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Behaviour of patch repair of axially loaded reinforced concrete beams

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Abstract

Experimental investigation is conducted to assess structurally the effectiveness of patch repair in axially loaded columns. Two patch repair materials are selected with high and low modulus of elasticity. The concrete columns were patch repaired under loaded and unloaded conditions. The patch repair is structurally effective for concrete columns repaired in an unloaded state. While for concrete columns repaired in a loaded state, the patch repair is structurally effective only when additional loading is applied. The load distribution between the patch repair, concrete core and steel reinforcement depends on the modulus of elasticity and areas of these components in the composite section at the repaired zone. For patch repair to be structurally effective, it is recommended to relieve the loads before the patch repair is applied either partially or totally if constructionally possible.

Keywords: Patch repair; Axial columns; Concrete deterioration; Load distribution

1. Introduction

Deterioration of concrete columns in the Arabian Gulf area as shown in Fig. 1 is mainly attributed to the chloride induced corrosion of reinforcing steel. Moisture rises from the groundwater table in the concrete above ground level by capillary action followed by high evaporation rates due to high temperature. This leaves a heavy crest of chlorides in the zone above the ground level. Usually more salt penetrates than is leached out, thereby causing significant concentrations to develop within the concrete over the years. Chlorides dissolved in surface moisture are also deposited on the concrete surfaces and subsequently enter the pores of concrete by capillary action. Just above the ground level, all conditions required for triggering corrosion action are met as the oxygen becomes available. It creates microclimates within the concrete pores that initiate corrosive action. As the corrosion of steel reinforcement progresses, deterioration in the form of cracking and spalling of concrete columns occurs at the ground level. If a significant amount of material at the compression zone is lost, loads are transferred to the intact core of the compression member resulting in substantially higher stresses and subsequently detrimental to the structural integrity and safety [1–3].

The conventional approach to repair a corroding reinforced column due to chloride attack has been the use of patch repair in the damaged zones where cracking and spalling take place. The columns are generally repaired by removing the damaged concrete beyond the steel reinforcement. Then the reinforcements are either cleaned or replaced depending on the severity of the damage. Finally,

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Fig. 1. Deterioration of columns in the Arabian Gulf region.

a prepackaged cementitious repair material is applied [4]. The majority of column repair cases have taken place in a loaded state. However, when patch repair is considered for structurally critical columns, the columns are jacked to release or reduce the loads before any repair. It is essential that patch repair for a column must form an integral part of the composite member to be structurally effective [1].

This paper presents the structural behaviour of patch repaired axial columns. Experimental investigation is conducted to evaluate the structural effectiveness of patch repair contribution to the load resisting capacity of the columns. The patch repair was applied in loaded and unloaded states for the columns. Two types of patch repair material were used to represent the range of commercially available repair materials.

2. Experimental programme

2.1. Preparation of concrete columns

Fourteen concrete columns 250 × 250 mm in cross section and 1200 mm height were prepared. The columns were reinforced by 1% of its cross-sectional area. Eight 10 mm diameter bars were used as the main reinforcements and 8 mm diameter bars as stirrups. A typical column is shown in Fig. 2. The columns were cast using Type I Portland cement, dune sand and crushed limestone as coarse aggregates. The mix design is given in Table 1. The curing was done by wet burlap for 21 days.

2.2. Application of patch repair

A recess was made during casting using polystyrene blocks to form cavities on opposite sides for patch repair application as shown in Fig. 2. The recess was sandblasted before applying the patch repair. The patch repair was applied to columns in unloaded and loaded states. For

