VOL. 18, NO. 20, OCTOBER 2023 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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SEISMIC ASSESSMENT AND STRENGTHENING OF A RC BUILDING USING PUSHOVER ANALYSIS

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ABSTRACT

Many existing Reinforced Concrete (RC) buildings in moderate to high seismic hazard zones (including old RC buildings and historical structures in Palestine) have inadequate capacity to resist earthquake loads, most of the existing and old buildings were designed and constructed according to earlier codes, which did not satisfy modern seismic design requirements and current engineering standards, as well as other reasons which may also lead to failure such as the faulty structural design and improper construction, alteration of building functions, changes of seismic load characteristics in the area, etc. Procedures of performance-based analysis using nonlinear static analysis (pushover) were used here to study the performance of a proposed RC frame building in different seismic zones in Palestine, the seismic response and performance of these cases were discussed. The results and analyses of the studied cases showed that the proposed steel jacking system managed to avoid the collapse plastic hinges and to reduce displacements and drifts, it was found that the building fulfilled its seismic design criteria after the application of the strengthening strategy.

Keywords: reinforced concrete, pushover, steel jacketing, seismic assessment, strengthening.

Manuscript Received 26 July 2023; Revised 28 November 2023; Published 30 December 2023

1. INTRODUCTION

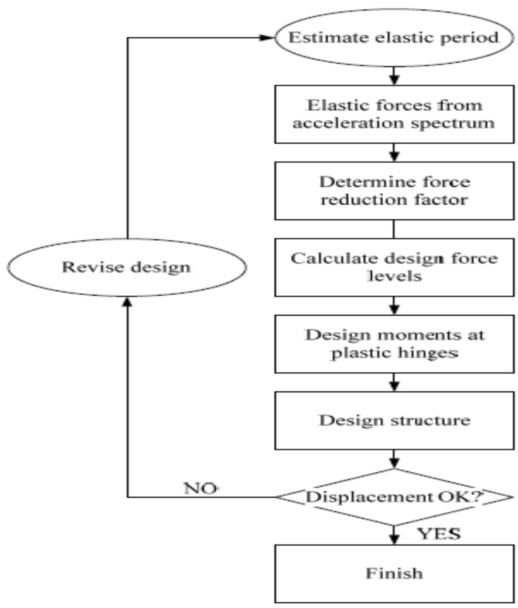
Classical seismic design codes in the world are generally based on elastic analysis methods, where the earthquake is presented as static Loads. This does not agree with the real state of the earthquake, where the structures can be exposed to large inelastic deformations in strong earthquake events, and this is not well accounted for in current force-based design methods.

Reyes and Chopra [1] presented the static procedures used by the available seismic design codes of concrete structures. The design lateral forces acting on any structure depend on the vibration properties of the structure and the site classification. Based on the estimated fundamental modal behavior of the structure, formulas are specified for calculating base shear, and then lateral forces are distributed over the height of the building accordingly. Static analysis of the building for these forces provides the design forces, including shears and overturning moments for the different stories and structural elements. In these methods, the inelastic behavior of the building is incorporated as a reduction factor "R" of the base shear force.

Liao [2], presented a flowchart describing the Force-based design process sequence as shown in figure 1, while figure 2 shows the process of calculating the base share of the structure, the seismic base shear force is generally reduced by a factor (R/I), where (R) represents the force reduction factor depending upon inherent ductility of the structural system, and (I) represents occupancy factor in order to increase the design base shear force for more important buildings according to the category of the building.

A design response spectrum is a graph that shows the maximum expected acceleration response of a structure to a seismic event, based on the site-specific ground motion characteristics. It is used in seismic design to ensure that the structure can withstand the expected seismic forces [4]. The seismic capacity spectrum represents the elastic and inelastic behavior of the structure, which is converted from base shear force versus top displacement into spectral acceleration and spectral displacement for equivalent SDOF. The resulting curve is known as the capacity spectrum curve for the building.

The process of determining the capacity curve relies on the use of nonlinear static analysis (pushover method). The performance point is defined as the intersection point between demand and capacity spectra where the ductility and energy dissipation of the structure are matched [5].



