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# **Comparative study on flexural behavior of corroded RC** beams strengthening using near surface mounted GFRP elements

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Abstract. In this study, corroded reinforced beam specimens failing in bending were strengthened using near surface mounted (NSM) technique and evaluated. Two types of glass fiber reinforced polymer (bar, mat) were investigated for the strengthening materials. A simulated corrosion rate of 25% was considered in the study. The maximum recorded load of the strengthened beams with GFRP bars showed enhancement in the ultimate strength which reached 89% of the undamaged control beam strength. While using of GFRP mat for strengthening the corroded beams increased only the ductility but had negligible effect on the improvement of ultimate strength. The results indicated that using near surface mounted technique prevents the occurrence of de-bonding failure which results in an enhancement in the crack load and failure load of the tested beams.

## 1. Introduction

In the last few decades, FRP materials play an important role in strengthening deteriorated structures due to its characterization of light weight, high strength and durability [1-4]. Researchers used FRP sheets and laminate by attaching them on the surface of the member that required strengthening. This technique is called externally bonded reinforcing (EBR) technique. Previous studies showed that EBR technique is not effective due to the risk of premature de-bonding failure at the interface between the FRP sheets and the concrete member [5, 6]. On the other hand, members that strengthened with EBR technique are highly susceptible to fire, substantial damage, variation of temperature [7]. To conquer these drawbacks, a new concept of strengthening was developed which called near surface mounted strengthening technique (NSM). In this method, the FRP strengthening materials set into grooves through the concrete cover of the members to be strengthened [8]. Several researches were conducted to analyse the bond performance of this technique [9]. The researches pointed out that the NSM technique is only applicable for some applications [10-13] and provides several benefits in terms of durability. The FRP strengthening materials required a high-strength epoxy adhesive for bonding with concrete. In this study, the flexural capacity of corroded beam specimens strengthened with GFRP bar and GFRP mat using NSM technique are discussed and compared.

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## 2. Experimental work

#### 2.1. Materials

Concrete mix was prepared using locally supplied ingredients to give a 28 days compressive strength of 40 MPa. Reinforced bars with diameters of 10 mm and 8 mm were used for the main reinforcement and stirrups, respectively. The GFRP elements were used in the forms of 10 mm bar and a unidirectional mat of 0.3 mm dry thickness. Conmix Nano Grout SG was used as adhesive to bond the GFRP elements to the concrete surface. The mechanical properties of the used materials are presented in Table 1.

Material type	Tensile strength	Elongation	Modulus of Elasticity	
	(MPa)	%	(GPa)	
Steel Ø10	590	9	200	
Steel Ø8	530	8	200	
GFRP bar	1200	3	60	
GFRP mat	2300	3.9	90	

Table 1. Mechanical properties of the used materials

#### 2.2. Specimens' details and strengthening techniques

In the experimental work, 4 reinforced concrete beams of 1200 mm long, 150 mm wide and 200 mm height were tested. One beam was used as a reference beam (RB0). The other three beams were subjected to simulated corrosion of 25%. This has been achieved by removing one bar from the main reinforcement in the tension zone. Two of the corroded beams (RBG1) and (RBM1) were strengthened using near surface mounted technique with one GFRP bar and 4 layers of GFRP mat, respectively. While the other beam (RB1) was left un-strengthened for comparison. The beams layout and details of reinforcement are shown in Fig.1 and summaries in Table 2. All beams were tested following three points loading method for the flexural capacity.



(b) Section A-A

Figure 1. Specimens layout and details of the reinforcement

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Beam label	Tension	Compression	Corrosion	Strengthening
	steel	steel	percentage	type
RB0	4Ø10	2Ø10	0%	
RB1	3Ø10	2Ø10	25%	
RBG1	3Ø10	2Ø10	25%	GFRP bar
RBM1	3Ø10	2Ø10	25%	GFRP mat

Table 2. Reinforcement details of the tested beams.

## 3. Results and observations

## 3.1. Cracks pattern and Failure mode

Fig. 2 shows a photograph for the crack spread of the reference beam RB0. The applied load for each increment is marked on the beam next to the cracks location. The photograph indicates that the crack patterns of the reference beam are mainly flexural. The first crack was observed at the mid span of the beam under the applied load point. The length and numbers of the flexural cracks then increased as the applied load increased until failure. Figure 4 shows the crack patterns and failure modes of the unstrengthened and strengthened corroded beams. It can be seen that all the three corroded beams showed similar patterns of the flexural cracks to that of reference beam RB0 up to failure. However, the number and length of the cracks of strengthened beams RBG1 and RBM1were higher than the unstrengthened beamRB1which indicates the improvement of the flexural behaviour. On the other hand, beam RBM1 that strengthened with GFRP mat showed less cracks distribution at failure which reflect the lower failure load compared to RBG1strengthened beam. For all the tested beams, the cracks continued propagating starting from the mid span of the beam in a vertical direction with the increase of the applied load. At the failure load, pure flexural cracks were observed for all tested beams without any concrete crush at the top of the cross section of the beams.



