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Optimal Improvement of a Medium-Sized Steel Flexure Frame Designed with Code 2800, Third Edition

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Abstract

Given the prevalence of earthquakes globally, including those in Iran, it has become essential to recognize certain outdated and ineffective practices in the country, elevate the expertise of professionals, and develop updated versions of structural and earthquake codes. Additionally, due to the significant amount of construction in the nation and the frequency of earthquakes, structures equipped with steel flexural frame systems need seismic upgrades to comply with the latest versions of the Iranian Code 2800. In light of these observations, the current research aims to enhance medium-sized steel flexural frames by applying the technical standards set forth in the Iranian Code 2800 (Third edition) and using SAP2000 software. To achieve this, software models were created for buildings with 5 and 10 floors, respectively, with designs following the Iranian Code 2800 (Third edition) and the tenth topic of the National Building Regulations (Design and implementation of steel buildings). These structures were then subjected to seismic forces, and their desired improvements were realized through two methodologies: nonlinear static analysis and nonlinear time history dynamic analysis. Structures designed in accordance with the Iranian Code 2800 (Third edition) have shown a reduction in issues such as story drift, roof story displacement, and target displacement; the enhanced structures exhibit improved performance levels. Moreover, the type and positioning of plastic connections are now more effective and demonstrate superior behavior compared to their conditions prior to the enhancement.

Keywords: Optimal improvement, 2800 Iranian code third edition, Medium-sized steel flexure frame, Nonlinear static analysis, Nonlinear time history dynamic analysis.

1 | Introduction

Constructed structures have different parameters in engineering regulations, depending on the effect of various factors such as the type of use and the type of load-bearing system. These parameters cause the constructed buildings to behave differently during operation and the occurrence of severe earthquakes. This

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difference in behavior has led engineers to develop regulations appropriate to the different conditions governing the types of structures so that they can apply all the necessary parameters to the buildings using them [1]. When designing and implementing structures, engineers always act in a way that meets the minimum requirements specified in the engineering system regulations. Using these rules and regulations, they try to ensure that the constructed structure has sufficient safety. In building engineering regulations, different performance levels are defined so that structural design engineers can determine the appropriate performance level for the building and design and implement appropriate improvement parameters. According to the building improvement regulations, the improvement of a building generally has five stages, as follows [2]:

I. Review of building characteristics: In this stage, parameters such as building characteristics, including the characteristics of structural and non-structural components, the level of earthquake risk at the construction site, the initial results of the seismic resistance assessment, the building's past and future operation history, as well as specific economic, social considerations, and applicable laws and regulations, must be reviewed by the designer and in coordination with the employer before any improvement action is taken.

II. Selection of improvement goal: The project implementer must determine the improvement goal based on existing guidelines. This goal must be placed in one of the five performance levels specified in the seismic improvement regulations.

III. Collection of information on the current state of the building: The existing and accessible information on the building, including executive drawings and other technical documents, must be collected and categorized for use in subsequent stages.

IV. Reviewing the need for improvement: Buildings that are designed and implemented based on the latest edition of the Iranian Standard 2800 and taking into account a specific degree of importance do not require seismic assessment and improvement unless their current degree of importance is higher than that considered in the initial design or the seismic hazard level of the site is different from the hazard level considered in the initial design. In these cases, seismic improvement is mandatory. These buildings must have all technical information, including calculation books and executive drawings.

V. Presenting an improvement plan: The proposed plan for improvement must be evaluated by analyzing the improved model of the structure. Based on the methods specified in the instructions, structural engineers subject their desired structures to the improvement process to improve their performance to the desired level. In this research, medium ductility steel frames designed according to the Iranian code 2800 will be retrofitted to the desired performance level using the seismic retrofitting code for buildings.

Azizi et al. [3] studied the seismic retrofitting of a low-rise steel structure, which was a school in a relatively high-risk area. The school is two-story, has a steel frame, and is located in a highly seismic area. The structure was modeled using ETABS version 9.7.0 software, and the structural components were evaluated separately according to the guidelines for seismic retrofitting of existing buildings. The results of this study showed that the use of metal braces is one of the appropriate and effective methods for seismic retrofitting of low-rise steel structures [4].