 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Figure-1. Force-based design process sequence [2].

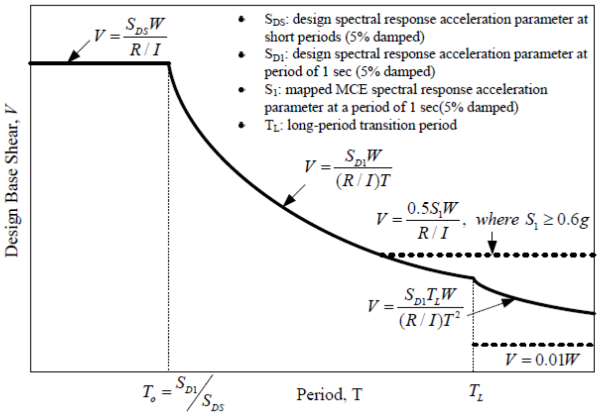


Figure-2. Design response spectrum for seismic design [3].

With the development of a performance-based seismic design concept, pushover analysis (PA) began to be another effective tool for the seismic design of structures.[6, 7]. In pushover analysis, a structure is pushed with certain distributed loads until a predetermined target displacement is reached, to estimate the seismic behavior of the structure under severe earthquakes. Lots of research work has been done on pushover analysis of high-rise buildings [8-10] and the accuracy of pushover analysis has been verified by comparing with the results of nonlinear time history analysis NTHA [11-14] and shaking table tests [15].

Performance level of buildings against earthquakes focusing on assuring limited failure that is assumed to be accepted for a given structure and horizontal excitation. Moreover, RC building collapses, danger to life safety of occupants in the RC building due to the failure, and post-earthquake serviceability of the structure ensures the failure state of the structure. Added to that, the structural performance level against earthquakes is composed of both the performance of structural and nonstructural elements. The following Table-1 describes the building performance levels according to the Applied Technology Council ATC [16].

The main seismic sources are faults and fault zones that are likely to generate significant (> 6) earthquakes in Palestine. The only two instrumentally recorded significant earthquakes are the 1995 7.2 MW Nuweiba earthquake occurred on the Aragonese Fault and was associated with a mean slip of 1.4-3 m [17], and the 1927 6.25 ML Dead Sea earthquake, which resulted in hundreds of casualties and a severe damage. All other information is based on geodetic, geologic, prehistoric, and historic evidence [18-20]. The faults constitute potential sources for earthquakes that can cause different sorts of damage, including ground motion and acceleration, landslides, liquefaction, surface rupture, and tsunamis. The following map (Figure-3) shows the Dead Sea Fault which lies between the Arabian and African plates, many major Palestinian cities lie on this fault (Tabaria, Jericho, and Elat).

Table-1. Building Performance Levels [16].

Building Performance Levels

	Collapse Prevention Level	**Life Safety Level**	**Immediate Occupancy Level**	**Operational Level**
Overall Damage	Severe	Moderate	light	Very light
General	Little residual stiffness and strength, but load bearing Columns and walls function. Large permanent drifts. Some exits blocked. Infills and unbraced Parapets failed or at incipient failure. Building is near collapse	Some residual Strength and stiffness left in all stories. Gravity-load-bearing elements function. No Out-of-plane failure of walls or tipping of parapets. Some permanent drift. Damage to partitions. Building may be beyond economical repair.	No permanent drift. Structure substantially retains original Strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. Elevators can be restarted. Fire protection operable.	No permanent drift; structure substantially Retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. All Systems important to normal operation are functional.
Non-structural Components	Extensive damage.	Falling hazards mitigated but many architectural, mechanical, and electrical systems	Equipment and contents are generally secure, but may not operate due to mechanical	Negligible damage occurs. Power and other utilities are available, possibly from

