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Research paper

Shear recovery of patched reinforced concrete beams with web reinforcements

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Abstract: Damage occurring on a reinforced concrete beam (e.g. spalling) can reduce beam's capacity to withstand external loads. The damage becomes more critical if it is occurred in the shear span since it may lead to shear failure. Patching to the damage zone by suitable patch repair material could be the best option in restoring the shear capacity of the beam. This research investigates the shear recovery of patched reinforced concrete beams with web reinforcement. The patching material used is unsaturated polyester resin mortar. The shear recovery is assessed on the basis of the patched beam's behavior under flexure-shear load in comparison with those of normal beams. The behavior observed include cracking failure mode, strains of the reinforcements, and load-deflection behavior. The results indicate that the UPR mortar is capable to restore the strength of the damage reinforced concrete beam. The characteristic of UPR mortar (low elastic modulus and high strength) can be the origin of the overall behavior of the patched reinforced concrete beams.

Keywords: patch repair, reinforced concrete beam, shear, unsaturated polyester resin, web reinforcements

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1. Introduction

Reinforced concrete has been widely utilized as structural elements for various types of buildings. As part of the structural elements, reinforced concrete beams must be designed to meet the requirements specified in the Building Codes [1–3]. These requirements can be categorized into strength requirements and serviceability requirements. The strength of reinforced concrete beams (e.g. flexural strength), is provided by the composite action between the compressive force on the concrete and the tensile force on the reinforcement. The presence of flexural reinforcement that carries this tensile force allows reinforced concrete beam to be designed in a ductile manner. Meanwhile, the ductile failure mode of reinforced concrete beams tends to be difficult to achieve in design against shear loads. Alghazali and Myers [4] showed the ductility of shear beams made from high volume fly ash-self compacting concrete (HVFA-SCC) were only 3–4%. Other experimental results indicated that concrete beams experienced a sudden collapse once diagonal cracks formed under the dominant shear loads [5]. This sudden failure mode is undesirable. Therefore, reinforced concrete beams must be designed to have a conservative shear capacity compared to flexural capacity. This is so to ensure that the flexural failure mode can precede shear failure.

Although reinforced concrete beams may have been designed to meet the strength requirements and the flexural failure mode has been analytically confirmed to precede the shear failure, but over time damages can occur on reinforced concrete beams due to a variety of causes. Examples are damages by corrosion of reinforcement, large earthquake load, fire, and others. Such damages will certainly reduce the strength of reinforced concrete beams, which further reduces the safety factor of the building. The decrease in the safety factor in the shear span will be more worrying than the decrease of safety factor in the bending area [6–8]. A decrease of safety factor of the beam shear strength can be expected if the damage of concrete (for example in the form of spalling) appears within the shear span. In this area of spalling, the shear strength provided by the concrete is reduced considering that the concrete cross-sectional area in the damaged section becomes smaller [9]. In this situation, a shear failure can precede the flexural failure mode. Hence, the building is at a risk of experiencing sudden collapse without any prior warning to its occupants.

Repairing the spalling of concrete in the shear span is necessary to recover the shear strength of reinforced concrete beams and avoid the occurrence of shear failure which is very dangerous. Repair by patching becomes an easy choice; however, this method requires patch repair material that must be compatible to the substrate concrete so that the shear capacity of reinforced concrete beams is completely restored [10]. Various repair materials have been developed which indicate their capability to restore the structural performance of patched RC elements. However, most of the patch repair materials were applied to recover the flexural performance of the damaged RC beams [6, 11–13]. With regard to shear performance, the repair materials were not utilized as patching materials. Instead, they were used as strengthening of the shear deficient beams [14–18]. The current research proposes the use of unsaturated polyester resin (UPR) mortar as patching material to recover shear deficient beams. This material has been applied to repair the spalling of reinforced concrete beam, slab and column elements [9, 10, 19–21]. With regard to the shear strength of beam, it was shown that UPR mortar could restore the shear strength of patched reinforced concrete beam without web reinforcement [9, 10]. Further investigation is proposed in the current research to investigate the efficacy of UPR mortar to recover the shear strength of patched reinforced concrete beam with web reinforcements.

