Evaluation of the Seismic Performance of RC Buildings in KSA According to the Seismic Requirements of the Saudi Building Code and Suggesting the Retrofit Systems

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***Abstract*— The first Saudi Building Code (SBC) was issued in 2007 to be verified and tentatively applied reaching to the obligatory application. In the recent decades, many quakes have hit the Kingdom of Saudi Arabia (KSA). The hollow block slab system is widely used in the residual and commercial buildings due to the variety of advantages they introduce. This study presents a performance assessment analysis of hollow block slab type R.C buildings designed as a gravity load or prior to the application of the seismic requirements of the SBC. The sample building is assumed to be located in three cities with different seismic intensities (small, medium and high). The 3-D nonlinear pushover analysis procedure is utilized in evaluating the seismic performance of the original building.Three different retrofit techniques are proposed and analyzed. The design response spectrum suggested by the SBC for the selected cities are used in the nonlinear pushover analysis. This is along with using a real compatible earthquake in carrying out a time history analysis. A comparative quantity and cost analysis between the proposed retrofittedsystems is also carried out. It is found that the gravity load designed hollow block slab building completely fails, in many cases, from meeting the response spectrum suggested by the SBC. The three suggested retrofitting methods can highly increase both the strength and stiffness of the original building and hence its spectral acceleration. All the suggested retrofitting systems enable the original building to meet all of the applied response spectrum at reliable performance points. The study also shows how every suggested retrofitting system can upgrade the seismic behavior of the original building. Quantity and cost analysis comparison study is also carried out.**

***Index Term*— seismic evaluation, nonlinear pushover analysis, hollow block slab building, retrofit systems.**

I. INTRODUCTION

The seismic performance evaluation and upgrading of non-seismic designed building structures located in new seismic zones is considered as an innovative challenge for seismic engineers and researchers. This concept has become an urgent issue in Kingdom of Saudi Arabia after the potential damage observed for many buildings during the 1995 quake in Tabuk, and also the quakes that shock the Kingdom in years 1999, 2009 [1]. The seismic risk analysis of buildings is important for identifying the seismic vulnerability of structural systems under the effect of seismic ground motions and achieve the purpose of seismic seismic hazard mitigation [2], [3]. A great task for seismic engineers and researchers is to decide how to retrofit an existing structure to upgrade its seismic capacity and to whatlevel of protection [4]. Flat and hollow blocks slab building structures are widely used due to many advantages they have over the moment resisting frames. They provide lower building heights, unobstructed space, architectural flexibility and easier frame work. However, due to lack of deep beams and/or shear walls, the resulted transverse stiffness will be low. This may lead to potential damage when subjected to earthquakes even with moderate intensity. The brittle punching failure due to transfer of shear forces and unbalanced moments between slabs and columns may cause serious problems. These systems are also susceptible to significant reduction in stiffness resulting from the cracking that occurs from construction loads, service gravity and lateral loads [5], [6]. Moreover, in the Kingdom of Saudi Arabia, columns with relatively small thickness are usually used in buildings. Due to the previous mentioned reasons effective and economic retrofit systems should be provided for the weak buildings.

There are many retrofit systems developed for RC buildings. Essentially, there are two main retrofitting techniques, the first is considered as non-conventional method, which incorporates base isolation and energy dissipation systems. This technique aims to increase the structural ductility and hence reduce the earthquake demand. The practical applicability of this technique is somehow limited. The second one is the system of strengthening and stiffening which is considered the most common seismic performance improvement strategies adopted for buildings with inadequate lateral force resisting systems. Typical systems employed for stiffening and strengthening include column strengthening and the addition of new vertical elements as moment resisting frames, shear walls or braced frames. The philosophy here is to provide systems that are strong enough to resist the seismic forces and light enough to keep the structuralelements from needing further reinforcement [7], [8]. Most of the existing methods need emptying the building during the retrofitting process, which creates serious problems. Therefore, it is highly preferable that these systems could be installed quickly [9].

Nonlinear time history analysis of a detailed analytical model may be the best decision for estimating the damage. However, there are many uncertainties due to the selection of specific input and with the analytical models representing the behavior of the structure. Pushover analysis monitors the progressive stiffness degradation of a structure as it is loaded into the post elastic range. The inelastic static pushover analysis is an effective option for estimating the strength capacity and highlighting potential weak areas in the structure. The method allows tracing the sequence of yielding and failure of the members and also captures the overall capacity curve of the structure. The static pushover procedure has been recommended as a tool for design and assessment purposes by many associations as the National Earthquake Hazard Reduction Program 'NEHRP' (FEMA 273) [10] guidelines for the seismic rehabilitation of existing buildings and the Seismic Evaluation and Retrofit of Concrete Buildings ATC-40 [11]. The technique has been used and evaluated as the main tool of analysis in several studies [12]- [16].

The seismic design provisions and analysis methods appeared in the Saudi Building Code - Structural requirements for Loads and Forces - (SBC 301) [17] are considered a significant step toward improving the seismic performance of buildings constructed in KSA. The concept of retrofitting and upgrading gravity load designed or designed according to earlier codes that do not guarantee seismic protections is considered important. However, the SBC 301 or the Saudi Building Code for concrete structures SBC 304 [18] do not offer provisions about how to deal with such branch neither recommendations about the suitable approaches of evaluations and the acceptable performance limits.

