
International Journal of

CIVIL ENGINEERING AND CONCRETE STRUCTURES



ISSN : 2455-7714

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Experimental investigation on the behaviour of patched reinforced concrete column under eccentric loading: a case of compression failure

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Abstract

There are many potential reasons why a reinforced concrete (RC) element's performance is inadequate. Maintaining the structure's strength and serviceability requires taking the necessary steps to restore the defective element's performance. Spalling of the concrete cap is one way to detect a defective RC column member. One option would be to choose a patching approach that would restore the damaged region and, ideally, restore the original strength of the RC column. The purpose of this study is to determine if patch repair material is effective in restoring the functionality of broken RC columns. This study compares the performance of patched RC columns to that of a matching regular RC column in order to draw conclusions. In order to cause compression failure of the RC columns, eccentric loading has been put up in this experiment. Unsaturated polyester resin mortar (UPR mortar) is used to mend the damaged region in the simulation. Evidently, the patched parts do not trigger the manner of failure, according to the findings. Because stress is redistributed at the patched section due to the presence of patching, longitudinal reinforcements and the undamaged zone experience more stress transfer than the regular column. Patched RC columns can only hold 71% to 92% of the typical RC column's capacity.

Keywords Compression failure · Eccentric loading · Patch repair · RC column · Unsaturated polyester resin mortar

Introduction

Reinforced concrete (RC) structures must meet the requirements of strength and serviceability in their design to guarantee the safety and functionality of the buildings for their entire service life. Limits of strength and serviceability may need to be more conservatively set for certain structural parts than for others. The "strong column weak beam" idea, for instance, requires special consideration when designing RC columns. This indicates that the beam, and not the column, should fail in the event that the structure experiences loads that are excessive relative to its design. The RC column's cautious design is evident from the strength reduction factor allocated to this element, which is around 0.6 and lower than the 0.8 assigned to the RC beam in flexure (Committee 2008). A structural member that can endure both axial and flexural loads is the RC column. In an RC column, the capacity is

building an RC column. This flawed concrete is what causes the RC column's structural deficiencies, which might cause it to fail to meet the strength and serviceability standards (Achillopoulou and Karabnis 2015). Despite the RC structures' flawless construction, non-compliance with structural performance may still arise in the future. There are many potential reasons for RC structures to degrade over time. These include being exposed to harsh environments, corrosion of the embedded reinforcement, fire, seismic loads, and so forth. The structures' maximum strength and usefulness may be compromised by the degradation. Therefore, in order to keep the RC column's strength and serviceability within an acceptable range, it is imperative that any indications of degradation be promptly addressed. In any other case, catastrophic events may be triggered by the RC column's weakness. If an RC column were to fail, it might cause the whole structure to collapse, in contrast to an RC beam, which could only cause a local collapse. In light of the above, it is critical to find solutions that restore or maybe expand the capacity of the damaged RC column in order to reduce the likelihood of building collapse. Current materials, technologies and methods for retrofitting RC column include: (a) increasing cross-section (Abdollahi et al. 2012; Tsonos 2010), (b) retrofitting using steel-jacket and infill concrete to form composite structures (He et al. 2017) and (c) retrofitting through confinement mechanisms using expanded metal mesh/EMM (El-kholy and Dahish 2016), fibre glass fly mesh/FGFM (Zhao and Hadi 2011), fibre-reinforced polymer/FRP (Vincent and Ozbakkaloglu 2013), steel-reinforced polymer/SRP (Napoli and Realonso 2016), textile reinforced concrete/ TRC (Tsessarsky et al. 2013), fibre reinforced cement-based matrix/FRC (Basalo et al. 2012), steel ring (Safitri and Imran 2017), etc. repaired RC columns is lower than that of the undamaged RC columns after using this material for repairs. The severity of the damages determines the exact percentage of decrease, which may reach 22%. After heating a circular RC column, Yaqub and Bailey (Yaqub and Bailey 2011) fix it using epoxy glue. The findings suggest that a

given by the concrete and embedded reinforcements working together. One possible failure mechanism of an RC column under ultimate stress is compression failure. This condition often manifests itself when the RC column is subjected to heavy axial loads. Conversely, RC columns are prone to failure due to tension reinforcement yielding when flexural loading is the main loading type. Regardless of the RC column's failure mechanism, the design required to meet the specified strength and serviceability limits included in the Codes (Committee 2008; FIB Model Code 2010). There are a number of reasons why the structural performance of an RC column could not match its design compliance with the stipulated codes. Inadequate consolidation of new concrete during, say, the casting process may lead to casting imperfections such big voids

The primary factor influencing the decision between repairing and retrofitting damaged RC structures is the nature of the damage. Before implementing a retrofitting method to reinforce the weak RC column, a patching method should be used to recover the size of the damaged concrete in the event of spalling or delamination of the concrete cover (Yaqub and Bailey 2011). According to Rio et al. (2008), the suggested steps for using the patching technique are to remove portions of the broken concrete, clean the exposed reinforcement, apply a patch repair material to the damaged region, and finally, cure it. The qualities of the repair material chosen will determine how effective the patch repair process is. European Standard 1997 and the International Concrete Repair Institute's Guide to Material Selection and Specification for Concrete Surface Repair are two examples of codes and guidelines. Technical Requirements Series No. The repair material must meet the minimum qualities specified by the International Concrete Repair Institute (03733, Virginia, United States of America, 1996), which include flexural strength, compressive strength, bond strength, shrinkage, creep, coefficient of thermal expansion, and more. When it comes to structural performance, the goal is to restore the strength and serviceability of the repaired RC structure by using an appropriate repair material and a patching procedure (Kristiawan et al. 2016). Patching the defective RC column may not need further retrofitting work if this is successful. Repairing broken RC columns with various materials does not result in a strength recovery, according to previous studies. A high strength fiber-reinforced thixotropic material was used to fix the casting flaw of RC square columns by Achillopoulou and Karabnis (2015). The load-carrying capability of the

post-heated RC column with spalling might have its capacity increased by 15% when patched with epoxy resin, in comparison to a post-heated RC column without spalling. But without the FRP composite covering, the patching won't be able to bring the unheated RC column back to its original capacity. Porto et al. (2012) repaired

RC square columns using a variety of cementitious mortars treated with polymers. Repaired RC columns do counterparts. In order to determine whether the repair material is suitable for restoring the RC columns, they identified its elastic modulus and compressive strength as crucial features. It is anticipated that the repair material would reinstate the structural performance of the damaged RC columns since its elastic modulus and compressive strength are most comparable to the concrete substrate.