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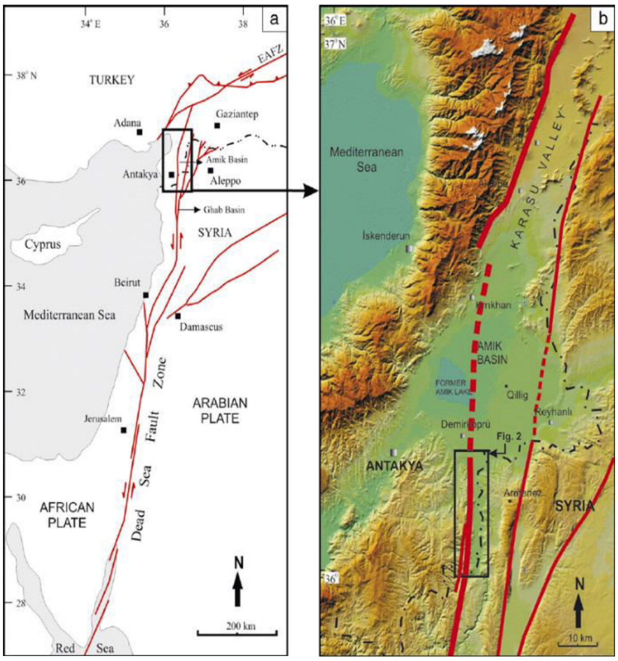

Figure-3. General Map of Dead Sea Fault Zone [21].

Many previous studies focused on using the Pushover Analysis (PA) as a predicting tool for reinforced concrete structures in order to make a satisfactory rehabilitation strategy in neighbor countries, no previous papers were conducted on different seismic locations in Palestine. This research article is devoted to checking the efficiency using Pushover Analysis as a seismic assessment tool of an assumed RC frame building. The methodology will be conducted using the software ETABS, the seismic behavior of the structure will be studied for different seismic regions in Palestine before and after proposing a strengthening technique using the steel Jacketing.

2. MODEL DESCRIPTION

2.1 RC Building Details

The test building is a G+5 story reinforced concrete building, located in four proposed locations in Palestine (Yaffa, Al Quds, Haifa, and Tabaria), it was constructed as a Reinforced Concrete (RC) structure, and the cities were chosen carefully to represent the seismic activity from low to high respectively. The building is symmetrical in plan with 3 bays of 4 meters each along the x-axis and y-axis.

The height of the ground floor was 4 meters and the others were 3 meters, making the total height of the building 16 meters. RC slab of 200mm thickness was provided; the base of the foundations of the structure was located at a depth of 2.5 meters below the ground level. All beams including the plinth beams were 300mm×400mm and all columns were 300mmX300mm in size. Only the reinforcement percentage was varied for the beams. Figure 4 presents the typical frame elevation showing column grid and beam layout.

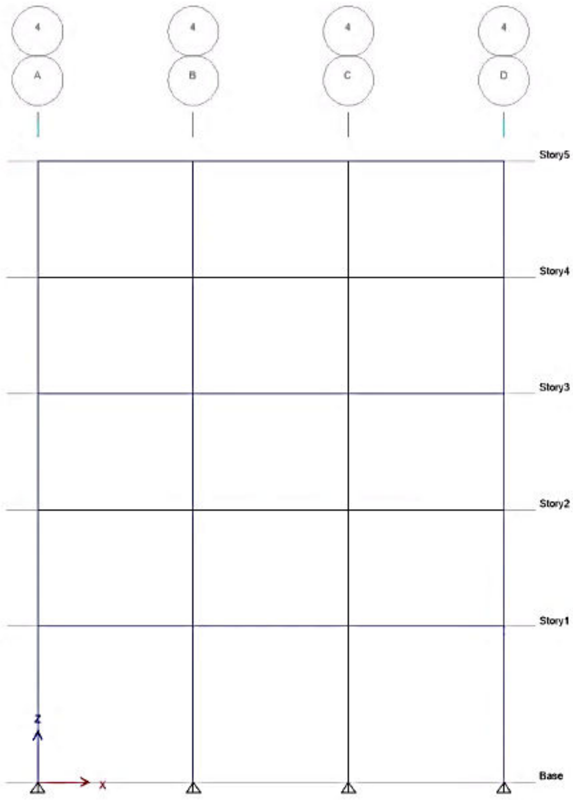

Figure-4. Typical frame elevation.