The purpose of this study is to offer a seismic performance evaluation of a gravity load, or designed prior to the application of the SBC, six stories hollow block slab building with plan dimensions of 32.0 m x 15.0 m. The level of seismic protection provided by the original building when located in three cities with different seismic intensities (small, medium and high) is examined. Different retrofitting systems are to be proposed and examined, in this study, as strengthening the columns, introducing shear walls or utilizing steel chevron bracing. 3-D nonlinear pushover analysis is adopted to evaluate the performance of the existing and retrofitted structure. Moreover, an elastic time history analysis is carried out. A comparative quantity and cost analysis between the proposed retrofitted buildings is also carried out. The objectives of this investigation can be summarized as:

(i) To examine the seismic performance of non-seismic hollow block slab building located in three cities with different seismic intensities and different soil properties.
(ii) Suggest three different retrofitting systems and compare their performances.
(iii) Apply the approach of nonlinear pushover analysis and compare it with the elastic time history analysis.
(iv) Present comparative quantity and cost analysis.

II. ORIGINAL BUILDING: DESCRIPTION AND MODELING

The studied building is a six stories reinforced concrete office building. The plan measures 32.0 meter by 15.0 meter. The configuration of the building is shown in Fig. 1. The building has six stories with height from the ground of 19 m, the typical story height is 3.0 m except the first storey which has a height of 4.0 m, no basement is presented. The gravity load resisting system consists of 0.25 m thick one way hollow block slabs carrying the floor loads to interior solid slabs and external dropped beams and hence to the interior columns and perimeter frames. The lateral load resisting system is only the relatively rigid slabs through frames and columns. The perimeter frames consist of beams and columns with tee and square sections, relatively.

The compressive strength of concrete used in the building is 22.50 MPa while the used steel is mild steel with yield strength of 280 MPa. The three dimensional nonlinear pushover and linear time history are constructed and analyzed using ETABS software package, nonlinear version 9.6 [19].

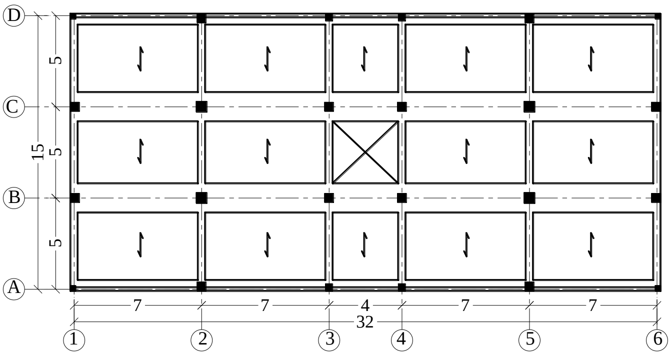

Fig. 1. Plan of the investigated original building

III. SPECTRAL RESPONSE ACCELERATION INSBC

The Kingdom of Saudi Arabia has been divided into seven regions for determining the maximum considered earthquake ground motion in the SBC. The considered spectral response acceleration suggested by this code is shown in Fig. 2.

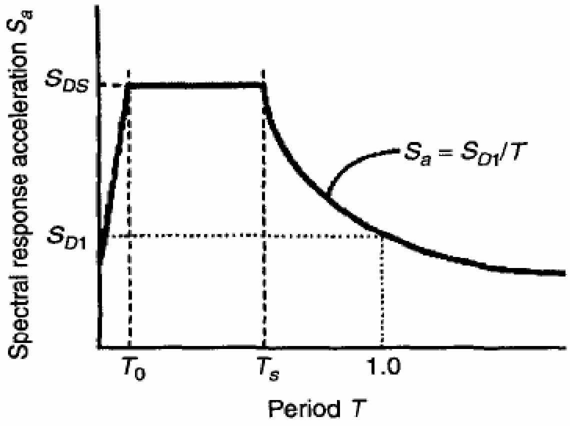

Fig. 2. Response spectrum in Saudi Building Code

Where:

$$S_{MS} = F_a S_S \quad (1)$$

$$S_{M1} = F_v S_1 \quad (2)$$

$$S_{DS} = \frac{2}{3} S_{MS} \quad (3)$$

$$S_{D1} = \frac{2}{3} S_{M1} \quad (4)$$

In which

S_{MS} : The max considered earthquake, 5% damped, spectral response acc. at short periods.
F_a : Acceleration – based site cooefficient.
S_s : The mapped max considered earthquake, 5% damped, spectral response acc. at short periods.
S_{M1} : The max considered earthquake, 5% damped, spectral response acc. at a period of 1 sec.
F_v : Velocity–based site coefficient at 1.0 sec. period
S_{DS} : The design, 5% damped, spectral response acceleration at short period.
S_1 : The design, 5% damped, spectral response acceleration at a period of 1 sec.

The values of the above mentioned parameters are specified by the SBC in the form of tables and graphs.

