Evaluation of the behaviour of reinforced concrete beams repaired with glass fibre reinforced polymer (GFRP) using a damage variable

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ABSTRACT. The use of fibre reinforced polymers (FRP) for increasing the strength of reinforced concrete (RC) structures became a usual method. FRP presents easy application and demands low space and provide significant strength increase. Usually, the decision for FRP use is made in terms of applied loads and deflections. However, such quantities can vary significantly depending on the characteristics of the structural element e.g. span, effective depth and concrete resistance. Therefore, this paper aims to present an alternative control variable to analyse the behaviour of RC beams repaired with glass fibre reinforced polymer (GFRP), called damage. Such damage variable accounts for concrete cracking and it was experimentally measured before and after the application of GFRP. Note that the application of GFRP increased the ultimate load for all repaired beams. The damage values of such beams also increased when collapse was reached. Furthermore, it was observed that the collapse mechanism shifted to shear and did not occurred the failure of the GFRP.

KEYWORDS. Glass fibre reinforced polymer; Repair; Reinforced concrete beams; Damage.

INTRODUCTION

The necessity of strengthening or repair of reinforced concrete (RC) structures can emerge of its natural deterioration, as well as changes of loading due to alteration of the structure use. Structural strengthening consists in intervention at an existing structure, increasing its loading capacity before reaching its limit state, while repair is the...
The four reinforced concrete beams utilised in the experiments were designed to collapse by bending moment. The beams cross section dimensions are 10 cm of base and 15 cm of height, while its total length is equal to 70 cm and the span (distance between supports) is 60 cm. Longitudinal reinforcement is comprised of two steel bars with 10 mm of diameter, which represents area of steel equal to 1.57 cm², and yield stress of 500 MPa. Transversal reinforcement is formed by steel stirrups of yield stress of 600 MPa and 5.0 mm of diameter, which is equivalent of 2.12 cm²/cm of area of steel. Fig. 1 shows the reinforcement of one of the beams.

The cement used to manufacture the beams was CP II Z-32 (Portland cement composed with pozzolanic materials and compressive strength at 28 days equal to 32 MPa) from a Brazilian brand whose specific mass is 3.03 g/cm³ determined according to technical standard NBR 16605 [26]. Tab. 1 presents the aggregates characterisation.

One of the casted beams is experimented up to collapse and the other ones were reinforced with unidirectional glass fibre fabric VEW130 (Fig. 2), after certain ultimate load ratios. Such reinforcement was manufactured in the USA and it was applied with a Brazilian brand epoxy resin. The data of the glass fibre, provided by the manufacturer, is described in Tabs. 2, 3 and 4.

The dosage of the concrete mixture followed the ACI/ABCP method [31], aiming to obtain a characteristic compressive strength (f cm) equal to 30 MPa. Thus, was adopted the following proportion of cement, sand, gravel 0 and gravel 1: 1:2.21:1.30:1.30. The water-cement ratio was 0.52. The result of the slump test for the mixture was 120 mm, measured

\[ f_{cm} = 30 \text{ MPa} \]

\[ \text{Water-cement ratio} = 0.52 \]

\[ \text{Slump test} = 120 \text{ mm} \]
according to the technical standard NBR NM 67 [32]. In addition to the beams, two specimens of 200 mm of height and 100 mm of diameter were moulded to determine the compressive strength of concrete in accordance with the technical standards NBR 5738 [33] and NBR 5739 [34].

