Pushover Analysis of Reinforced Concrete Buildings Using Full Jacket Technics: A Case Study on an Existing Old Building in Madinah

Tarek M. Alguhane, Ayman H. Khalil, M. N. Fayed, Ayman M. Ismail

***Abstract*—**The retrofitting of existing buildings to resist the seismic loads is very important to avoid losing lives or financial disasters. The aim at retrofitting processes is increasing total structure strength by increasing stiffness or ductility ratio. In addition, the response modification factors (R) have to satisfy the code requirements for suggested retrofitting types. In this study, two types of jackets are used, i.e. full reinforced concrete jackets and surrounding steel plate jackets. The study is carried out on an existing building in Madinah by performing static pushover analysis before and after retrofitting the columns. The selected model building represents nearly all-typical structure lacks structure built before 30 years ago in Madina City, KSA. The comparison of the results indicates a good enhancement of the structure respect to the applied seismic forces. Also, the response modification factor of the RC building is evaluated for the studied cases before and after retrofitting. The design of all vertical elements (columns) is given. The results show that the design of retrofitted columns satisfied the code's design stress requirements. However, for some retrofitting types, the ductility requirements represented by response modification factor do not satisfy KSA design code (SBC- 301).

***Keywords*—**Concrete jackets, steel jackets, RC buildings pushover analysis, non-linear analysis.

I. Introduction

MANY existing reinforced concrete structures in Kingdom of Saudi Arabia were built without considering the effect of seismic loads. With the progression of national building codes, additional load cases of seismic effects on buildings become essential and have significant effects on safety of structures. Re-design of these structures has emphasized a number of structural insufficiencies and failure mechanisms, either for some elements or for the structure system. Therefore, to avoid these weaknesses, retrofitting technics for those elements should be evaluated.

Using pushover analysis method by many researchers approves the advantages of this method for checking the ability of existing structure for resisting seismic loads [1]. However, they suffer from the ability of common programs in analyzing the existing structure. So, many researchers check available common programs in designing and analyzing the existing buildings [2]. Several researches [3]-[5] investigated effectiveness of different types of column jackets either by numerical analysis in post-earthquake and pre-earthquake retrofitting or by experimental test for different types.

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Ayman [6] investigated the seismic performance of a residential building in Cairo using nonlinear static analysis. He checked the behavior of all columns before retrofitting and after adding additional layer jackets (carbon fiber reinforced polymer (CFRP), partial steel elements, full steel jackets and reinforced concrete jackets). He compared and checked the ability of previous jacket types for enhancing seismic performance of the studied building. Spoelstra and Monti [7] studied the effects of the confinement introduced by the FRP wrapping for the reinforced concrete with FRP.

Savoia et al. [8] compared the results obtained from the test program and finite element analyses using two programs SAP2000 [9] and SeismoStruct [10]. He approved the ability of these programs in analyzing nonlinear static behavior of retrofitting structures. Tarek et al. [11]-[13] evaluated the seismic performance of existing buildings in Madinah city KSA using either ambient vibration technic or based on ASCE procedures.

A 5-storey RC typed building, studied in this paper, is representative of old building type constructed in Madina City 30 years ago. In addition to the insufficiency observed in the planning of the structural system, deficiencies such as low quality of concrete, inadequate transverse reinforcement, and usage of plain bars with relatively lower yield strength also exist. The seismic behavior of this building is investigated using nonlinear static analytical procedure (Pushover) before and after retrofitting.

During the analysis of the original structure, unconfined concrete stress–strain relationship was used for determining the contribution of concrete. Analysis of the retrofitted members by reinforced concrete jackets or steel plate jackets was carried out by using a trilinear confined concrete stress–strain model. A parametric study for the effects of type of retrofitting jackets using steel plates or concrete jackets with different thickness on the response modification factor (R) was checked using pushover. The analytical results showed that steel plat jackets and reinforced concrete jackets of this type of deficient columns enhanced the overall structural seismic performance.

II. Pushover Analysis Methods

A. Purpose of Pushover Analysis

The goal of the pushover analysis is to gauge the predictable performance of a structural system by valuing its strength and deformation strains in designing the building to resist earthquake using a static inelastic analysis, then comparing these results to existing capacities at the concert degrees of interest. The evaluation is based on an assessment of important performance parameters, including global drifts, inter-story drift, inelastic element deformations with respect to yield stress value, relative deformations and connection forces.

The inelastic static pushover analysis can be considered as a method for predicting seismic force and deformation demands, which accounts in an estimated manner for the redistribution of internal forces occurring once that no further could be resisted within the elastic range of structural behavior. The pushover is expected to supply informative data onto many response characteristics that cannot be obtained from an elastic static or dynamic analysis. The next are samples of such response characteristics [14]:

- The representative stresses on actually brittle elements, for example columns' axial forces, applied stresses on brace connections, stresses on beam-to-column connections due to flexure moments, shear stresses in deep reinforced concrete, etc.
- Evaluations of the elements, which have the ability to dissipate the energy affected by effects of ground motion on the studied structures.
- Influence of strength deterioration of specific elements on the performance of the structural systems.
- Locate the critical highly affected regions by the deformation demands.
- Verification of the completeness and adequacy of load path, considering all structural parts, connections, the stiff nonfunctional elements have significant strength, and the building's foundation.