In this study, three different cities having different seismic intensities (low, medium and high) are considered. The chosen cities and the corresponding values of S_S and S_1 are illustrated in Table I.

TABLE I
SEISMIC VALUES FOR THE CHOSEN CITIES

Town	***S_S***	***S_1***	***Grade***	***Symbol***
Jeddah	*30.0*	*10.9*	*low*	*JED*
Maghna	*57.79*	*17.0*	*medium*	*MAG*
Hakl	*86.56*	*28.10*	*high*	*HAK*

Two types of soils are used as a foundation for the case of study building which are soil type D and soil type E. Soil type D represents stiff soil with 180 m/s ≤ vs ≤ 370 m/s. Soil type E represents a soil with vs ≤ 180 m/s. where vs is the shear wave velocity. Figs. 3, 4 introduce the 5% response spectra adopted for the selected cities with soil types D and E, respectively.

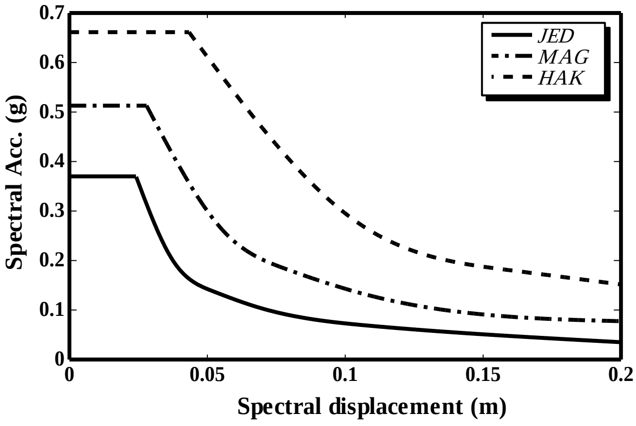

Fig. 3. Response spectrum of soil type D

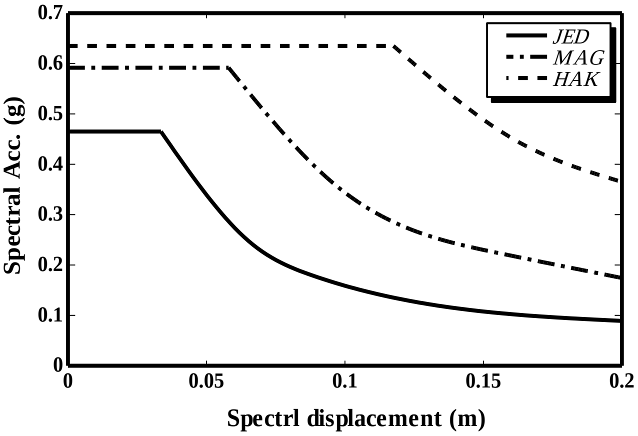

Fig. 4. Response spectrum of soil type E

IV. SEISMIC BEHAVIOR OF ORIGINAL BUILDING

Load displacement and modal analysis results are combined to generate the required acceleration displacement response spectrum(ADRS). A 5% percent damped elastic demand response spectrum for each of the three studied cities are generated and applied to the capacity spectrum of the original building either founded on soil type D or soil type E as shown in Figs. 5 and 6. It can be observed that the lateral capacity of the original building is very small. The original building completely fails to intersect the elastic spectra for HAK or MAG cities when founding on soil type E while it fails to intersect the elastic spectrum of HAK citywhen founding on soil type E.