2.2 Loadings

Floor Finish load of the slab has been taken as 5 KN/m2. The Live load has been taken as 4KN/m2, no reductions in accordance with ASCE 7-10 has been considered. The seismic loads are obtained as the following and checked up by using ETABs software:

Based on ASCE 7-16, $S_1 = 0.08$, $S_s = 0.30$and $T_L = 11sec.$ The seismic maps and response spectrum for each selected region for Palestine are shown in Figures 5 & 6 respectively.

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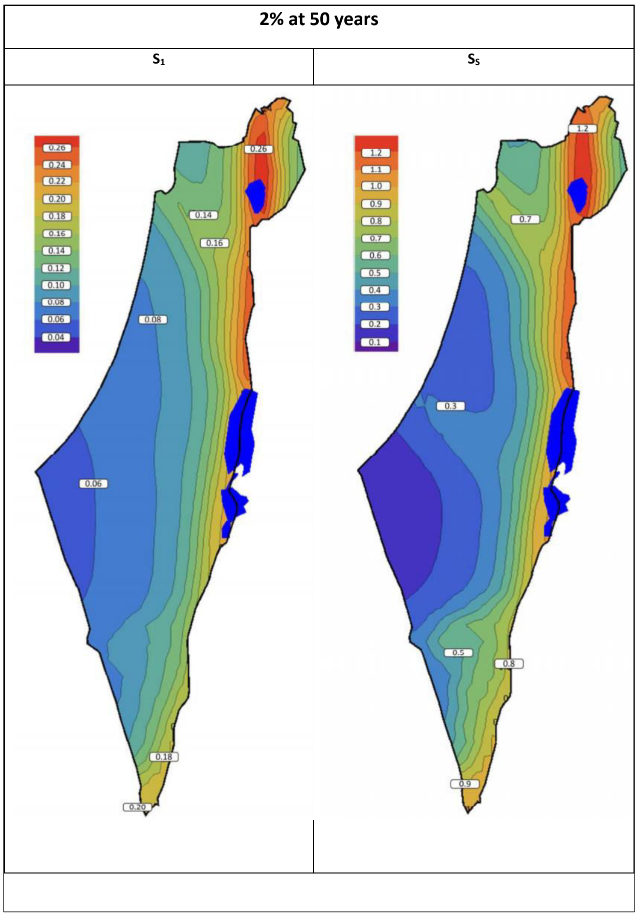
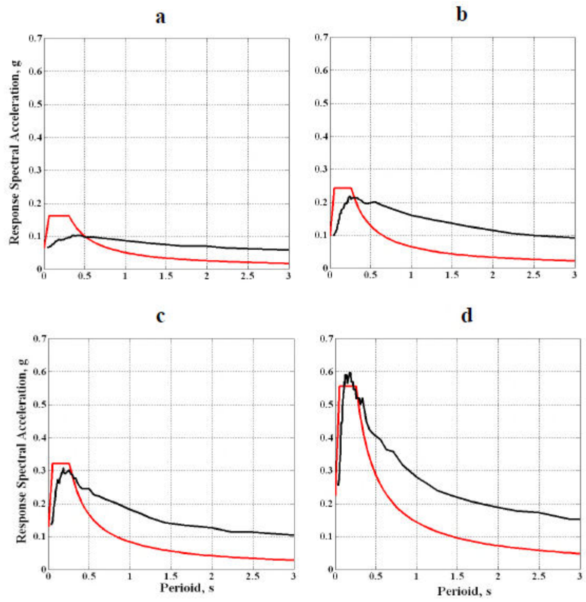


Figure-5. Seismic parameter S1 & SS as per SI 413-5.



a) Yaffa , b) Al Quds, c) Haifa, d) Tabaria

Figure-6. Response Spectrum for four locations.

The pushover analysis is achieved by displacement control strategy, where the lateral load pattern displacement reaches a target value. The minimum number of states used is 10 and the maximum is 100. Pushover analysis is performed in four different regions in Palestine as shown in the previous Figure-6.

