Original research paper (Oryginalny artykuł naukowy)

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The behaviour of R.C. beams patch-repaired and strengthened with CFRP strips subjected to impact loading

Zachowanie belek żelbetowych naprawionych miejscowo i wzmocnionych taśmami CFRP poddanych obciążeniom udarowym

DOI: 10.15199/33.2024.07.01

Abstract. This paper presents an experimental investigation of the structural behaviour of reinforced concrete (R.C.) beams, patch-repaired with a cementitious grout and strengthened with carbon fibre reinforced polymer (CFRP) strips subjected to impact loading. The results of this study show that strengthening patch-repaired R.C. beams subjected to impact loading using CFRP plates, restores the load-carrying capacity of the beams. The strengthened beams exhibited ductile behaviour with no debonding between the patch repair and the substrate concrete. The primary failure mode of the strengthened beams was intermediate crack (I.C.) debonding. In addition, the beams with longer patch length exhibited higher flexural strength.

Keywords: CFRP-strengthened; patch repairs; I.C. debonding; impact loading.

Streszczenie. Artykuł przedstawia eksperymentalne badanie zachowania belek żelbetowych, naprawionych miejscowo za pomocą zaprawy cementowej i wzmocnionych taśmami z polimerów zbrojonych włóknem węglowym (CFRP), poddanych obciążeniom udarowym. Wyniki tego badania pokazują, że wzmocnienie miejscowo naprawionych belek żelbetowych za pomocą płyt CFRP przywraca nośność tych belek, poddanych obciążeniom udarowym. Wzmocnione belki wykazywały zachowanie plastyczne bez odspajania się naprawy miejscowej od betonowego podłoża. Głównym trybem zniszczenia wzmocnionych belek było odspajanie się pęknięć pośrednich. Dodatkowo, belki z dłuższą strefą naprawy wykazywały większą wytrzymałość na zginanie niż z krótszą.

Słowa kluczowe: wzmocnione CFRP; naprawy miejscowe; odspajanie się pęknięć pośrednich; obciążenie udarowe.

The acceptable performance levels and serviceability of R.C. structures are always the priorities of the assets managers, engineers and researchers. R.C. structures in service may fail to perform adequately due to increased loading and material deterioration, such as corrosion of steel reinforcing bars [1]. The economic loss from damage caused by the corrosion of reinforcing bars is arguably the most significant single infrastructure issue facing R.C. structures [2]. Corrosion attack on R.C. structures reduces the bond strength between reinforcement and the concrete matrix, concrete spalling, loss of cover and a reduction inhe cross-sectional area of reinforcing steel bars [3]. This deterioration inevitably results in reducing the load-carrying capacity of R.C. beams. Therefore there is a growing need to repair and strengthen R.C. elements subject to corrosion of reinforcing steel. The load-carrying capacity can be restored by strengthening using CFRP plates. Repair and strengthening of the R.C. elements require careful selection of materials to ensure compatibility between substrate concrete and new concrete and between CFRP and repair materials. This study focuses on the structural behaviour of repaired and strengthened R.C. beams subjected to impact loading.

Patch repair is an effective strategy for maintaining and restoring the serviceability of R. C. structures. Patch repairs can be successful, provided all the corroded reinforcement are well treated [4]. Nevertheless, concrete repair is a complex process, and it presents unique challenges to those linked to new concrete construction [5]. Depending on the level and the extent of deterioration due to the corrosion of steel rebars in R.C. elements, it may be necessary to combine patch repairs with CFRP strengthening methods [6]. The use of carbon fibre-reinforced polymers (CFRP) as a strengthening material has more advantages than disadvantages compared to other strengthening techniques [1, 7, 8].

The main contribution of this study is summarised in the listed study objectives: i) investigate the bending stiffness of tested R.C. beams, and the associated deflection responses, ii) investigate the propagation of damage, including the cracking patterns and the modes of failure and the composite action between various layers of materials of patch-repaired and CFRP-strengthened R.C. beams, and iii) assess the effects of varying patch repair lengths on the stiffness and cracking patterns of patch-repaired and CFRP-strengthened R.C. beams.

