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Research Article

Numerical Modelling of Retrofitted Reinforced Concrete Building Frames

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Abstract: This study presents an overview and investigates the adequacy of the retrofit concept used in the reinforced concrete building frame of a distressed office building complex. The retrofit assessed consists of steel members welded together to form a steel frame with a reinforced concrete beam as base, acting as support for two floor slabs and roof truss of the building. Reinforced concrete building frame with and without retrofit steel frames were analysed using STAAD Pro structural analysis software and the results were compared with recommended standards from relevant codes of practice. Criteria considered include moments, shear forces and displacements/deflections. Results obtained revealed that the retrofit concept meets up with all the recommended standards. The efficiency of the retrofit used was determined in order to evaluate the extent by which the retrofit affects deflection of the beams. For all critical sections, the efficiency of the adopted retrofit concept varied significantly between 49.1-63.2%, 48.3-85.34% and 45.3-90.9%, respectively when deflection serviceability limit state, bending moment and shear force was considered respectively.

Keywords: Building collapse, modelling, reinforced concrete, retrofitting, STAAD Pro, steel

INTRODUCTION

Reinforced concrete structures consist of structural elements that are monolithically connected. Its application is numerous ranging from buildings, bridges, dams and storage tanks to mention a few. Generally, structures deteriorate due to many reasons such as internal reinforcement corrosion, freeze-thaw action, excessive loading, fire damage and poor initial design (Zongjin, 2011; Awoyera, 2014; Awoyera *et al*., 2014). Many buildings become unsuitable due to structural failure; this refers to loss of the load-carrying capacity of a component or member within a structure or of the structure itself. Structural failure is initiated when the material is stressed to its strength limit, thus causing fracture or excessive deformations (Roddis, 1993).

However, Chung (1999) opined that failures in buildings are partly as a result of misinterpretation of drawings and specifications; poor communication with the architect and engineer; poor coordination of subcontracted work; ambiguous instructions or unqualified operators/workers; and inadequate supervision on site. Also, extra loads due to unauthorized change of usage through additions and alterations made to the building can lead to failure (Allen and Schriver, 1972; Afolayan and Abdulkareem, 2005). This implies that old buildings must either be upgraded or rebuilt in order to ensure safety.

In another related investigation, Afolayan (2003) and James (2007) identified design issues including drawing comprehension and build ability as important and also the role of human efforts in supervision and communication with the wide range of task participants as also of great significance (Adekeye and Awoyera, 2015). Therefore, to ensure a notable reduction in the cases of building collapse due to structural element failures; the concept of member retrofitting is very pertinent to be adopted. Conversely, repair works which are carried out on buildings by patching up of superficial defects, was identified by Arya (2006) as detrimental, in that, it will not restore the lost strength. It will only hide the cracks, leaving the building in a weakened state.

Hence, it is becoming both economically and environmentally preferable to upgrade structures rather than rebuilding them, especially when rapid, effective and simple strengthening methods are available through retrofitting techniques (Balendran *et al*., 2001). Retrofitting is the process of making changes to the

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systems inside the building or even on the structure itself at some point after its initial construction and usage. According to Roddis (1993), retrofitting works are carried out in building to prevent anticipated failure due to observed distress and defects on the structural members. He further stressed that when such distress are allowed to continue progressively, may eventually lead to failure and collapse of the building. Crawford (2002) highlighted the redundant load path retrofit concept used to provide an alternative transfer route for loads in building frame by either providing steel frame constructed interior to the building frame at each floor level or constructed outside the building frame spanning multiple floors. More so, Bhuvaneshwari and Mohan (2015) explored the restoration of strength and stiffness in shear damaged beams through retrofitting, with cement-based composites as binders. Their findings revealed that load carrying capacity of the retrofitted damaged shear deficient beams was enhanced and also the formation of shear cracks was arrested.