The concrete cover's spalling or delamination may

take place at any point along the RC column's height. Previous studies demonstrate repair in cases when damages happen either locally or along the height of the RC column, as mentioned in the previous paragraph. But when the damage is concentrated in the area around the beam-column junction, a serious situation develops. Seismic loads and other strong horizontal loadings often cause this kind of localised damage. The loads cause a limited area of damage at the joint due to an excessive superimposed moment and shear. Patching or a mix of patching and other retrofitting techniques may fix the damage. In order to predict future loadings, the choice must be based on the amount of damage and the structure's desired performance. This procedure should be used if patching is the last resort for fixing the broken RC column. can ensure that the repaired RC column will function similarly to the unharmed RC column. This research aims to investigate the structural perfor-

mance of patched RC columns. The structural performance of the patched RC columns will be compared with that of normal RC column to assess the suitability of patch repair material to restore the performance of the damaged RC column. The localised damages at near the joint are chosen for this investigation with a variety of depths and zones of repair. The patch repair material is unsaturated polyester resin (UPR) mortar. This type of patch repair material has been developed by authors and its performance to restore the flexural and shear strength of RC beams has been identified (Supriyadi et al. 2015; Kristiawan et al. 2017). For this particular research, a case of RC column with compression failure mode under eccentric loading is set up for the investigation.

Experimental investigation

Materials

The following ingredients were used to make the patch repair material: sand, cement, fly ash, and unsaturated polyester resin (UPR) with its corresponding hardener. What we call UPR mortar is really a patch repair substance. The YUKALAC® 157 BQTN-EX UPR, a polymerised mixture of di-carboxylic acids and glycols, was used in this study as an unsaturated orthophotic type resin. It is the curing ingredient (hardener) that starts the thermo-setting process in this material. For one cubic metre of UPR mortar, the following

not function as well structurally as their unharmed

Table 1 Mechanical properties of concrete and UPR mortar

Specimen ID	Concrete		UPR	morta
	Compressive strength (MPa)	Elastic modulus (MPa) ^a	Compressive strength (MPa)	Elastic modulus (MPa)
CN	22.40	22,244.45	—	—
CR-1	24.29	23,163.89	68.00	9366.68
CR-2	27.90	24,825.61	68.00	9366.68
CR-3	27.98	24,861.17	65.00	10,031.32

^aEstimated by $4700 \sqrt{f'_c}$

materials were used: 950 kilogrammes of sand, 808 kilogrammes of cement, 143 kilogrammes of fly ash, 475 kilogrammes of UPR, and 14.25 kilogrammes of hardener. Both the mechanical (Kristiawan and Prakoso, 2016) and shrinkage-related (Kristiawan and Fitrianto, 2017) features of UPR mortar have been the subject of prior investigations. The primary mechanical characteristics of UPR mortar are summarised in Table 1. The parent concrete (RC columns) were made from concrete with an average strength of 25 MPa. As demonstrated in Table 1, the casting concrete's actual strength for RC column manufacture might vary. When analysing the outcomes, the strengths' variability will be considered. At the same time, the yield strength of the steel reinforcements is about 296 MPa.

RC column specimens

In preparation for the investigation, four RC column specimens were made. Similar reinforcement ratios and layouts are used in all of the RC columns. The RC column has a cross section of 110×150 mm² and an effective height of 1000 mm. An option among CN RC columns, shown in Figure 1a, were cast like standard RC columns without any artificial damage. Different simulated dams were used to cast the remaining RC columns. The specimens were placed in the laboratory room and covered with damp hessian for 21 days after casting. They were then left to mature for 90 days. By this point, UPR mortar had been used to repair the simulated damage. Numbers CR1, CR2, and CR3 were assigned to the three patched RC columns (Fig. 1b-d). We tested all of the RC columns under eccentric axial strain the day after we patched them.

Testing RC column

As the horizontal beam at the base of the RC column sits on top of the base plate, the column was positioned on top of it. Several anchors were used to secure the base plate to the hard floor. The horizontal beam was topped with upper steel plates on each side of the vertical column. Using the matching nuts and four threaded bars, each plate was fastened to the base plate. Tightening the nuts would stop the RC column specimen from moving in any direction, including translation and rotation. This would lead one to believe that the RC column is immobile at its bottom joint (i.e., not capable of translation or rotation) and completely free at its top joint (i.e., capable of both). Utilising a loading jack, the column was subjected to axial loading. The loading jack was connected to the top of the column by inserting a loadcell. The magnitude of the applied load was measured by this loadcell. An eccentric application of the axial load was made. The axial load that was applied had an eccentricity of 10 mm. This irregularity caused the RC column to be subjected to both axial and flexural loads. It was anticipated that the RC column would burst by a compression failure mechanism at this eccentricity of 10 mm. The specimen was subjected to loading increments of 100 kg until it reached the final value that ruptured it. Dial gauges were used to monitor lateral deformations while strain gauges were used to measure axial deformations at each load increment. Near the junction, strain gauges are fastened to the surface of the concrete or UPR mortar.