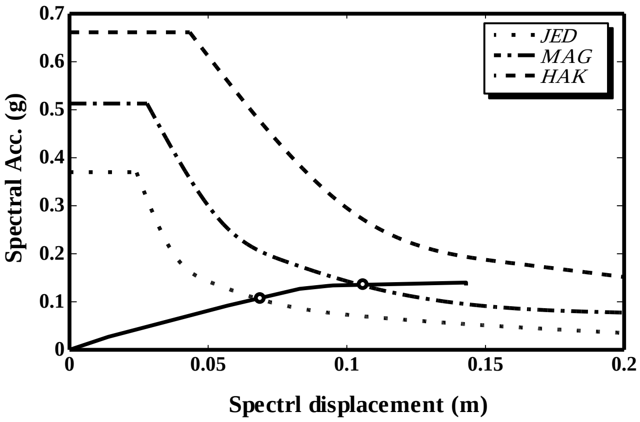

Fig. 5. Five percent damped elastic spectrum: original building soil type D

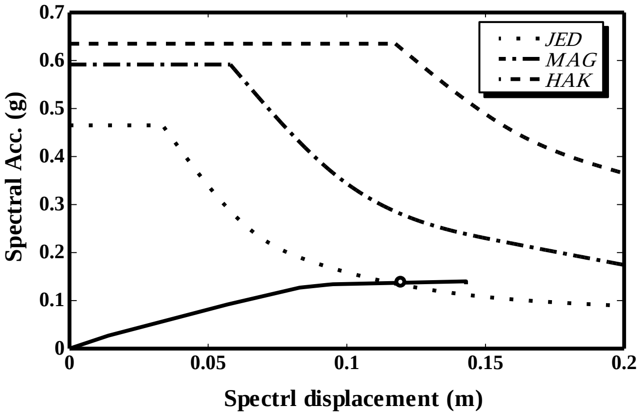

Fig. 6. Five percent damped elastic spectrum: original building soil type E

The effective inelastic damping ratios calculated for HAK city soil type D reaches up to 15%. This inelastic response enables the original building to meet the demand inelastic response spectrum of the mentioned city.Although using the inelastic response spectrum, the original building still far away from intersecting the demand response spectrum of HAK city when founding on soil type E.It can just meet the response spectra of MAG city at the end of performance when founding on the same soil. The shown figures and discussed results about the lateral capacity of the original building compared to the elastic and inelastic demand spectra of the applied response spectrum of the chosen cities emphasizes that a seismic retrofitting program is required. The required retrofitting systems should increase the strength and stiffness of the original building to prevent collapse under earthquakes with high seismicity and enhance its behavior under medium and low quakes. The inelastic response is shown in Figs. 7 and 8.

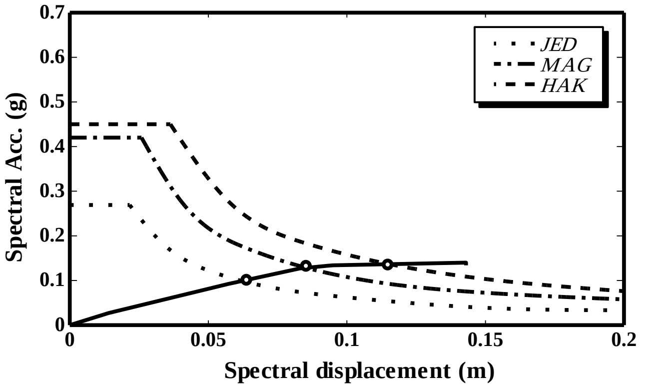

Fig. 7. Effective inelastic response spectrum: original building soil type D

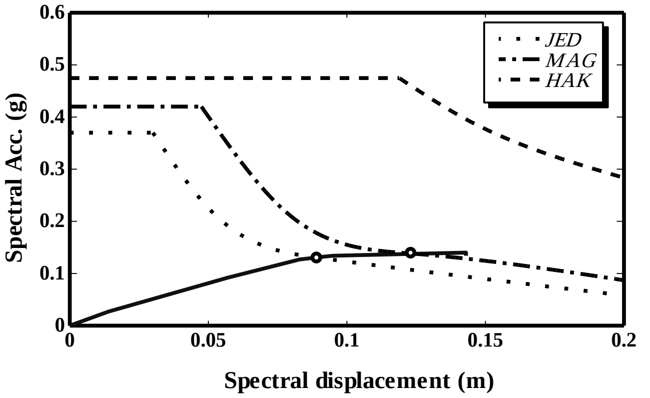

Fig. 8. Effective inelastic response spectrum: original building soil type E

V. SUGGESTED RETROFITTING SYSTEMS

A preliminary approach to design the suggested retrofitting systems using the nonlinear pushover analysis to find performance points within required deformation limit is carried out. The applied systems are briefly described as follows:

System I, Adding R. C. column jackets (CJ) to all the existing columns, the thickness of the column jacket is 0.075 m from each side. Same steel bars, in number and diameter as in the existing columns, are utilized in the column jacket.

System II, Adding shear walls (SW): Two shear walls in the short direction are added to the original building. The ratio of the total length of the added shear walls, in the mentioned direction, to the total height of the building is designed to be equal to 0.25. Achieving this, the length of each shear wall is taken 2.30 m. One shear wall is added in the longitudinal direction with length equal to 4.0 m. The thickness of all shear walls is taken equal to 0.20 m. The configuration of the shear walls, in both directions is illustrated in Fig. 9.

System III: Inserting steel chevron bracing (Br.): Chevron bracing elementsare applied to two originally existing exterior frames in the short direction, axis 1 and 6. The cross section of the bracing is hollow square box section of 0.20 m width and variable thickness. The thickness of the bracing elements varies every two floors; it is 0.01, 0008 and 0.006 m from bottom floor to top floor. In the long direction chevron bracing is also applied to one frame along axis D. The configuration is shown in Figs. 10 to 12.

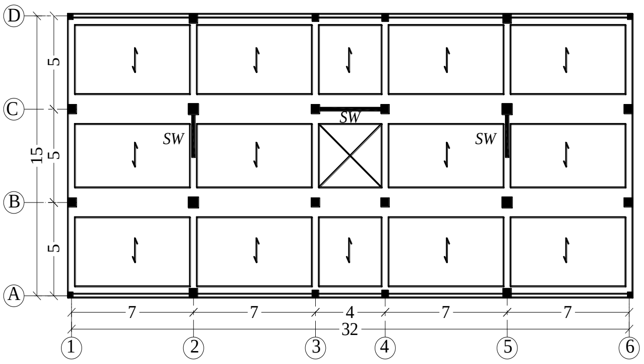

Fig. 9. Plan of the retrofitting system: shear wall (SW)