A pushover analysis is conducted by subjecting a structure to a monotonically increasing pattern of lateral loads, representing the inertial forces, which will be experienced by the structure when afflicted by earthquake acceleration. With increasing loads incrementally, sequential formation of plastic hinges in structural elements may happen. As a result, at each occasion, the structure has a loss in stiffness. Utilizing a pushover analysis, a characteristic nonlinear force displacement relationship could be determined.

B. Plastic Deformation Curve

Fig. 1 shows the monotonic force-deformation relationship. For this figure, the deformations (or rotations) value corresponding to points B, C, D and E should actually be supported experiments or rational analysis. Three points tagged IO (Immediate Occupancy), LS (Life Safety) and CP (Collapse Prevention) are used to outline the acceptance criteria for the hinge. The suggested plastic rotation capacities for RC columns and beams are specified in ATC-40 [15] and FEMA 356 [16].

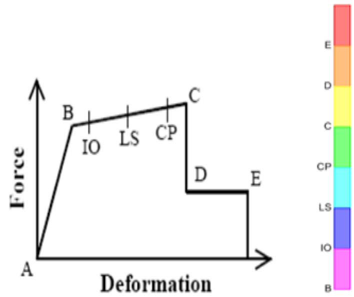


Fig. 1 Force-deformation relation [9]

C. Nonlinear Static Procedures

In this study, the nonlinear static (pushover) procedures, presented in the ATC-40 [15] and FEMA- 356, 273, 440 [16]-[18], are used to find out the displacement demand imposed on a building.

III. Description of the Building

Fig. 2 Position of building in Madinah city from Google

Fig. 3 Photo of the studied building in Madinah

The structure is an old existing 5-storey reinforced concrete hotel building in Madinah City. The location of the building from google site and its photos are shown in Figs. 2 and 3 respectively. Figs. 4 and 5 illustrate the plan of a typical story above basement as well as the plan and elevation for building dimensions. This building consists of reinforced concrete skeletons i.e. columns, beams and solid slab. The brick wall thickness is equal to 0.12 m and the storey height is about 3.00

m. Material properties for the building are illustrated in Table I. Stress-strain curves for concrete, steel bares and brick wall are illustrated in Fig. 6.

TABLE I
MATERIAL PROPERTIES FOR BUILDING

concrete strength*	20000 kN/m²	F'c
rebar yield strength	243700 kN/m²	Fy
modulus of elasticity of concrete	20000000 kN/m²	Ec
modulus of elasticity of rebar	2.0E+8 kN/m²	Es
Shear modulus	10356491 kN/m²	G
Poisson's ratio	0.2	Y

* These properties were obtained from test on drilled concrete core specimens.

Mander's model for confined concrete [19] is used for the old concrete (Fig. 7).

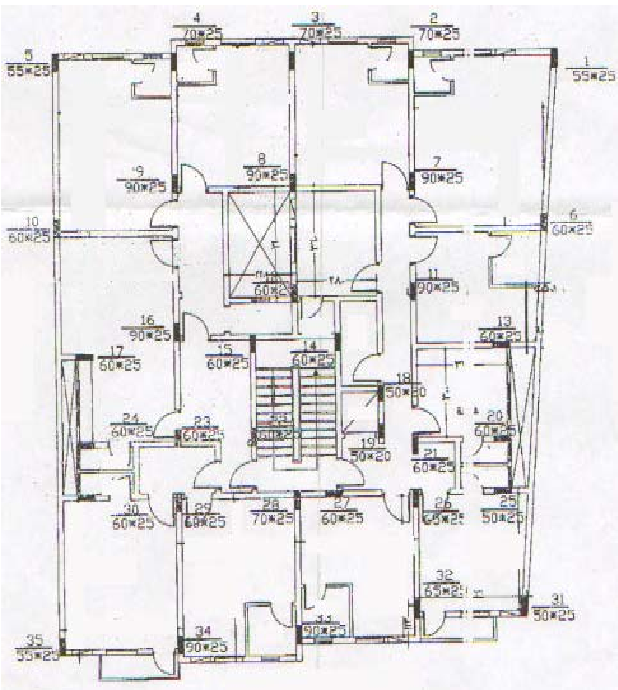
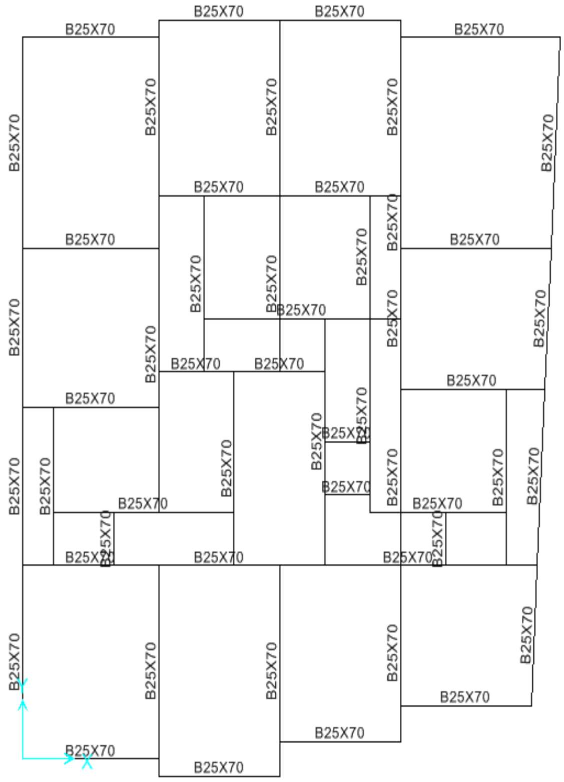


