Proposing new design and retrofitting objectives for seismic design of hospital structures - A case study of Imam Khomeini Hospital in Eslamabad-e Gharb

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Research Article

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Proposing new design and retrofitting objectives for seismic design of hospital structures - A case study of Imam Khomeini Hospital in Eslamabad-e Gharb

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Abstract

This paper compares two methods for retrofitting an existing hospital concrete structure to improve its seismic performance: internal and external retrofitting. Internal retrofitting involves adding chevron braces, reinforcing shear walls with Fibre-reinforced plastic (FRP) coating, and wrapping the walls, columns, and beams using steel jackets. External retrofitting uses two braced exterior steel frames connected to the concrete building using dampers. The paper also proposes a new design objective for hospital structures that ensures immediate occupancy performance level under earthquake hazard level-1 and prevents collapse under higher ground motion intensity. The paper evaluates the base structure, the two retrofitting schemes, and the proposed design method using pushover and nonlinear dynamic analyses under 20 selected earthquake records. The paper then compares the probabilistic seismic risk models using fragility curves. The results show that external retrofitting is more effective and economical than internal retrofitting and that the proposed design objective can significantly reduce the seismic risk of hospital structures.

Keywords · Hospital structures · Seismic retrofitting · Internal retrofitting · External retrofitting · Seismic performance · Probabilistic seismic risk

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1 Introduction:

Hospitals are one of the most crucial components in the crisis management plan and play a significant role in reducing human casualties after earthquakes [1]. If these buildings sustain damage in a severe earthquake, they should be promptly retrofitted and returned to active service. Failing to do so will result in a significant increase in casualties. Currently, most retrofitting and improvement efforts for deficient hospital structures focus on local and internal retrofitting schemes, which bring about problems such as interruptions in healthcare services during the retrofitting and reinforcement operations, as well as being time-consuming and costly.

Following the 2017 Kermanshah earthquake in Iran (measuring 7.3 on the Richter scale), the Imam Khomeini Hospital, situated in Kermanshah city, suffered severe damage. The construction was recently designed with a design base acceleration of 0.3g, according to the Iranian seismic code. As mandated by the code, essential buildings like medical centers should exclusively adopt lateral load-resisting systems classified as "special." By definition, these systems are expected to withstand controlled failure during a design earthquake, but they lose functionality after a severe earthquake, potentially leading to increased losses. However, the design regulations stipulate the assumption of continuous services during an earthquake, creating a conflict with the system's behavior. Designing a structural system based on these specialized assumptions causes the structures to deviate from their expected performance. Images depicting the damage to the Imam Khomeini Hospital building can be seen in Fig. 1.

Fig. 1 The images of Imam Khomeini Hospital damaged after the Kermanshah earthquake in 2017

The retrofitting of high-rise buildings, prompted by factors such as aging, deficiencies under future loading, changing building usage, and unexpected lateral loads, began decades ago in various countries. With increasing knowledge about the evaluation and impact of earthquake ground motions on buildings, more existing structures are being identified as deficient in their ability to withstand strong earthquakes.

Fig. 2 illustrates various schemes of seismic retrofitting and reinforcing methods. While rare seismic retrofitting schemes specifically tailored for hospital buildings can be found in accessible technical documents, they remain relatively uncommon. In a well established study, the seismic performance of Wenchuan Hospital in Wenchuan County, Sichuan Province, Southwest China, was assessed following a strong earthquake in May 2008. The hospital structure is a four-story reinforced concrete frame incorporating 46 viscous dampers. This irregular building stands 18.35 meters tall and covers a total area of 17,000 square meters. Viscous dampers were strategically placed around the structure to achieve a more effective reduction of structural responses.

The seismic performance of structures equipped with viscous dampers was evaluated using various methods, including elastic analysis during frequent earthquakes and strength evaluation of structural elements under intermediate and strong earthquakes. The study also examined the effects of viscous dampers on the structure's internal forces, deformations, and energy dissipation. According to the findings, the hospital structure without dampers fails to meet the expected limits required by the codes in intermediate earthquake conditions, such as maximum floor drift and member force criteria. However, with the addition of dampers, the structure complies with the code requirements. Additionally, a practical method for calculating the additional damping ratio provided by viscous dampers has been proposed [2].