Furthermore, Harries *et al*. (1998) used Fibre Reinforced Polymer (FRC) material for jackets when retrofitting columns. This sufficiently confines the columns and failure occurrence through the formation of a plastic hinge zone is prevented. The use of FRP for concrete strengthening was pioneered by Jones *et al.* (1989), they inferred that FRPs have very low self-weight but high strength-to-weight ratio and do not exhibit any corrosion problems. This results in low maintenance costs. Meanwhile, Jirsa and Kreger (1989) tested one-story infill walls using four specimens, they used three of the specimens as one-bay, single-story, non-ductile reinforced concrete frames designed with wide spacing in the column shear reinforcement, for the fourth specimen, longitudinal reinforcement was added adjacent to the existing columns to improve the continuity of the steel. The first three specimens had brittle failures due to the deficient column lap splices, even though the infill strengthened the frame. The fourth specimen enhanced both the strength and ductility of the frame.

So far, inference made from previous investigations carried out by different researchers revealed that the concept of retrofitting a distressed structural member is beneficial, in that it reduces cost and also guarantees adequate safety of structures. Hence, the need to strengthen structural elements of a building undergoing failure in order to prevent collapse through retrofitting works remains essential. Therefore the present study is focused on the numerical modelling of retrofitted reinforced concrete building frames of a distressed office complex in the precinct of the Federal University of Technology, Akure, Nigeria.

METHODOLOGY

STAAD Pro 2007 software was used for the analysis conducted on the affected building used for the investigation. The software is a popular structural engineering package for 2D and 3D model generation, analysis and multi-material design. It uses integrated finite element analysis and employs major international design codes for analysis and design of structures.

Prior to modelling the structure in STAAD Pro, the structural members of the existing distressed reinforced concrete building frame were inspected and measured in order to ensure accurate dimensions in modelling. Thereafter, the reinforced concrete building frame was modelled along with the retrofit (steel) frame. Meanwhile, the loads of the slab was estimated considering the loading system arrangement and applied on the concrete beam as appropriate in accordance with the requirements of BSI (British Standards Institution)BS 8110-1 (1997) and BSI (British Standards Institution)BS 6399-1 (2000). The load combinations considered are:

Dead load and Imposed load (ultimate):

$$n = 1.4\ G_K + 1.6\ Q_K \text{ all span} \tag{1}$$

Dead load and Wind load:

$$n = 1.4\ G_K + 1.4 W_K \text{ all span} \tag{2}$$

Dead load, Imposed load and Wind load:

$$n = 1.2\ G_K + 1.2\ Q_K + 1.2\ W_K \tag{3}$$

Dead load, Imposed load and Wind load (Serviceability): $n = 1.0\ G_K + 1.0\ Q_K + 1.0\ W_K$ (4)

where,
n = Design load
G_K = Total dead load
Q_K = Imposed load
W_K =Wind load

Other material properties considered for the structural analysis are as follows:

Earth pressure of 200kN/m^2, characteristics concrete strength 'Fcu' of 25 N/mm^{2}characteristics steel strength' Fy' of 460 N/mm^2 (reinforcement for concrete).

The measured member parameters were: Bending moment, shear force, member and nodal displacements. The effects of the introduced supports to the building through erected retrofit frames were noted by comparing the analysis results of the reinforced concrete building frame without retrofits with that of the reinforced concrete frame with retrofit frame. Results obtained were compared with the recommendations of BSI (British Standards Institution)BS 8110-1(1997) for concrete and BSI (British Standards Institution)BS 5950-1(2000) for steel.

Design criteria for progressive collapse mechanism developed by (General Services Administration (GSA), 2003) was also applied. The potential for progressive collapse is evaluated based on a Demand Capacity Ratio (DCR) given as:

$$DCR = \frac{Q_{UD}}{Q_{CE}} \leq 2.0 \tag{5}$$

A structural member is considered to have failed if its DCR exceeds 2.0 for typical structural configurations; thus strengthening of the member is required.

Q_{UD} is acting force determined in component or connection/joint (moment, axial force, shear and possible combined forces).

Q_{CE} is expected ultimate factored capacity of the component and/or connections/joint (moment, axial force, shear and possible combined forces).