Fig. 4 Typical floor plan

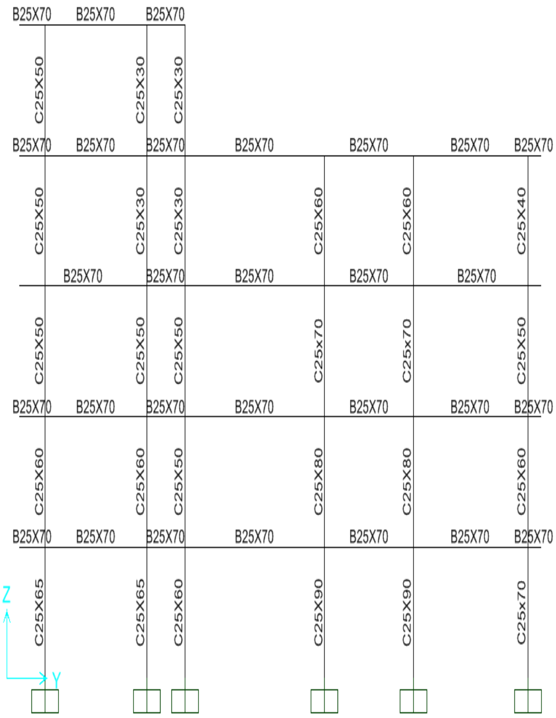
TABLE II
TOTAL LOADS FOR RC BUILDING DUE TO EQ AND WIND LOAD CASES

Case	load (kN)	factored load (kN)
EQX	873	873
EQY	873	873
Wind x	257	411
Wind y	208	332

Factor loads for EQ=1.0 and for W=1.6 according to Saudi code (SBC301-2008)

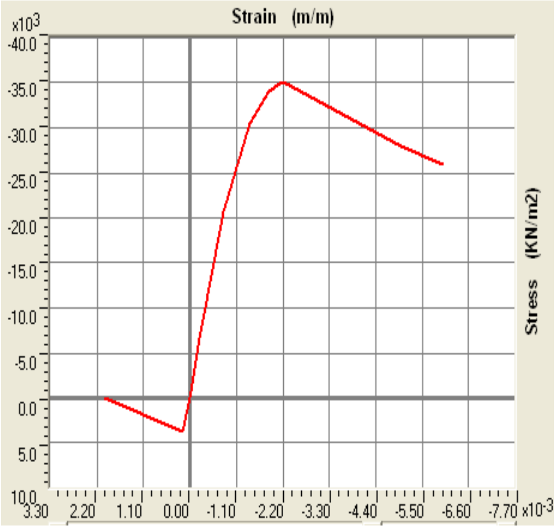


(a) Beams' dimension (Typical Plan) [20]

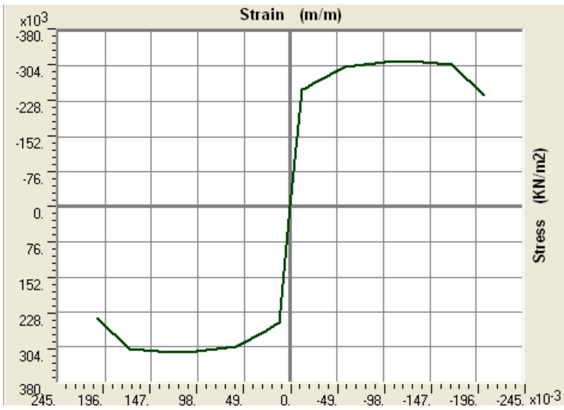


(b) Beams' and columns' dimension (Elevation) [20]