2. Materials and method

2.1. Materials

Concrete used for the production of beam specimens was proportioned following the relevant Indonesian Standard [22] to achieve a mean strength of 35 MPa. The obtained mix design per m^3 volume of concrete was as follows: 513 kg of cement, 581 kg of sand, 1032 kg of gravel, and 225 kg of water. Meanwhile, the patching material (UPR-mortar) was prepared by mixing the following ingredients per m^3: 950 kg of sand, 808 kg of cement, 143 kg of fly ash, 475 kg of UPR, and 24 kg of hardener. No water was included since UPR and its hardener acting as a binding material. The strength gain of UPR mortar is fairly rapid i.e. it can attain a compressive strength of 55 MPa within 1 day. Cement and fly ash were introduced as fillers, but it is also expected that these materials will improve the strength and durability of the UPR mortar when it is exposed to water (Fig. 1). Deformed reinforcements with diameter of 16 and 19 mm were chosen for tensile longitudinal (flexural) reinforcements, while a 6 mm diameter of plain reinforcement was selected for compression longitudinal reinforcements and for assembling the web reinforcements. The actual properties of the materials for the production of beam specimens are presented in Table 1.

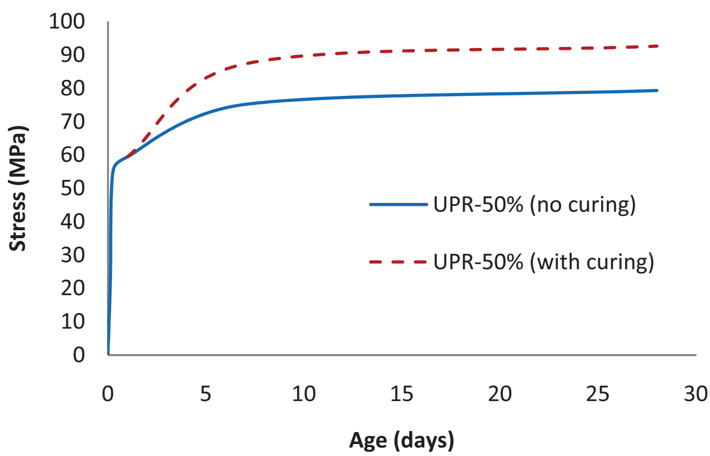


Fig. 1. Strength improvement of UPR mortar when exposed to water

Table 1. Properties of materials for the production of beam specimens

Material	Compressive Strength (MPa)	Tensile Strength (MPa)	Elastic modulus (GPa)	Yield Strength (MPa)
Concrete	31.39	2.99	21.30	–
UPR-mortar	72.50	21.00	13.41	–
Reinforcement (D19 mm)	–	–	200.00	475
Reinforcement (D16 mm)	–	–	200.00	438
Reinforcement (D6 mm)	–	–	200.00	338

