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Effectiveness of Seismic Retrofit for Existing Concrete Buildings using Nonlinear Static-Analysis

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Abstract

In the present study, the effectiveness of the various retrofit methods for concrete structures are investigated and compared. Six methods has been presented and three most used methods; i.e. Steel Jacket, Steel Bracing and Shear Wall; are selected for further comparison and studies. The behavior of reinforced concrete structures is assessed using nonlinear static analysis and the capacities as well as demand are calculated for the target performance level. For this purpose, a weak five story concrete structure was utilized. Due to its weak design, it was recognized that the building needs re-design and retrofitting. The performances of the structure before and after retrofit by three proposed methods were compared with each other. Results of numerical Simulations show that all three retrofit methods are effective in reduction of lateral displacements, increasing of ductility and improvement of the structural capacity. However, steel bracing and shear wall are most effective for reduction of lateral displacements.

Keywords: Concrete Structure, Nonlinear Static Analysis, Retrofit, Steel Bracing, Steel Jacket, Shear Wall

1. Introduction

Seismologically, Iran is a highly active and risky region and unfortunately heads the list of countries where earthquake has claimed many lives and caused extensive damage to property. Doubtless, casualties and property damage can be minimized by securing the hazardous environments. In this respect, depending on their purpose they serve, residential buildings receive special emphasis. Further, it is on the agenda of the national researchers to prepare and improve building seismic procedures. In civil engineering, strengthening means "To increase the strength of a structure (building) against the forces applied. Nowadays, the term is often used for the force caused by earthquake. Scientifically, "strengthening" is not an entirely proper term for this purpose because by "strengthening" is definitely not meant "to increase the strength against the force of earthquake"; rather, it is "to improve the performance of the structural elements (building) against the earthquake forces. For this reason, the term "improvement", and specifically for the earthquake force, "seismic improvement" is preferable. Therefore, the term "strengthening" as used in this paper, means "seismic improvement". As reminded earlier, strengthening is applied to prefabricated buildings. Basically, for buildings under construction, adherence to the technical standards and code is unavoidable and that strengthening has no particular significance. Therefore, the target audience must note that when there is reference to strengthening, the implication is both the new and old buildings already completed rather than those waiting to be built[1,2]. In this study, the stages in the seismic improvement of a 5-story reinforced concrete building are described. For this purpose, when the target building has been introduced, the need for structural improvement is established by using simulation and nonlinear analysis. To make proper seismic

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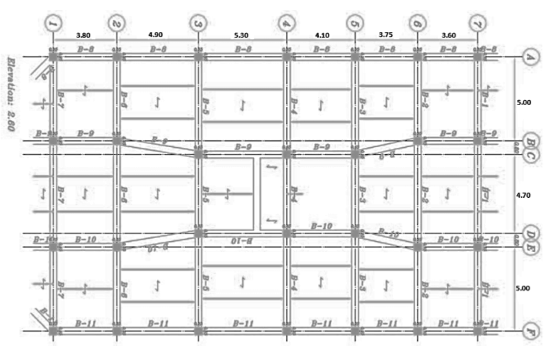
improvements, first, the general improvement methods and procedures for concrete structures are analyzed and compared to one another and then preferable options are presented in view of the better results from nonlinear analysis. Upon comparison of the results from nonlinear analysis before and after seismic improvement, the effects of improvement options are discussed.

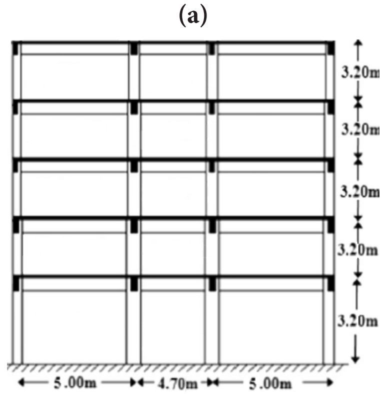
2. Case Study

2.1 Building Introduced

The target building is residential in nature, with a lateral load-bearing system and a reinforced-concrete panel of medium ductility. The roofs are of reinforced-concrete cross members measuring 27.85 m. Figure 1. (a) and (b) show the plan and profile of the building. The building has been designed in accordance with code 519 for reinforced concrete structures (Chapter IX: Building National Code[26]) and Standards 2800; and that for the vertical structural loads, Standards 519[3-5], have been used. The field data record for geometrical and structural skeleton as well as the studies conducted indicate the need for seismic improvement due to poor execution and failure to meet the standards at certain stages of the above building.