Figure 2. Crack pattern and mode of failure for the uncorroded reference beam



Figure 3. Crack pattern and modes of failures for the corroded beams

#### 3.2. Cracks loads and load carrying capacity

The crack load, yielding load and ultimate load in addition to yield deflection and ultimate deflection were summarized in Table 3. A comparison between the crack load and ultimate load for the tested beams were shown in Fig. 4. The first visible crack of the reference beam RB0 was observed under the applied load point in the tension zone at load about 21 kN. After increasing in the number and length of flexural cracks, the reference beam failed at ultimate load of 73 kN. This load level is comparable to the theoretical failure load of the reference beam. The crack load of un strengthened corroded beam RB1 was initiated at 13 kN at the mid span. Consequently, it fails with ultimate load of 62 kN.

A strengthened corroded beam with one bar of GFRP (RBG1) has improved the initial crack to be observed at load level of 18 kN. In contrast, there was no improvement for the beam that strengthened with GFRP mat (RBM1). Strengthened beams RBG1 and RBM1 showed very limited increase on failure load compared with un-strengthened beam RB1. The ultimate load of beams RBG1 and RBM1 were 65 and 63, respectively

Table 3. Test results of the beams under study								
Sampl	Pcr	Ру	$\Delta_{\mathrm{y}}$	$\mathbf{P}_{\mathbf{u}}$	$\Delta_{\mathrm{u}}$	Pcr	Pu	$\mu = \Delta_u /$
e	(kN)	(kN)	(m	(kN)	(mm)	Pcr(RB0)	$\overline{Pu(RB0)}$	$\Delta_{ m y}$
			m)					
RB0	21	68	7	7	12			1.7
				3				
RB1	13	52	5	6	14	0.62	0.85	2.8
				2				
RBG1	18	60	6	6	10	0.85	0.89	1.66
				5				
RBM1	11	54	5	6	13	0.52	0.86	2.6
				3				



Figure 4. Initial cracking and maximum loads of the tested beams

## 4. Discussion

#### 4.1. Effect of corrosion

Due to the amount of time that required for the natural corrosion process, the corrosion damage of reinforced steel was simulated by removing one of the four tension bars. This gives a simulated corrosion percentage of 25% of the tension steel area. Fig. 5 clearly shows the effect of removing one steel bar from the tension steel of beam RB1 on the ultimate load capacity. It is obvious that while longitudinal tension bars number decreased the load carrying capacity decreased. The failure load of un-strengthened corroded beam RB1 decreased by 15%, compared with the reference beams RB0.Similarly, the first crack load and yielding load decreased as presented in Table3. This decrease however followed with noticeable increase in the ductility of the tested beam. It should be mentioned that all the tested beams exhibited pure flexure failure and showed flexural cracks mode along the pure flexural span.



Figure 5. Applied load and recorded deflection curve of un-corroded and corroded beams

## 4.2. Effect of strengthening with GFRP bars

Fig. 6 shows the curves of the applied load and the recorded deflection of the reference beam RB0, unstrengthened corroded beam RB1and corroded beam strengthened with one GFRP bar RBG1. The crack load of the strengthened beam RBG1 was higher than it counterpart corroded beam RB1which reflect the improvement of the crack capacity of the beam. However, the enhancement seems to be limited to 85% of the un-corroded Reference beam RB0. Even the yield load was increased compared to the un-strengthened corroded beam RB1, the failure load of the strengthened beam was only 3% higher than its un-strengthened beam counterpart. Similarly, it accounts for 89% of the un-corroded reference beam. This behavior might be resulted from the brittle behavior of GFRP bar which shows noticeable improvement until yielding stage. Although both un-corroded reference beam RB0 and corroded strengthened beam RBG1 showed comparable ductility index, the brittle behavior of GFRP bar affects the ultimate carrying load capacity of the strengthened beam



Figure 6. Effect of strengthening with one GFRP bar on load -deflection curves

#### 4.3. Effect of strengthening with GFRP mat

Fig. 7 displays the performance of strengthening with 4 layers of GFRP mat on load- deflection behavior of corroded beam (RBM1) in comparison with the behavior of un-strengthened corroded beam (RB1and un-corroded reference beam RB0. The presence of GFRP mat in the section had no

effect on both the crack and ultimate load capacity of the beam. This behavior could be attributed to the limited bonding strength between the GFRP mat and the concrete surface of the corroded beam. As a result, the difference in the ductility index of the strengthened and un-strengthened corroded beams was limited to only 7%.



Figure 7. Effect of strengthening with 4 layers of GFRP mat on load –deflection curves

## 5. Conclusions

- It is noted that the fracture modes of the reference beam are mainly flexural. The initial crack was occurred under the applied load point
- Strengthening corroded beam with one bar of GFRP (RBG1) has improved the initial crack to be recorded at load level of 18 kN compared to 13 kN for the un-strengthened corroded beam. In contrast, there was no improvement for the beam that strengthened with GFRP mat (RBM1)
- It is obvious that the ultimate load capacity, the initial crack load and yielding load decreases with the decrease of longitudinal tension bars number.
- The crack load of the strengthened beam RBG1 was higher than it counterpart un-strengthened corroded beam which reflect the improvement of the crack capacity of the beam. However, the enhancement seems to be limited to 85% of the un-corroded reference beam RB0. Even the yield load was increased in comparison with the un-strengthened corroded beam, the failure load of the strengthened beam was only 3% higher than its corroded beam counterpart. Similarly, it accounts for 89% of the un-corroded reference beam.
- The presence of GFRP mat in the section has no impact on both the crack and ultimate load capacity of the beam.

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