Narimanifar et al. [5] studied identifying weaknesses and investigating common methods for seismic retrofitting and retrofitting existing buildings against earthquake forces in Iran. Also, the characteristics of various improvement methods at different functional levels were analyzed. This research was conducted using computational software such as SAP2000. Finally, the results were compared with the operations of increasing the load-bearing capacity, improving the deformability, and increasing the energy dissipation ability of the structures [6].

Tahmasbi Birgani et al. [7] investigated the necessity of seismic improvement of existing concrete buildings based on the new requirements of the "Building design code against earthquakes" [8]. In this research, the existing concrete building, which was designed based on the second edition of the 2800 Code, was modeled, analyzed, and redesigned, and the criteria of the fourth edition were applied to it. Then, the strengthening operation was carried out by using cross-type convergent steel braces and increasing the dimensions of the columns connected to the braces on the pilot floor. The results showed that redesigning the building according to the fourth edition criteria significantly increased the base shear, thus necessitating seismic retrofitting. By adding braces in both X and Y directions and strengthening the relevant columns, the lack of structural capacity against the new base shear was met [9].

Fadaei et al. [10] studied the effect of the differences between the second and third editions of Code 2800 on the design and seismic retrofitting of reinforced concrete flexural frames. Based on recent earthquake-earthquake experiences and considering some structures' poor performance, this study investigated the practical application of seismic retrofitting using ETABS and SAP2000 software. This study performed detailed modeling of the structures, and by drawing comparative curves, design outputs such as relative floor displacement were examined. The results showed that the difference in criteria in different editions affects the design method and the necessity of seismic retrofitting [11].

In a case study involving a 5-story steel building with a pitched roof and an area of 577 square meters, nonlinear static analysis using SAP2000 showed that retrofitting based on the criteria outlined in the 360 publication yields more practical and implementation-aligned results compared to those of the Behsazi publication and the 2800 code. This analysis was performed using the nonlinear static analysis method and SAP2000 software. The final results of the study indicated that retrofitting based on the criteria in the 360 publication provides more appropriate results and is closer to the implementation reality [12].

Makrami et al. [13] evaluated the performance of concrete structures designed based on the ACI 318-99 and UBC 97 codes. This study analyzed three frames at different heights (6, 10, and 15 stories) using 360 and SAP2000 software. By applying nonlinear time history analysis, plastic hinges created in the frames were identified and target displacements were investigated. This study analyzed the weaknesses and performance of the structures under seismic loading in detail and provided valuable results.

Considering the studies conducted in the field of rehabilitation of existing buildings and their components, sufficient information in the areas where the third edition of the code has been used is very limited. The differences in theoretical foundations between the third and fourth editions of the code have posed significant challenges to engineers, which need to be addressed through research and case studies. In addition, many buildings designed and constructed according to the third edition require retrofitting according to the fourth edition guidelines. Also, the differences between the first and third editions of the 2800 Code and the challenges related to the desired retrofitting according to the Seismic Retrofit Code are other important and controversial issues that need to be examined and resolved. Therefore, considering the existing research gaps, conducting this research is very important and can bring valuable results.

2 | Research Method

2.1 | Frames Under Study

The frames under study have been analyzed using SAP2000 software and two methods: linear static analysis and nonlinear static analysis (Pushover). In the first step, using the linear static analysis method, the cross-sections of the frame members have been determined. These cross-sections have been selected so that the range of structural components (Columns and beams) is within a logical range and has appropriate engineering proportions. In this regard, an effort has been made to ensure that the selected cross-sections, while capable of withstand and transfer the applied loads, are also economically viable. In other words, the design of the frames must be acceptable in terms of structural performance and economic optimization. Some of the most important features of these frames, shown in *Fig. 1*, will be examined and evaluated below.