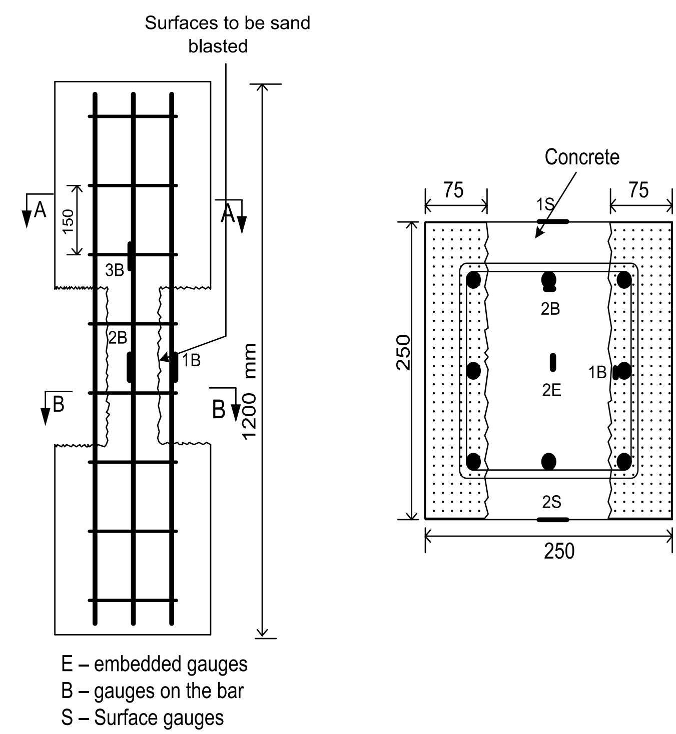

Fig. 2. Details of a typical column specimen showing repair schemes.

Table 1
Mix proportion for concrete column

Material	Unit	Quantity
Cement + microsilica	kg/m^3	355 + 30
Free water	kg/m^3	154
Fine aggregate	kg/m^3	680
Coarse aggregate (10 mm/20 mm)	kg/m^3	485/625
Superplasticizer	l/m^3	1.4
Slump	mm	110

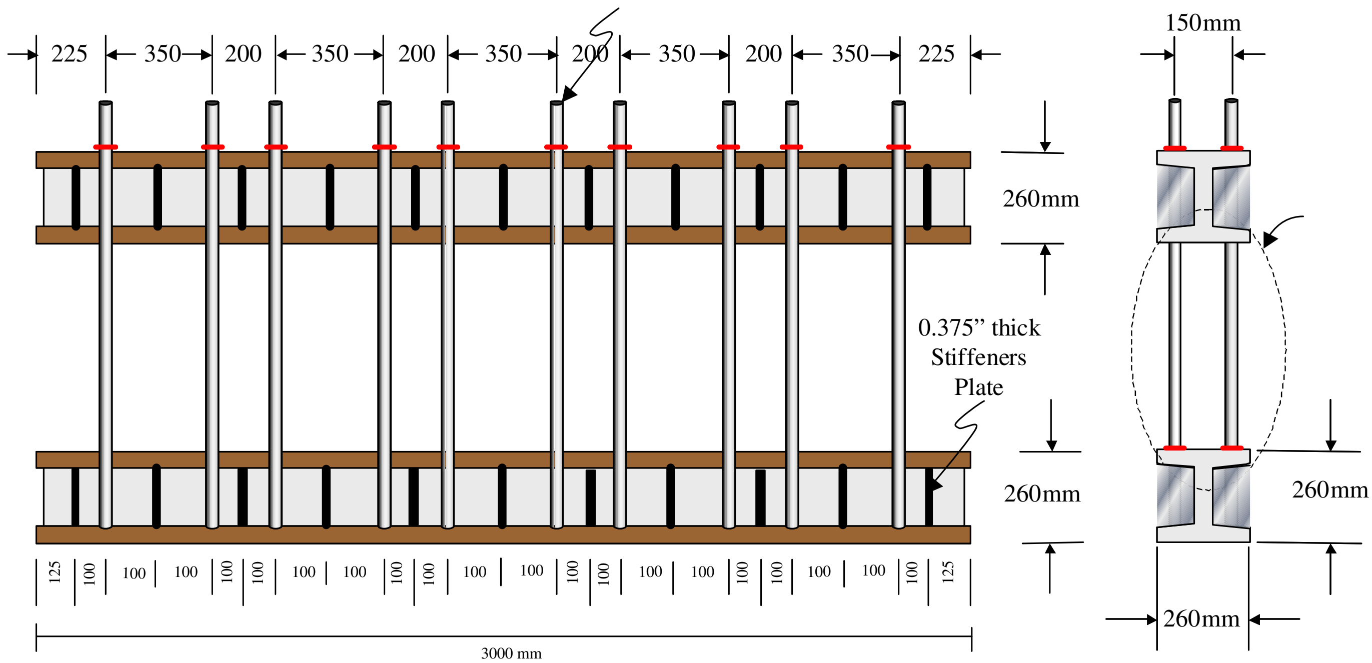

Fig. 3. Loading frame for column repaired in a loaded state.