Outline of retrofitting method using steel frames: The retrofit steel frame that was fabricated and analysed in the study consists of steel sections members bolted and welded together. It was built into the existing reinforced concrete frame. The retrofit steel frames consist of the following steel sections:

Universal Columns-UC203×203×86
Universal Angles-UA80×80×6
Universal Angles-UA45×45×4
Channels - CH254×76
Rectangular Hollow Sections-RHS 90×90×6
Reinforced Concrete Beam 500×500 mm

The reinforced concrete beam built into the ground floor slab formed the base for the retrofit steel frame; the universal columns were welded to the steel base plates which in turn were bolted to the reinforced concrete beam that serves as base. The universal columns extended from the ground floor beam to the soffit of the first floor slab and to the second floor slab.

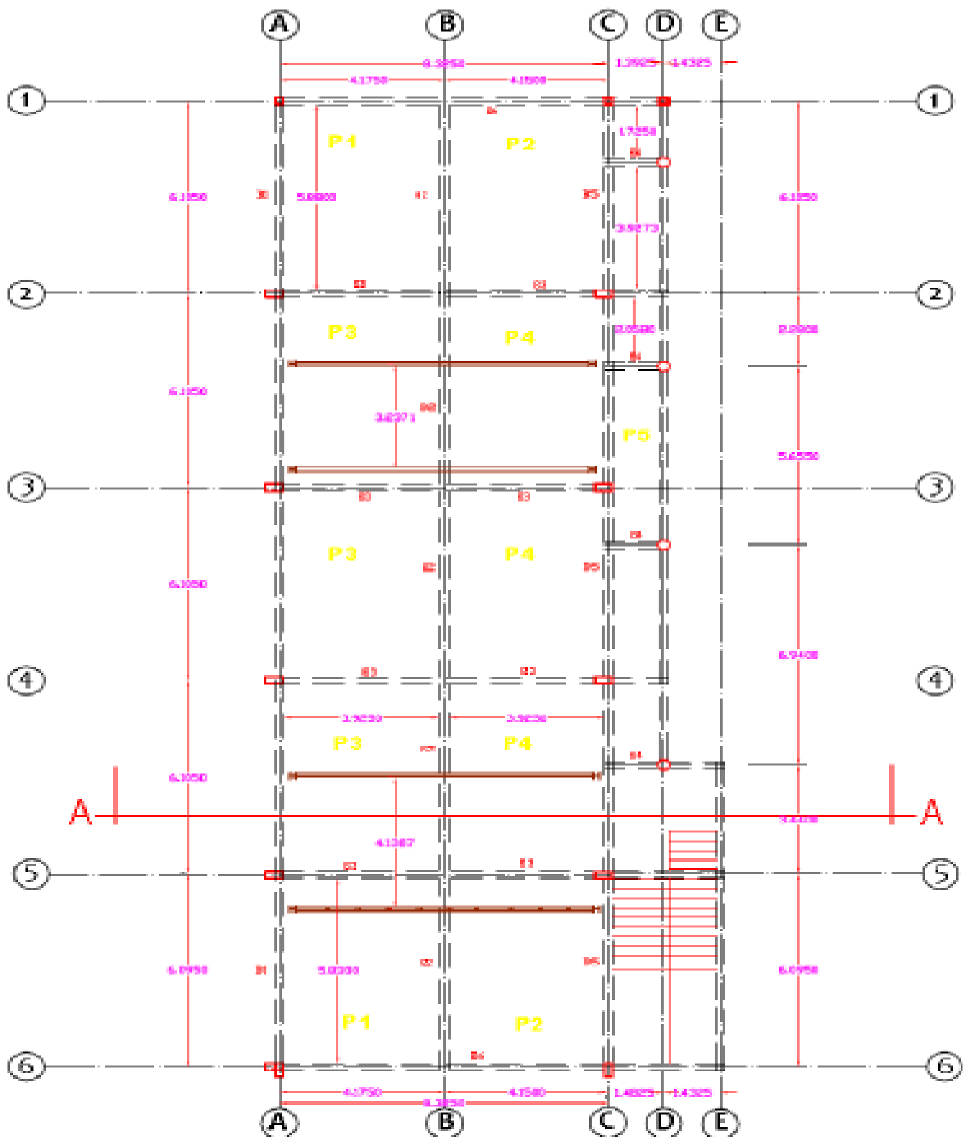
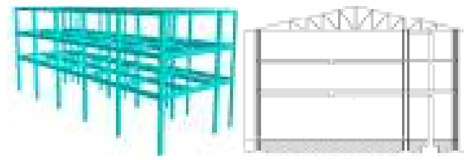


Fig. 1: First and second floor plan layout

Rectangular hollow sections were however fixed withthe universal columns at second floor slab and extended to the roof truss.