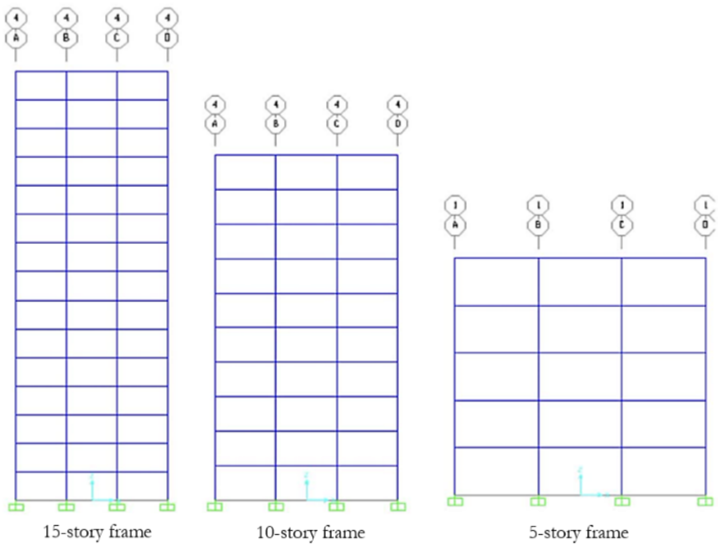

Fig. 1. Frames examined in the research.

2.2 | Dynamic Analysis

Dynamic analysis is performed using spectral analysis and time history analysis. This analysis must be performed concerning ground motion, which is described below. The regulation considers the spectral dynamic analysis method sufficient for the design of buildings covered by this regulation, and it requires three-dimensional dynamic analysis for irregular structures in a plan that requires dynamic analysis.

The effects of ground motion can be determined in one of two ways:

I. Design reflection spectrum.

II. Time history of acceleration changes.

In Code 2800, ground motion is defined as an earthquake with a probability of occurring less than 10% during the building's 50-year useful life. This earthquake is called a "design earthquake", and the corresponding acceleration reflection spectrum is known as the design spectrum.

Standard design spectrum

This spectrum is obtained by multiplying the following values:

I. Building reflection (B).

II. Base acceleration (A).

III. Building importance factor (I).

IV. Inverse of building behavior factor (1/R).

This spectrum is determined based on a 5% damping ratio.

Site-specific design spectrum

This spectrum is prepared according to the geological, geotechnical, seismicity, risk level, and soil characteristics in different building layers and assumes a 5% damping ratio. If the type of building or the earthquake level requires a different damping ratio, this can be used as the basis for preparing the spectrum.

The obtained spectral values should be multiplied by the building importance factor (I) and the inverse of the behavior factor (1/R). It should be noted that the resulting spectral values, before applying these factors, should not be less than two-thirds of the corresponding values of the standard design spectrum.

2.3 | Nonlinear Time History Dynamic Analysis

In recent years, the use of nonlinear analysis in international codes has increased. In Iran, this type of analysis has been included in Publication 360 and the third and fourth editions of Standard 2800 since 2006. Nonlinear analyses are widely used due to their higher accuracy and ability to study the actual performance of the structure, especially in seismic improvement projects and research studies. In this method, the lateral force of the earthquake is determined using the dynamic reflection of the structure during ground motion. This analysis can be performed in the form of spectral analysis or time history analysis. This analysis can be performed in two dimensions and separately in each extension for regular or height-regular buildings.

However, suppose an irregularity in the plan causes a combination of motions in both directions. In that case, the analysis must be performed in three dimensions to include the effects of combined motions of oscillatory modes. In this method, the structural reflections are calculated at each instant of the earthquake, taking into account the actual accelerograms at the base of the building. This method can be used for elastic (Linear) or inelastic (Nonlinear) analyses. Finally, a comparison between the results of the elastic analysis (With standard or special design spectrum) and the linear time history analysis is required, and any differences must be documented and justified in a technical report.