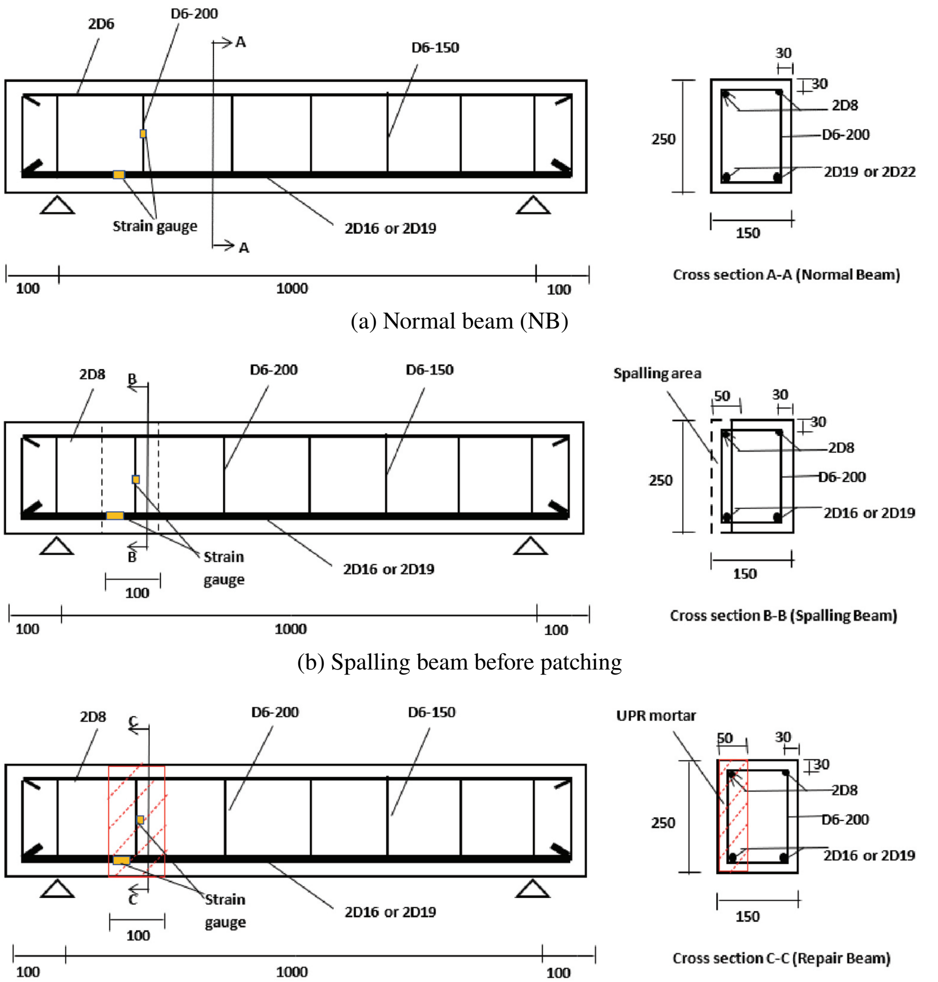
2.2. Beam specimens

Two types of reinforced concrete beams were made: the first was a normal reinforced concrete beam (NB) representing the beam without damage and the second was a patched reinforced concrete beam (RB) representing the beam which had been patch repaired with UPR-mortar. The damage area was simulated by cutting out the concrete beam in the shear span (Fig. 2b), which eventually was repaired using UPR mortar. Two longitudinal reinforcement ratios were prepared for each type of beam. The two reinforcement ratios were represented by the use of D16 and D19, respectively. The dimension of the beams and their corresponding reinforcements lay out were given in Fig. 2. The loading point was set at the middle span of the beam. This gave shear span a to effective depth d ratio of 2.27.

The reinforcements have been calculated in such a way so that the flexural strength of the beam is higher than the shear strength. This analytical calculation will ensure that the beam should fail by shear failure mode. The web reinforcements in the left shear span (D6-200 mm) are less than those of the right shear span (D6-150). Consequently, the shear failure mode is expected to occur at the left shear span. Table 2 summarizes all types of beam specimens.

Table 2. Types of beam specimens

Beam ID	Type of beam	Tensile reinforcement	Compressive reinforcement	Stirrup at left shear span	Stirrup at right shear span
NB-16	Normal	2D16	2D6	D6-200	D6-150
RB-16	Repair	2D16	2D6	D6-200	D6-150
NB-19	Normal	2D19	2D6	D6-200	D6-150
RB-19	Repair	2D19	2D6	D6-200	D6-150



(a) Normal beam (NB)

(b) Spalling beam before patching

(c) Patched repair beam (RB)

Fig. 2. Beam specimens and their reinforcements lay out

2.3. Testing beams

The beams were tested under three points of loading at about 3 months after casting. A day before testing, the RB was patched using UPR mortar. The load was applied at the middle of span (Fig. 3). The load was continuously increased at an increment of 10 kN until the beam rupture by shear failure mode. The deflection of the beam was monitored by using dial gauge. Strain gauges were installed on the surface of both longitudinal and web reinforcement (Fig. 2). Other parameter observed during the loading test were cracking evolution. Cracks were monitored visually and their appearances at each increment of load were sketched on the surface of the beam.