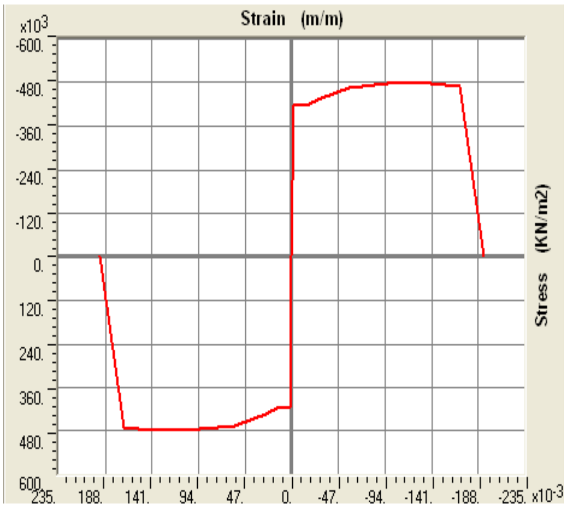
Fig. 5 Dimensions of columns and beams



(a) Stress-strain curve for new concrete



(b) Stress-strain curve for old steel bare



(c) Stress-strain curve for jacket steel bare

Fig. 6 Stress-strain curves introduced in SAP2000

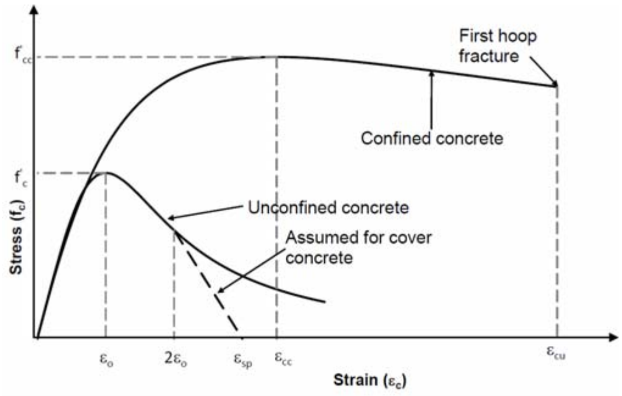


Fig. 7 Stress-strain relation for monotonic loading of confined and unconfined concrete - [19]

IV. Loading Cases

The following loading cases for dead and live loads are considered:

1) Total Dead Load is equal to DL+SDL+CL, where: DL = Dead load equal to the self-weight of the members and slabs. SDL = Super-imposed dead load equals to 3.0 kN/m². CL = Cladding load applied only on perimeter beams.
2) Live Load (L) is equal to 2.0 kN/m².

Seismic loads and Wind loads cases according to Saudi Code (SBC 301) (2008) [21] are given in Table II. The values in show that the EQ loads are the dominant in design.

V. Retrofitting Techniques

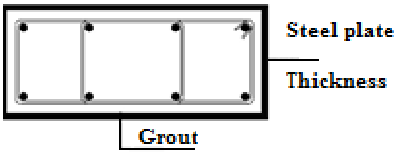
Different retrofitting techniques are considered in this study specifically for full steel jacketing and reinforced concrete jacketing. The retrofitted jacket is assumed to fully contact with the original columns.

A. Full Steel Jackets

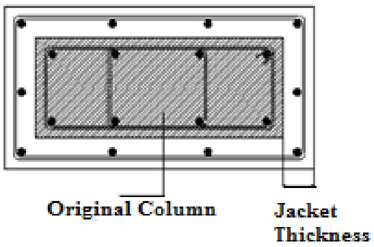
Steel jacket is utilized; (Fig. 8 (a)) using welded steel plates with a thickness of 12 mm. The yield strength for steel plates is considered as 420 MPa.

B. Reinforced Concrete Jackets

In the last retrofitting alternative, all columns of the building were assumed to be enlarged upon the well-known reinforced concrete jacketing technique (Fig. 8 (b)). A jacket thickness of 100 mm and 150 mm was considered for this purpose. Both longitudinal and transverse reinforcements were selected in a way that the minimum requirements stated by the SBC 304-2008 code for design and the construction of concrete structures [22] are satisfied. The characteristic compressive strength of the concrete jacket was selected as 35 MPa. Deformed steel bars of 16 mm diameter were longitudinally placed with 100 mm intervals. The characteristic yield strength of used reinforcement bars was 420 MPa.



(a) Full steel jackets



(b) Reinforced concrete jackets

Fig. 8 Typical jacket details for reinforced concrete columns

VI. Results and Discussions

A mathematical model, for the exciting building (without retrofitting), was created using SAP2000 program, Fig. 9. (Frame elements without infill wall). Displacement-controlled pushover analyses were performed on the model for 5-storey RC building in order to determine the maximum base shear can carry by the structure and corresponding top deformation before retrofitting versus after retrofitting.

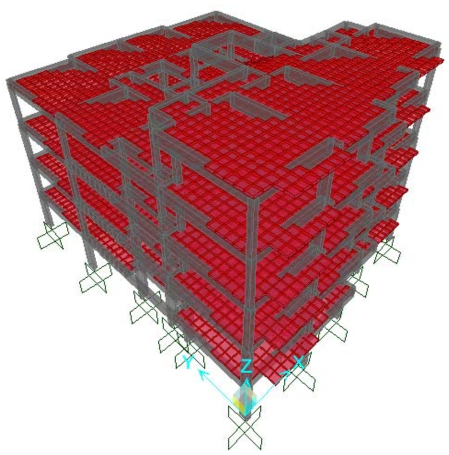


Fig. 9 Model for the building (frame element + slab)

The lateral load pattern in Madinah City is applied according to Saudi Building Code (SBC 301-2008). The load pattern is calculated using load combination (DL+SDL+0.25LL) for the evaluation of the seismic load. Following the FEMA 356 guidelines, auto P-M2-M3 interacting hinges are provided at both ends for the columns, while in case of beams M3 auto hinges are provided.