2.4 | SAP2000 Software

SAP2000 software is one of the advanced software in the field of design, analysis, and determination of the performance level of structures that are constantly being developed and updated. This software provides engineers with a complete set of different structural analysis methods and all design needs in an integrated manner and on a single platform. SAP2000 is used not only in theoretical studies but also practically in the construction of structures [14].

Some of the most important capabilities of SAP2000 software are:

I. Performing various static and dynamic analyses.

II. Ability to perform linear and nonlinear analyses, including various seismic analyses.

III. Ability to analyze moving truck loads for bridge design.

IV. Support for P-Delta analysis.

V. Ability to model 2D and 3D frames, including beams, columns, trusses, as well as membrane and shell behavior.

VI. Use of shell structural elements (Shell elements).

VII. Having nonlinear elements such as springs and connections.

VIII. Support for multiple coordinate systems.

IX. Definition of different types of constraints.

X. Ability to define and apply different types of loads.

This spectrum is determined based on a 5% damping ratio.

2.5 | Accelerograms Input to the Software

In *Table 2*, the specifications of the earthquake input to the software are specified.

Table 1. Characteristics of earthquakes used in the research.

NO.	RECORD	STATION	Magnitude	PGA(g)
1	Northridge	01Beverly Hills	6.7	0.462
2	Duzce	Turkey-Bolu	7.4	0.834
3	Hector Mine	Hector	7.1	0.752

Table 1. Continued.

NO.	RECORD	STATION	Magnitude	PGA(g)
4	El Centro	Array #11	7.1	0.803
5	Kobe-Nishi	Akashi	7.3	0.835
6	Kocaeli	Turkey-Duzce	7.4	0.847
7	Landers	Coolwater	6.1	0.622
8	Loma Prieta	Capitola	6.9	0.752
9	Manjil	Iran-Abbar	7.5	0.863
10	Superstition Hills	02-Poe Road	7.3	0.841

6.2 | Scaling of Accelerograms According to Iranian Code 2800

The selected accelerograms shall be scaled according to the following steps: a) Each accelerogram shall be scaled so that the maximum acceleration in the component with the larger maximum is equal to the acceleration of gravity g. b) The response spectrum of each scaled accelerogram shall be calculated considering a damping ratio of 5%. And c) The response spectra of each accelerogram are combined using the Square Root-Sum-of-Squares (SRSS) method and a combined response spectrum is obtained for each accelerogram. d) Each accelerogram is scaled such that for each period in the range T0/2 to T1/5, the average value of the root-sum-of-squares spectrum concerning all components is not more than ten percent less than 1/3 times the corresponding value of the standard design spectrum.

Table 2. Earthquake scale factors used in the research.

Earthqualke NO	1	2	3	4	5	6	7	8	9	10
Scale Factor	4.36	5.89	5.21	5.68	5.82	5.78	4.87	5.03	5.93	5.78

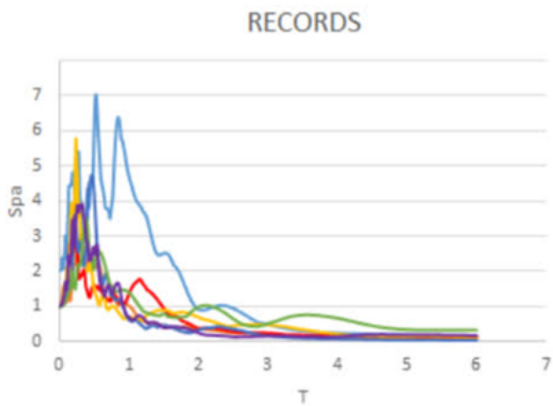

Fig. 2. Comparative diagram of earthquakes used in nonlinear structural analysis.

7.2 | Nonlinear Static Loading Patterns

This study uses three types of nonlinear static loads in SAP2000 software to apply loads to the structure. The patterns of these loads are as follows:

I. PATTERN EQ load: This load is of the nonlinear static type, and its pattern is defined as follows: Pattern Load, EQ, 1 (Load type, load name, scale factor).

II. UNIFORM load: This load is also nonlinear static, and its pattern is as follows: Accel, Ux, -1 (Load type, load name, scale factor).