2.3 Materials Properties

The Load Combinations taken for analyzing the structure were as per ASCE 7-10, modelling a building involves the modelling and assemblage of its various load carrying elements, the model must ideally represent the mass distribution, strength, stiffness, and deformability. Modelling of the material properties and geometric details is as per the details mentioned below:

Table-2. Materials properties.

Item	Value
Grade of Concrete	B250 & B300
Grade of Reinforcement	Fy 420 MPa
Poisson Ratio of Concrete	0.2
Poisson Ratio of Reinforcement	0.3
Density of Concrete	25 KN/m2
Density of Reinforcement	78.5 KN/m2
Young's Modulus of concrete (B250)	21,538 KN/m2
Young's Modulus of concrete (B300)	23500 KN/m2
Young's Modulus of reinforcement	$2.0X10^{8}$ KN/m2
Damping Factor	5 % (as per ASCE 7-10)

Beams and columns are modelled by 3D frame elements. The beam-column joints are assumed to be rigid, beams and columns in the present study were modelled as frame elements, with the centerlines joined at nodes using commercial software ETABS Ver 21. The dead weight of the beams and columns was calculated by the program using the material densities and the geometrical dimensions of the respective members, the floor slabs were modelled to act as diaphragms, which ensure integral action of all the vertical lateral load-resisting elements. The weight of the slab was taken into account by self-weight calculation by the program using the material properties and geometrical dimensions.

3. PRE-STRENGTHENING SEISMIC EVALUATION

3.1 Pushover Curve

Pushover curve for the RC frame building is presented in Figure-7; the pushover curve represents the global behavior of the frame in terms of stiffness and ductility. Under incremental displacement control loading, the structural element may be yielded sequentially. At every step, the structure experiences a loss in stiffness. Therefore, the slope of the pushover curve gradually decreases.

VOL. 18, NO. 20, OCTOBER 2023 ISSN 1819-6608
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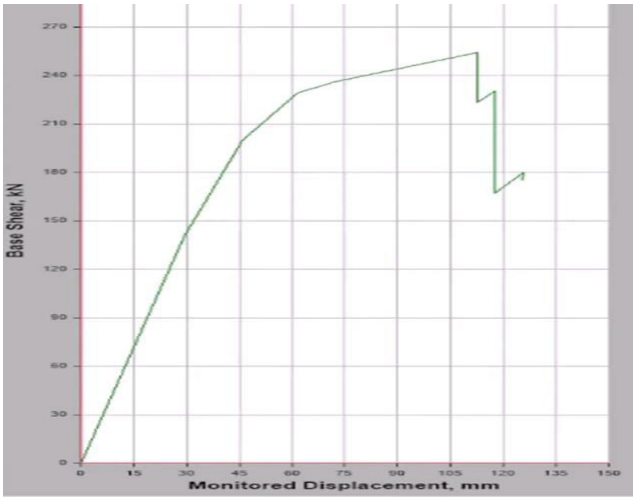

Figure-7. Pushover Curve.

3.2 Performance Point

Performance point for each region was recorded, by superimposing demand spectrum on capacity curve into spectral coordinate. Table-3 shows performance points for the four regions. The performance points are the intersection between demand curve and capacity curve.

Table-3. Performance points for each seismic region.

	V (kN)	D (m)	Step
Yaffa	228	0.061	3
Al Quds	593	0.071	5
Haifa	722	0.079	7
Tabaria	790	0.091	12

3.3 Description of Failure for Each Region

At every deformation step of pushover analysis determine the plastic rotation hinge location in the elements and which hinge reach the FEMA limit state, which are IO, LS, and CP using colours for identification. Plastic hinges formation has been obtained at different displacement levels or performance points.

Yaffa: The element response is still not dangerous at this performance point. Yield occurs in some elements but none of them exceeds IO (Immediate Occupancy) level. The outer columns still behave in the elastic range. Figure-8.a shows the deformed shape of the frame.

Al Quds: Most of the elements are in yield condition. The damage to the building is still limited since yielding occurs at event B (yielding) to IO (Immediate Occupancy). Figure-8.b shows the deformed shape of the frame.