Columns isometric shapes of hinge status at target displacement for the studied model are illustrated in Figs. 10 and 11 for XX and YY directions respectively. From these figures, it is observed that:

- Plastic hinges are located in most of the stories and there will be sever damages throughout the height of the building during an earthquake.
- Comparison between the base shear-displacement curves and the corresponding plastic hinges of the building shows more stiffness in Y direction than that in X-direction.
- From these curves, it is clear that there is a weakness for the building ductility of the two directions especially in X-direction. Tarek et al. [11], [12] give the lowest resultant response reduction factor R about 1.82 and 2.04 for the two directions. These values of R are lower than that required by the SBC-301(2008) and give a good indication of poor ductility of this building.

The required retrofitting processes of columns is shown in Fig. 12, which gives the design state of all columns. Fig. 13 shows the building capacity response up to failure for the studied models in X direction and in Y direction.

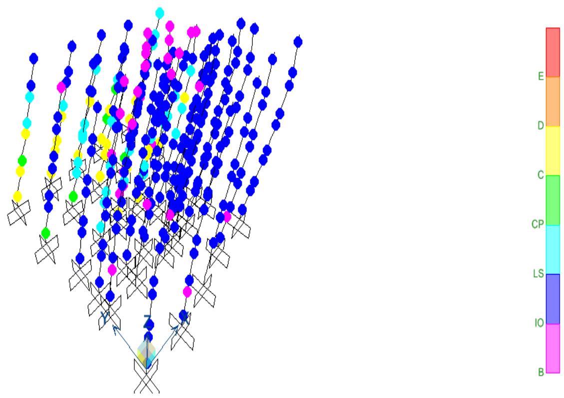


Fig. 10 Columns hinge status at target displacement, static nonlinear analysis XX

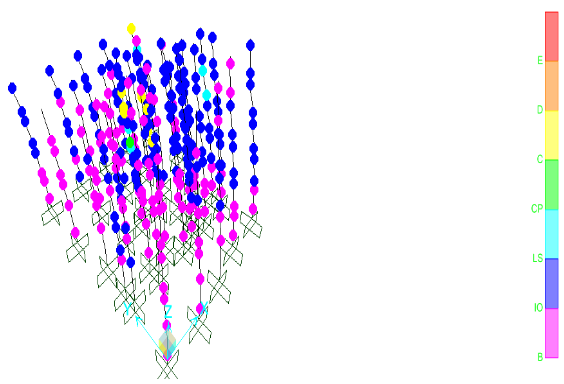


Fig. 11 Columns hinge status at target displacement, static nonlinear analysis YY