(a)



(b)

Figure 1. **(a)** Building Plan; **(b)** Profile of the building.

2.2 Purpose of Improvement

In this study, the purpose of improvement occupies an especial place. In respect of opting for an especial improvement, the building performance is placed at a higher level than for the desired level. Therefore, as explained below, the building is expected to be capable of uninterrupted use for earthquake hazard level I as well as of providing security for the lives of the building residents for hazard level II. Overall, the purpose of making improvements to the above building is as follows:

- Due to potential earthquakes, the strength and stiffness of the structural elements would not change and uninterrupted use would be possible (Performance level for capability of uninterrupted use),
- Due to potential earthquakes, the structures would suffer; however, the damage would not be to such extent as to claim lives (Performance level for capability of human protection),
- Due to potential earthquakes, the structures would suffer extensive damage; however, the building would not cave in and casualties would be minimized (Performance level for cave-in threshold).

3. Nonlinear Static Analysis

In the target structure, based on the modeled vertical loads and calculated lateral loads, nonlinear static analysis was conducted by inputting the study data to the software. For this method, the internal forces of the elements were assessed in view of their nonlinear behavior. The purpose of the analysis was to assess the expected performance of the structural system by estimating the demands for strength and their change in the design earthquake, and by comparing the demands with the available capacities on the performance level. For this method, the lateral load from the earthquake is applied statically and increased gradually to the structure until such time as displacement at a particular point (i.e. control point) reaches a given value (target displacement) or caves in under lateral load. In nonlinear static analysis too, the mass center of the roof is taken as the displacement control point. Finally, the deformations and internal forces from the nonlinear static analysis must be compared against acceptability and control standards. When the modeling of the target structure using nonlinear static analysis and extracting the pushover (= capacity) graphs for the structure are completed, the weaknesses of the structure are identified and structural improvement is made using the results obtained. Figure 2 shows the pushover graph of the structure considering the P-Δ effect before improvement.

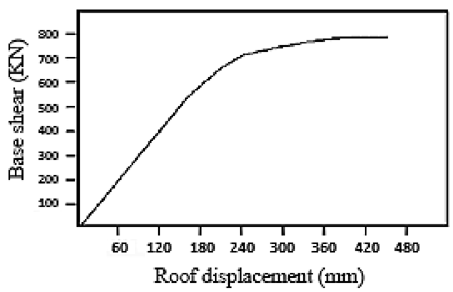


Figure 2. Graph for structural capacity before improvement.

4. Lateral Displacement Control for Structure

Table 1 Results from the controlled lateral displacement for the target structure.

Table 1. Results from the controlled lateral displacement for structure

Story	Item	Load	Drift X	Drift Y
Story 5	Max Drift X	EX	0.04171	
Story 5	Max Drift Y	EY		0.04171
Story 4	Max Drift X	EX	0.06120	
Story 4	Max Drift Y	EY		0.06120
Story 3	Max Drift X	EX	0.08360	
Story 3	Max Drift Y	EY		0.08360
Story 2	Max Drift X	EX	0.05791	
Story 2	Max Drift Y	EY		0.05791
Story 1	Max Drift X	EX	0.02497	
Story 1	Max Drift Y	EY		0.02497

$$\text{Drift Max} = \frac{\Delta W}{H} \le 0.\frac{025}{0.2R} = 0.\frac{025}{0.2*5} = 0.025$$

$$\text{Drift Max} = \frac{\Delta W}{H} = 0.\frac{08360}{3}.2 = 0.026125 > 0.025$$

As seen from the output results of software[6], the relative lateral displacement values for the base of each story divided by the height of a corresponding story exceed the permissible limits in Code 2800 and the lateral displacement values of the stories fail to meet the requirements of the above code. Using the results from the nonlinear static analysis, the structural weaknesses for uninterrupted use capability and safety are obvious; therefore, the target structure must be improved. Figure 3 shows the performance level of the target structure.

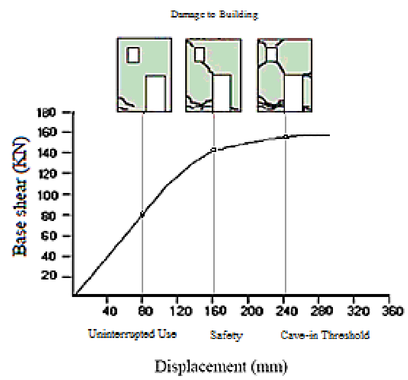


Figure 3. Structure performance levels.