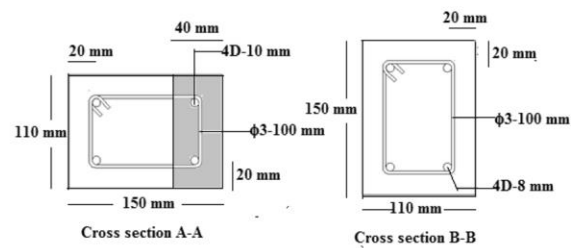
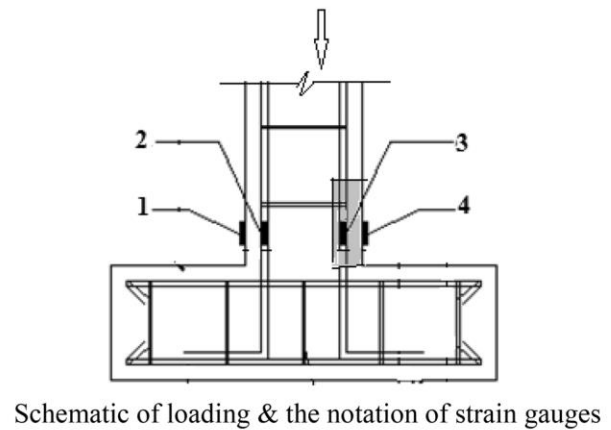
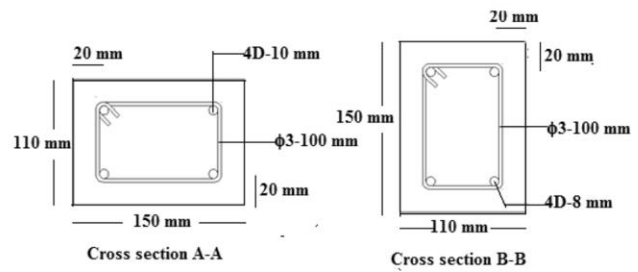
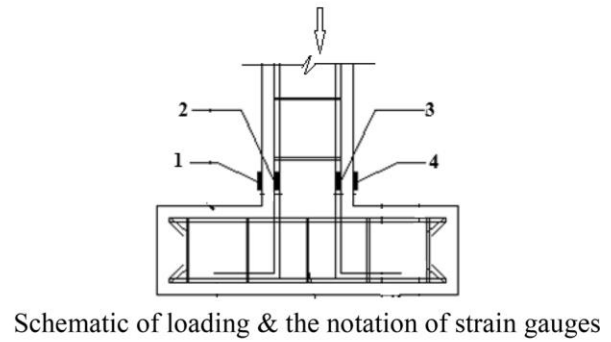
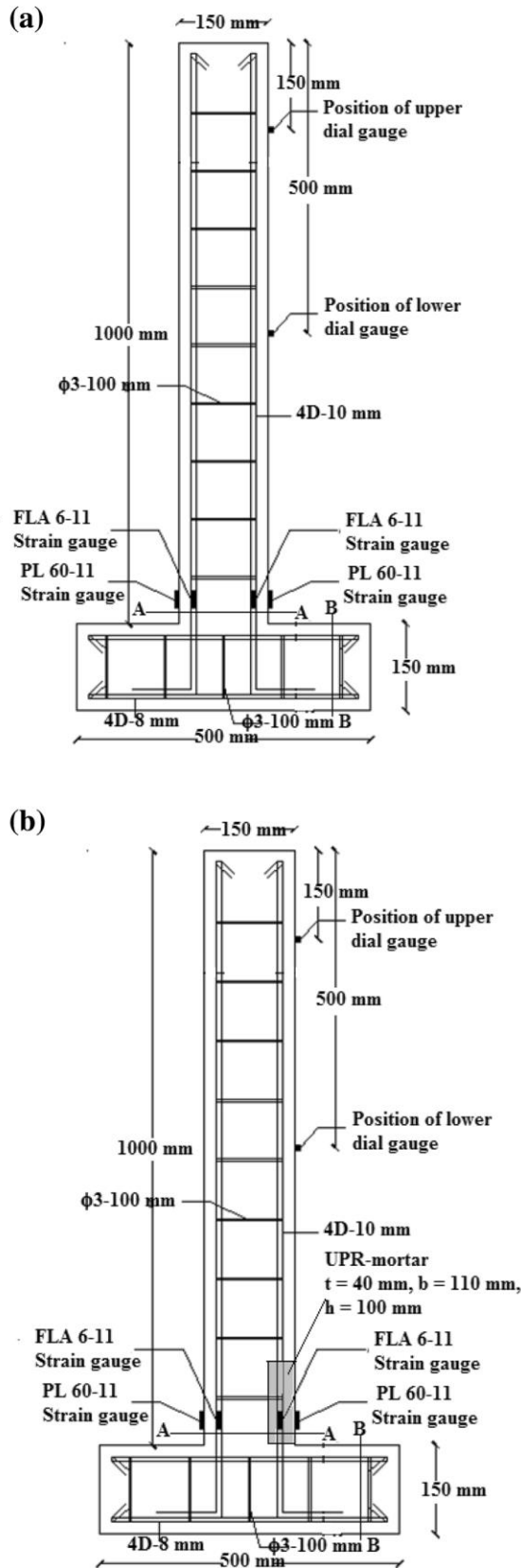
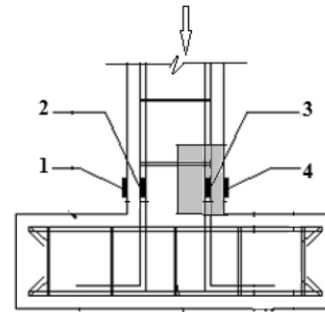
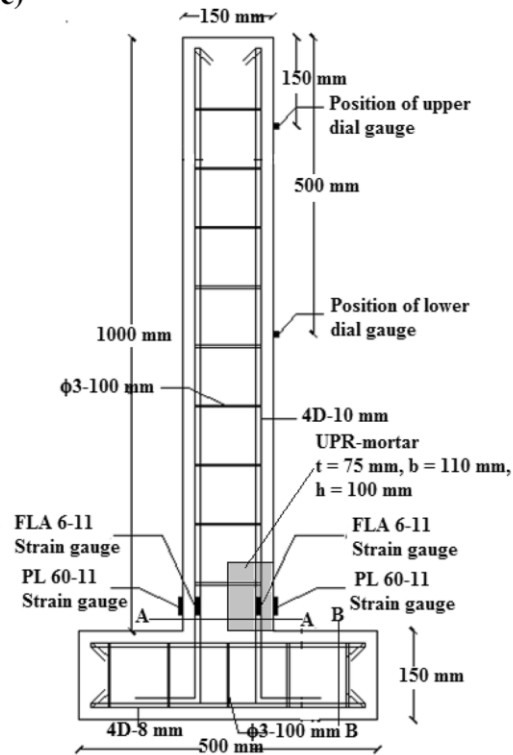
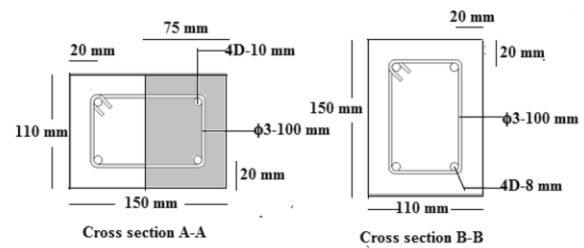


Fig. 1 a Reinforcements detail of CN column. b Reinforcements detail of CR-1 column. c Reinforcements detail of CR-2 column. d Reinforcements detail of CR-3 column

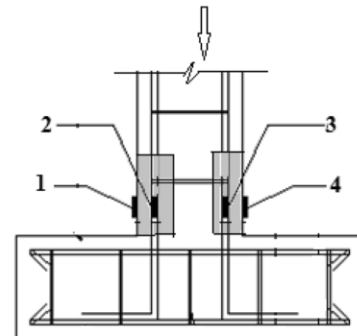
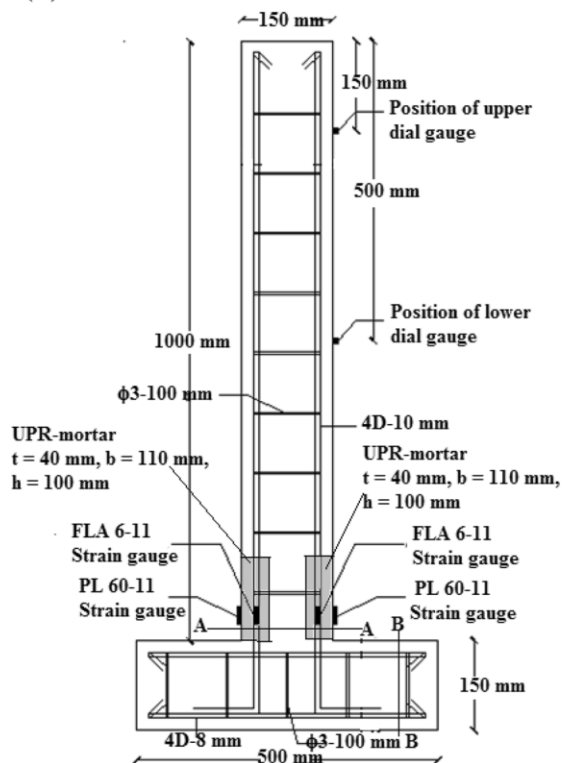
(c)