Haifa: Although the element response is generally adequate at this performance point, the response is more severe than in previous regions. The yielding at the lower beams occurs at event IO (Immediate Occupancy) to LS (Life Safety). The yielding at the lower beams from one side occurs at CP (collapse prevention) event. Figure-8.c shows the deformed shape of the frame.

Tabaria: the frame is not adequate due to the lower beams yield exceeding collapse prevention and C (Collapse) condition. Figure-8.d shows the deformed shape of the frame.

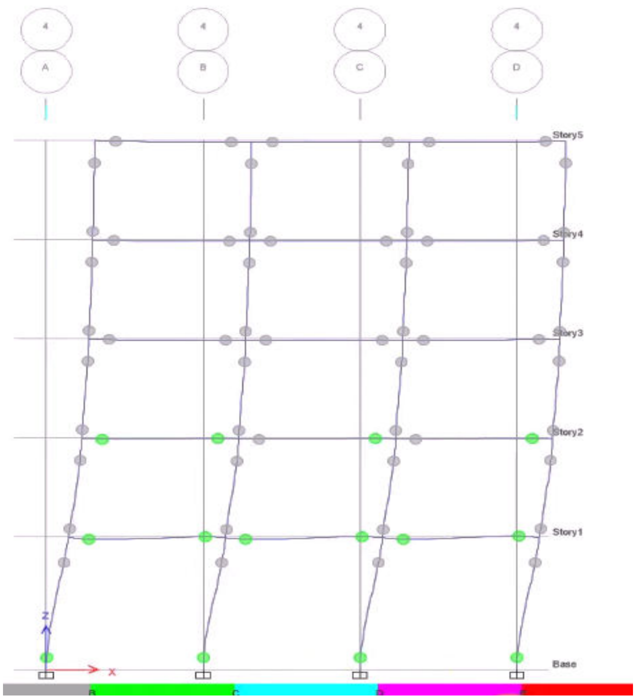

Figure-8.a. Deformed shape of the frame (Yaffa).

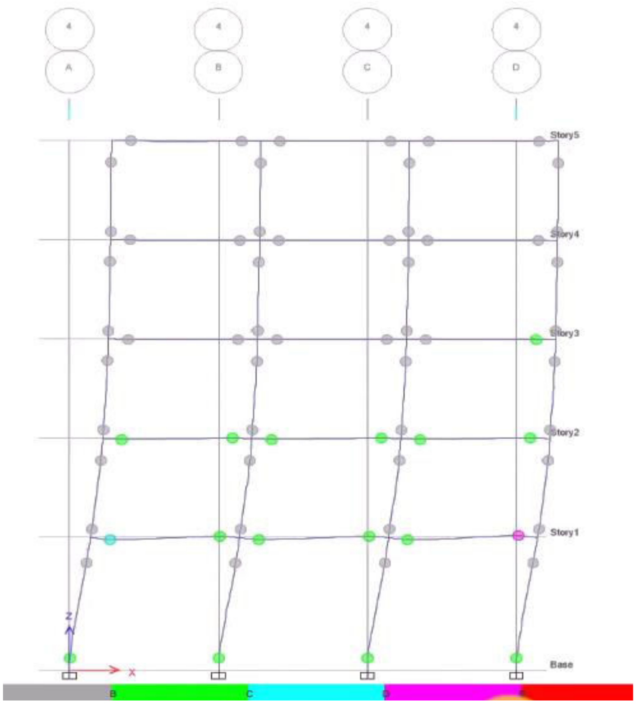

Figure-8.b. Deformed shape of the frame (Al Quds).