Further, in view of the Figure 3 for structural capacity and the results from the controlled lateral displacement of the target structure, the problem areas or vulnerable elements of the structure are identified. Consequently, improvement of the structure becomes indispensable. Figure 4 shows the plastic joints and vulnerable elements of the structure.

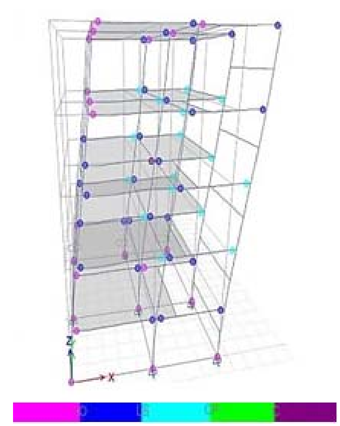


Figure 4. Plastic joints of the target structure.

In view of the need for seismic improvement of the structure, first, general procedures are proposed for the plan involving reinforcement and then seismic improvement to concrete structures are made individually or in combination with one another to the target structure.

- Local improvement to the structural elements with poor performance during earthquake,

- Eliminate or minimize disorder in the existing building,
- Provide lateral stiffness required for the entire structure,
- Provide the strength required for the entire structure,
- Utilize seismic isolator systems,
- Utilize inactive energy-loss systems, and
- Make changes to building use.

With respect to the above and the conditions of the target structure, it is impossible to reduce disorder in the structure to improve the performance; nor is it possible to changes the building use. The building mass can be reduced by using polystyrene in place of concrete blocks. However, for this purpose, all the roofs must be destroyed and re-executed. All the inner connections of roofs, columns, and walls must be properly executed which is difficult and costly. Therefore, alternative structural seismic improvement procedures become the focus of attention. For this reason, to acquire access to alternative effective options for improvement, the stages of making seismic improvement to concrete structures and gaining access to preferable options are addressed.

5. Stages for Making Seismic Improvements to Concrete Buildings

5.1 Evaluation of Structural Data and Status

Structural data such as the plan dimensions can affect the decisions about improvement options depending on the distribution of forces, quality, execution, and vulnerability of building by using the existing capacity. Generally, the bounds for recording the geometric and skeletal data of the structure, approximate status evaluation of the structural elements, initial typification, and finally preparation of the plans for initial evaluation will be made based on typification such that parallel with the initial evaluation operations, the details of structural plans will be completed conventionally and the data required for modeling will be prepared.

To gain access to the technical specifications of the materials, definitions are provided for a number of tests. The number of such tests are determined by collecting data using conventional methods. Due to the necessity of expediting the process of doing improvement studies and the skeletal status of the building, evaluation of the existing structural status will be made in three major stages referred to below:

- Completing the data and responding to the major questions developed in collecting the initial data playing a critical role in deciding about skeletal work, modeling, and structural analysis.
- Conducting tests to determine the specifications of the materials and collect the data required about the most appropriate points.
- Preparing plans about the existing status of the structures considering the recorded geometric and technical data and revision on the adequacy of points with respect to the minimal values needed and the final results from the building skeletal work.

5.2 Preparation of Preliminary Improvement Plan

For architectural, technical, executive, and economic reasons, evaluation of possible improvement options are the major aim of the preliminary improvement aim which ultimately results in selecting a superior option. Generally, to make seismic improvements to a building, there are multiple procedures[7-9], including local improvements made to the structural elements, elimination or minimization of disorder in the building, providing lateral stiffness for the structure, reducing the building mass, utilizing seismic isolator systems, utilizing energy-loss inactive systems, changing the use of the building, etc., which are discussed, and depending on the conditions and results from the structural analysis, one of the proposed options is used.

5.3 Optimization of Improvement Options

Every year huge costs are paid to promote civil construction plans. Allocation of resources to appropriate sectors has been a constant concern of the sector. Studies conducted in this area indicate the greater emphasis placed on applying optimization methods in managerial systems. Among others, reference can be made to the evaluation of the parameters contributing to the seismic improvement of buildings[10], evaluation of profits and costs for reducing earthquake-caused damage[11], and studies made on the contributors to optimized design of buildings aimed at increasing sustainability[12]. In view of the approach of this study, definition of priorities, classification and comparison of standards, evaluation of proposed improvement options, and finally, making decisions about selecting the best options are of great importance[13].