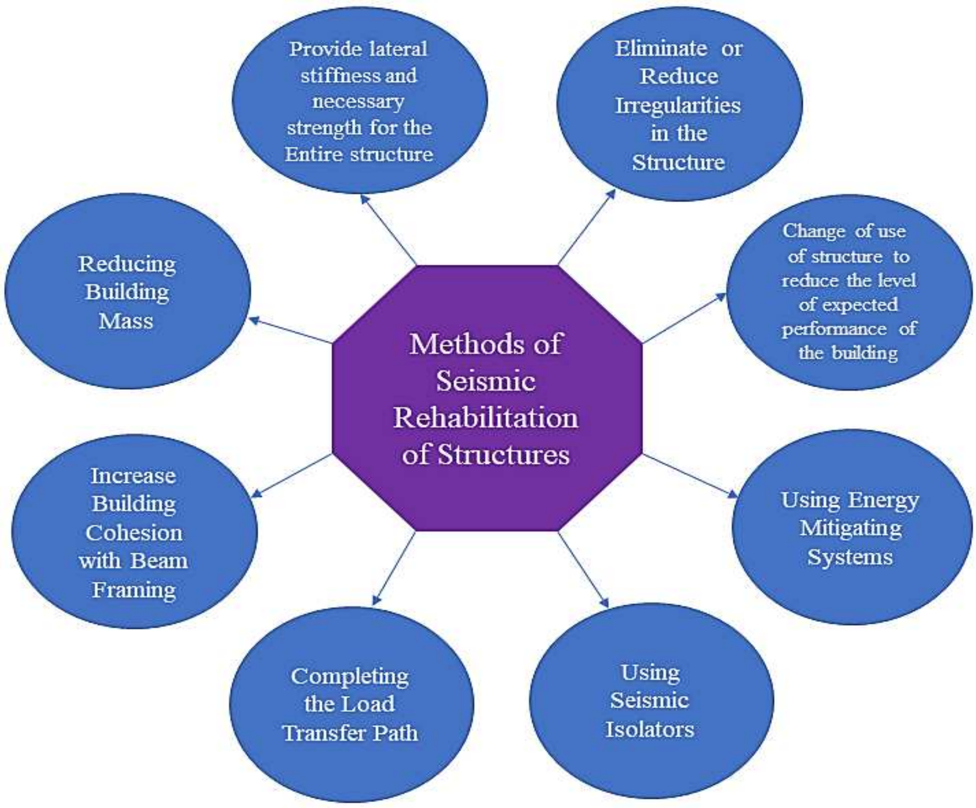


Fig. 2 A flowchart for introducing a variety of seismic Retrofitting methods

Another study focused on a numerical investigation of steel frames with and without Buckling Restrained Braces (BRBs), which are commonly employed in essential structures like hospitals. The objective of this study was to examine the impact of seismic sequences on such structures situated on the soft soil of Mexico City. To achieve this, three-, six-, and nine-story frames were designed based on different criteria and subjected to analysis using artificial earthquake sequences. The aim was to understand the influence of BRBs on the maximum and residual drift. The results of the study indicated that the effects of aftershocks are transient in nature, and their intensity in terms of maximum ground velocity is comparable to that of the main earthquake.

Furthermore, it has been demonstrated that while the effects of aftershocks on the structure cannot be completely eliminated, employing a suitable design approach using dual systems can help mitigate their impact. Based on the study findings, a method was proposed to estimate the maximum and residual drift considering both the main shock and subsequent aftershock sequences. The analysis results showed that the proposed method exhibited acceptable accuracy; however, it should be noted that the method's applicability was limited to buildings utilizing BRB frames and for a relatively short period of time [3].

In another study, the seismic response of a retrofitted hospital center using Buckling Restrained Braces (BRBs) was compared to a conventional bracing system. The hospital, located in Puebla, Mexico, was subjected to the September 19, 2017, earthquake at its epicenter. The existing structure was a typical moment-resisting frame with certain structural deficiencies, including reduced lateral stiffness and a soft story.

Three different methods for seismic retrofitting were proposed and discussed, incorporating pushover analysis and Incremental Dynamic Analysis (IDA). In the first and second methods, the building was retrofitted with BRBs using various configurations, while the third method considered a conventional bracing system. The seismic response of the existing building prior to retrofitting was also studied as a baseline (Case 0).

The results revealed that Cases 1 and 2, which utilized BRBs, outperformed Case 3, which employed the conventional bracing system. Additionally, it was observed that the configuration of BRBs significantly influenced the energy dissipation capacity of the structure [3].

On the contrary, the utilization of conventional braces resulted in significantly poor performance during earthquake simulations, exacerbating soft story issues due to premature buckling of the braces.

The following are two examples of hospitals that have recently undergone seismic Retrofitting:

Kaiser Santa Clara Hospital, located in the state of California, USA, is a significant healthcare facility with 327 beds and a total area of 65,960 square meters. Situated between the San Andreas Fault in the west and the Hayward Fault in the east, this hospital is exposed to a high seismic load and an increased probability of earthquake damage due to its proximity to the fault zones. To enhance the seismic performance of the steel frame structure, Kaiser Santa Clara Hospital has undergone retrofitting, specifically incorporating 120 Buckling Restrained Braces (BRBs). These BRBs are designed to improve the structure's ability to withstand seismic forces and minimize potential damage during earthquakes [4].

Another notable example is the Shahid Mohammadi Hospital, located in the Hormozgan province of Iran. This hospital is a concrete structure consisting of two blocks, one with six stories and the other with three stories, covering a total area of 16,000 square meters. Given the critical importance of uninterrupted healthcare services, the retrofitting and reinforcement plan for Shahid Mohammadi Hospital was executed without disrupting the building's operations. The plan involved a systematic approach that included the evacuation of each floor before proceeding with the retrofitting activities. The brickwork, interior finishing, and associated facilities were removed from the evacuated areas. Additionally, any worn or damaged concrete components, such as beams, slabs, and columns, underwent repair using MonoTop mortar, latex adhesive, and resin. Furthermore, these components were strengthened by wrapping them with Glass Fiber Reinforced Polymer (GFRP) sheets. The concrete shear walls from the basement to the top were reinforced by installing rebar and subsequently casting concrete to ensure their structural integrity.

In general, many seismically weak and deficient buildings may not have the potential to perform retrofitting due to continuing operation before and after a significant earthquake. Essential buildings such as healthcare centers, electricity, gas, water, and telecommunication distribution networks, require continuous operation and are examples of structures that fall into this category.

The current methods of reinforcement and retrofitting often focus on internal retrofitting techniques. While these methods are well-established and beneficial, they come with certain drawbacks when applied to critical structures like hospitals. Disruptions in the hospital's operation, the lengthy and costly process, and the need for a significant number of personnel including workers, security guards, and engineers are some of the disadvantages associated with internal retrofitting methods.

On the other hand, external retrofitting methods offer an alternative approach. In the case of important structures that are not surrounded by neighboring buildings, connecting an exterior frame structure to the main structure can be a viable solution to enhance their performance. By installing these exterior frames, the seismic damage to the main structure can be mitigated, thus reducing the potential risks and improving overall safety. This approach can be particularly effective in improving the seismic resilience of critical structures such as hospitals. In Fig. 3 , views of buildings retrofitted with exterior braced frames are depicted, showcasing the implementation of the external retrofitting method.