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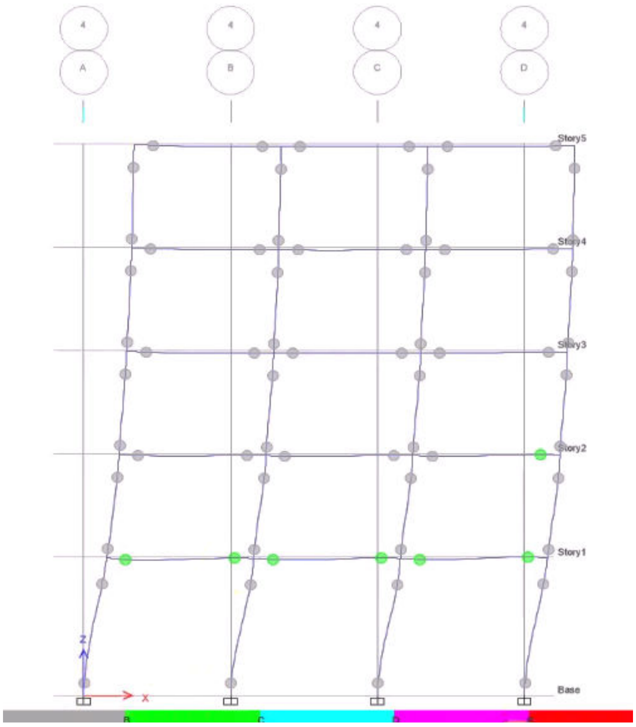

Figure-8.c. Deformed shape of the frame (Haifa).

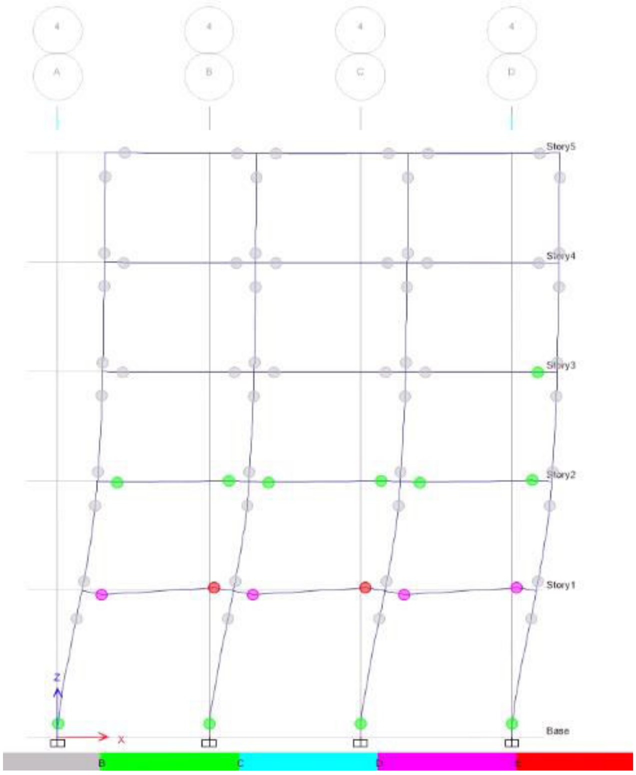

Figure-8.d. Deformed shape of the frame (Tabaria).

4. POST-STEEL JACKETING ASSESSMENT

The main objective of this part is to study the strengthening effect on the proposed RC frame; the strengthening technique will be used as steel jacketing of the existing RC beams only in the first story (it is the only story where the performance points exceeded the collapse prevention event for some regions). The proposed section is shown in the following Figure-9, the strengthened section was drawn using the section designer tool by ETABS, the strengthened section used is 32×42 cm, the steel thickness is 20 mm, and the steel type used is Fy=340 MPa.

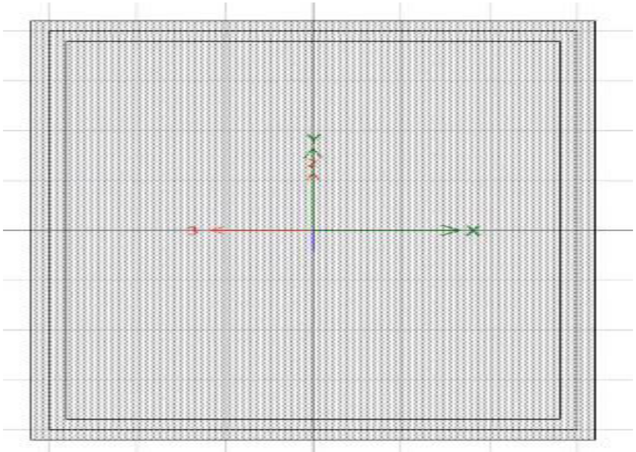

Figure-9. Proposed strengthened section.