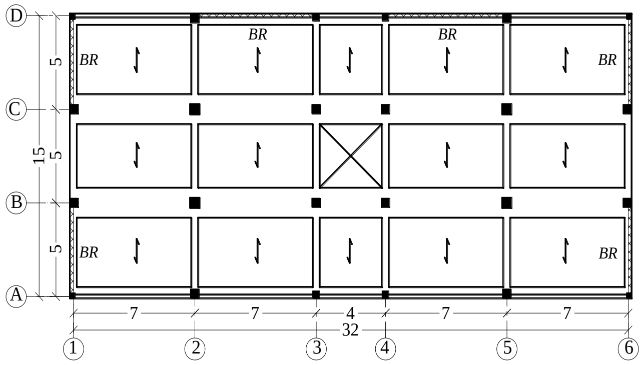

Fig. 10. Plan of the retrofitting system: Steel chevron bracing (BR)

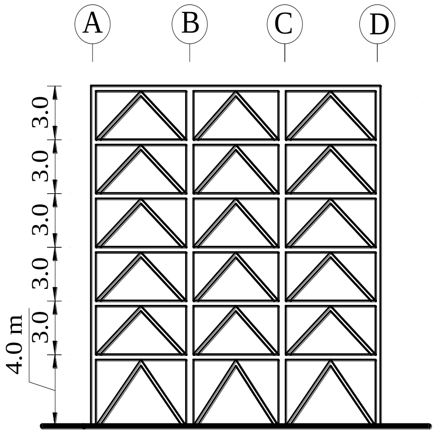

Fig. 11. Elevation of exterior frame along axis 1 and 6 in short direction

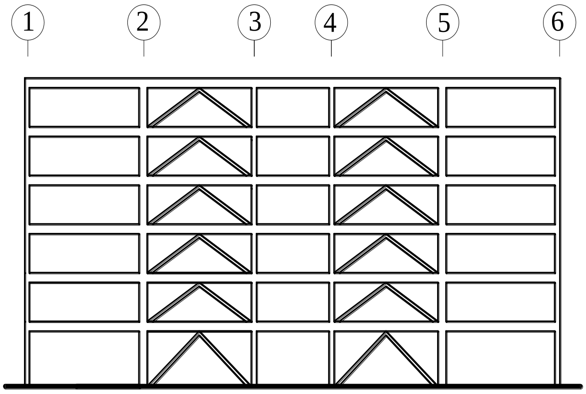

Fig. 12. Elevation of exterior frame along axis D in long direction

VI. SEISMIC BEHAVIOR OF THE RETROFITTED BUILDING

3-D nonlinear pushover analysis is applied to the retrofitted building with a procedure similar to that applied to the original building. As the primary elements of the retrofitted building are combinations of the existing and new elements, the structural behavior type is selected as type B [9]. The classical capacity curves represented by base shear and lateral displacement for the original and retrofitted building are obtained as shown in Fig. 13. The mechanism of the retrofitting systems can be clearly observed from this figure.The suggested systems can highly increase the lateral strength of the original building depending on the retrofitting type. The highest ratio of increase in the strength is observed for the BR system. The observed base shear for this system is increased to about 228%. The second ratio of increase is obtained for the SW system with a percentage of 200%. The lowest one in the percentage increase isobserved for the CJ system which is 128%. The aforementioned ratios are calculated relative to the original building. The observed stiffness of the retrofitted building with different systems isalso increased. The highest value is observed for the BR system while the lowest value is observed for the CJ system. The monitored lateral displacement of the original building is also increased due to using retrofitting systems. Unlike the strength and stiffness, the highest ration of increase is observed for the CJ system with a percentage increase equal to 66%. The percentage increase for the other two systems does not exceed about 25%.