Experimental details

The present experimental study investigated the effect of varying patch repair lengths on the behaviour of R.C. be-

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ams under impact loading induced by dropping weight from various heights. Fifteen R.C. beams with dimensions 155 x 254 x 2000 mm except the patch repair length divided into five groups (with three in each group) were tested under consecutive impact loading. Group 1 was control beams (C.B.), and group 2 up to group 5 were patch-repaired and CFRP-strengthened R.C. beams (S.B.). The S.B. groups were SB1 with 450 mm patch repair length, SB2 with 800 mm patch repair length, SB3 with 1300 mm patch repair length and SB4 with 1800 mm patch repair length. The depth of each patch repair was 105 mm. Corrosion was simulated by grinding off about 14% of the crossectional area of the tension bars over the damage length. Figure 1 shows the reinforcement detailing of a typical patch-repaired and CFRP-strengthened R.C. beam used throughout this study.

Table 1. Material properties
Tabela 1. Właściwości materiałów

Properties/ Materials	Average compressive strength [MPa]	Tensile strength [MPa]	Yield Strength [MPa]	Flexural strength [MPa]	Modulus of elasticity [GPa]
CFRP plate/strip	–	2800 (Min.)	–	–	165 (Min.)
CFRP sheet/fabric	–	4300 (Min.)	–	–	234 (Min.)
Adhesive/Epoxy	75.000	24 – 27	–	–	11.2
Steel bars:					
main bars	–	–	502	–	200
stirrups	–	–	250	–	200

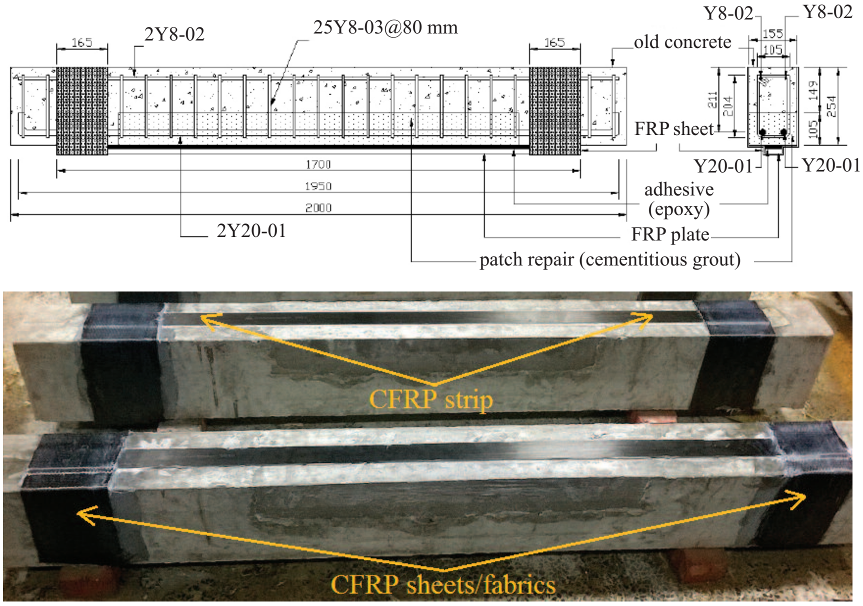

Fig. 1. Reinforcement layout of a typical patch-repaired and CFRP-strengthened R.C. beam
Rys. 1. Układ zbrojenia typowej belki żelbetowej naprawionej miejscowo i wzmocnionej CFRP

The average compressive strength of the concrete used was 55 MPa, and the average compressive strength of the cementitious grout used was 70 MPa. Table 1 summarises the properties of CFRP, epoxy and steel bars used in this experimental study.

The damaged areas of the steel bars, including the previously ground rebar, were cleaned with a wire brush to remove rust deposits. The substrate concrete was cleaned and coated with astructural bonding agent to ensure the bond between the substrate and the cementitious grout is achieved. One 1700 mm long CFRP strip was bonded to the prepared surface of each rehabilitated R.C. beam. A 165 mm wide CFRP sheet was used to anchor the CFRP at both ends of the CFRP, as illustrated in Figure 1.