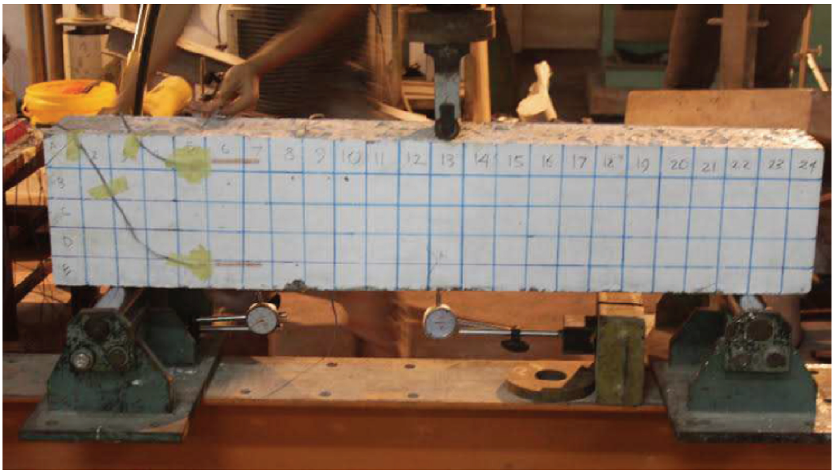


Fig. 3. Experimental setup NB-16 beam

3. Results and discussion

3.1. Cracking failure mode

Flexural cracks first appear around the mid-span where the maximum bending moment occurs. The load causing these flexural cracks in the normal beams (NB) and repair beams (RB) are approximately similar i.e. in the range of 20–40 kN. The final cracks patterns of NB and RB are shown in Fig. 4–5. It is noticed that at the final stage more flexural cracks are formed in the RB beams than normal beams. The presence of UPR mortar disrupts the proportionate distribution of the tensile stresses in the concrete i.e. the load path is shifted in such a way to cause more tensile stresses are spread to the right of UPR mortar. This

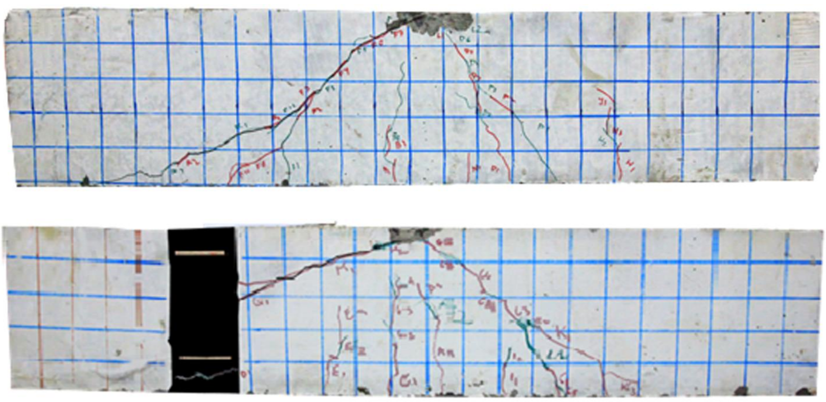


Fig. 4. Cracking failure mode of NB-16 (top) and RB-16 (bottom)

behavior has also been observed in the patched repair beam without web reinforcement [10] and can be related to the low elastic modulus and high tensile strength of UPR mortar. Meanwhile, a primary diagonal crack causing shear failure occurs on the shear span with lower web reinforcement i.e. left shear span as expected. For the NB beams the primary diagonal crack appears in the shear span that extend along the loading point and support. On the other hand, in the RB beams the UPR mortar is capable to arrest the primary diagonal crack so the patching zone remains solid. This can be attributted to the high tensile strength of UPR mortar. The capability in maintaining the repair zone to remain solid is beneficial to promote the RB beam to be able to take a higher load before rupture. It was observed that the ultimate shear load of NB-16 and NB-19 were 120 kN and 130 kN, respectively. The use of UPR mortar to repair the beams increased the shear loads of RB-16 and RB-19 to 130 kN and 135 kN, respectively. The increase of shear load on the repair beams confirms the capability of the UPR mortar to restore the shear strength of damaged beams. Finally, all beams failed in shear-compression failure, as indicated by concrete crushing in the biaxial compression zone.