III. MODE 1 load: This is another nonlinear static load that is defined with the following pattern: Mode, 1, 1 (Load type, load name, scale factor).

3 | Findings

1.3 | Optimal Sections (Stress Ratio) from Static Analysis

In this section, the results from the static analysis are presented. These results determine the optimal sections used to perform nonlinear static analysis as well as nonlinear time history dynamic analysis.

The optimal sections, obtained based on the stress ratio, are shown in *Fig. 3* and *Fig. 4*.

5-story structure

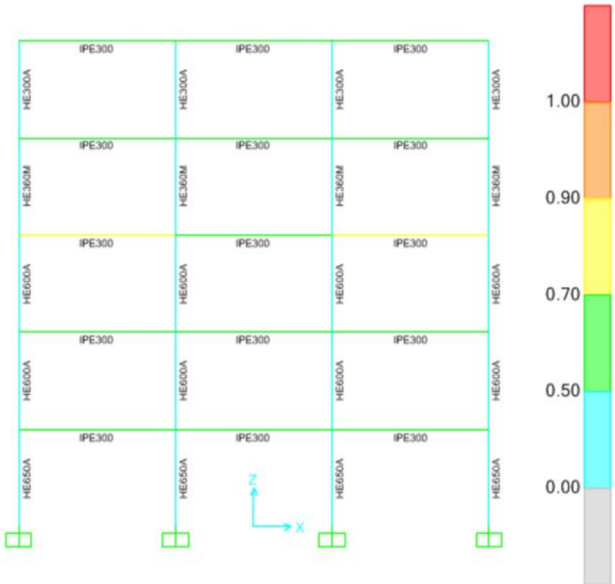

Fig. 3. Stress ratio in elements in a 5-story frame.

10-story structure

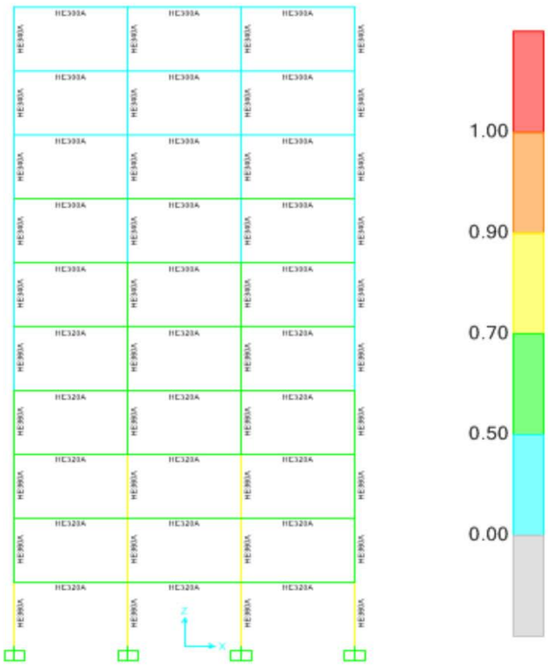

Fig. 4. Stress ratio in elements in a 10-story frame.

The analysis results show that the structure behaves appropriately concerning the static and gravity loads applied in the software in terms of matching the existing capacity and the generated demand. Considering the stress ratios observed in the structural members, which are mainly in the green range, it can be concluded that the structure has optimal and acceptable cross-sections; these cross-sections are also justifiable from a theoretical and operational (economic) point of view. Therefore, considering the desirable behavior of the structure in the static analysis, it is possible to ensure its performance and perform nonlinear analyses on it with sufficient confidence.