Schematic of loading & the notation of strain gauges



(d)



Schematic of loading & the notation of strain gauges

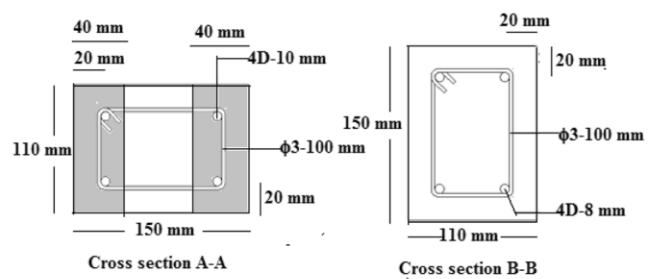


Fig. 1 (continued)

at the ends of the fibres. The surface of the longitudinal reinforcements was also equipped with strain gauges (see to Fig. 1a-d for details). Fig. 2 shows that dial gauges are used to measure the columns' lateral displacement at 500 mm (lower level) and 800 mm (higher level).

Results and discussion

Modes of failure

The eccentricity of 10 mm is used to apply the axial load. The whole segment of the column is therefore anticipated to experience compressive forces of varied intensities. In a perfect world, the eccentric load would exert its greatest compressive force at the very tip of the RC column, where the extreme fibres meet. The area just under the applied load is likewise likely to have a larger stress concentration. The failure modes provide more evidence of this (refer to Figure 3). The concrete cover spalls in the zone of highest load concentration; this is the same failure mechanism that affects all RC columns. An extra mechanism of failure has been noticed for the CN column. There are fissures in the column where the beam meets the column. Spalls are

The zone at the beam that is subject to a greater combined flexure-shear stress is known as the flexure-shear type. This

occurrence might be caused by the concrete used to make the CN column having a lower real strength.

Load-axial strain

We use PL-60-11 strain gauges to measure the axial stresses of the concrete/UPR mortar and FLA-6-11 strain gauges to measure the longitudinal reinforcement caused by the applied load. A unique identification number is assigned to the spot where the strain gauges are installed in every RC column: Figure 1 shows the locations of strain gauges for measuring axial strain on the extreme fibre of concrete/UPR mortar, and for measuring axial strain on the longitudinal reinforcements, the locations are #3 and #4. Additionally, the figure indicates the eccentricity of the applied load. Figure 4 displays the findings of axial stresses as a function of load. In most cases, the cross sections of RC columns experience compressive stress, as seen by the negative axial stresses that almost cover the whole section. The strain at #1, which is the axial strain on the concrete opposing the eccentric load, is the lowest of all the strains observed. This action is in line with the most little tension that may be felt at #1. It is possible to replace the tension caused by an eccentric load with a mixture of stresses caused by a concentric

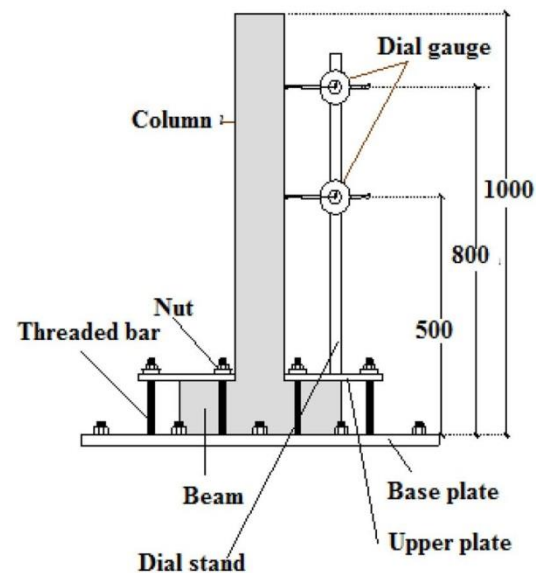
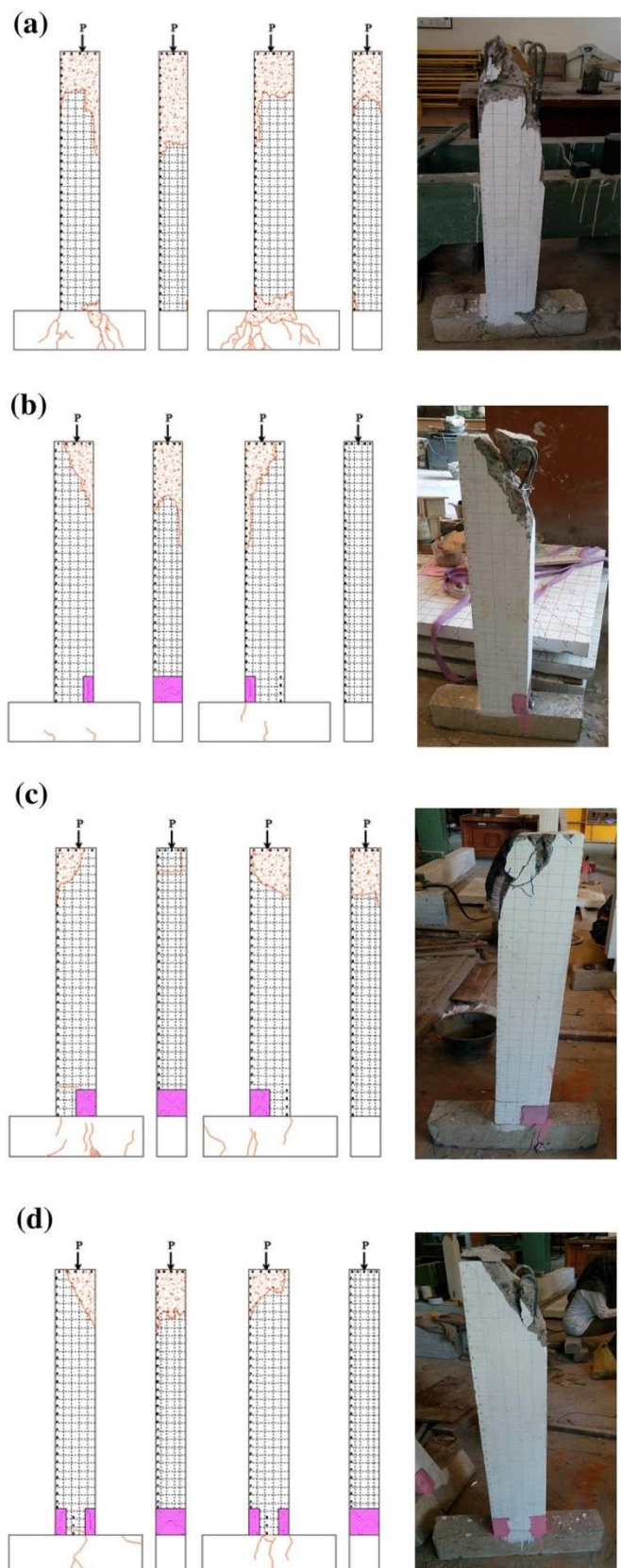