Figure-10 shows the deformed shape of the Tabaria region after strengthening the beam with steel jackets, it is clear that the element response is converted to not dangerous case at this performance point. Yield occurs in some elements but none of them exceeds IO (Immediate Occupancy) level. The outer columns still behave in the elastic range.

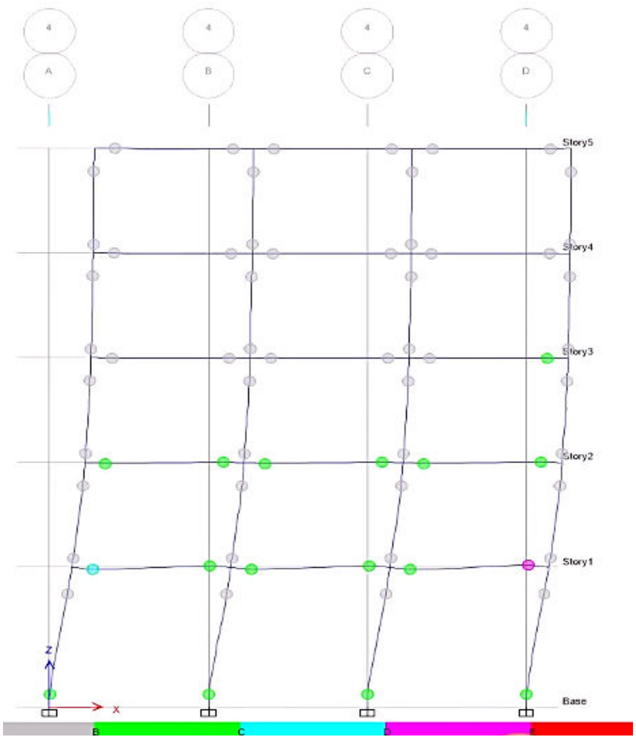

Figure-10. Deformed shape of the frame (Tabaria) after strengthening.

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

The following Table-4 shows the maximum displacements and base shear values for the different seismic proposed regions before and after the beam's strengthening process, it is clear that the maximum displacement value that occurred at the performance point of the RC frame for the Tabria area decreased significantly 27.5 %. Due to strengthening the section of the beam with steel jackets, the maximum base shear found was also decreased by 11.3 % for the ultimate seismic region case.

Table-4. Displacement and Base Shear after strengthening.

	Before Strengthening		**After Strengthening**		**Decrease % of displacement**	**Decrease % of Base Shear**
	V (kN)	**D (m)**	**V (kN)**	**D (m)**		
Yaffa	228	0.061	201	0.044	27.9 %	11.8 %
Al Quds	593	0.071	511	0.050	29.6 %	13.8 %
Haifa	722	0.079	650	0.058	26.6 %	9.9 %
Tabaria	790	0.091	710	0.066	27.5 %	11.3 %

5. CONCLUSIONS

The tested RC frame is investigated using pushover analysis. These are the conclusion obtained from this study:

- Pushover analysis is a simple way to investigate nonlinear behavior of the building. The result obtained gave an understanding of nonlinear behavior, which is the real behavior of the structure.
- Pushover analysis is an approximation method based on static loading. It may not accurately represent dynamic phenomena. It is recommended to do a full dynamic analysis for complicated RC frame buildings in the near future.
- The performance level of the structure is indicated by the intersection of demand and capacity curves and the hinges developed in the beams and the columns. The results show the frame that was designed only for gravity load is found inadequate for the Tabaria region. However, the frame still can be considered for other regions.
- Pushover analysis can identify weak elements by predicting failure mechanisms and account for the redistribution of forces during progressive yielding. It may help engineers take action for rehabilitation work.
- After reinforcing the beams that collapsed in the Tabaria region with steel jackets (20 mm thickness), the behavior changed to immediate occupancy which is safe for seismic events, more over both the maximum base shear and maximum displacement values were significantly decreased for all regions.

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