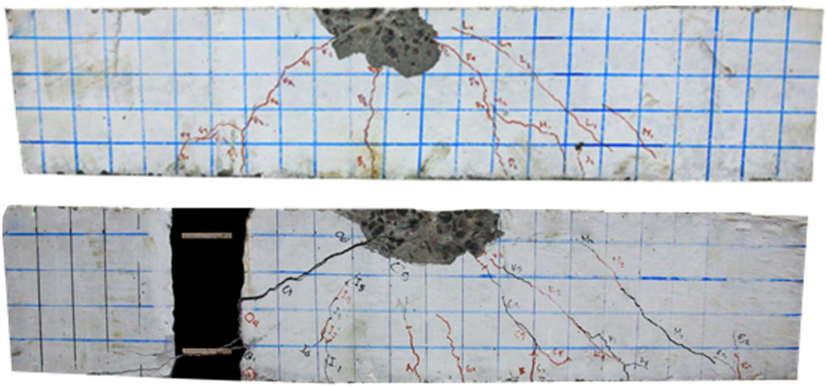
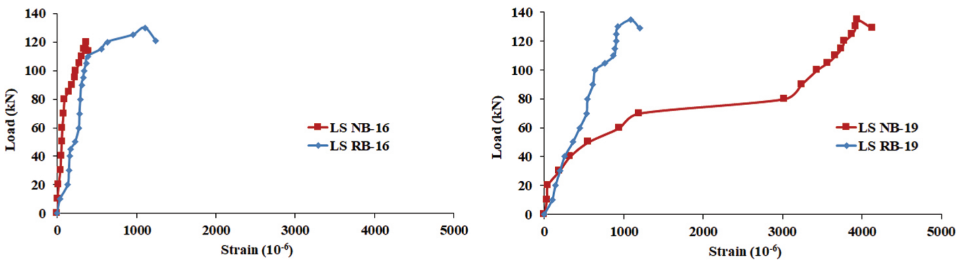


Fig. 5. Cracking failure mode of NB-19 (top) and RB-19 (bottom)

3.2. Reinforcements strains

The development of strains observed on the longitudinal reinforcement of normal and repair beams along with the increment of loading can be seen in Fig. 6. To be able to interpret this figure, one must consider the following: the observed strains are localized strains and so their values depend on the strain gauges location (see Fig. 2) with respect to the cracks formation (Fig. 4–5). For this reason, it is not always easy to compare one to another when the cracks formation is dissimilar. Additionally, the modular ratio of concrete to UPR mortar, concrete to reinforcement, and UPR mortar to reinforcement will influence the stress distribution. Replacing the concrete with the UPR mortar in the repair zone will reduce the stress in the UPR mortar; but it may cause an increase distribution of stress in the reinforcement. Fig. 6a. could be an example of such situation. The strain in RB-16 is greater than that of NB-16. It is also noticed that at the later stage of loading the strain in the RB-16 is increase significantly. The significant increase of strain in RB-16 at later stage may be explained as follows: at a load of about 118 kN a very intense cracks are formed in RB-16 while UPR mortar is still capable to arrest diagonal crack. The formation of cracks causes redistribution of stresses to non-cracking area. The repair zone instantly takes a higher stress and provoke a significant distribution of stress in the longitudinal reinforcement as indicated by significant increase of strain. The final strain (1244×10^{-6}), however, does not reach the yield value (2190×10^{-6}).