Fig. 2 Fitting the RC column specimen to restrain translation and rotational movement at the beam-column joint

Fig. 3 **a** Failure mode of CN column. **b** Failure mode of CR-1 column. **c** Failure mode of CR-2 column. **d** Failure mode of CR-3 column



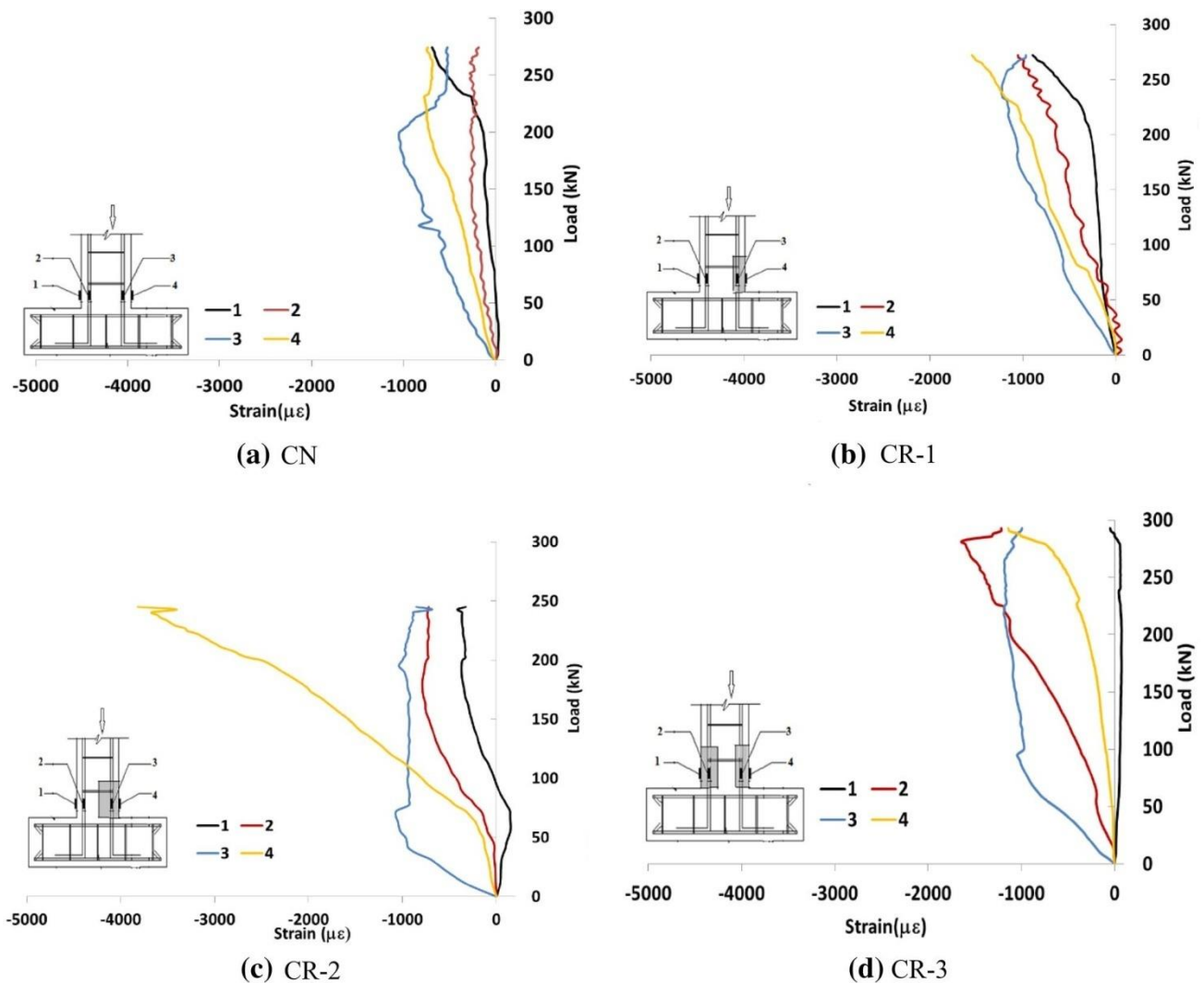


Fig. 4 Load-axial strain relationship

stresses and their associated moments. Concentric load compressive stress will be superimposed by moment-induced stress. The produced compressive stress caused by the concentric load at #1 is reduced by the largest positive moment operating at that position. Therefore, the compressive stress at point #1 is reduced to its minimum. Since the compressive stress caused by the biggest negative moment at #4 would superimpose the compressive stress from concentric load, it stands to reason that strain at #4 would be the greatest. This inquiry could not, however, find any evidence to support the claim. The distribution of stresses over the section for all columns at different load levels is shown in Figure 5. At low load levels (less than 40% of the ultimate load), stresses at #4 are clearly lower than strains at #3 for all RC columns, as shown in Figure 5. It is possible that the conduct is connected to the constricting impact of the stirrup. There is a great concentration of stress in this area since the stirrup confines the concrete column's core.

enclosed space. However, the stirrup's capacity to tolerate significant stress may be compromised at a high load level. Therefore, stress will be redistributed, with the concrete cover taking a disproportionately large hit.