5.4 Identification and Evaluation of Effective Improvement Procedures for the Target Building

As reminded earlier, to evaluate the improvement options[10], the effective parameters needed for this purpose must be identified. By studying the relevant methods and procedures[4,14-16], the experience gained, studies involving evaluation so improvement options for concrete buildings to improve the structural behavior and increase the strength of the structural elements, six improvement options suitable to the target structure involving reinforcement by executing a sectional wall, using steel jackets, or steel wind-bracers, adding in a concrete panel, reinforcing the walls by shotcreting, repairing and reinforcing by applying proper grout are discussed.

Another major problem is to maintain the building use while executing the project which applies to certain buildings with specific uses. In such cases, using reinforcement options from outside the building could work. Figure 6 compares the seismic improvement options proposed for the target building[17].

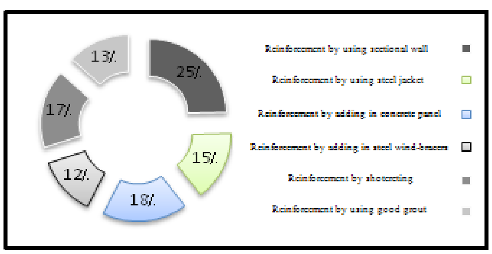
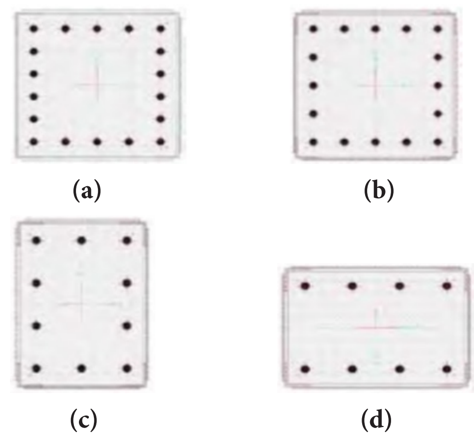


Figure 5. Seismic Improvement Options Compared.

Finally, the evaluation results indicate that decreased interference and increased effect of reinforcement options using steel wind-bracers, add-in sectional walls, and steel jackets are superior options with the following application and results.

5.4.1 *Using Steel Jacket*

Steel jacket usage is a common practice in the plan for concrete reinforcement structures aimed at increasing the ductility and strength of the elements of beams and columns[18,19]. With respect to the cross-sections of the beams and columns in the target building, one type of beam and three types of columns with steel jackets are proposed for reinforcement of the target structure[20]. The model reinforced using software was evaluated using nonlinear static analysis. The results from the conditions for permissible lateral displacement per code and the stress ratio based on the analysis indicate their acceptability. The cross-sections of the beams and columns with steel jackets are shown in Figures 6 (a)-(d).



(a) Column 40*40 cm reinforced with 4 sheets 0.5 cm thick each
(b) Column 40*40 cm reinforced with 4 sheets 0.5 cm thick each
(c) Column 30*40 cm reinforced with 4 sheets 0.5 cm thick each
(d) Column 30*40 cm reinforced with 4 sheets 0.5 cm thick each

Figure 6. Cross-sections reinforced with steel jacket.

5.4.2 *Using Steel Wind-Bracers*

Generally, steel wind-bracing is a desirable system for seismic improvement of structures. Increased strength and ductility, relatively easier execution, relatively simpler quality control method, less load applied to the structure, possibility to use openings and doors in braced openings are among the advantages of this method. Using wind-bracers in the target structure not only helps to bear lateral loads but also better distributes the loads, considerably reducing the lateral displacement of the structure. It should be noted that when the modeling for wind-bracers and nonlinear analysis were completed, it was observed that a number of the columns on the first floor were still poor in strength. For this reason, not only were steel wind-bracers used but also in accordance with the details of the target columns, steel jackets were used to improve and reinforce the cross-sections.

5.4.3 Adding in Sectional Wall

The other seismic improvement method for concrete structures is using a sectional wall. Of the advantages of this method, reference can be made to the increase in the total strength of the structure and the concrete elements, and considerable decrease in the lateral displacement of the structure. In the target structure, a 20 cm wall was used. The wall sections were L-shaped so that firstly it should increase the structural stiffness and secondly a smaller number of columns need repair and reinforcement, and lastly the executive operations be further centralized[21-25].