(a) Longitudinal strain (LS) on NB-16 and RB-16

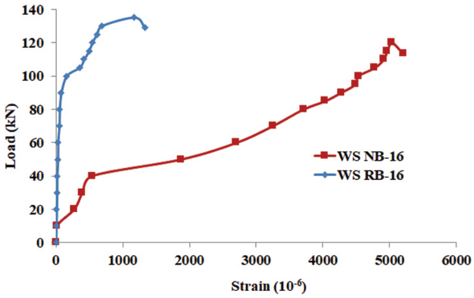
(b) Longitudinal strain (LS) on NB-19 and RB-19

Fig. 6. Load-longitudinal strain behavior of normal and repair beams

In the case of higher reinforcement ratio (NB-19 & RB-19), initially the strain of NB-19 increases almost linearly with an increment of load. However, the strain starts to deviate from linear behavior when the load attains 20 kN. Further increase of load (i.e. at 70–80 kN) causes the longitudinal reinforcement of NB-19 deforms rapidly indicating that the reinforcement reaches its yield value. Above 80 kN a strain hardening start to occur. Very different behavior is observed with regard to the strain on the longitudinal reinforcement of RB-19. Even though at the beginning the rate of strain is higher compared to the NB-19, but this rate of strain remains the same even at a high load level. The maximum strain observed in RB-19 reinforcement is 1200×10^{-6}, which is still below the yield value. The maximum strain of RB-19 reinforcement is only about 29% to that of NB-19 reinforcement. The lower observed strain in the RB-19 longitudinal reinforcement could be due to the fact that the diagonal cracks which dictates the shear failure is arrested by UPR mortar. The diagonal crack does not intersect the longitudinal reinforcements of RB-19. In turn, no localized stress transfer occurs in the longitudinal reinforcement of RB-19.

Reverse trends to those of longitudinal strains are identified with regard to the strains on the web reinforcement of NB and RB beams. Comparing Fig. 6 and 7, one can see that the higher the longitudinal strain, the lower the web reinforcement strain, and vice versa. However, this statement should not be regarded as a general conclusion since cracking intensity and its pattern together with the strain gauge location will affect the observed strain behavior.

For a lower reinforcement ratio (NB-16), a large strain of web reinforcement starts to occur when a load above 40 kN is imposed. It is also interesting to note that this web reinforcement still be able to take a higher stress even though its strain already reaches the



(a) Web reinforcement strain (WS) on NB-16 and RB-16

(b) Web reinforcement strain (WS) on NB-19 and RB-19

Fig. 7. Load-web reinforcement strain behavior of normal and repair beams

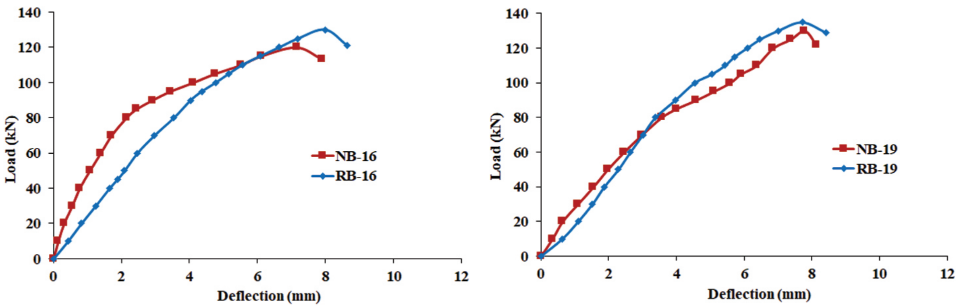
theoretical yield value (1690×10^{-6}). A higher stress in the web reinforcement indicates that this reinforcement is effective in its contribution to the shear transfer mechanism once a diagonal crack crosses over it. For RB-16, its seems that the web reinforcement begins to carry shear transfer after the imposed load attains 100 kN. This may be related to the fact that this web reinforcement is covered by the UPR mortar where no cracks are observed in this repair material. Hence, a shear transfer to this web reinforcement is limited. However, at high load level (beyond 100 kN) numerous cracks in the un-repair zone causes much of the stresses are redistributed to the remaining solid zone (i.e. patch repair area) and so significant increase of stress is transferred to the web reinforcement.