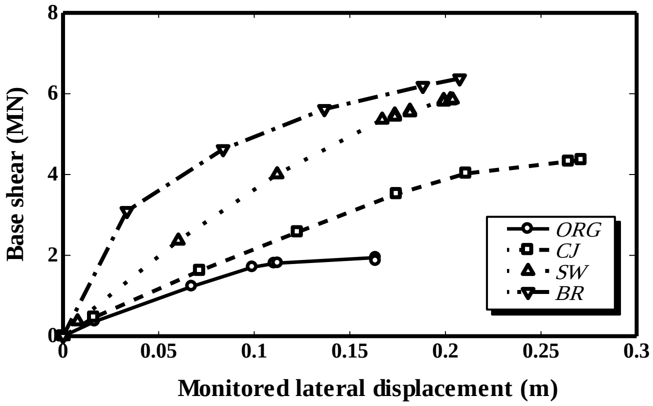

Fig. 13.Base shear versus lateral displacement for all the studied systems

The capacity spectrum curves defined by spectral displacement and spectrl acceleration (ADRS) are calculated and plotted for the building with different retrofitting systems relying on the pushover analysis. The performance points resulting from the intersection between nonlinear capacity spectrum and reduced effective spectra, of the different studied cities, are also calculated. The obtained results for the building utilizing different retrofitting systems when founded on either soil type D or soil type E are displayed in Figs. 14 to 19. It can be realized that all suggested retrofitting systems succeed in highly increasing the spectrum acceleration and displacement associated with the original building. This increase in the mentioned spectrum enables the original building to meet all the target spectraof the different case of study buildings in a very reliable performance points.This increase is considered as a direct result of increasing the lateral stiffness and strength of the building. The ratios of maximum increase in spectrum acceleration is not less than 123 %, relative to the original building, this ratio increases to reach up to 355 %. The highest ratios are observed for BR, SW, and CJ systems, respectively, the ratios of percentage increase in acceleration are shown in Table 2. As the suggested retrofitting systems are applied to increase the stiffness and strength of the original building rather than increasing its ductility, the percentage increase in spectral displacement for the retrofitted building has small values relative to the spectral acceleration when using either BR or SW systems. The percentage increase in the spectral displacementsdoes not exceed 5% as also shown in Table II. Higher ductility is observed when using the CJ system with a percentage increase of about 50%. This increase in the mentioned spectra enables the original building to meet all the target plastic demand spectra of the suggested different retrofitting systems in a very reliable performance points. As mentioned before, the original building completely fails, in many of the study cases, from meeting the target acceleration displacement spectra in any performance point. As founding on soil type E is considered as the worst case for the original building, that it fails to meet the spectrums of MAG and HAK cities. Using any of the suggested retrofitting systems can completely eliminate this problem. However, the performance points of the retrofitted building, when founding on soil type E, are shifted, rather than founding on soil type D, somehow towardsto the end of performance. This was observed for all the suggested retrofitting systems.

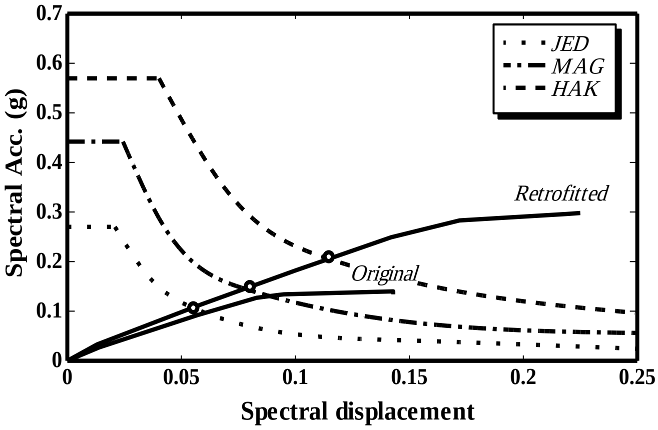

Fig. 14. Response spectrum for CJ system (soil type D)

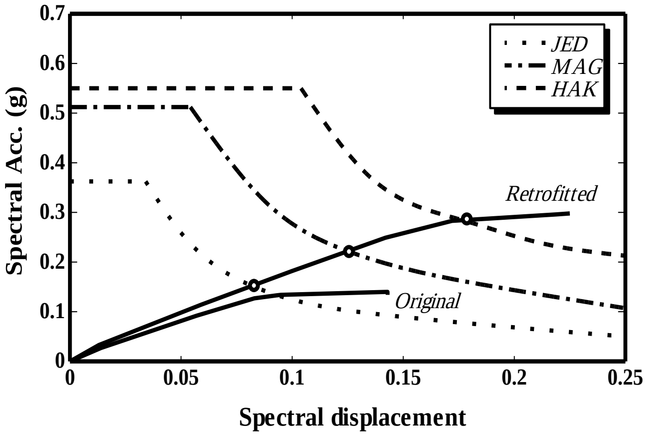

Fig. 15. Response spectrum for CJ system (soil type E)

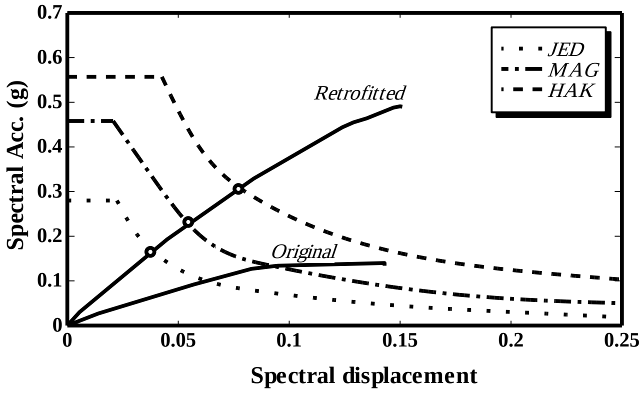

Fig. 16. Response spectrum for SW system (soil type D)

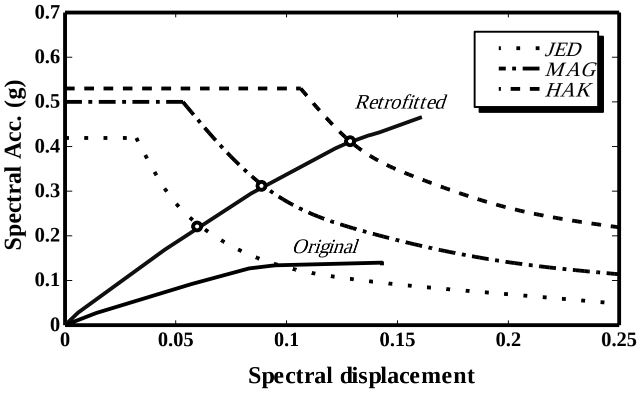

Fig. 17. Response spectrum for SW system (soil type E)