Once the modeling by software and structural analysis was completed, a considerable decrease in lateral displacement was noticed. Moreover, when structural designing with an add-in sectional wall was completed, the stress ratio in the elements considerably decreased. It should be noted that since good connections were in place, like in the previous mode, the analysis was made with the initial behavioral coefficient. To compare the improvement methods used in the target structure, first, the graph representing the structural capacity following improvement is shown in Figure 7. Then, to compare the improvement methods used in the structure, the parameters for lateral displacement in the two major directions are compared with the results shown in Figure 8.

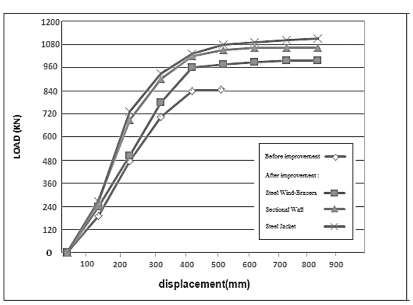
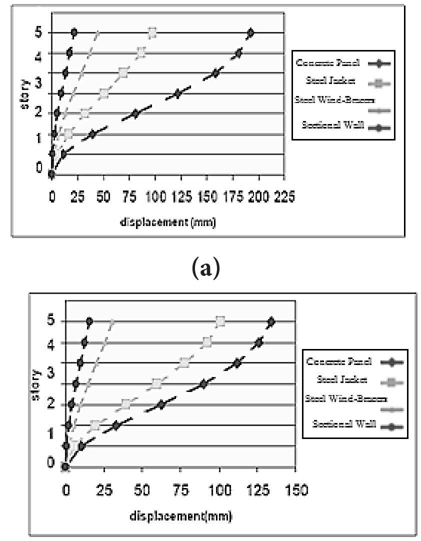


Figure 7. Structural Capacity before and after Improvement.

Figure 7 reveals that each structural characteristic including "capacity", "lateral displacement", and "ductility" has improved considerably following the improvement method used including the use of steel wind-bracing, add-in sectional wall, and steel jacket.



(a)

(b)

Figure 8. Maximal Lateral Displacement before and after Improvement **(a)** along X; **(b)** along Y.

Figure 8 reveals that the decrease in lateral displacement in the structure improved with a sectional wall and steel wind-bracing is considerable in both directions and indicative of a desirable performance due to the options used.

6. Discussion and Conclusion

In this context, using simulation and applying nonlinear static analysis at a higher speed with a simplified interpretation of the results and acceptable accuracy, first, the need for making seismic improvements is established, and then, working procedures commensurate with the target structure are presented. To evaluate the improvement options for the target building, six improvement options, suitable to the target structure, including reinforcement by executing a sectional wall, using a steel jacket, steel wind-bracers, add-in concrete panel, reinforcing the walls by shotcreting, as well as reinforcing and repairing by using a good grout were proposed. Based on the evaluations including the results from nonlinear analysis, vulnerability of the building current status, preferable options were selected, executed, and compared in accordance with the design standards and the effect of the design on architecture. A comparison of the results indicates improved structural performance, increased ductility and energy absorption by the target structure. Further, the results from the simulation of the target structure before and after improvement can be discussed as follows:

- In the static analysis of the existing structure, not only has the earthquake code been violated for the lateral displacement of the structure but also the beams and columns have failed to meet the standards for bearing the lateral forces.
- By executing steel jackets in the seismic improvement of the target jacket, about 45% of the columns and 25% of the beams were improved and reinforced.
- By using steel wind-bracers for improvement of the target structure, a desirable performance was achieved for all the elements which were improved and reinforced. A number of the columns, too, found to need further reinforcement were improved and reinforced by using steel jackets proportionate to their cross-sections.
- By adding in a sectional wall to reinforce the structural behavior and performance a desirable effect was achieved. However, to ensure the adequacy of the columns used as boundary elements, they were additionally reinforced by using steel jackets.
- Generally, in improving the target structure, the proportion of the decrease in the lateral displacement is as follows:
  - 50% decrease by using steel jackets,
  - 85% decrease by using steel wind-bracers, and
  - 90% decrease by using sectional walls.
- In evaluating other parameters such as the degree of destruction, costs, labor intensiveness of improvement operations, using the steel wind-bracing method can be considered preferable to the two other methods.
- Finally, it can be said that the three improvement methods used are good options; however, the two methods involving the use of steel jackets and sectional walls where needed in a smaller number for seismic improvement or in especial cases, are considered better options whereas using steel wind-bracers is a good option subject to proper execution and accurate quality control inspection.