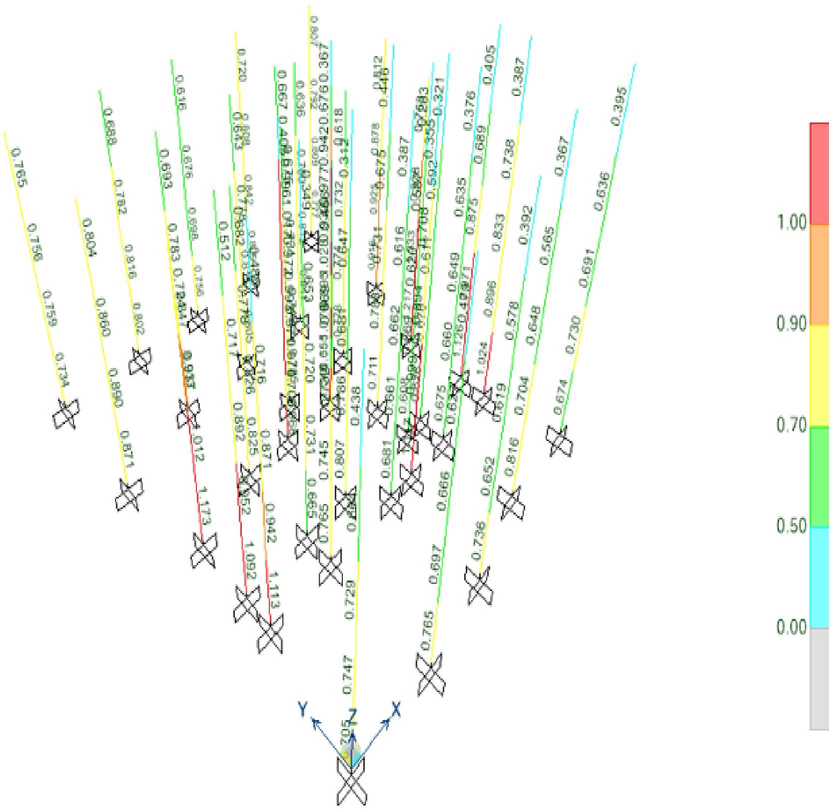


Fig. 12 Design status before retrofitting

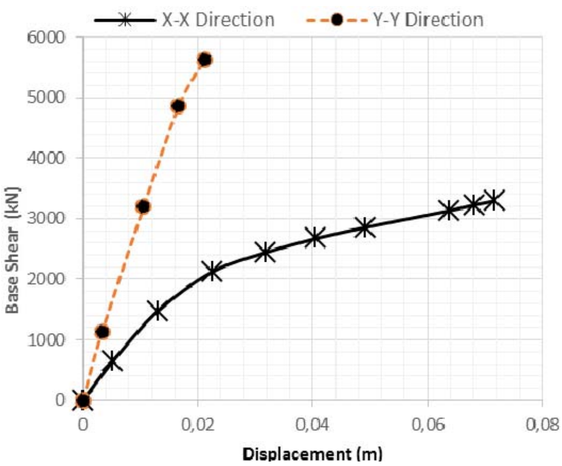
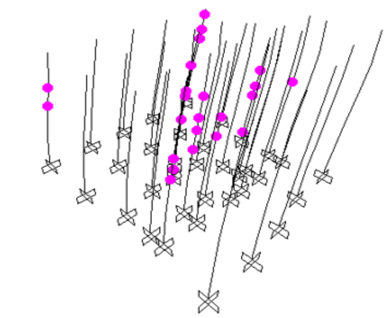
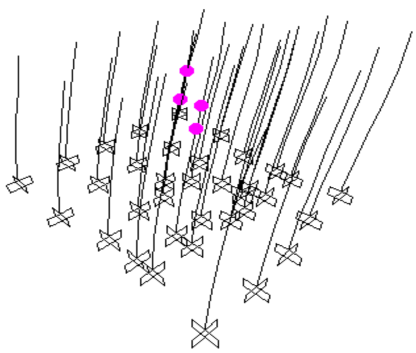


Fig 13 Static Nonlinear Analysis (Pushover Curve)

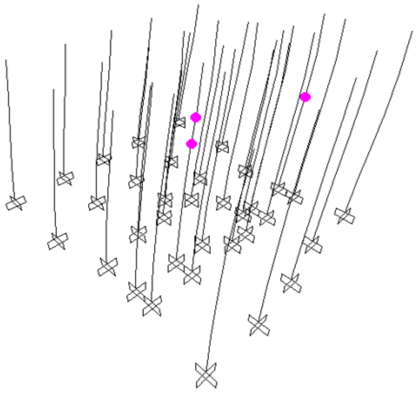
Figs. 14 (a)-(c) show columns' isometric shapes for hinge status at target displacement for the retrofitting processes of unsafe columns. It is observed that there were plastic hinges on few sections of the columns at full EQ load level with response modification factors (R) (first initial yielding of the structure). Figs. 15 (a)-(c) show that design requirements as per SBC 304-2008 are satisfied for the retrofitted columns either using full steel plates or using full concrete jackets with various thickness.