Load-lateral deflection

The lateral deflection responses of the columns due to the corresponding applied eccentric loads are given in Fig. 6 for each column individually; whereas in Fig. 7 the load-lateral deflections of all columns are presented in a single diagram either the one representing the lateral deflection measured at an upper level or a lower level. For each column, a higher lateral deflection is obviously shown at an upper level of measurement. The present of patching gives a distinctive load-lateral deflection behaviour. In normal column (CN), plastic response can be detected after the load reaches about

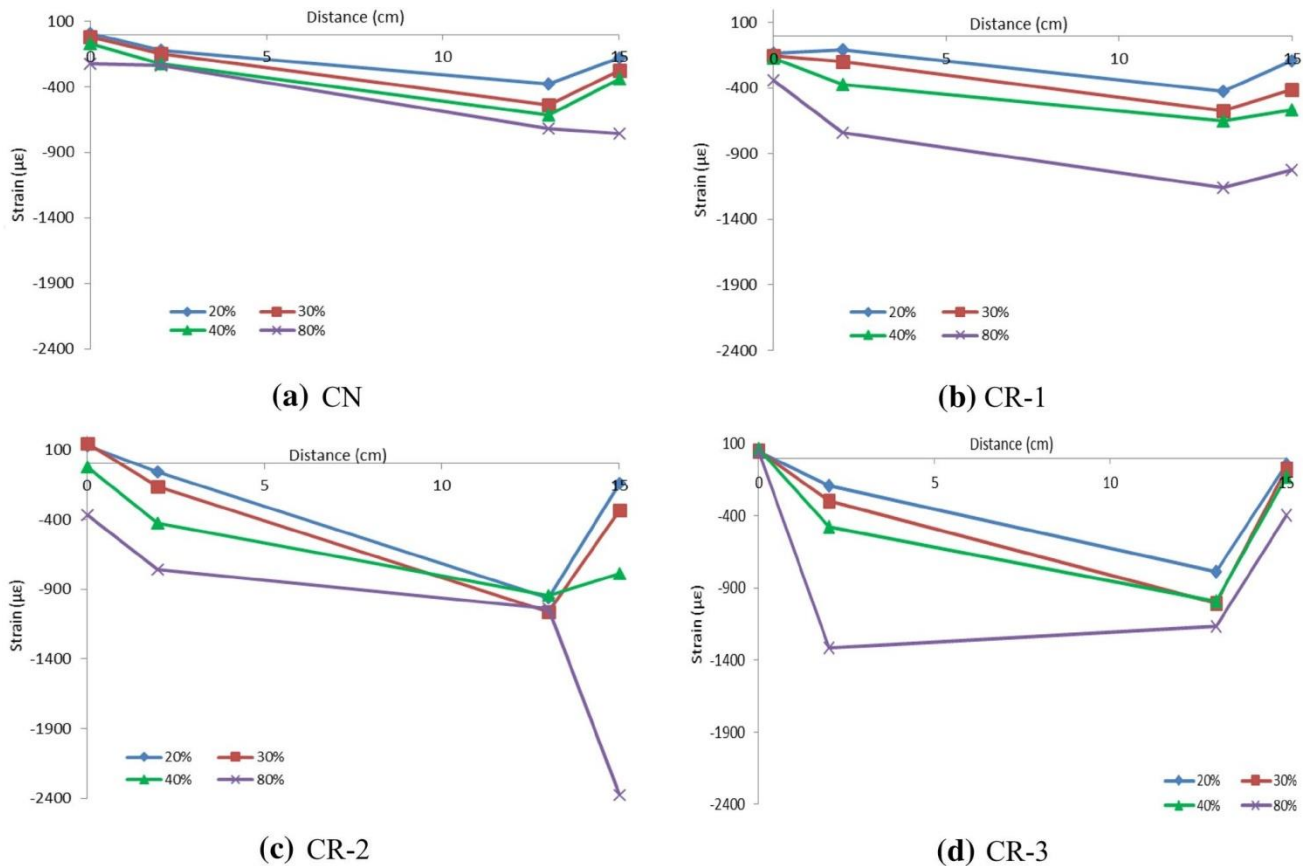


Fig. 5 Strain distribution across the section at various load level

two thousand tonnes. Even a little increase in load beyond this point results in large lateral deflections at the top and bottom of the measuring scale. At both the higher and lower levels of the measurement, the CN column exhibits a final lateral deflection of about 21.5 and 12.99 mm, respectively. Despite the fact that all columns exhibit non-linear responses, particularly under heavy loads, no plastic reactions are discernible in the repaired columns. To get to the bottom of things, it would be wise to look into it thoroughly. The CN column's plastic reaction may be associated with the specimen's lower strength concrete, as compared to the patched RC columns (refer to Table 1). Cracking at the beam-column connection is an additional failure mechanism associated with concrete with lesser strength. Beam fractures of the flexure-shear kind are shown in Figure 3a. The 20-ton load is the breaking point for the beam-column junction. The fractures propagate with increasing load, which in turn increases stress transfer to the reinforcements. The plastic behaviour of the CN column is dictated by the reinforcements, which undergo accelerated deformation due to stress transfer; this includes both the column's longitudinal reinforcements and the beam. Regrettably, it is not possible to record this kind of activity.

according to the strain gauged on the individual reinforcing. There are cases when the yielding section of reinforcement

does not coincide with the local strain measured by the strain gauge, which only extends 6 mm along the longitudinal reinforcement of the column. Compressive strain measurements taken on longitudinal reinforcement #3 reveal this to be the case. As shown in Figure 4a, the strain measurement is disrupted when the first fractures emerge at the beam-column junction under a 20 tonne load, leading to a dramatic reduction in strain #3.

Figure 7 shows the load-lateral deflection behaviour as a function of patching zone and patching thickness. Normalising the load according to the compressive strength of each kind of concrete used to make the column specifications is desirable for comparative purposes (Table 1). One way to normalise the load of the patched repair column is to take the ratio of the compressive strength of concrete CN to that of concrete CR-1, CR-2, and CR-3. To get the normalised loads of the repaired columns, we multiply the measured loads on each patched repair column by the corresponding ratio. The comparison between the normalised loads and the lateral deflections found in the