7. References

1. International Conference of Building Officials. Uniform Building Code, Section 1910.2. Whitter, California; CA, 1997.
2. International Conference of Building Officials. International Building Code, Section 2101.4. Whitter, California; CA, 1997.
3. Standard 2800, National Iranian Building Design Code for Earthquake, 4th ed. Building and Housing Research Center. 2014; 34–5.
4. Instruction for Seismic Rehabilitation of Existing Buildings, Office of Deputy for Strategic Supervision Department of Technical Affairs. 2013; 133–97.
5. Section VI: National Iranian Building Code, Office for Development and Promotion of the National Building Code. 2013; 13–117.
6. ETABS Ink. ETABS/Theory User Manual, Version 9, Chapter 3-5. 2009.
7. Techniques for the Seismic Rehabilitation of Existing Buildings. 2006 Oct.
8. Simmon foo-norenaumoski-nuratsaatsiogh Seismic Hazard building Code and mitgation Option for Canadian Building office of critical infrastructure protection and emergency preparedness, University of Ottawa: Canada. 2001.
9. Somerville P. Characterization of near field ground motions. US–Japan workshop: effects of near-field earthquake shaking, San Francisco. 2000; 21–9.
10. McCaffrey J. The Analytic Hierarchy Process, Test Run: The Analytic Hierarchy Process. MSDN Magazine. 2005; 08(1):21.
11. Azmoodeh BM, Moghadam AS. Optimum Seismic Retrofitting Technique for Buildings. Civil Engineering and Environmental System. 2011; 28(1):61–74.
12. Grossi PA. Assessing the Benefits and Costs of Earthquake Mitigation. Financial Institution Center, The Wharton School-University of Pennsylvania. 1998; 1–12.
13. Federal Emergency Management Agency, FEMA 356, Prestandard and Commentary for the Seismic Rehabilitation of Buildings. ASCE Standards Program and the Structural Engineering Institute. 2000; 1–9.
14. Balcomb JD, Curtner A. Multi-Criteria decision-making Process for buildings. 35th Intersociety Energy Conversion Engineering Conference and Exhibit, IECE, Las Vegas. NV. 2000; 528–35.
15. American Society of Civil Engineers (ASCE). Prestandard and commentary for the Seismic rehabilitation of buildings, prepared for the SAC joint venture, Federal Emergency Management Agency, FEMA-356, Washington (DC). 2000; 1:1–35.
16. Guidelines for Studies of Ancillary Services in Rehabilitation Projects. Office of Deputy for Technical Affairs Technical Criteria Codification and Earthquake Risk Reduction Affairs Bureau. 2007; 3–47.
17. Asghar VO. Methods and Execution Details of Building Improvement against Earthquake. Tehran: Shahid Rajaei University; 2007.
18. Hadi MNS. Retrofitting of shear failed reinforced concrete beams. Composite Structure. 2003; 62(1):1–6.

19. Orozco G, Ashford SA. Effects of large pulses on reinforced concrete bridge columns, Pacific Earthquake Engineering Research Center. PEER Report 2002/23, College of Engineering. Berkeley: University of California; 2002.
20. Daudey X, Filiatrault A. Seismic evaluation and retrofit with steel jackets of reinforced concrete bridge piers detailed with lap-splices. Canadian Journal of Civil Engineering. 2000; 27(1):1–16.
21. Tasnimi AA. Strength and Deformation of Mid-Rise Shear Walls under Load Reversal. Engineering Structures. 2000; 22(4):311–22.
22. Su RKL, Wong SM. Seismic Behavior of Slender Reinforced Concrete Shear Wall under High Axial Load Ratio. Engineering Structures. 2007; 29(8):1957–65.
23. Perry A, Ahmed MM, Bryson M. Test of High Rise Core Wall: Effective Stiffness for Seismic Analysis. ACI Structural Journal. 2007; 104(5):549–59.
24. Ibrahim AMM. Linear and Nonlinear Flexural Stiffness Models for Concrete Walls in High-Rise Buildings. Canada: University of British Columbia; 2000.
25. Kia A, Sensoy S. Assessment the effective ground motion parameters on seismic performance of R/C buildings using artificial neural network. Indian Journal of Science and Technology. 2014 Dec; 7(12).
26. Section IX: National Iranian Building Code, Office for Development and Promotion of National Building Code. 2013; 177–373.