Universal Angle, UA80×80×6 were assembled to form trusses supporting the first floor slab and the second floor slab, while the Universal Angle, UA45×45×4 were also assembled to form a truss supporting the existing roof truss of the reinforced concrete frame. Channel Section, CH 254×76 formed the lower part of the trusses of the first and second floor slab. The trusses supporting each floor were welded together to the channel section and constructed in such a way as to accommodate and support the existing reinforced concrete floor beam 225 mm×450 mm dimension.

Figure 1 shows the first and second floor plan layout for the building with points of application of retrofit frames. Figure 2a and b shows 3D view of the model for distress building reinforced concrete frame without retrofit frame and its section view respectively. Figure 3a and b shows 3D view of the model for distress building reinforced concrete frame with retrofit frame and its section view respectively.



(a) (b)

Fig. 2: (a):3D view for model distress reinforced concrete building frame without retrofit frame; (b): Section view

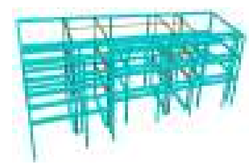


Fig. 3: 3D view for model distress reinforced concrete building frame with retrofit frame

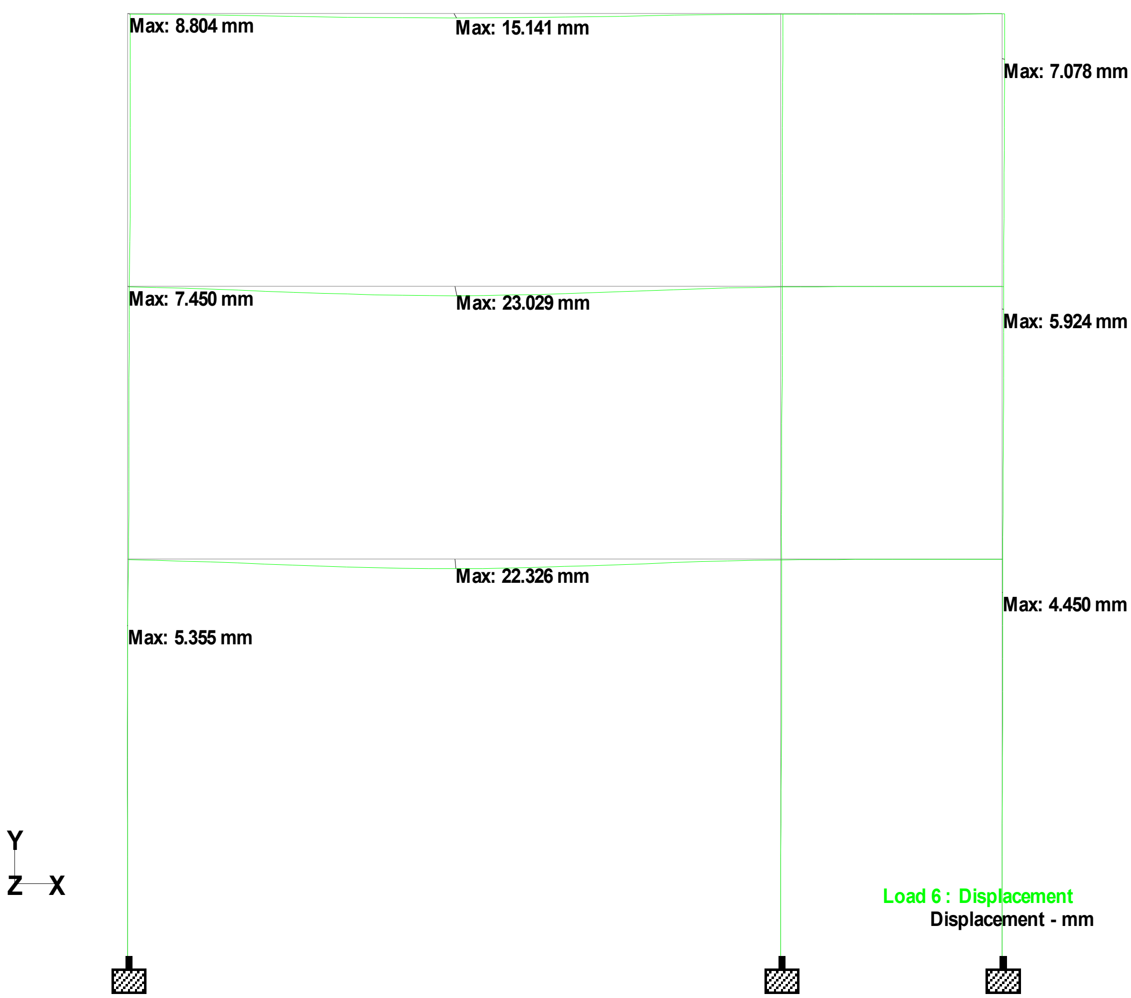
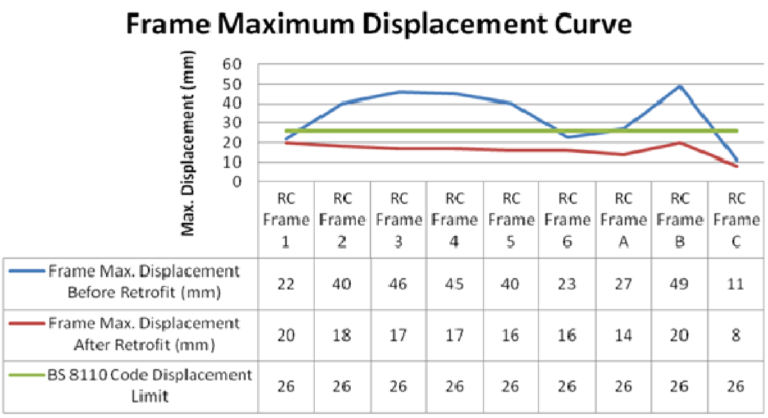