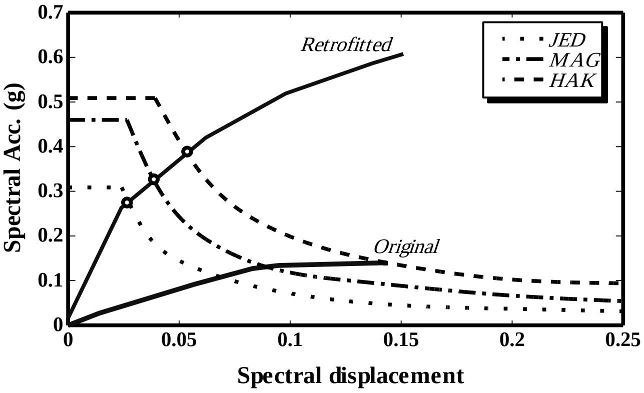

Fig. 18. Response spectrum for BR system (soil type D)

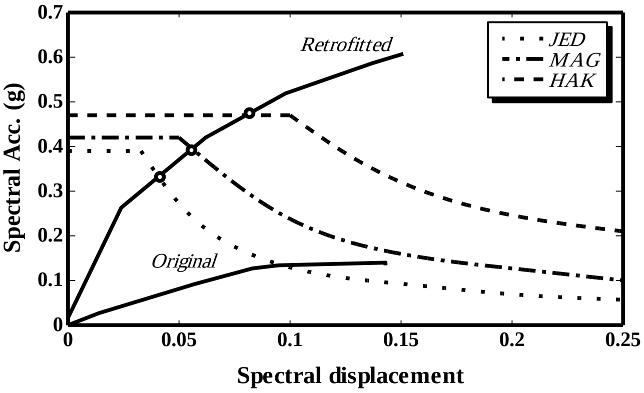

Fig. 19. Response spectrum for BR system (soil type E)

TABLE II
SEISMIC VALUES FOR THE CHOSEN CITIES

System	*CJ*	*SW*	*BR*
Spectralacceleration	*123%*	*219%*	*355%*
Spectral displacement	*50%*	*5%*	*5%*

VII. TIME HISTORY ANALYSIS

To carry out a 3-D linear time history analysis using a real quake, the NORTHRIDGE EQ 1/17/94is selected. The peak value of the 5% response spectra of this quake is close to that of the response spectrum suggested for HAK city by the Saudi Building Code. This earthquake hit a city with soil propertiesclose to that of soil type E.The acceleration time history of the utilized quake is shown in Fig. 20 while the response spectrum of the quake is shown in Fig. 21. For brevity, the results of the input energy for the different retrofitting systems versus the original building are illustrated in Fig. 22. It can, to somehow, be concluded that the obtained values of the time history analysis for the original building and the retrofitted ones can verify the results obtained for the nonlinear push over analysis. It can be observed that the time history of the building retrofitted using the CJ system is close to the original one while the maximum values of the input energies of the retrofired building using either the SW or BR system are higher than that is obtained for the original one. The obtained percentage increase in input energy is small for the CJ retrofitting system with a value of only 10%. This percentage increases to be 64% for the SW system, while it highly increases for the BR system with a value of about 300%.