Fig. 4. Columns repaired in a loaded state left to cure.

the loaded state, the columns were mounted in a loading frame as shown in Fig. 3. The columns were maintained under loading equivalent to 20% of its ultimate capacity. The patch repair was applied to these stressed columns and left to cure as shown in Fig. 4.

Two repair materials were selected to represent high and low elastic modulus. The high elastic modulus repair material is FMCX which is a flowing microconcrete suitable for mass infill to structural repair. The other material is PFSM which is a low elastic modulus and polymer modified cementitious material with silica fume and fibres. The major characteristics of the two repair materials are given in Table 2.

Table 2
Properties of the repair material

Test method	Age (days)	Typical result
Drying shrinkage ASTM C157-93	7	:<300 microstrains
	28	:<500 microstrains
Permeability DIN 1048 Part 5		:<10 mm
Flexural strength BS 6319 part 3	28	:>9 N/mm^2
Tensile strength BS 6319 Part 7	28	:>5 N/mm^2
Compressive strength BS 1881 part 116	28	:>60 N/mm^2
Modulus of elasticity	28	:>33 GPa
Drying shrinkage ASTM C157-93		Not provided
Flexural strength ASTM C-348	28	:>7–9 N/mm^2
Adhesive tensile strength ACI 503	28	:>1.5–2.5 N/mm^2
Compressive strength ASTM C-109	28	:>45–55 N/mm^2
Modulus of elasticity (Static)		:>25 GPa

2.3. Groups of columns

The prepared concrete columns are divided into six groups as follows:

Group I: Three columns without recess (UC1, UC2 and UC3) which represent undamaged concrete columns.

Group II: Three columns with recess (RC1, RC2 and RC3) and without patch repair to represent damaged concrete columns.

Group III: Two columns repaired with FMCX material (FMCX1 and FMCX2) applied in an unloaded state.

Group IV: Two columns repaired with FMCX material (FMCX3 and FMCX4) applied in a loaded state.

Group V: Two columns repaired with PFSM material (PFSM1 and PFSM2) applied in an unloaded state.

Group VI: Two columns repaired with PFSM material (PFSM3 and PFSM4) applied in a loaded state.

2.4. Loading and measurements

The speed application of the load was kept at 5 kN/s. Initially, a load of 25–30 kN was applied and the strains on opposite faces of the specimens were monitored to check for any eccentric loading and do the necessary adjustment.

Destructive load tests were conducted on the ten columns of groups I, II, III and V. For the other four columns of groups IV and VI, the load was increased from the initial 20% to the final 40% of the columns ultimate capacity as the setup of the frame did not allow for destructive testing.

The measured strains for steel embedded in concrete and patch repair, for concrete both in core and at surface and for patch repair were monitored at mid-height of the column as shown in Fig. 2.

3. Results and discussion

The load versus the measured average strain for the different groups are presented. Then the percentage load distribution between the different components of the columns at failure or maximum applied load is shown.

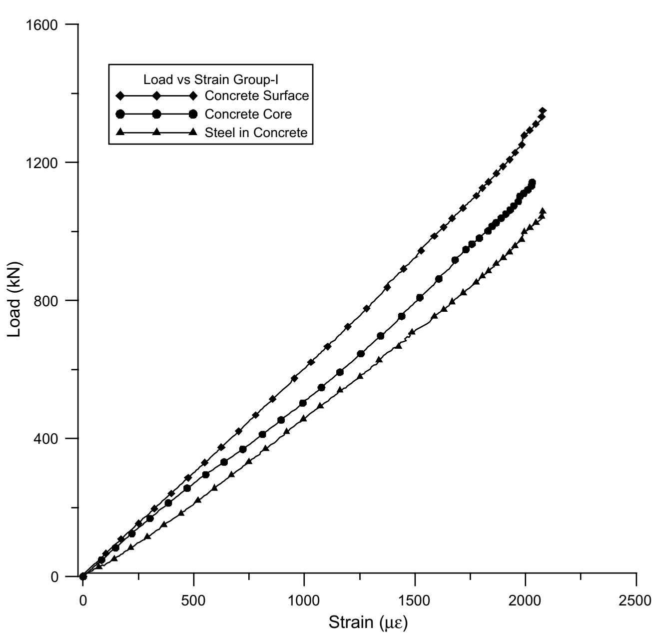

Fig. 5. Load versus average measured strain for group I.