The four beams were demoulded 24 hours after casting and cured submerged during 28 days. After curing, the reference beam (RB) was subjected to a cyclic 3-point bending test with displacement control (Fig. 3), with test velocity of 1 mm/s. In order to obtain the maximum strength, the beam was loaded until to rupture, in 14 loading cycles. Then, on the remaining three beams, loads equivalent to 100% (beam #1), 80% (beam #2) and 60% (beam #3) of the maximum force were applied, with 7, 5 and 5 loading cycles, respectively. The tests were performed with universal testing machine EMIC/INSTRON model DL 2000.

| Aggregate | Characteristic          | Results | Technical standard |
|-----------|-------------------------|---------|--------------------|
| Sand      | Specific mass (g/cm³)   | 2.64    | NBR NM 52 [27]     |
|           | Maximum diameter (mm)   | 4.8     | NBR NM 248 [28]    |
|           | Fineness modulus        | 2.69    | NBR NM 248 [28]    |
| Gravel 0  | Specific mass (g/cm³)   | 2.65    | NBR NM 53 [29]     |
|           | Maximum diameter (mm)   | 9.5     | NBR NM 248 [28]    |
| Gravel 1  | Specific mass (g/cm³)   | 2.65    | NBR NM 53 [29]     |
|           | Maximum diameter (mm)   | 19.0    | NBR NM 248 [28]    |

Table 1: Aggregates characterisation.

| Property           | Results |
|--------------------|---------|
| Density (g/cm³)    | 1.85    |
| Fibre percentage (%/peso) | 69     |
| Thickness (mm)     | 0.02    |

Table 2: Physical properties of fibreglass [30].
Maximum stress | Results (MPa)
--- | ---
Longitudinal traction | 682.58
Longitudinal compression | 682.58
Transverse traction | 220.63
Transverse compression | 220.63
In-plane shear | 103.42
Longitudinal bending | 689.48
Transverse bending | 206.84

Table 3: Resistance of fibreglass [30].

Elasticity moduli | Results (MPa)
--- | ---
$E_x$ | 36.13
$E_y$ | 11.03
$G_{xy}$ | 5.24
$E_{x,bending}$ | 34.34
$E_{y,bending}$ | 10.48

Table 4: Elasticity moduli of fibreglass.

After the bending tests, the beams were reinforced. Initially, a layer of epoxy resin was applied to serve as an interface between the concrete and the glass fibre fabric. After that, the fibre was applied on the entire longitudinal section and, finally, another layer of resin was added (Fig. 4). The resin cured after a week and then further tests were made.

Figure 3: Beam during the test.  
Figure 4: Glass fibre application.
After the glass fibre reinforcement of the beams, new cyclic 3-point bending tests were made, which were applied 7, 6 and 6 loading cycles in the beams #1, #2 and #3, respectively. This time, all three beams were loaded to collapse in order to visualise its behaviour when compared to the reference beam, which had no fibre-reinforcement.

**EXPERIMENTAL DAMAGE MEASUREMENT**

The experimental response of the beams can be given by:

\[
P = Z(D)(w - w_p)
\]

(1)

where \(P\) is the applied load, \(w\) is the total deflection, \(w_p\) is the plastic/permanent deflection that measures the steel reinforcement yielding and \(Z(D)\) is the current stiffness of the beam (Fig. 5), considering concrete cracking, given by:

\[
Z(D) = (1 - D)Z_0
\]

(2)

being \(Z_0\) the initial stiffness, i.e. when the concrete is intact, and \(D\) the damage variable which accounts for the concrete cracking.

Thus, the damage variable can be measured by experiments using the following relation:

\[
D = 1 - \frac{Z(D)}{Z_0}
\]

(3)

Mathematically, the damage variable is nil if there is no cracks in concrete and tends to one if the beam is about to split in two parts. However, despite this mathematical definition, the collapse is reached for damage values smaller than one [35]. According to Lemaitre and Chaboche [35], most materials fail for damage values between 0.20 and 0.50. For reinforced concrete beams, the bearing capacity is usually achieved for damage values around 0.60 [14]. Such value is defined as ultimate damage (\(D_u\)) and can be calculated by the classic RC theory or experimentally measured. In both cases, such value is associated to the bearing capacity of the element.