Fig. 4: Deflection of a typical reinforced concrete frame (RC Frame 6) under loading without the retrofit

RESULTS AND DISCUSSION

Displacements: Figure 4, shows the deflection of a typical reinforced concrete frame (RC Frame 6) under loading without the retrofit. The span/effective depth ratio of the section was used in checking the deflection of the structural reinforced concrete member of a particular frame which was in accordance with provision of BSI (British Standards Institution)BS 8110-1 1997). Displacement results of reinforced concrete frame without retrofit revealed that some typical beams fail the deflection criterion, while with the introduction of retrofit, it was seen that the deflections of the beams reduced and are below the code limiting value. This is expected since the retrofit frame is to aid in sharing the loads from the reinforced concrete member. The displacement characteristics for the reinforced concrete frames with and without retrofits are plotted in Fig. 5. For all critical sections, the efficiency of the adopted retrofit concept varies significantly between 49.1 and 63.2% when deflection serviceability limit state was considered. Likewise, the deflection on retrofit steel frame members in Universal Columns, Channel section, Rectangular Hollow Section and the Angle bars are quite negligible; thus satisfying the deflection criterion.

Bending: To properly check the adequacy of the retrofit frame, critical concrete and steel members were analysed for maximum bending moment (Mmax) and compared with their appropriate Moment Capacities(Mc) based on requirement of BSI (British Standards Institution)BS 8110-1(1997) for concrete and BSI (British Standards Institution)BS 5950-1



	RC Frame 1	RC Frame 2	RC Frame 3	RC Frame 4	RC Frame 5	RC Frame 6	RC Frame A	RC Frame B	RC Frame C
Frame Max. Displacement Before Retrofit (mm)	22	40	46	45	40	23	27	49	11
Frame Max. Displacement After Retrofit (mm)	20	18	17	17	16	16	14	20	8
BS 8110 Code Displacement Limit	26	26	26	26	26	26	26	26	26

Fig. 5: Displacement characteristics for the reinforced concrete frames with and without retrofits