3.2 | Results from Nonlinear Static Analysis before Structural Improvement

5-story structure

Push-up curve (Monolinear)

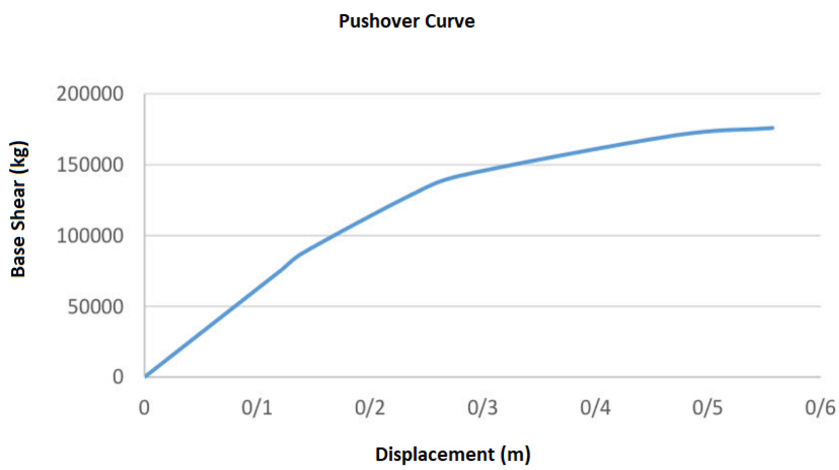

Fig. 5. Single-line pushover curve of a 5-story structure before structural improvement.

Pushover curve (Bilinear)

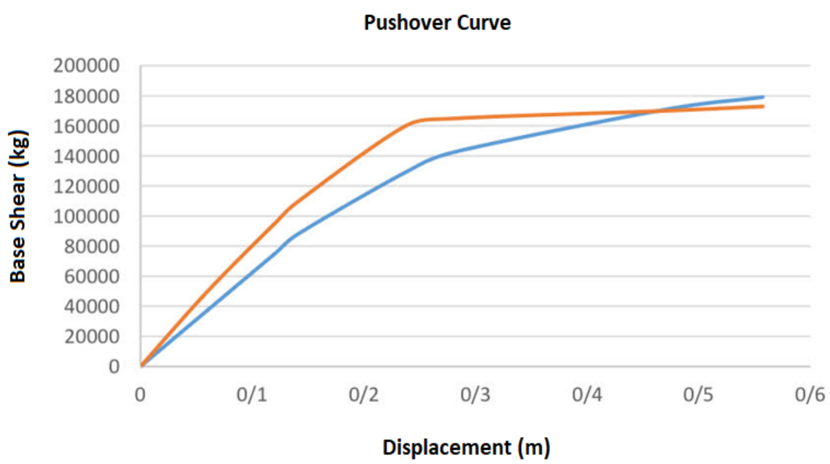

Fig. 6. Bilinear pushover curve of a 5-story structure before structural improvement.

Due to the structure's demand and capacity, at some points, the structure exceeds its capacity and bears more load. This decreases the performance level of the structural elements, and as a result, minor failures occur in these elements. Over time, these failures may spread to the main elements of the structure.

10-story structure

Push-over curve (Single line)

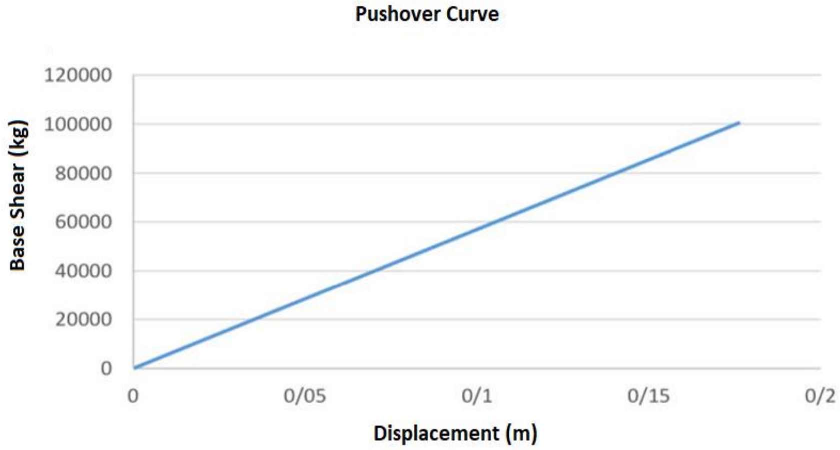

Fig. 7. Single-line pushover curve of a 10-story structure before structural improvement.