![Figure 5: Graphical representation of damage measurement.](image)

**RESULTS**

The cyclic flexural test of the reference beam is presented in Fig. 6. The bearing capacity of the beam is 76.62 kN and its ultimate damage is 0.53. The damage for each cycle of the reference beam and the repaired beams #1, #2 and #3 are depicted in Fig. 7 in terms of the bending moment at the centre of the beam.
Before repair, the beam #1 (Fig. 8) was loaded up to 76.10 kN and the resulting damage was 0.45. After repair, the beam #1 was loaded up to collapse, which occurred with the applied force of 83.98 kN and the damage at the end of the test was 0.57. Beam #2 achieved 0.37 of damage before repair, which consists of 61.01 kN of applied force. When repaired, the beam #2 (Fig. 9) reached 86.43 kN of maximum force and 0.52 of measured damage. Finally, beam #3 (Fig. 10) was loaded up to 46.06 kN and the damage at that point was 0.30. After repaired, such beam presented maximum bearing capacity of 83.98 kN and the damage was 0.50 when the test was concluded. The values of maximum force and damage for all beams are summarised in Tab. 5.

An important observation during the experiments is that the collapse mechanism of the repaired beams shifted to shear (Fig. 11). Note that the repaired beams presented similar bearing capacity, which is close to the shear strength of such beams, calculated as:

$F_s = \frac{0.27}{250} f_c b_w d$

being $b_w$ the basis and $d$ the effective height (10 cm).

The behaviour shift is evident for beam #1 since there are cracks at the mid-span characterising flexure failure. These cracks appeared in the pre-loading step i.e. when the beam was without GFRP. Then, after repair, such beam presented severe shear cracks (Fig. 11). The mid-span cracks at the beams #2 and #3 are not severe, since both were repaired after submitted to loads considerably smaller than the collapse force. However, in these last two beams, the shear cracks occurred as well.

![Figure 6: Force-displacement response of the reference beam.](image)

![Figure 7: Bending moment and damage values at each cycle.](image)
Figure 8: Beam #1.

Figure 9: Beam #2.
**Table 5: Maximum force and damage values before and after repair.**

| Beam | Maximum force before repair (kN) | Maximum damage before repair | Maximum force after repair (kN) | Maximum damage after repair |
|------|---------------------------------|-----------------------------|-------------------------------|---------------------------|
| Reference | 76.62                           | 0.53                        | \                            | \                         |
| #1     | 76.10                           | 0.45                        | 83.98                        | 0.57                      |
| #2     | 61.01                           | 0.37                        | 86.43                        | 0.52                      |
| #3     | 46.06                           | 0.30                        | 83.98                        | 0.50                      |

**CONCLUSION**

This paper aimed to investigate the behaviour of reinforced concrete beams, which were repaired with glass fibre reinforced polymer (GFRP), measuring the integrity of the beams with the damage variable. At first, it was obtained the results of displacement and damage for the reference beam (without GFRP), for a comparison with the other ones. The reference beam presented collapse for 0.53 of damage. Such value is considered the ultimate damage for these beams i.e. the damage value when the load bearing capacity is reached. The analysed beams were previously loaded with a percentage of the collapse load, obtained in the reference beam, equal to 100% (beam #1), 80% (beam #2) and 60% (beam #3). After the repair using GFRP, these three beams were reloaded up to collapse. Note that, for all repaired beams, the ultimate load increased in comparison with the obtained for reference beam, even when preloaded with 100% of its strength. Besides that, when analysing the failure mode, it is possible to observe that the collapse mechanism of the repaired beams shifted to shear, without occurring the failure of the GFRP. The damage values for the repaired beams varied from 0.50 (beam #3) to 0.57 (beam #1). Such range is near to values considered as collapse for RC beams without FRP. However, since those beams were repaired by GFRP and the collapse mechanism shifted to shear, further studies are needed to determine the ultimate damage at these conditions. For future works, it is recommended to carry out an extensive experimental campaign as an attempt to characterise for which damage values the RC beams should be reinforced/repaired with GFRP and other techniques.
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