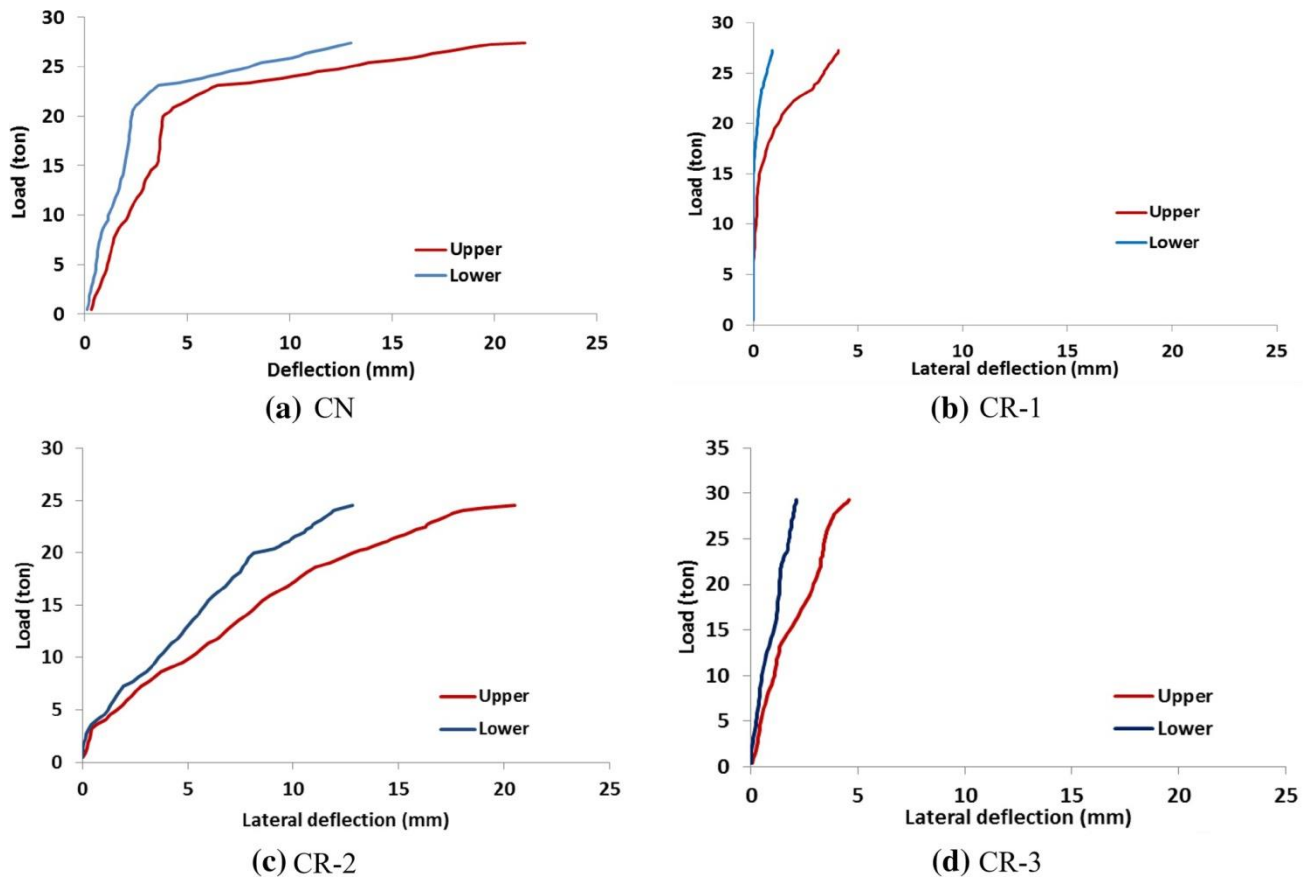


Fig. 6 Load-lateral deflection of column

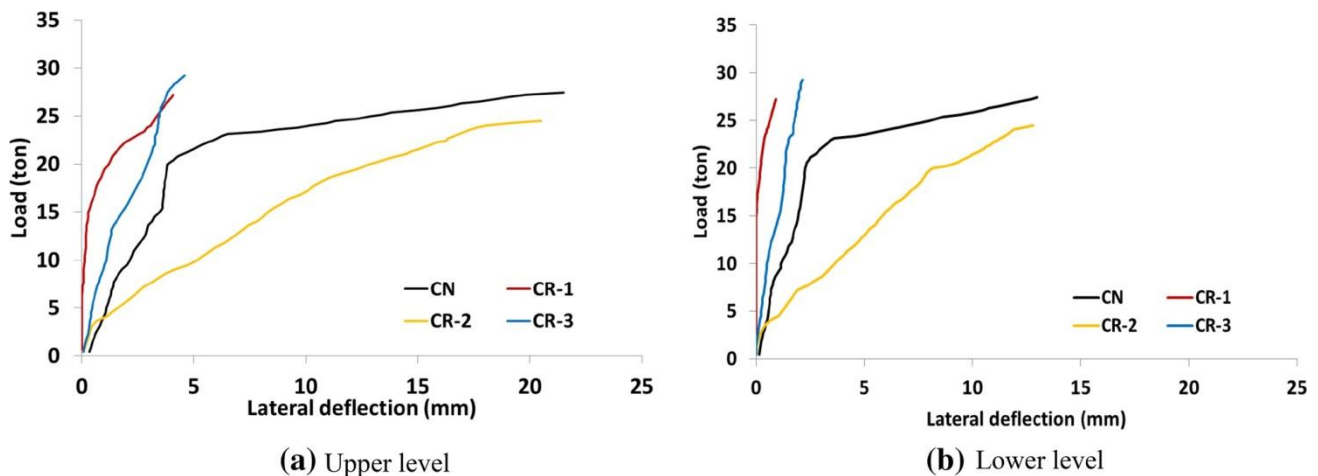


Fig. 7 Effect of patching on the load-lateral deflection

Figure 8 displays the columns. Figure 8 shows the load-lateral deflection at a load of 20 tonne, which is lower than the load that causes the plastic reaction of the CN column. This load is chosen for the sake of comparison. This image clearly shows that the lateral deflection of the CR-1 and CR-3 is reduced compared to the relative to the CN column. Contrarily, CR-2 initially displays a rigidity that is similar to

that of the other columns. On the other hand, compared to other columns, CR-2's stiffness begins to drastically decrease with loads greater than 2.72 tonne, resulting in a larger lateral deflection. The actions that