Impact loading testing

The impact load was applied consecutively for varying drop heights at the mid-span of the simply supported R.C. beam using a 332.403 kg impactor as described in [11] and [12]. The appropriate supporting system was used to prevent the lifting action of the specimen generated by developed inertial effects, followed by vibrations induced by impact loads. The following drop heights were used: 150, 300, 400, 500, 600, 700, 800 and 1000 mm. The contact force, the progression of damage, including cracking patterns and mode(s) of failure, and the resulting deflection response were recorded for each drop height.

Experimental results and discussion

A total of 120 tests were performed on 15 R.C. beams with 8 consecutive impact loadings on each beam while recording deflections and contact forces which combined the inertial forces and true bending forces. The data extracted from the experimental investigation are presented and discussed according to the following research parameters and observations: i) the recorded contact forces; ii) the deflection (vertical displacement) response associated with the forces in (i); iii) the progression of damage, including the cracking patterns and the modes of failure and the composite action between various layers; iv) the effects of varying patch length on the recorded contact force and damage propagation.

Contact forces. The contact forces were captured using a load cell transducer. The recorded contact force loading history combined both maximum contact forces and rebound forces. However, it should be noted that this study focused on the maximum values of contact forces. Figure 2 shows the contact force variation with displacements for each drop height, with lower displacements representing lower drop heights.

Generally, there is a small difference between the control beam (C.B.) and the damaged beams. Thus, different layers composing patch-repaired and CFRP-strengthened R.C. beam worked together and behaved almost as a monolithic specimen. In addition, the degradation of stiffness due to consecutive drop tests was almost the same, despite the type of the beam under test. The 14% reduction of cross-sectional area from main reinforcing steel bars was adequately compensated with the used CFRP materials.

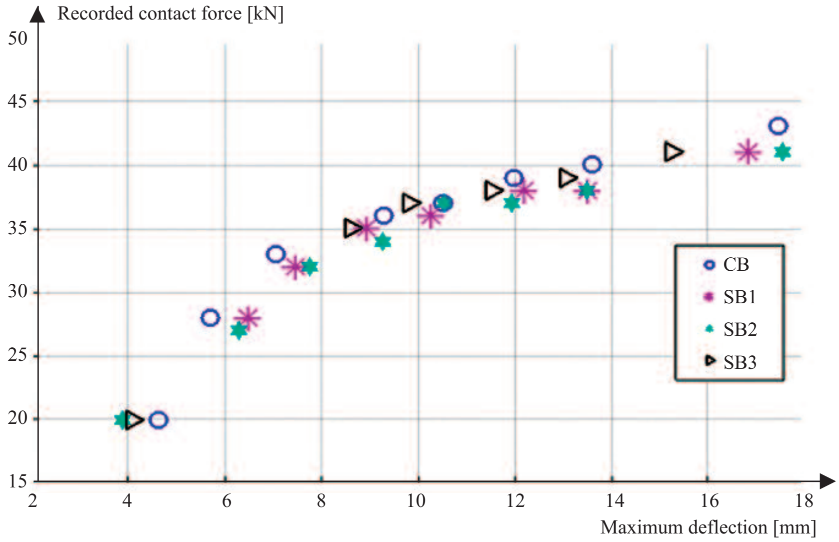

Fig. 2. Recorded contact force vs maximum deflection for each drop height
Fig. 3. Zarejestrowana siła kontaktowa w zależności od maksymalnego ugięcia w przypadku każdej wysokości uderzenia

Deflections. Figure 3 shows the variation of maximum deflection with drop height. The maximum deflection results from the control beam (C.B.) 450 mm damage (SB1), 800 mm damage length (SB2) were practically the same, whereas maximum deflections for 1300 and 1800 mm damage lengths were slight. The reduced steel bars and the intentionally damaged concrete area were compensated accordingly through patch repairs and CFRP strengthening applications.