(a) Concrete jacket 100mm thick reinforced by ϕ16@100mm



(b) Concrete jacket 150mm thick reinforced by ϕ16@100mm

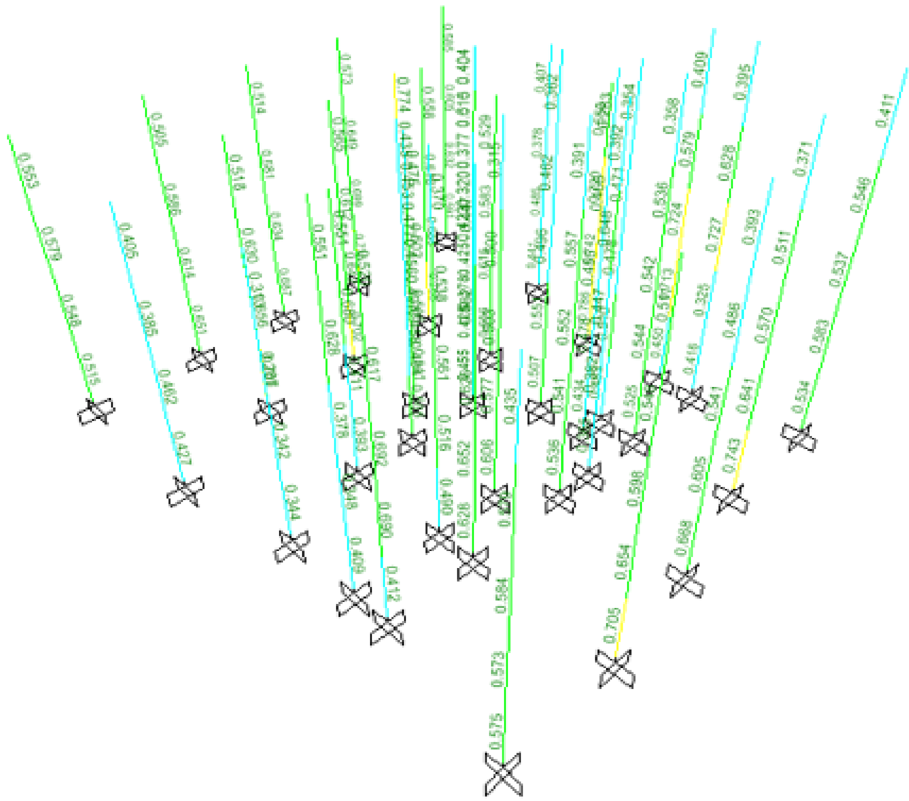


(c) Steel jacket thick 12 mm

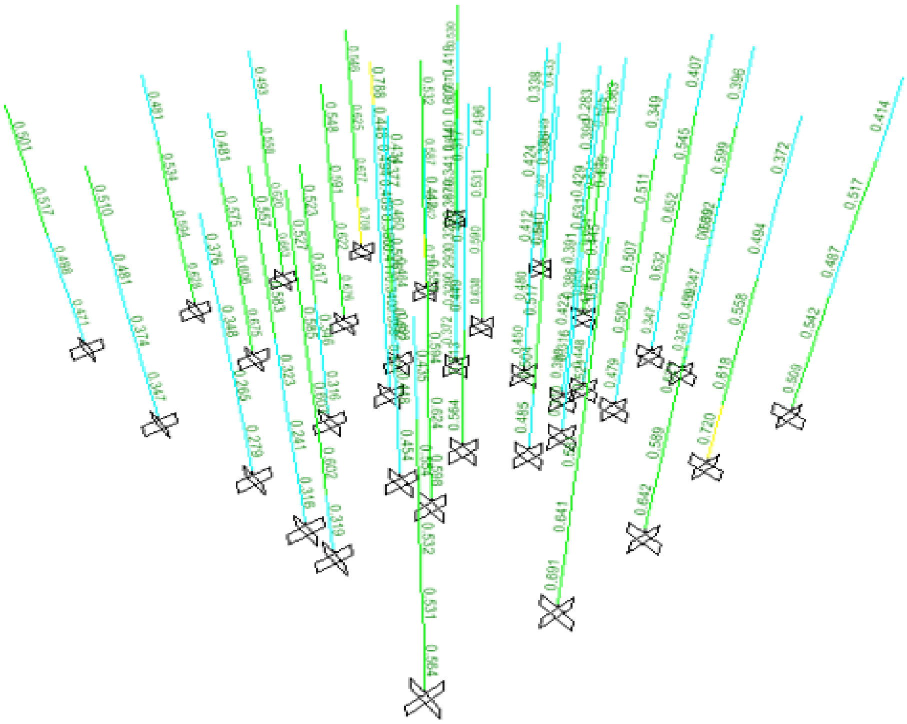
Fig. 14 Columns hinge status at target displacement, static nonlinear analysis XX for all jackets types

The building capacity response up to failure relationships obtained by pushover analysis for original and retrofitted structures are presented in Fig. 16 for reinforced concrete jacketing cases with thickness of 100 mm and 150 mm reinforced by ϕ 16 each 100 mm and for full steel jackets with 12 mm thick steel plates.

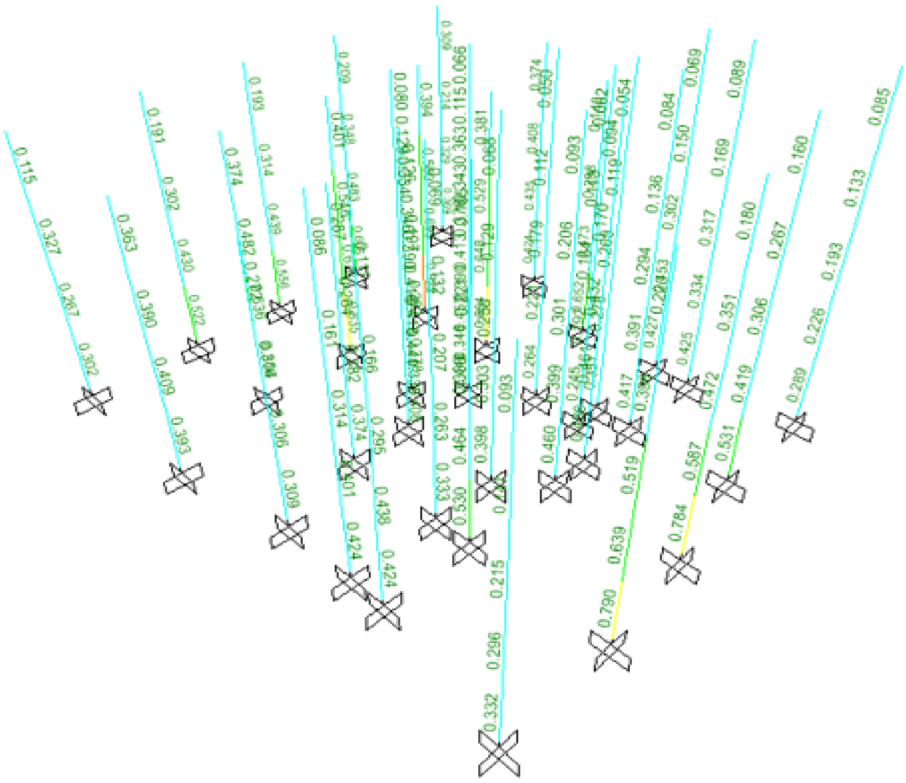
The comparative study with the initial building results that all retrofitted techniques improved the strength and plasticity characteristics of the building. The concrete jacketing with 100 mm thickness provided sensible displacement capability however less lateral strength than different jacketing thickness. The structure retrofitted by concrete jacketing with larger thickness gives a lot of rigid behavior, therefore, structural and non-structural parts may suffer less destruction.