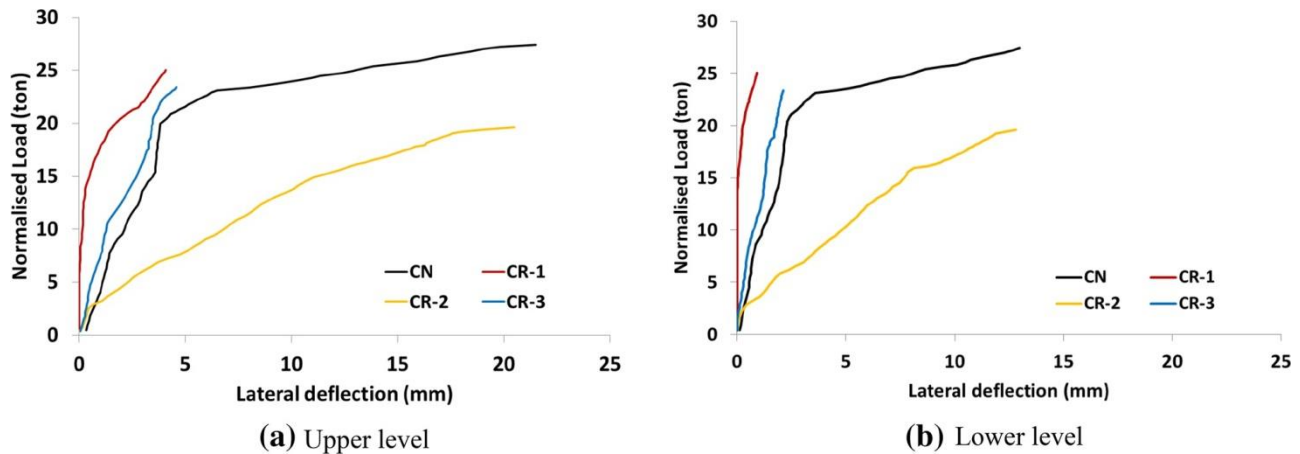


Fig. 8 Effect of patching on the normalised load–lateral deflection

One possible explanation is that the stresses in the patched section are distributed more evenly in the undamaged portion because of the presence of UPR mortar, which has a lower elastic modulus than parent concrete (see to Table 1). The longitudinal reinforcements also take a heavier load. Figure 9 shows the condition where the stresses and strains recorded by strain gauges #1, #2, #3, and #4 (refer to Fig. 1) are calculated under a load of 10.8 tonne. The distribution of these characteristics over the columns' section at 0, 2, 13, and 15 cm from the left extreme fibre (or strain gauge #1) is represented by these strains and stresses. In order to offset the moment caused by the eccentric load, the figure shows that a larger compressive stress is seen at longitudinal reinforcement #3 when there is patching. The columns' stability may be maintained with the help of this counteraction. But for CR-2, the increased patching thickness (almost half of the section) causes higher stresses in the patching region, which impacts the column's deformation.

Ultimate load

Damaged repair columns have a failure load that is similar to a normal column (CN)—between 24.5 and 29.3 tonne. Nevertheless, when the specific compressive strengths of the concrete used to construct each column are considered, the failure (normalised) load of the repaired and patched columns drops to 19.6–25.3 tonne. This load range accounts for 71–22% of the typical column (CN). A column with a planned compressive strength of 22.4 MPa and a reinforcement arrangement identical to the columns under investigation is shown in Figure 10, which is an interaction diagram. Theoretically, the diagram shows that CN column can sustain both axial (P_n) and flexural (M_n) stresses. Results demonstrate that the CN column's experimental P_n and M_n values lie outside the interaction diagram, suggesting that the column's real capacity exceeds its theoretical one. Yet, RC columns' normalised capacity falls short of the theoretical maximum. Therefore, the initial strength of RC columns could not be restored using a patching approach utilising UPR mortar.

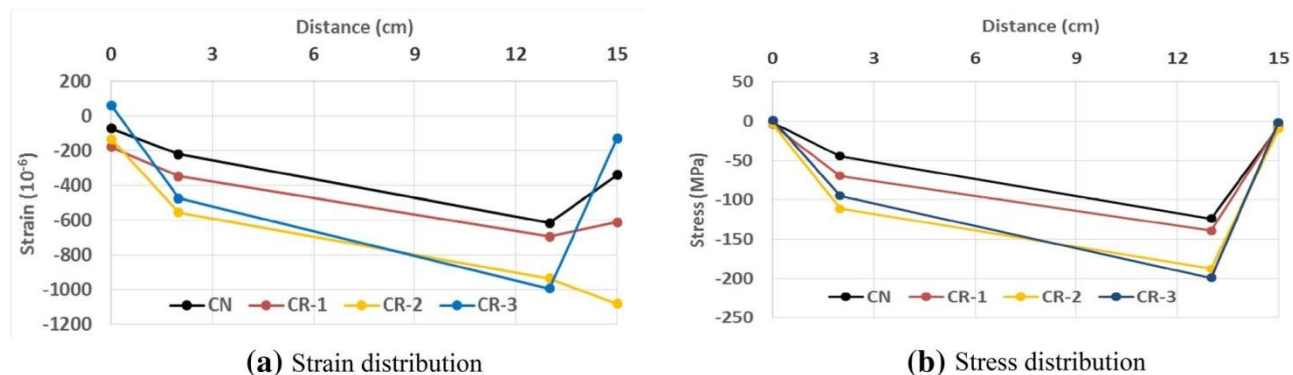


Fig. 9 Strain and the corresponding stress distribution at a load of 10.8 tonne

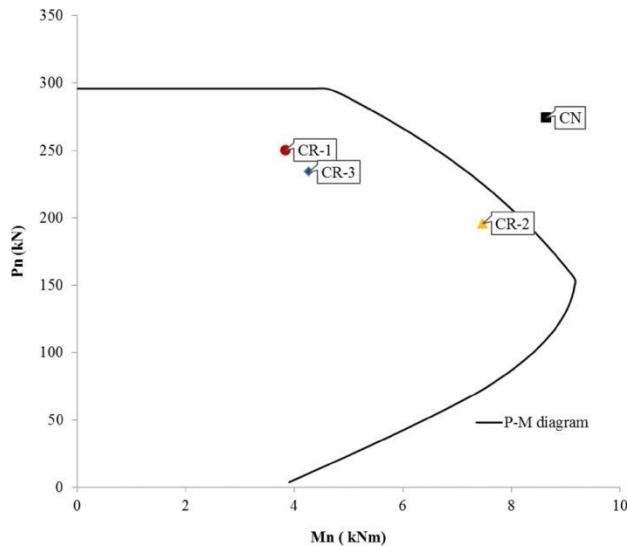


Fig. 10 Experimental value of P_n and M_n compared to theoretical interaction diagram of CNs

Conclusions

Based on our experimental findings, we can say the following about the performance of patched RC columns:

- Spalling of the concrete cover in a zone with greater stress concentration, i.e. directly beneath the applied load, is an indicator of the compression failure mode of a patched RC column.
 - The uneven distribution of stresses in the unconfined zone is caused by the confinement of the stirrup, which affects the fluctuation of stresses throughout the patched section.
- When there is patching, the stress is redistributed at the patched section. As a result, the undamaged zone and longitudinal reinforcements experience more stress transfer than the regular column.
- The load-lateral deflection behaviour of patched RC columns is affected by the thickness and zone of patching. This behaviour may be connected to the distribution of stress over the patched sections.
 - RC columns would not be able to recover to their former capacity when patched with UPR mortar.

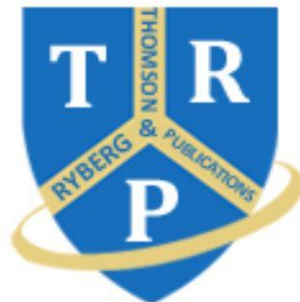
Acknowledgments The research is financially supported by Directorate Research and Community Services, the Ministry of Research, Technology and Higher Education, Indonesia through Competence Based Research Scheme (Contract No. 873/UN27.21/PP/2017).

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