Progression of damage, including the mode(s) of failure and the composition action between various layers of patch-repaired and CFRP-strengthened beams. In order to properly monitor and assess the progression of damage and associated modes of failure, each specimen was tested eigth times from various drop heights. Directly after each drop test, each crack that appeared was marked and labelled with the number of the strike by which it was formed. All observations related to the damage progression during the impact load testing were marked and recorded. Figure 4 illustrates the typical observations made during the drop testing of the different beams.

All the tested beams presented uniformly spaced flexural cracks, some flexure-shear cracks and shear cracks. However, the extent of cracking profiles showed some slight differences. Moreover, all tested beams failed in concrete crushing in the vicinity of the impact point, causing concrete spalling on the distal side of the impact point. In addition, CFRP intermediate crack (I.C.) debonding failure was observed for the patch-repaired and CFRP-strengthened beams.

On the one hand, five out of twelve CFRP-strengthened beams (41.7%) exhibited the start of CFRP debonding after the third drop test. Five out of twelve CFRP-strengthened beams (41.7%) displayed the start of CFRP debonding after the fourth drop test. Two out of twelve CFRP-strengthened beams (16.7%) exhibited the start of CFRP debonding after the fifth drop tests. On the other hand, two out of twelve CFRP-strengthened beams i.e. 16.7% displayed the end (total) of CFRP debonding after the fifth drop test. Seven out of twelve CFRP-strengthened beams (58.3%) exhibited the end (total) of CFRP debonding after the sixth drop test. Three out of twelve CFRP-strengthened beams (25%) displayed the end (total) of CFRP debonding after the third drop test. Thus, the earliest CFRP debonding was observed from the third drop test, while the last CFRP debonding was observed from the fifth drop test. The earliest total CFRP debonding was observed from the fifth drop test, while, the last total CFRP debonding was observed from the seventh drop test.

Increasing the patch length for the CFRP-strengthened R.C. beams reduced the number of flexural cracks. Therefore, the following classification of more cracks that developed, from lower to higher, might be established starting with SB4, SB3, SB2 and SB1. No visible and noticeable cracks were observed on any interfaces, except for the SB4 group, where a few small cracks (micro-cracks) were observed between patch repair and the old concrete of those beams (Figure 4).

Effects of varying patch repair lengths. The evaluation of the effects of varying patch repair lengths on the behaviour of various patch-repaired and CFRP-strengthened beams was examined on the basis of various results. These were mainly the recorded contact for-

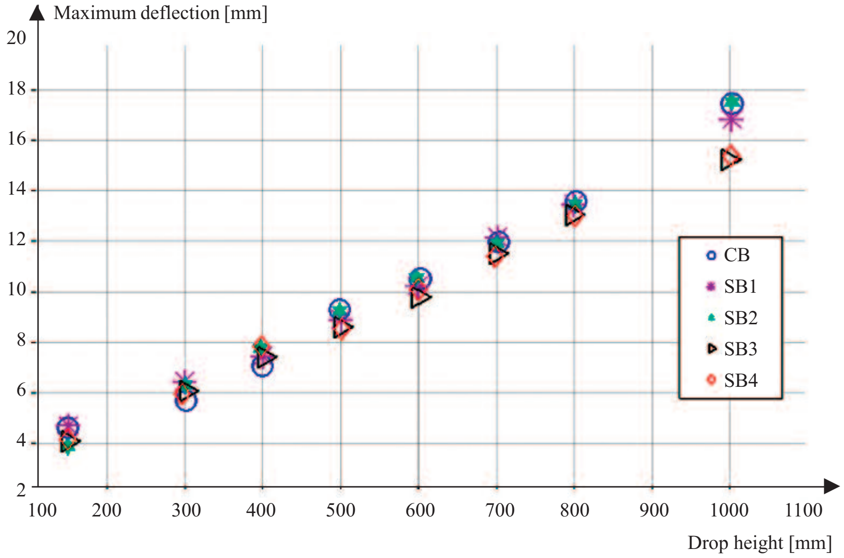

Fig. 3. Maximum deflection vs drop height
Rys. 3. Maksymalne ugięcie w zależności od wysokości uderzenia