It is evident that each retrofitting method possesses its own set of advantages and disadvantages. However, when it comes to external retrofitting, the advantages outweigh the disadvantages. Some of the notable advantages include:

Advantages:

- Quick and Effective Strengthening: External retrofitting with bracing frames offers a rapid and efficient solution to enhance the strength and stiffness of structures that fail to meet code requirements and expected performance levels, particularly in specific directions.

- Minimal Disruption: The process of attaching these bracing frames to the structure can be carried out without disrupting the building's performance and serviceability during operation. This ensures that essential functions, such as healthcare services in hospitals, can continue uninterrupted.
- Easy Inspection and Maintenance: The presence and visibility of the bracing frames allow for easy identification and inspection of any potential issues following an earthquake. If necessary, individual elements can be replaced or repaired without significant impact on the main structure.

Disadvantages:

- Alteration of Architectural Appearance: One drawback of external retrofitting is that it may result in changes to the architectural aesthetics of the building. Depending on the type of bracing used, it may be necessary to install the frames in front of windows and skylights, which can affect the visual appeal.
- Complex Design and Implementation: The design and implementation of connections between the bracing frames and the base structure require careful attention and strict adherence to requirements. It is crucial to ensure that these bracing frames function as an integral part of the structure to effectively withstand seismic forces.

a) Building of Applied Chemistry and Chemical Engineering, Tohoku University, Sendai, Japan

b) Concrete Dormitory, Berkeley University, California, USA

Fig. 3 Seismic Retrofitting of buildings using exterior braced frame

In this research, the focus is on addressing the limitations of internal retrofitting methods in hospital buildings by introducing external retrofitting schemes using dampers to connect support-braced frames to the base structure. Two types of dampers, namely viscous and friction dampers, are examined and compared for their effectiveness.

The research explores the concept of designing support-braced frames with higher stiffness and resistance than the base structure. The dampers installed between these two structures serve to dissipate seismic input energy, thereby preventing damage to both structural and non-structural components of the existing building. The objective is to ensure the uninterrupted provision of healthcare services in hospital structures.

To achieve this, a design method is proposed that considers the use of ordinary lateral resisting systems with appropriate response modification factors in both directions of the structure. Additionally, special reinforcement requirements for the main structural members are recommended to ensure safety against collapse.

The next section of the research discusses the proposed external retrofitting method and compares it with an internal scheme applied to retrofit Imam Khomeini Hospital in Eslamabad-e Gharb, Iran. Numerical modeling of the buildings is conducted using commercial software SAP, making the study more practical and applicable.

The research aims to provide a new perspective on designing hospital structures by redesigning the existing structure and comparing its seismic performance with the rehabilitated one. By evaluating and comparing these different approaches, the study contributes to enhancing the seismic resilience of hospital buildings.

2 Case Study Structures and Methodology

The building selected for study in this research is Imam Khomeini Hospital, located in Eslamabad-e Gharb, Kermanshah. The schematic plan of the building is depicted in Fig. 4. The hospital consists of six stories, with a distinction in the plan between the first four stories and the upper two stories.

For floors 1-4, the plan comprises five spans in the north-south direction and eight spans in the east-west direction. On the other hand, for floors 5-6, there are four spans in the north-south direction and eight spans in the east-west direction, as illustrated in Fig. 5. The basement has a height of 5 meters, while the other stories are 4 meters in height. The width of the spans measures 5.7 meters in the north-south direction (Y) and 6.6 meters in the east-west direction (x).

In this building, the structural system employed in the east-west direction (x) is a special reinforced concrete moment-resisting frame. In the north-south direction (Y), the dual system is utilized, which includes the special reinforced concrete moment-resisting frame and the special reinforced concrete shear walls. This configuration ensures the structural stability and resistance to seismic forces in both directions.

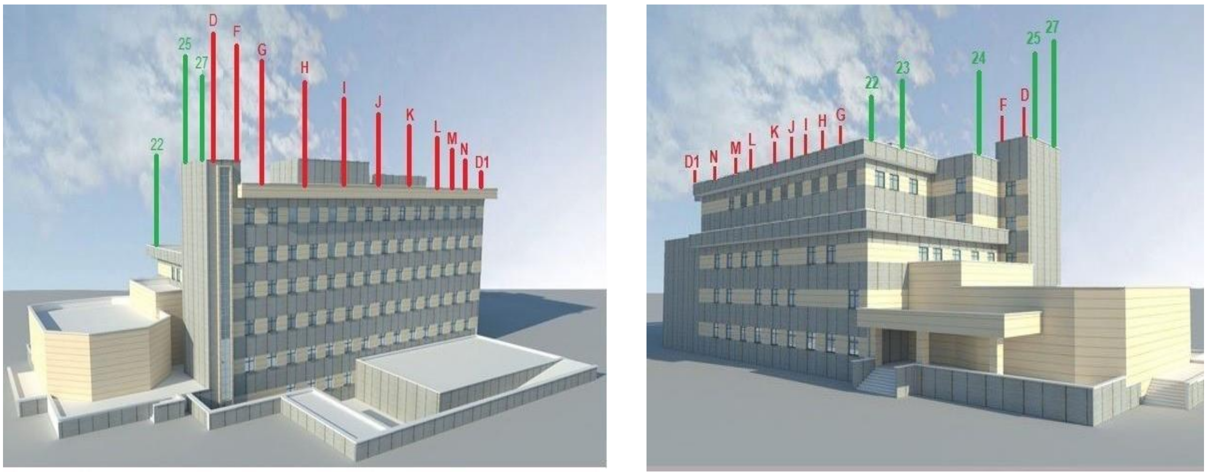
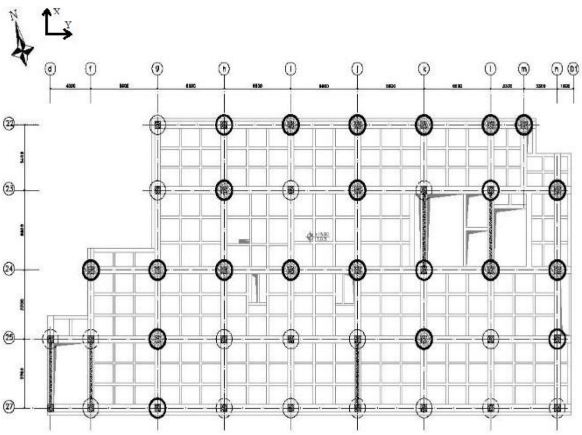
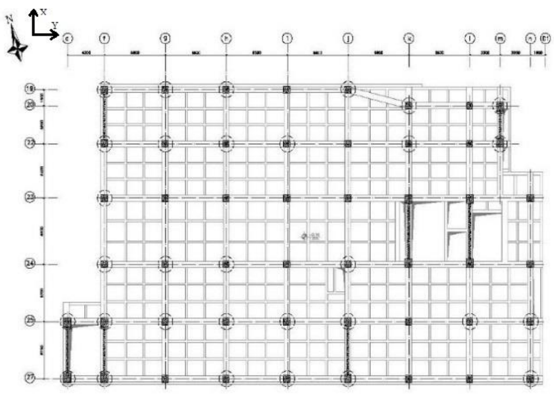


