% is noticed. While, increases for all loadings are recorded by the strain gauge (g4), ie approximately 1238% for the 19th cycle (Figure 9, Table 1).

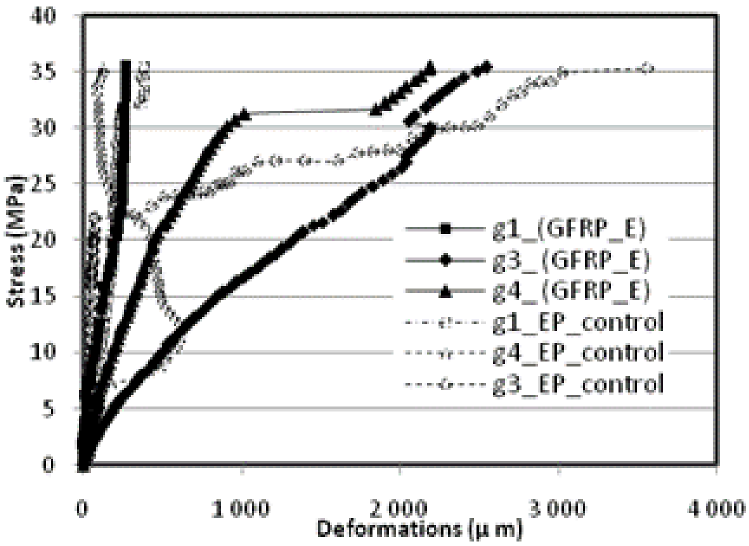

Fig 9. Stress/Strain (g1) for 1st loading cycle of the beam (GFRP_65% _E) and the control beam.

3.4 Fissuration

Figure 10a illustrates that the control beam subjected to 4-point bending has undergone a shear rupture, taking into account the type of cracking. The diagonal cracks were born on the lower supports and propagated towards the points of application of the upper load.

Whereas the beam (EP_65% _E) was repaired by GFRP, under a load of fatigue in the service state, the rupture was not yet reached even after 19 loadings thus showing the effectiveness of the repair adopted in this work (Figure 10b). Moreover, no peeling of the composite was detected during the tests and the beam passed the fatigue test successfully. The ductile failure mode has not been distinguished for beams repaired under fatigue loading for a service level; this will be reached in static.

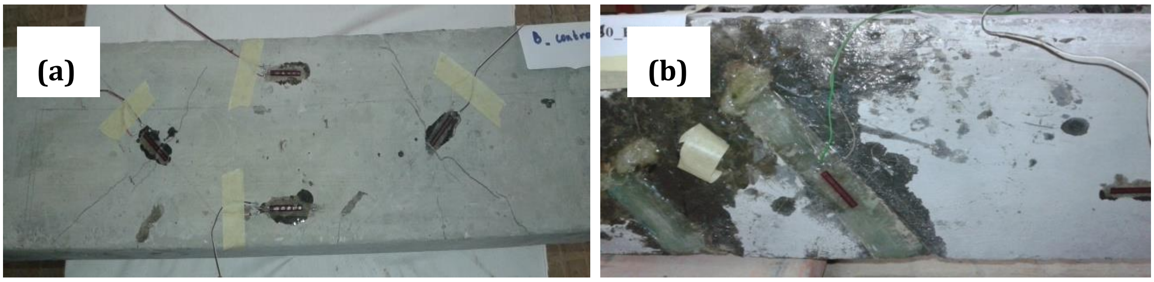

Fig 10. Failure modes

a) Control beam b) Beam preloaded at 60% then repaired by GFRP.

4. Conclusions

In this study, it was shown that the repair of beams using SCR technique exhibited good fatigue behavior. The mode of failure of the repaired beam has not yet been reached even for 19th loading cycles. This result is very encouraging and must be confirmed by other tests in the future work. It is worth noticing that the presence of the composite in the shear zone not only reduced the potential crack propagation during fatigue cycles, but also stiffened the beams. Therefore, this technique has a very good resistance to fatigue loading.

Acknowledgments

The authors would like to acknowledge Mr BOUDJEHEM H from the Architecture laboratory of University of Guelma having to facilitate the access to the experimental machine.

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