According to the diagram, the following conclusions can be reached:

I. The generated push-up curve does not have a suitable slope, which makes the transition from elastic to plastic conditions inappropriate.

II. The displacement generated in the structure under base shear forces is relatively large. Improvement methods should reduce this.

Push-up curve (Bilinear)

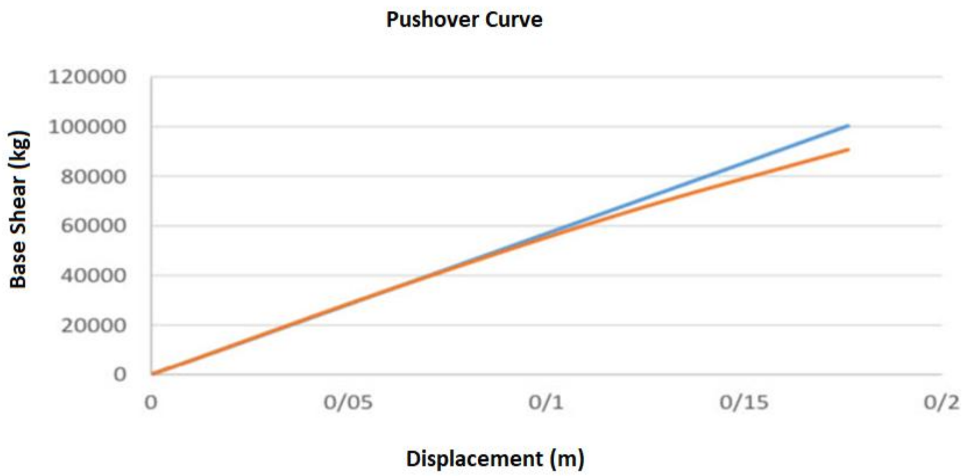

Fig. 8. Bilinear pushover curve of a 10-story structure before structural improvement.

4 | Conclusion

One of the most important results of the analyses is the significant reduction in the amount of floor drift after the structural improvement. In the analyses conducted, it was observed that the floor drift in 5- story and 10-story structures after the improvement has decreased significantly compared to the pre-improvement state. This significant reduction indicates an improvement in the structure's performance against seismic loads. The drift reduction is especially important in the upper floors of the structure, which are more affected by seismic forces, and indicates an improvement in the elastic performance of the structure and the prevention of structural failures. This reduction in drift is mainly due to the appropriate distribution of forces on the structure through the optimization definition and adaptation of plastic joints in beams and columns. Plastic joints enable the structure to behave better and distribute the load effectively. Also, this makes the structure capable of absorbing energy and mitigating the effects of seismic forces in critical conditions such as large earthquakes.

Another of the most important assessments after the renovation is to examine the behavior of the structure in various behavior diagrams. After the renovation, the behavior curves of the 5-story and 10-story structures showed much more appropriate and balanced behavior. Among these curves, the pushover curve of the structures is of particular importance. By comparing the pushover curve before and after the renovation, it was found that this curve became wider after the renovation, indicating the greater ability of the structure to absorb and withstand seismic loads.

This expansion in the pushover curve is observed especially in critical areas such as yield points and ultimate capacity, which indicates an increase in energy absorption capacity and a decrease in the possibility of extensive damage to the structure. As a result, the structure exhibits greater strength against seismic loads and severe force changes, and therefore its capacity to resist earthquakes increases. This improvement in the behavior curves is important, especially in areas close to the yield point. It gives the structure more strength to change large deformations without losing its performance. Overall, the reduction in floor drift and the improvement in the behavior of the structure in the behavior curves, especially in the push-over curve, are evidence of more optimal performance and increased capacity of the structures to withstand seismic forces after the improvement. These cases indicate a fundamental change in how the load is distributed and the energy absorbed by the structure, which increases safety and reduces the possibility of severe earthquake damage.

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Data Availability

Data are available from the corresponding author upon reasonable request.

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