Fig. 4 Schematic view of the hospital building



Floor plan 5-6



Floor plan 1-4

Fig. 5 Plan view of the hospital structure

The floor and roof slabs of the Imam Khomeini Hospital are constructed using longitudinal and transverse joists, which are considered rigid diaphragms within their planes. The seismic design of the building was performed in accordance with the Iranian seismic standard [5]. The dead load for the structure is 5 kN/m², while the live load for the floor and roof is 2 kN/m² and 1.5 kN/m², respectively. Due to its critical nature, the building is assigned an importance factor coefficient of 1.4. Table 1 provides the mechanical properties of the steel and concrete materials utilized in the structure. Additionally, according to the Iranian seismic standard, the soil in the region is classified as type III, with a shear wave velocity ranging from 175 m/s to 375 m/s. The building is located in seismic hazard zone region 2, where the maximum ground acceleration is 0.3g. Further details regarding the seismic coefficients and design parameters are outlined in

Table *2*. According to this reversion (the previous one) Iranian Seismic Standard, the behavior factor for the reinforced concrete moment resisting frame in the x-direction is 10, while for the dual system of the special reinforced concrete moment resisting frame and the special reinforced concrete shear walls in the y-direction, it is 11.

Table *3* presents the dimensions of the beams, columns, and shear walls used in the structure.

Table 1 Specifications of steel and concrete used in the structure

Concrete	concrete low boundary strength $Fc = 30.5\ MPa$	Concrete tensile strength $Fr = 3\ MPa$	Expected Elastic modulus $Ec = 30500\ MPa$
Steel	Minimum Reinforcement Yield strength $Fy = 400\ MPa$	Minimum Reinforcement Tensile strength Fu=600 MPa	Expected Elastic modulus Es=200000 MPa

Table *2* The seismic design parameters

Structure	Direction	T[6] (sec))	A[5]	B[4]	I[3]	R_u[2]	C[1]	$\delta_t(m)$
Base structure	X	0.92	0.3	2.38	1.4	10	0.128	0.314
	Y	0.59	0.3	2.75	1.4	11	0.154	0.294

Table *3* Cross-sectional dimensions of beams, columns, and shear walls

Structure	Component	Storey 1	Storey	Storey 3	Storey 4	Storey 5	Storey 6

[1] Seismic coefficient
[2] Behavior factor
[3] Importance factor
[4] Building response factor
[5] Design base acceleration ratio
[6] Natural Period

			2				
Base structure	Beam	B60x80	B60x80	B60x70	B60x70	B60x60	B50x60
	Interior Column	C60x60	C60x60	C60x60	C60x60	C60x60	C60x60
	Exterior Column	C65x65	C65x65	C65x65	C65x65	C65x65	C65x65
	Shear walls	The width of the wall is 30 cm					

2.1 Modeling assumptions

In the modeling of the concrete frame, a concentrated plasticity approach is employed. Nonlinear hinges are applied to the ends of the beams and columns, and their behavior is characterized by a generalized force-deformation curve, as shown in Fig. 6. The parameters a, b, and c in the curve are defined based on the guidelines provided in Tables 9-7.1, 9-7.2, and 8-9 of ASCE 41-17 [6].

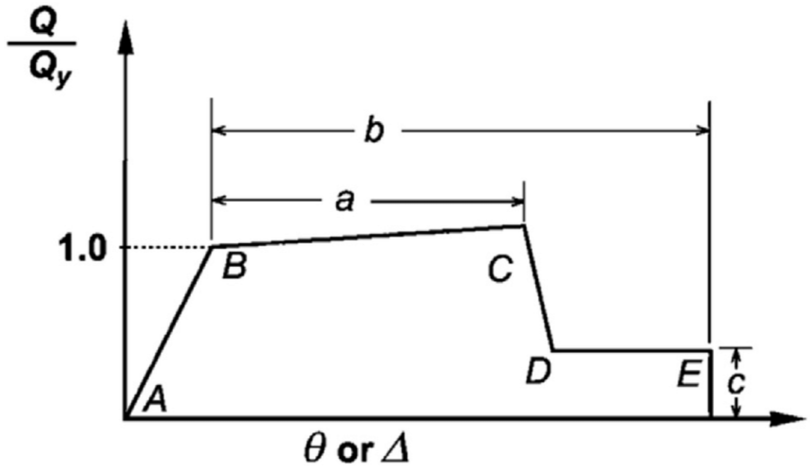


Fig. 6 Generalized force-deformation relationship for steel components or elements [6]

2.2 Proposing Redesign Methodology

After identifying predictable failures in the original design, a special resisting system was incorporated into the redesign of Imam Khomeini Hospital structure, following the guidelines of the Iranian seismic code. The goal of the redesign methodology is to achieve reliable performance at the expected earthquake risk levels, specifically targeting the Immediate Occupancy (IO) performance level at the BSE-1 (a 10% chance of exceedance in 50 years) and the Life Safety (LS) performance level at the BSE-2 (a 5% chance of exceedance in 50 years).