3.1. Columns without and with recess

The columns of groups I and II represent undamaged and damaged columns, respectively. The load versus the average measured strain for columns (UC1, UC2 and UC3) and columns (RC1, RC2 and RC3) are shown in Figs. 5 and 6, respectively. The strain at the surface of concrete is higher than that at the concrete core and on the steel for both groups. For group II, the average measured strain in the exposed steel bars is less than that of the embedded steel bars. For group I, the columns failed by crushing and spalling of concrete at the lower end of the column as shown in Fig. 7. While for group II, the columns failed in the recess portion by buckling of the exposed steel as shown in Fig. 8.

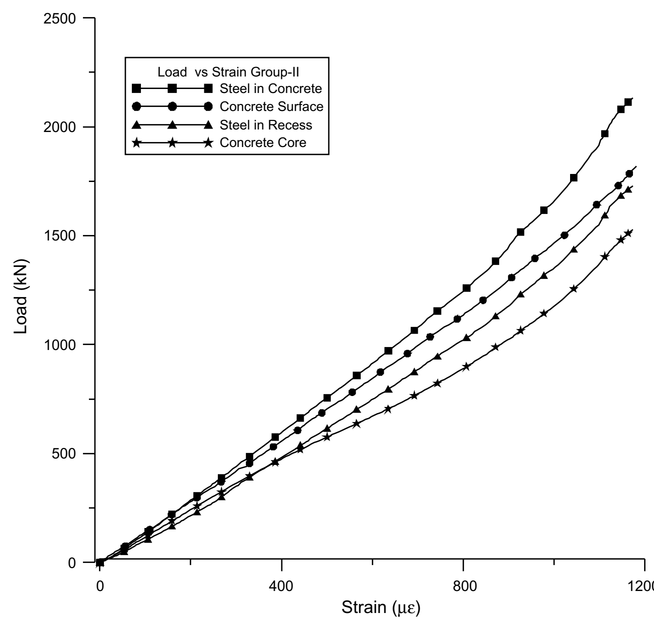

Fig. 6. Load versus average measured strain for group II.

Fig. 7. Column failure of group I.

Fig. 8. Column failure of group II.

The load distribution for the different components of the columns at failure for these two groups is shown in Fig. 9. It is apparent that due to the reduction area of the concrete due to the recess, the steel has picked up this additional load. The concrete contribution to support the load was reduced from 93% to 83% while the steel was increased from 7% to 17%. This clearly indicates that damaged columns subject the steel bars to higher stresses.

3.2. FMCX patch repaired columns

For columns repaired in an unloaded state, the load versus the average measured strain for the various components of columns (FMCX1 and FMCX2) of group III are shown in Fig. 10. The measured strain at concrete surface is higher than that at the concrete core. The measured strain of steel bars within the patch repair is lower than that at

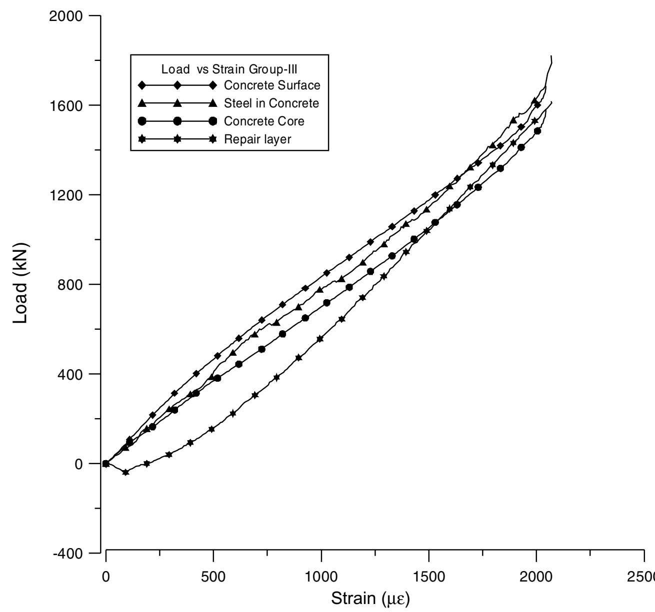

Fig. 10. Load versus average measured strain for group III.