(a) Concrete jacket 100mm thick reinforced by ϕ16@100mm



(b) Concrete jacket 150mm thick reinforced by ϕ16@100mm



(c) Steel jacket 12 mm thick

Fig. 15 Design status for all jackets types

Refer to calculated response modification factor, as shown in Table III; all retrofitting techniques improved the maximum base shear of the structure. Although using concrete jackets or full around steel plates jackets give the safety requirements by the design code, the ductility requirements represent by response modification factor did not achieve. (2.5 according to Saudi Building Code SBC 301) (Fig. 17). This depends on the characteristic and dimensional of the retrofitting jacket.

TABLE III
ANALYSIS RESULTS

Model	Maximum base shear (ton)	Calculated response modification factor (R)
Original model	330	1.82
With full steel jacket	685	2.52
With RC. (100mm) jackets	570	2.25
With RC. (150mm) jackets	595	2.47

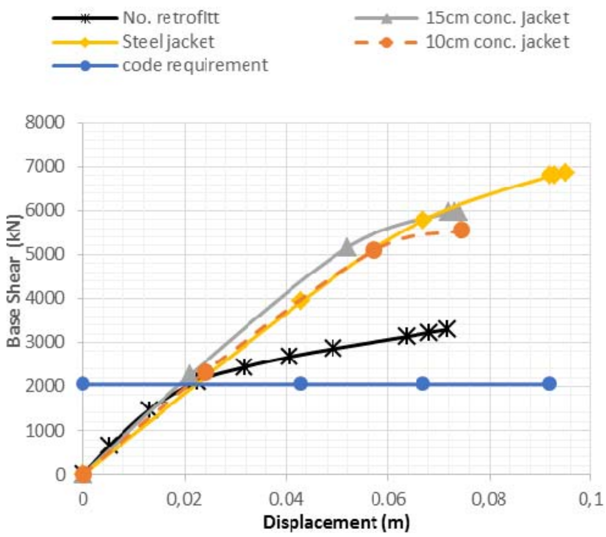


Fig. 16 Static nonlinear analysis (Pushover curve) X-X

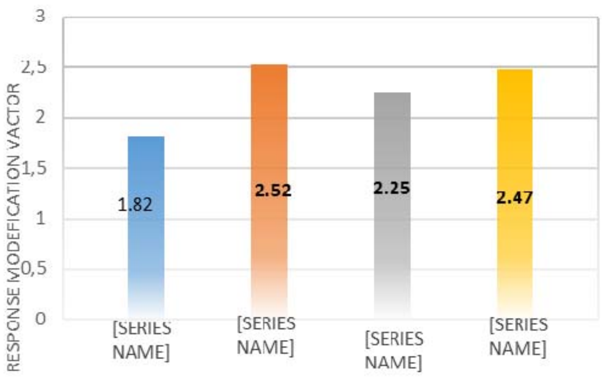


Fig. 17 Values of response modification factor for studied case

VII. CONCLUSION

From the inelastic analysis of a typical existing reinforced concrete structure before and after retrofitting, the following conclusions are obtained.

- All retrofitting techniques improved the ductility characteristics of the structure. The columns retrofitted with full steel jackets using steel plates developed the overall structural performance in terms of ductility and lateral strength more than that by using reinforced concrete jackets.
- Using concrete jackets with 150 mm thick is being more pronounced due to larger cross-sections and additional longitudinal reinforcement than that of 100 mm thick.
- Reinforced concrete jacketing is also additional preferred once lateral drifts are needed to be restricted; furthermore, that successively limits the damage.
- The design of all columns with all retrofitting types satisfy the safeties design requirements, however, the response modification factor (R), does not satisfy the code requirements for some retrofitting types. This depends on the characteristic and dimensional of the retrofitting jacket.

Generally, the structural retrofit enhanced lateral resistance of the building under the required limits of seismic loads and therefore the risk of structural collapse underneath these loads.

This study shows how the pushover analysis may be used in order to estimate the seismic resistance of existing or retrofitted structures as well as how the linear analysis may be followed by a detailed nonlinear analysis of part of the structure. One of the primary benefits of nonlinear pushover analysis more than the linear analyses are that the probability to locate failure mechanism and corresponding damage locations. The pushover analysis will provide valuable info concerning performance of building and their response modification factor (R) in expected future seismic events.

It should be observed that for getting more accurate and generalized results, extra particularized retrofit schemes with many load conditions should be examined.

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