To meet these performance levels, a behavior factor of 3, as specified by the Iranian seismic code, was adopted for the ordinary moment-resisting frame. The structure was then redesigned with special reinforcement measures to ensure proper performance at the BSE-2 level. Lateral displacement or drift was identified as a controlling design parameter for the moment-resisting frame, and examining these parameters facilitated the selection of appropriate component dimensions in the design process.
Through the redesign process, the earthquake coefficients in both directions were determined as Cx = 0.385 and Cy = 0.33. The dimensions of the redesigned structural members are provided in Table 4, and Table 5 compares the increased dimensions of the structural components with those of the base structure. These modifications and reinforcements are aimed at enhancing the seismic performance and resilience of Imam Khomeini Hospital, enabling it to withstand the expected seismic forces and ensuring the continued provision of healthcare services even after an earthquake event.

Table *4* Dimensions of beams, columns, and shear walls in the main structure

Structure	Component	Storey 1	Storey 2	Storey 3	Storey 4	Storey 5	Storey 6
Proposed redesign method	Beam	B60x100	B60x100	B60x100	B60x80	B50x60	B50x60
	Interior Column	C125x125	C105x105	C95x95	C90x90	C85x85	C85x85
	Exterior Column	C125x125	C105x105	C95x95	C90x90	C85x85	C85x85
	Shear walls	Most walls have a width of 40 cm, but in some storeys, the width of 50, 60, and 80 cm have been used.					

Table *5* Increase of cross-sectional dimension ratio of components in the proposed redesign method

Structural Component	Increase ratio (%)

Beams	40-60
Columns	38-79
Shear walls	33-166

2.3 Applied Retrofitted Method

In the Retrofitting method implemented by a consultant company, various techniques were employed to enhance the performance of different structural elements in Imam Khomeini Hospital. The columns were covered using a metal jacket, which provides additional strength and confinement to improve their load-bearing capacity. U-shaped metal sheets were utilized to cover the beams, providing reinforcement and enhancing their resistance to bending and shear forces. Shear walls, on the other hand, were strengthened using two layers of Carbon Fiber Reinforced Polymer (CFRP), which enhances their shear capacity and overall structural integrity.

To further enhance the structure's ability to resist lateral forces, more than 60 Chevron braces were added in both the longitudinal and transverse directions of the building. These braces, specified as 2UNP300 + 2PL350x20, are designed to effectively transfer lateral loads and improve the overall stiffness and stability of the structure.

Fig. 7 showcases images of the model, demonstrating the retrofitting interventions implemented in the hospital structure. Additionally, Fig. 8 provides an example of the sections utilized in the retrofitting process, showcasing the arrangement and installation of the added Chevron braces.

These retrofitting measures aim to significantly improve the seismic performance and resilience of Imam Khomeini Hospital, ensuring its ability to withstand earthquake forces and protect the occupants and critical healthcare services in the event of a seismic event.

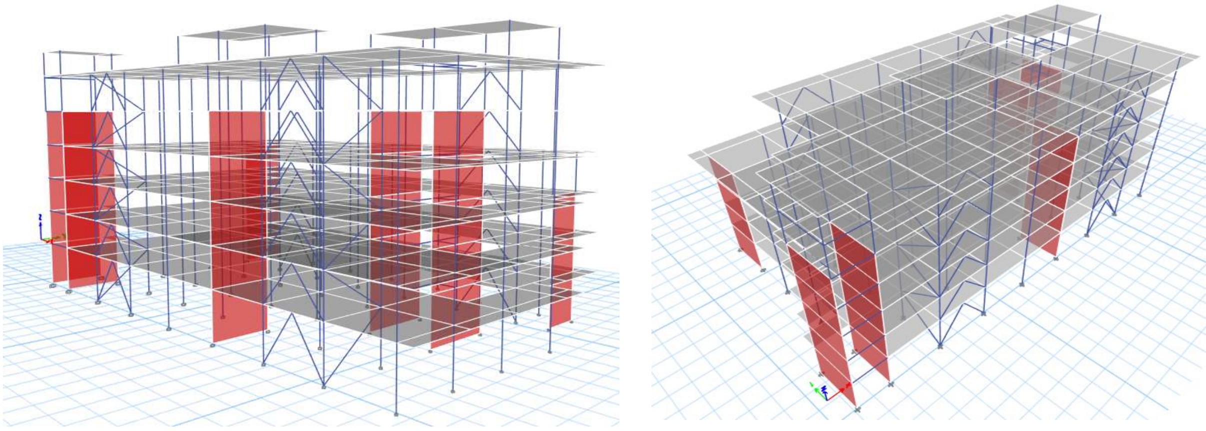
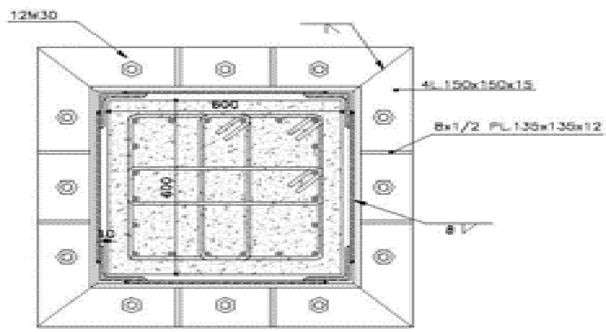
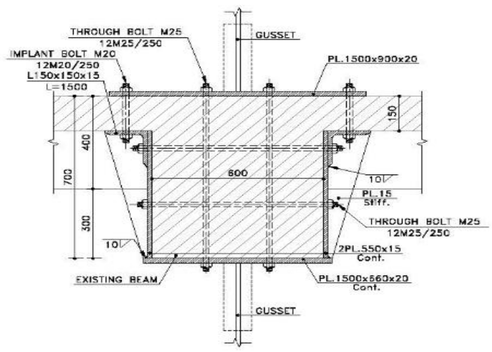