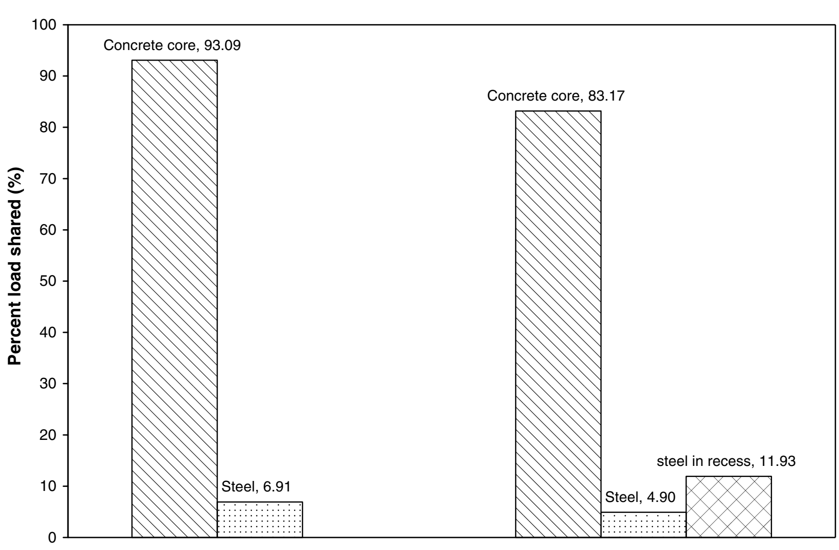

Fig. 9. Load distribution for groups I and II.

Fig. 11. Column failure of group III.

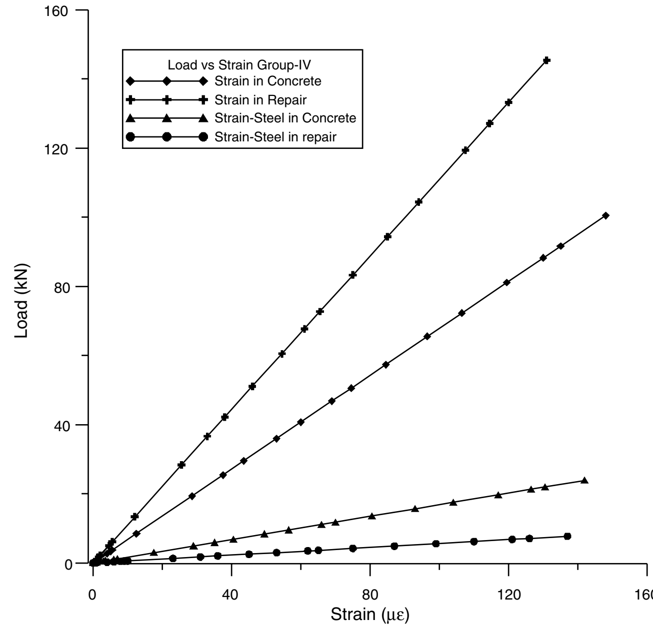

Fig. 12. 20–40% load of ultimate column capacity versus average measured strain for group IV.

concrete core. The columns failed by crushing of concrete at the top portion of the column as shown in Fig. 11.

The load versus the average measured strain for the various components of the tested columns (FMCX3 and FMCX4) of group IV are shown in Fig. 12. For these columns, the patch repair became an active part of the composite column after the load was increased. These columns could not be loaded to failure due to the testing setup. The load was increased from 20% to 40% of the ultimate column capacity. The increase in strain for the patch repair is less than that in concrete core. The increase of strain in steel within the patch repair is less than that embedded in concrete core.

The percentage load distribution for groups II, III and IV is shown in Fig. 13. The percentage load distribution presented for group IV represents the incremental increase from 20% to 40% of the ultimate capacity of the column. The contribution of the patch repair to the load carrying