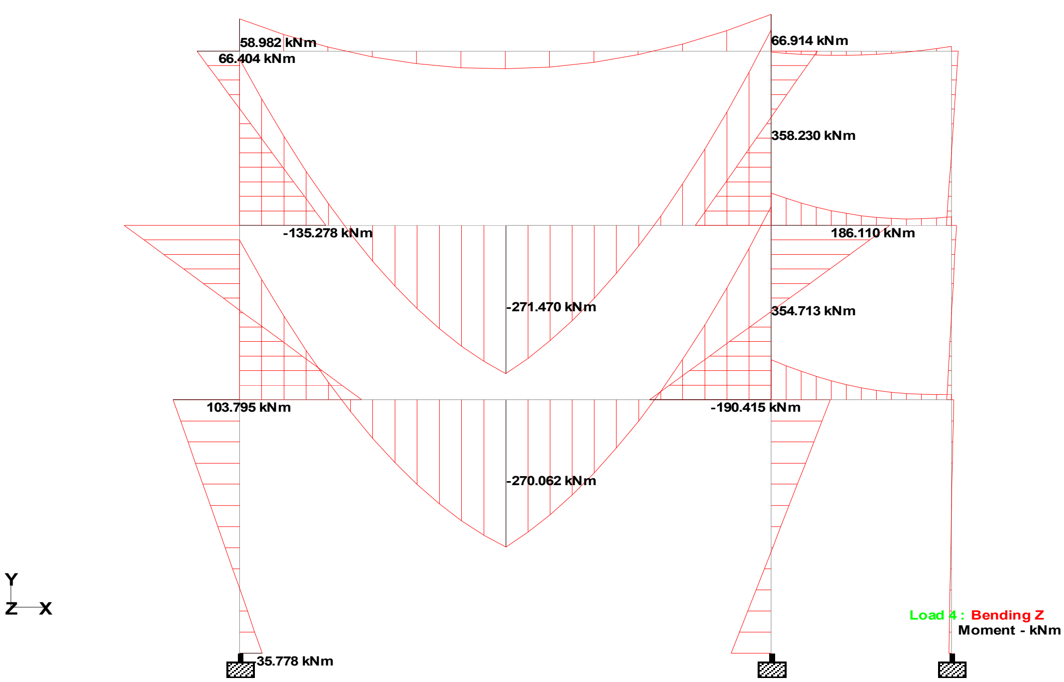
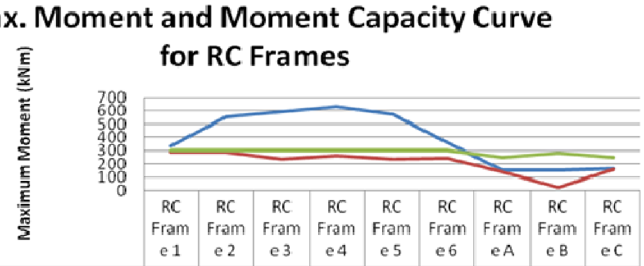


Fig. 6: Bending moment diagram of a typical reinforced concrete frame (RC frame 6) under loading without the retrofit



	RC Frame 1	RC Frame 2	RC Frame 3	RC Frame 4	RC Frame 5	RC Frame 6	RC Frame A	RC Frame B	RC Frame C
Frame Max. Moment Before Retrofit (kNm)	336	556	591	630	570	358	155	157	166
Frame Max. Moment After Retrofit (kNm)	290	287	240	261	235	244	137	23	159
Frame Moment Capacity (kNm)	303	303	303	303	303	303	250	281	250

Fig. 7: Maximum bending moment for reinforced concrete building frames with and without retrofits