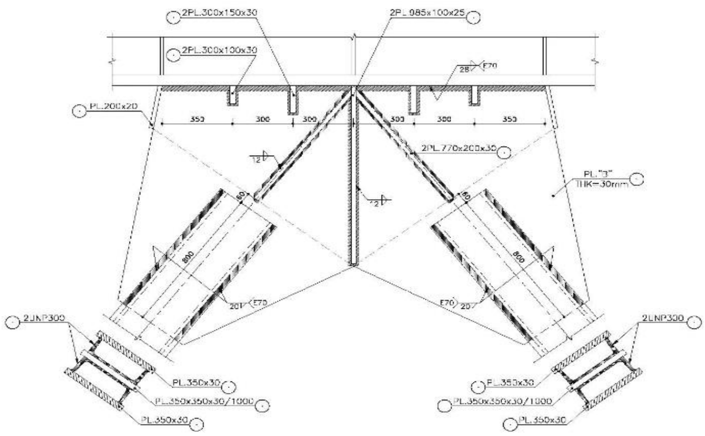
Fig. 7 3D Modeling Software Images of the Retrofitting Method applied by a consultant company



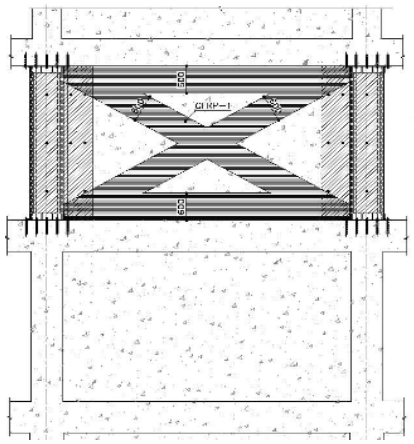
a)A typical cross-section of the reinforced columns



b) A typical cross section of the reinforced beam



c) In-frame braces joints



d) A typical shear wall reinforced by FRP

Fig. 8 Retrofitting members adopted by a Consultant company

Despite the effectiveness of the consultant's Retrofitting method in improving the structural performance of Imam Khomeini Hospital, it is important to acknowledge its associated drawbacks. One of the main disadvantages of this internal reinforcement approach is the disruption it causes to the hospital's healthcare services. The retrofitting process involves extensive work, including the placement of metal jackets on columns, installation of multiple braces within the spans in both directions of the structure, and reinforcement of beams and shear walls. These activities require significant time and effort, resulting in the prolonged closure of the hospital or restricted operation of certain areas.

The use of multiple contractors and laborers for different retrofitting tasks also adds to the overall cost of the process. Coordinating various teams and ensuring their synchronization can be challenging and may lead to increased expenses. Additionally, the need for specialized expertise and materials further contributes to the overall high cost of the retrofitting project.

Considering the limitations and disadvantages of internal retrofitting, alternative methods such as the proposed external retrofitting approach with dampers, as mentioned earlier, can offer advantages in terms of cost-effectiveness, reduced disruption to hospital services, and simplified implementation. These factors should be carefully considered when selecting the most appropriate retrofitting method for critical structures like hospitals, balancing the need for structural reinforcement with the operational requirements of the healthcare facility.

2.4 Proposing Retrofitting Method

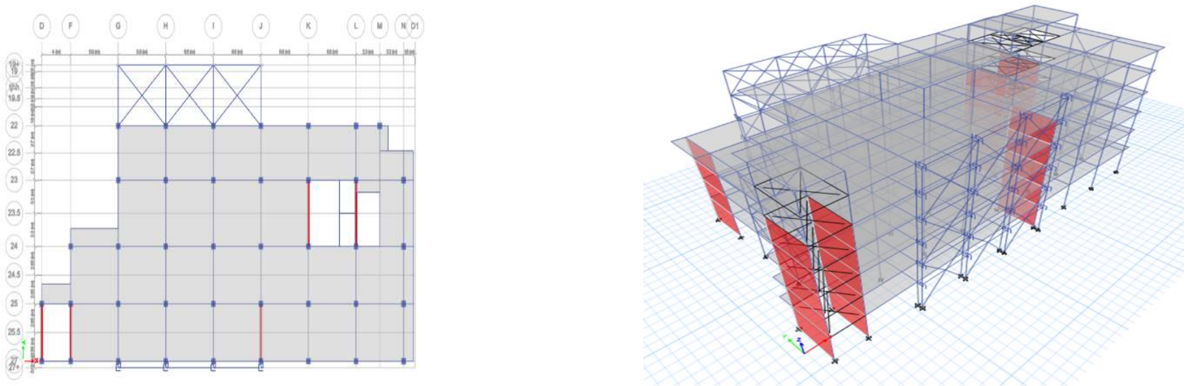
Two methods which are known as internal and external Retrofitting schemes have been employed to improve the performance of the structure. The internal Retrofitting method suggested by the consultant involves the use of Chevron braces, FRP wrapping for shear wall reinforcement, and metal jackets for columns and beams.

In the proposed Retrofitting plan of this research, a different approach is taken to ensure minimal disruption to hospital services. Two braced steel frames are positioned on the north and south sides of the structure, connected to the base concrete structure using dampers. However, due to architectural constraints, it is not feasible to install these frames in the other direction. Instead, the shear walls are reinforced using FRP materials. The aim is to achieve improved structural integrity and symmetry.