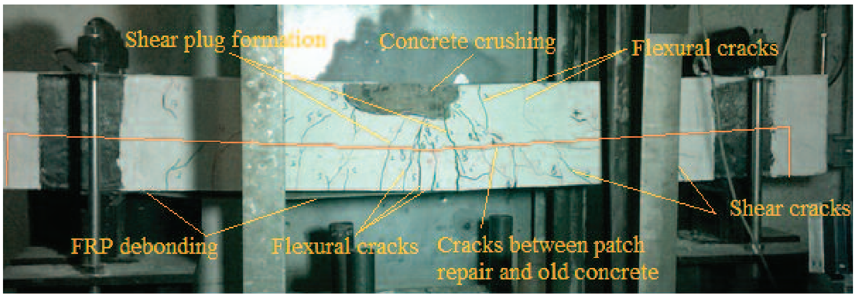

Fig. 4. Typical progression of damage, including cracking profiles and modes of failure observed during drop testing of patch-repaired and CFRP-strengthened R.C. beam (SB4_2)

Rys. 4. Typowy przebieg uszkodzeń, w tym profile pęknięć i tryby zniszczenia zaobserwowane podczas testów upadkowych belki żelbetowej naprawionej miejscowo i wzmocnionej CFRP (SB4_2)

ces and propagation of damage including the cracking patterns and modes of failure. Table 2 shows the available results of recorded contact forces obtained from the patch-repaired and CFRP-strengthened R.C. beams, only the results of the last four drop tests are shown on the said Table 2.

Table 2. Recorded contact forces results obtained from last 4 drop tests

Tabela 2. Zarejestrowane wyniki siły kontaktowej uzyskane z ostatnich 4 testów uderzeniowych

Results	SB1	SB2	SB3	Test No
Recorded contact forces (N)	36076	36713	36897	5
	38166	36682	38049	6
	37776	38342	391433	7
	40979	41096	41487	8

The results from the last four drop tests were chosen because of the considerable drop heights associated with the high impulse load, which led to a noticeable difference in results. Based on these results, it can be seen that the recorded contact force increased as the patch length increased. This can be attributed to the higher compressive strength recorded from the cementitious grout compared to concrete materials (Table 1). Thus, the longer the patch length, the higher the associated compressive strength; consequently, the recorded contact forces also increased. A greater amount of concrete broke off (through concrete spalling and scabbing) in SB1 and SB2 than in SB3 and SB4. Thus, the first two patch-repaired lengths – that is, the shorter patch lengths – lost more concrete than the last two patch-repaired lengths – the longer patch lengths. The following ascending order, with regard to the extent of cracking profile, can be established: SB4, SB3, SB2 and SB1. The differences in the extent of cracking profile as observed from the front view were slight. Moreover, as observed from the front view, these cracking profiles increased in density as the patch length decreased. This might be attributed to patch-repair materials' compressive strength and elasto-plastic ability.

Conclusion

In this study, the behaviour of rehabilitated R.C. beams with varying patch repair length was experimentally investigated under consecutive impact loading. Structural responses in terms of recorded contact force and deflections were used to assess the behaviour of various rehabilitated R.C. beams. The results of this study reveal that there was good compatibility between the patch repair and the substrate concrete of R.C. beams subjected to impact loading, that is, there was no debonding of the patch repair. The strengthened beams show ductile behaviour with flexural cracking uniformly distributed. The mode of failure for of the CFRP-strengthened beams was intermidieate crack debonding. While the beams generally exhibited ductile behaviour, the increase of patch repair length resulted in the reduction of both elastic (maximum deflection) and plastic (residual deflection) deformations of rehabilitated R.C. beams. Thus, the varying patch repair lengths can contribute to the increase of stiffness and flexural rigidity of patch-repaired and CFRP-strengthened R.C. beams. The combined use of patch repair and CFRP strengthening methods might increase the ability of rehabilitated R.C. beams to withstand the easy cracking propagation and consequently reduce the cracking density.

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Acknowledgements

The authors would like to highly acknowledge the support of the Concrete Materials and Structural Integrity Research Unit (CoMSIRU) and the Blast, Impact and Survivability Research Unit (BISRU) both, University of Cape Town.

Received: 08.05.2024
Revised: 03.06.2024