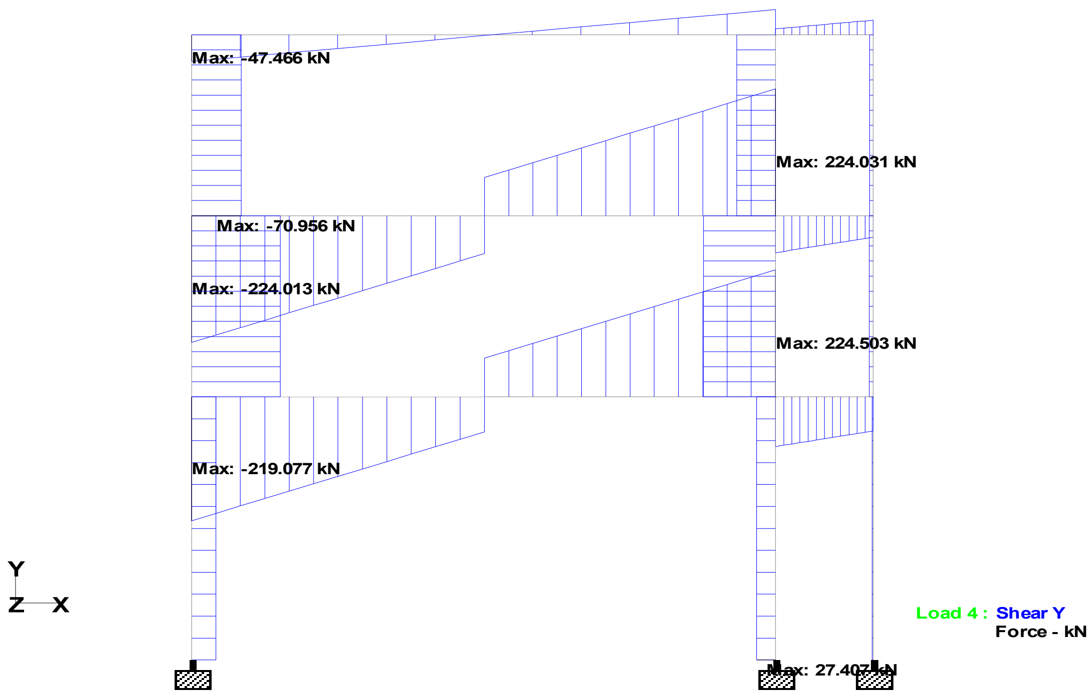


Fig. 8: Shear forces of a typical reinforced concrete frame within the model (RC Frame 1)

(2000) for steel. Figure 6 shows the bending moment diagram of a typical Reinforced Concrete frame (RC Frame 6) under loading without the retrofit. Figure 7 shows the maximum bending moment for members of the reinforced concrete building frame with and without retrofits, results showed that maximum moment for reinforced concrete frame 1, 2, 3, 4, 5 and 6 failed moment criteria under normal condition but satisfy moment criteria under retrofit condition.

Shear: The maximum shear forces for each critical reinforced concrete frame with and without retrofit were estimated. These results were compared with their estimated limiting shear stress to check if they satisfy shear criteria. Figure 8 shows the shear forces of a typical reinforced concrete frame within the model (RC Frame 1) and Fig. 9 shows the relationship of the shear forces in the reinforced concrete building frames with and without the retrofit. Based on limiting code values for shear stress given by Eq. (6), maximum shear forces for all reinforced concrete frames under retrofit condition satisfy shear stress criteria:

$$v = \frac{V}{b_v d} \leq 0.8\sqrt{f_{cu}} \text{ or } 5N/mm^2 \tag{6}$$

(BSI (British Standards Institution) BS 8110-1,(1997)

Demand Capacity Ratio (DCR): The potential for progressive collapse was evaluated for each section of thereinforced concrete frame of the buildingwith and

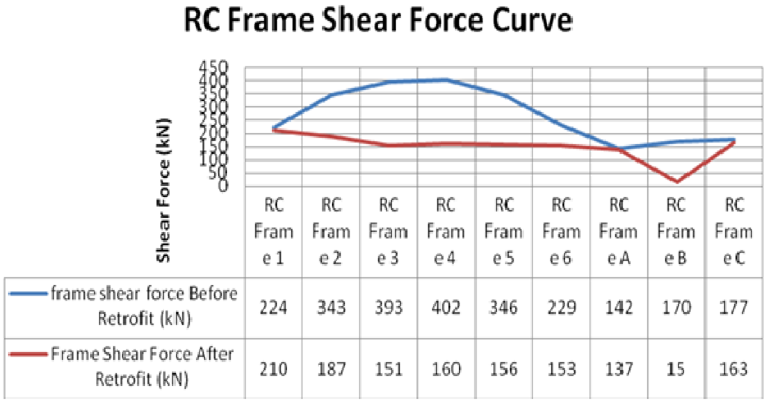


Fig. 9: Shear forces in the reinforced concrete building frames with and without the retrofit