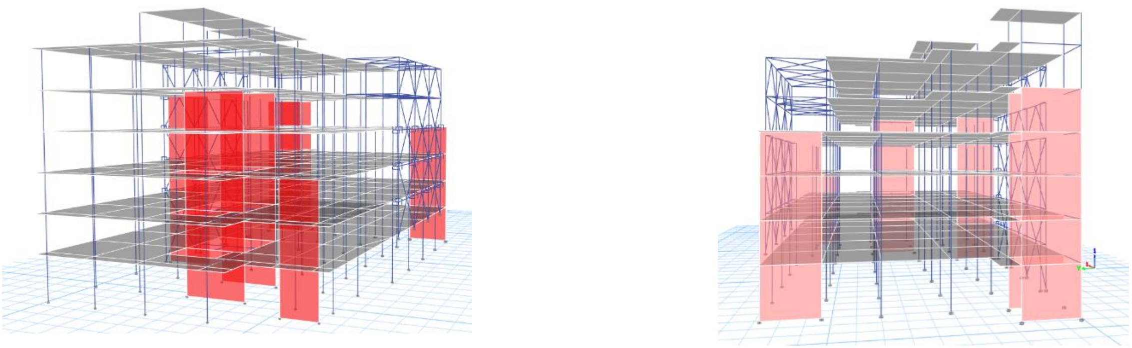
Views of the proposed Retrofitting method can be seen in Fig. 9 and Fig. 10. In stories 5 and 6, additional roof bracing is installed to enhance the integrity of the floors at the connection point between the north face external frame and the concrete structure.

The steel members of the supporting structure are designed in compliance with the Iranian National Building Code (No. 10) [7] to ensure that the structure meets the IO/BSE-1 and

LS/BSE-2 performance levels. The design sections for the bracing members, beams, and columns are provided in Table 6 and are based on the assumption of using ST-52 steel.

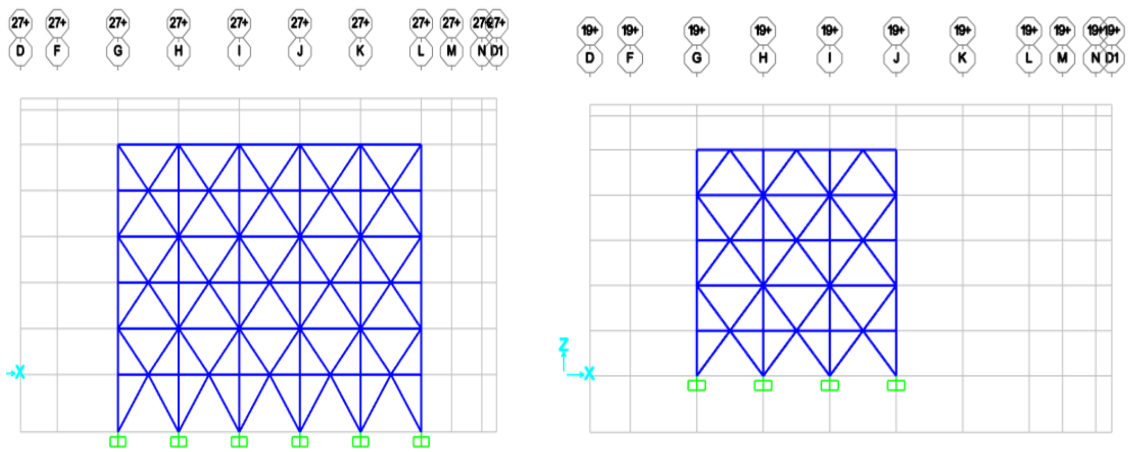


a) Structure plan in 5th and 6th stories and use of roof bracing



b) 3D view

Fig. 9 Various images of rehabilitated structures by the external method



Southside of the structure - reinforced by the frame

Northside of the structure - reinforced by the frame

Fig. 10 The exterior steel frames added in the external method

Table *6* Added braces, columns, and beams component

Brace	2UN400
Roof Brace	IPB300
Side columns	IPB450
Middle columns	IPB400
Beam	IPB300

In the proposed external Retrofitting method for Imam Khomeini Hospital, braced steel frames are utilized and connected to the base concrete structure using dampers in both the north and south directions. The added frame structure consists of various components designed to enhance the building's seismic performance.

For the roof bracing, 33 IPE300 beams are installed to provide additional support. These beams contribute to the overall stiffness and stability of the structure.

To connect the steel frame to the existing concrete building, 36 dampers are employed. These dampers play a crucial role in absorbing and dissipating seismic energy, reducing the impact of seismic forces on the structure.

The columns in the Retrofitting scheme include 22 IPB450 columns for the side columns and IPB400 columns for the middle columns. These columns provide vertical load-bearing capacity and contribute to the overall strength and stability of the building.

Furthermore, 66 Chevron braces of 2UNP400 are utilized in the Retrofitting process. These braces, positioned strategically throughout the structure, enhance its lateral stability and resistance to seismic forces.

In addition to the steel frame and bracing elements, the shear walls are reinforced with two layers of CFRP (Carbon Fiber Reinforced Polymer). CFRP is a high-strength material that helps improve the shear resistance and overall performance of the shear walls.

2.5 Selecting Earthquake Records

To conduct nonlinear time history analyses, a set of suitable earthquake records were selected. These records were chosen based on their compatibility with the seismic hazard of Eslamabad-e Gharb City in Kermanshah province.

A total of 20 pairs of accelerometers were used to collect the earthquake records. The selection process considered factors such as magnitude, source-to-site distance, soil type, and frequency content, ensuring that the records were representative of the site-specific acceleration spectrum for the desired location.