For a higher reinforcement ratio (NB-19 & RB-19), much of the stresses are carried by the longitudinal reinforcements (Fig. 6b) rather than the web reinforcements (Fig. 7b). A closer look at the NB-19 web reinforcement with respect to the diagonal crack (see Fig. 2 and 5), one can realize that the primary diagonal crack does not intersect the web reinforcement. For this reason, the reinforcement exhibits a low strain up to failure load. In the case of RB-19 web reinforcement, the strain behaves in similar manner to that of RB-16.

Considering all the discussions given in the previous paragraphs, the following can be highlighted: the observed strains of the reinforcements in the beams are affected by cracking intensities and their patterns, the location of measured strains, the modular ratio of reinforcements and concrete as well as modular ratio of reinforcements and UPR mortar. Considering particularly the influence of UPR mortar, the most noticable effect is to preserve the strain rate occuring in the reinforcement as the load increases. Only at a high load level, much of stresses are redistributed to the solid repair zone resulting in significant increase of the reinforcement strain.

3.3. Load-deflection behavior

Figure 8 shows the load-deflection behavior of the beam specimens. It seems that at low level of loading, the patched reinforced concrete beam (RB) exhibits slightly a lower stiffness compared to the normal beam (NB). However, at a high load the trend is reversed and the RB beam fails at greater load than the NB beam. The lower stiffness of the RB at early loading could be related to the presence of patching. The patch repair material (UPR mortar) has a lower elastic modulus than concrete (Table 1). Thus, stiffness of this beam at the repair zone is reduced. The reduction of the stiffness in this zone contributes to the reduction of overall stiffness of the RB beam. Consequently, the beam deforms more under the same load compared to the NB beam. However, at a high load the RB beams capable to maintain the repair zone to remain solid. A higher tensile resistance of the repair zone due to the UPR mortar results in the shear crack cannot propagate into the repair area. On the other hand, the shear crack propagates throughout the entirely tensile zone of the NB beam, which eventually reduces the stiffness of the beam.



(a) NB-16 and RB-16 (b) NB-19 and RB-19

Fig. 8. Load-deflection behavior

3.4. Shear strength recovery

Table 3 summarizes the main findings of this research which are expressed in various parameters. Generally, the repair beams have a better shear performance compared to the normal beams. The first appearance of significant diagonal cracks in the repair beams occurs at higher load compared to the normal beams. In addition, the peak load of the repair beams is increased by 5–10 kN or about 4–8%. These higher load capacities confirm

Table 3. Summary of the main findings

	Load (kN)				Deflection (mm)			
Beam type	NB-16	RB-16	NB-19	RB-19	NB-16	RB-16	NB-19	RB-19
First flexural cracks	20	40	30	30	0.31	1.65	0.64	1.10
First significant diagonal cracks	80	90	80	80	2.15	4.03	3.38	3.97
Peak	120	130	130	135	7.19	7.98	7.78	7.72
Failure	113	121	122	129	7.90	8.63	8.12	8.43

the efficacy of UPR mortar as patching material to recover the shear strength of damaged beams. Following the ultimate load, the beam can still withstand some load and deformation for a short time before finally failure. In term of maximum deflection, the repair beams also give higher values.

4. Conclusions

The main conclusion of this research are as follows:

1. The UPR mortar can recover the shear performance of damaged reinforced concrete beams as indicated by the greater shear strength and maximum deflection of the patched reinforced concrete beams over the undamaged (normal) beams. The finding confirms the efficacy of the UPR mortar to be used as patching material for repairing shear deficient beams with web reinforcements.
2. The efficacy of UPR mortar to recover the shear performance of the beams can be traced from the capability of this material to arrest the propagation of shear crack and so the repair zone remains solid. The solid repair zone contributes to the increase of the shear capacity of the patched reinforced concrete beams. A high tensile strength of the UPR mortar is a crucial factor of such capability.
3. The most noticable effect of UPR on the measured strain of the reinforcement covered by UPR mortar is to preserve the strain rate as the load increases. Only at a high load level, much of stresses are redistributed to the solid repair zone resulting in significant increase of the reinforcement strain.

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