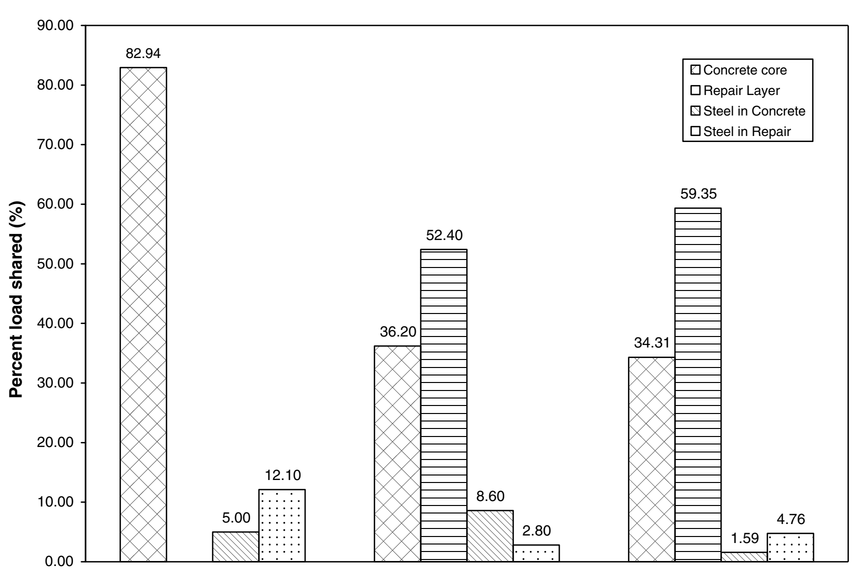

Fig. 13. Load distribution for groups II, III and IV.

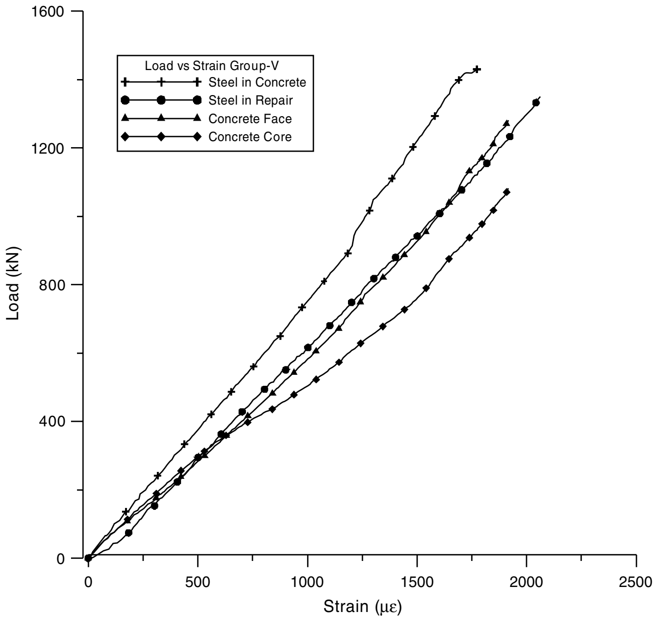

Fig. 14. Load versus average measured strain for group V.

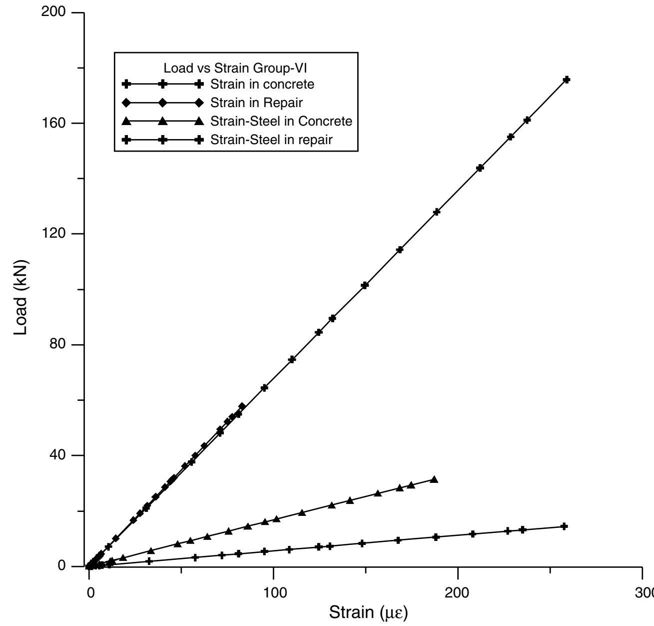

Fig. 15. 20–40% load of ultimate column capacity versus average measured strain for group VI.