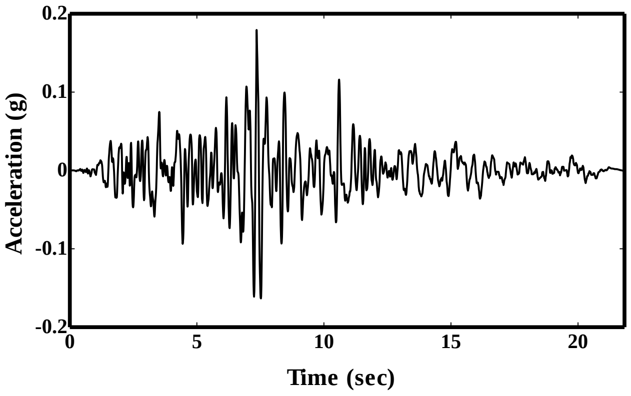

Fig. 20. Acceleration time history for Northridge quake

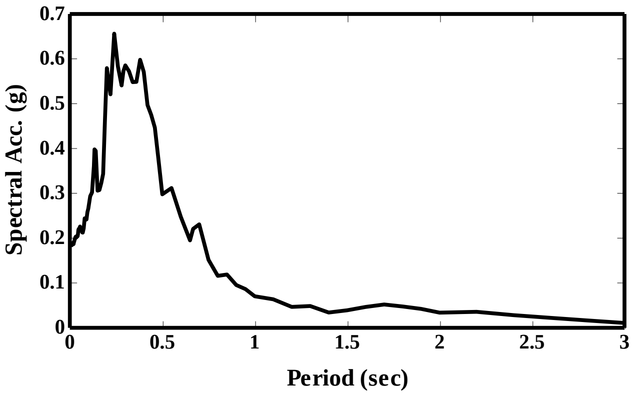

Fig. 21. Spectrum acceleration for Northridge quake

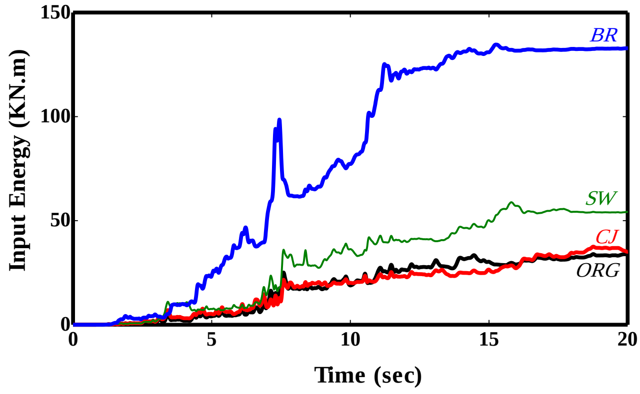

Fig. 22. Input energy time history for the different systems

VIII. COMPARATIVE QUANTITY AND COST ANALYSIS

A quantity and cost model study is carried out to report on the applicability of using the structural performance levels for the seismic retrofit designs. The objective of the quantity and cost analysis is to provide a comparison between the costs of retrofit of the different suggested retrofitting systems. The following assumptions are taken into consideration.

1- A foundation is made for the erected shear walls.
2- 20% of the section material is added to accommodate the connections in the case of the BR system.
3- The cost of finishingis not included.
4- The price of the one cubic meter of R.C required for the CJ retrofitting system is about 1.4 times the same amount required for the SW retrofitting system.
5- The cost of one ton of steel required for the erection of braces used in the BR retrofitting system is about 3.5 times the cost of 1 cubic meter of R.C required for the SW retrofitting system.
The quantities of the utilized materials are shown in Table III.

Depending on the aforementioned assumptions and the values mentioned in the table it is observed that the cheapest cost is applying shear wall systems. The second expensive one is the BR system with a cost about 1.61 times the cost of the SW system. The most expensive system is that using CJ, which is the most popular retrofitting system, with a cost of about 2.57 times the cost SW system.

TABLE III
QUANTITIES AND COST COMPARISON BETWEEN DIFFERENT RETROFITTING SYSTEMS

Retrofitting System	*SW*	*CJ*	*BR*
Reinforced concrete (m^3)	*39*	*66*	*-*
Steel for braces (ton)	*-*	*-*	*18*
Cost factor	*1*	*1.40*	*3.5*
Cost ratios	*1*	*1.61*	*2.57*

IX. CONCLUSION

An analytical seismic performance evaluation of hollow block slab type building designed, only, for gravity loads is carried out. Three different retrofitting systems are suggested and evaluated using 3-D nonlinear pushover analysis. However, comparison with linear time history analysis is also carried out. The response spectra suggested from the SBC for three cities with different intensities are utilized. The case of study buildings are assumed to be founded on either soil types D or E. Northridge quake is utilized in the time history analysis. The following conclusions may be drawn out.

1) The original hollow block slab type building is susceptible to the applied elastic 5% damped response spectrum, the building completely fails to meet the elastic response spectra of HAK city, either for soil type D or type E. The same is observed for MAG city when founding on soil type E.

2) Although utilizing the inelastic effective response spectra of the case of study cities, the original building still completely fails to meet the response spectrum of HAK city (soil type E). It can hardly meet the response spectra of HAK city (soil type D) and MAG city (soil type E) at almost the end of the inelastic response.

3) All the suggested retrofitting systems succeed in highly increasing the capacity base shear of the building and hence increasing the spectrum acceleration. All the suggested retrofitting systems can meet all the subjected spectrums in very reliable performance points.The percentage increase in spectrum acceleration ranges between 123 % and 355 %. Unlike the high increase in the spectrum accelerations the increase in the spectrum displacements is small; it ranges between 5% and 50%.

4) The highest increase in the values of response spectrum is observed for the BR system followed by the SW system and finally the CJ system.

5) The 3- D nonlinear pushover analysis proved to be a powerful tool in reasonably evaluating the seismic performance of original building, suggesting the suitable retrofitting systems and determining the locations, sequence and limit of plastic hinges.

6) The input energy calculated from the linear time history shows that the input energy increases for the suggested retrofitting systems rather than the original building. The orders of the increase are similar to that obtained for the spectrum acceleration obtained from the push over analysis.

7) From the carried out quantity analysis, it is found that the minimum cost between the three suggested systems is the SW system. The expected cost of the BR system is about 1.61 times the cost of the SW system while the expected cost of the CJ is the most expensive with a cost of about 2.57 times the cost of the SW system.

8) The BR system can provide a superior advantage rather than the other two suggested systems. It does need any evacuation of the building during the erection, all the required work is outside the building.

9) Finally, provisions about the procedures and accepted performance limits of gravity load 6designed buildings or buildings designed prior to the release of the SBC need to be presented by the Saudi Building Code.

10) The scope of this paper can be extended to assess other types of buildings as moment resisting and shear wall buildings.

ACKNOWLEDGMENTS

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