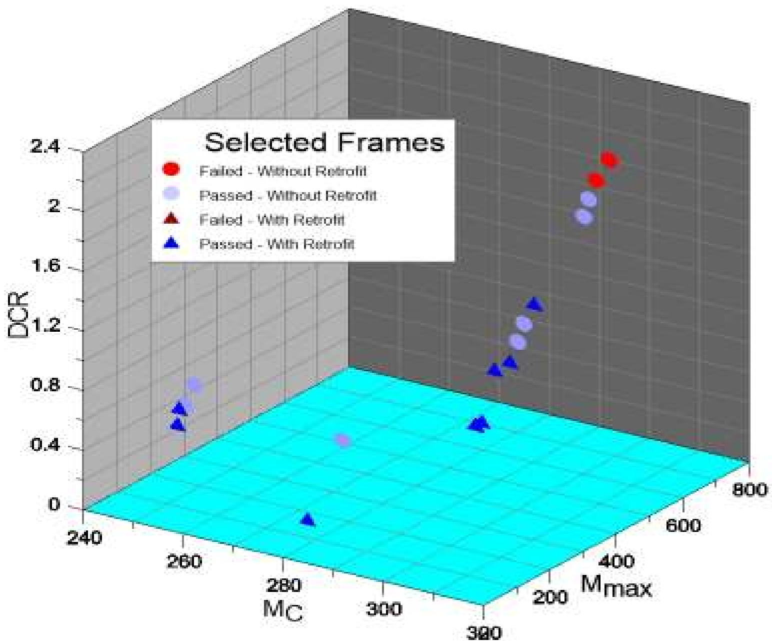


Fig. 10: Demand capacity ratio for reinforced concrete frames with and without retrofit

without retrofit; their results were compared as shown in Fig. 10, based on the procedures for estimating Demand Capacity Ratio (DCR) given by (General Services Administration (GSA), 2003). Where DCR is given by:

$$DCR = \frac{M_{max}}{M_c} \quad (7)$$

Still according to General Services Administration (GSA) (2003), member frame fails when DCR is greater than or equal to 2 and member frame passes when DCR is less than 2.

From the results presented in Fig. 10, it could be seen that all the retrofitted member frames in the selected building passed, whereas some member frames without retrofit failed. Thus, retrofit frame adopted to mitigate the state of partial collapse of the typical distressed reinforced concrete building is satisfactory for the sustenance of the members which had been subjected to progressive failure.

CONCLUSION

The analytical results showed that some members of the reinforced concrete building frame without retrofit fails to meet recommended standards based on selected criteria from the relevant codes, for displacements, some typical beams members of reinforced concrete frame without retrofit failed the deflection criteria. STAAD analysis results showed that, with retrofit, the deflections in the reinforced concrete beam members were reduced and therefore satisfied the deflection criteria. This is possible since the retrofitted frame resists some loads from the reinforced concrete member. For all critical sections, the efficiency of the adopted retrofit concept varies significantly between 49.1 and 63.2% when deflection serviceability limit state was considered.

For moments, STAAD analysis showed that typical beams of reinforced concrete frame without the retrofits do not satisfy moment criteria, with the retrofit in place, the maximum ultimate moment at beams support are reduced and moment criteria are satisfied by critical members. For all critical sections, the efficiency of the adopted retrofit concept varied significantly between 48.3 and 85.3% when moments were considered.

Furthermore, shear force criteria were satisfied for all critical members of the reinforced concrete building frame with the retrofit concepts. For all critical sections, the efficiency of the adopted retrofit concept varied significantly between 45.3 and 90.9% when shear force were considered.

Finally, the Demand Capacity Ratio (DCR) for the retrofitted reinforced concrete buildings frame showed that all frames of the building passed its failure criteria. Hence, it could be holistically concluded that the retrofit frame adopted to mitigate the state of partial collapse of the typical distressed reinforced concrete building is reliable.

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