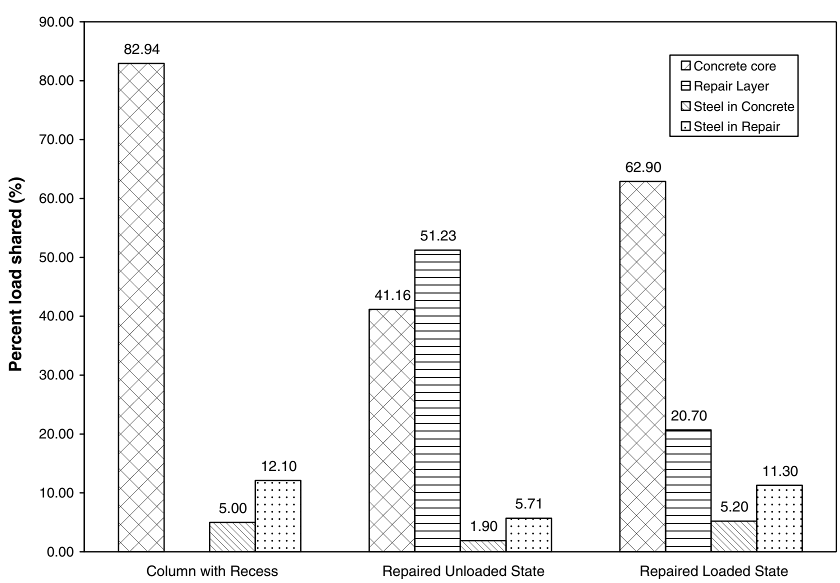

Fig. 16. Load distribution for groups II, V and VI.

capacity of the columns for groups III and IV has picked up 50% and 60% of the total load, respectively. This clearly indicates the structural contribution of the patch repair to the column carrying capacity. The contribution of steel to the load carrying capacity of the columns is reduced in groups III and IV as compared to group II.

3.3. PFSM patch repaired columns

The load versus the average measured strain for the different components of columns (PFMS1 and PFMS2) of group V and columns (PFMS3 and PFMS4) of group VI are shown in Figs. 14 and 15, respectively. These columns showed similar load-strain behaviour as that of groups III and IV.

The load distribution for groups II, V and VI is shown in Fig. 16. The contribution of patch repair to the load carrying capacity is similar to that of FMCX discussed in Section 3.2. However, the load carrying capacity for FMCX patch repair is slightly higher than that of PFMS due to its higher modulus of elasticity. The contribution of the patch repair for group VI showed much smaller value than the other groups. This could be due to some application default that the patch repair did not properly fill up the recess.

4. Conclusions

Experimental investigations carried out in this study have brought forth several important aspects which are of critical importance in patch repair of deteriorated columns. These include the following:

1. The spalling of concrete due to corrosion of reinforcement in columns leads to a reduction of the cross-sectional area of concrete. This results in a substantial increase in stress in the concrete core and steel reinforcement. In this state, the load carrying capacity of the column is substantially reduced and may lead to failure if subjected to high transient loads. Tests conducted on columns simulating the removal of deteriorated concrete show that the stress in the concrete core and steel may increase several fold in such columns.
2. For concrete columns, which are repaired in an unloaded state, the patch repair is structurally effective and carries the loads once the columns are reloaded. The load distribution between the repair layer, concrete core and steel reinforcement, depends on the modulus of elasticity and the areas of these components in the composite section at the repaired zone. For repair materials having a modulus of elasticity similar to concrete at the age of loading, the stresses in concrete and the repair are almost equal, whereas for low modulus of elasticity repair materials, the stresses due to applied load are substantially lower in repair as compared to concrete.
3. For columns repaired in a loaded state, the repair layer, which hitherto did not participate in sharing the loads coming to the column, swings into action on application of additional load after the repair material has achieved strength and stiffness. If the repair is carried out using a low modulus repair material, only a small portion of the additional applied load is shared by the repair layer. A major portion is taken by concrete which results in a significant increase in the stress in the concrete core. If the repair is carried out using a repair material having modulus of elasticity similar to concrete, the additional applied load is shared equally by the repair layer and the concrete core.
4. For patch repairs to be structurally effective in repaired columns, it is highly recommended to relieve all loads from the columns and then proceed with repairs. If it is difficult to relieve all loads from a column or if it is an uneconomical undertaking, it is recommended that at least the load coming to the column be partially relieved.

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