Among the selected records, the earthquake record of the 2017 Kermanshah earthquake, obtained from the station in Eslamabad-e Gharb city, was also included.

Table *7* provides a comprehensive description of the selected earthquake records. These records were specifically chosen to capture a range of far-field ground motions.

To visualize the frequency content of the selected records, the response acceleration spectra of the records were scaled to a peak ground acceleration (PGA) of 1.0g. Fig. 11 displays these spectra, demonstrating that the selected records exhibit similar frequency content across a wide range of structural frequency variations. This similarity ensures that the selected records adequately represent the expected ground motions for the analysis of the case studies.

Table *7* The Selected Earthquake Records

NO.	Event	Year	Station	Mw	RJB (Km)	VS30 (m/s)	Comp	PGA (g)
1	Kermanshah, Iran	2017	Eslamabadqarb	7.3	96.25	266	85	0.097
							175	0.135
2	Bam, Iran	2003	Abaragh	6.6	47.16	412.23	L	0.1684
							T	0.109
3	Tabas, Iran	1978	Boshrooyeh	7.35	24.07	324.57	L	0.105
							T	0.084
4	Mt. Lewis	1990	Halls Valley	5.6	12.37	281.61	0	0.1068
							90	0.1484
5	San Fernando	1971	Santa Felita Dam (Outlet)	6.61	24.69	389	172	0.1549
							262	0.1548
6	San Simeon, CA	2003	San Antonio Dam - Toe	6.52	16.17	509.04	021	0.093
							111	0.121
7	Landers	1992	Fun Valley	7.28	25.02	388.63	45	0.215
							135	0.206
8	Loma Prieta	1989	BRAN	6.93	10.72	476.54	0	0.4563
							90	0.5022
9	Imperial Valley	1979	El Centro Array #1	6.5	19.76	237.33	140	0.1412
							230	0.1362
10	N. Palm Springs	1986	Palm Springs Airport	66.0	10.08	312.47	0	0.1545
							90	0.1758
11	Northridge	2003	Sunland - Mt Gleason Ave	6.69	12.38	476.54	170	0.133
							260	0.1572
12	Kobe, Japan	1995	Amagasaki	6.9	11.34	256	0	0.276
							90	0.327
13	Cape Mendocino	1992	Fortuna - Fortuna Blvd	7.01	15.97	457.06	0	0.116
							90	0.114
14	Morgan Hill	1984	Corralitos	6.19	23.23	462.24	220	0.081
							310	0.11
15	Hollister-01	1961	Hollister City Hall	5.6	19.55	198.77	181	0.0589
							271	0.115
16	Kocaeli, Turkey	1999	Arcelik	7.51	10.56	523	0	0.204
							90	0.131
17	Superstition Hills-02	1987	Plaster City	6.54	22.25	316.64	45	0.137
							135	0.188
18	Darfield, New Zealand	2010	DFHS	7.0	11.86	344.02	E	0.471
							W	0.5
19	Hector Mine	1999	Hector	7.13	10.35	726.0	0	0.265
							90	0.3281
20	El Mayor-Cucapah, Mexico	2010	Chihuahua	7.2	18.21	242.05	0	0.248
							90	0.197

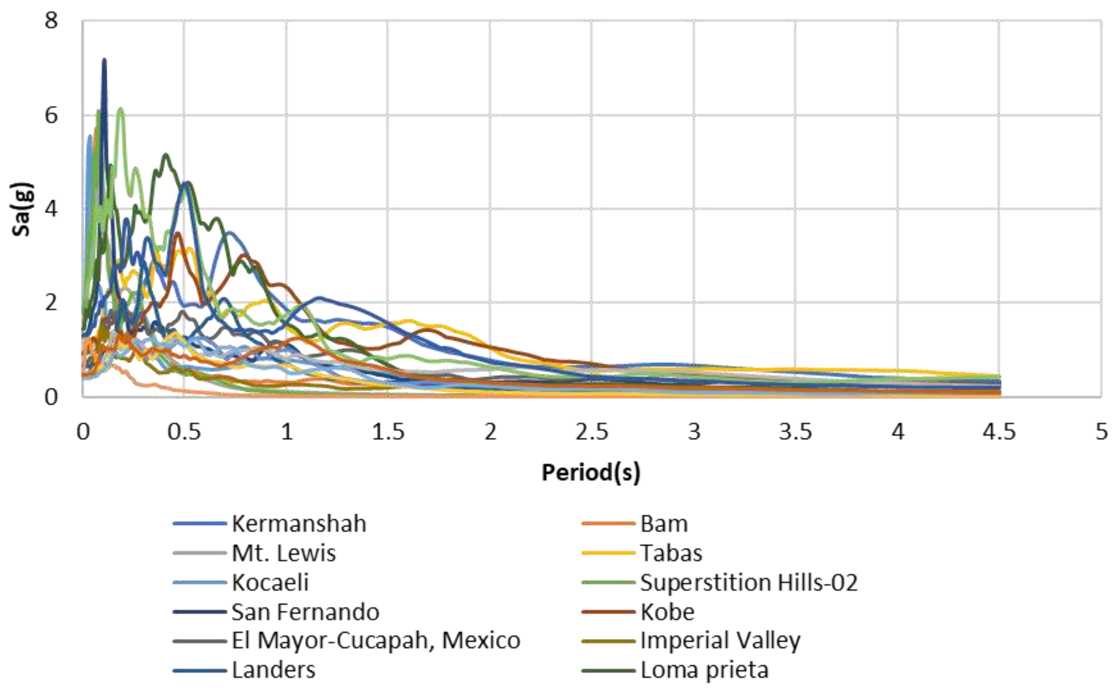


Fig. 11 Scaled Acceleration Response Spectra

3 Results and Discussion

In this section, the numerical analysis results are prominently presented and comprehensively elucidated. Multiple graphs are depicted, accompanied by a thorough description thereof.

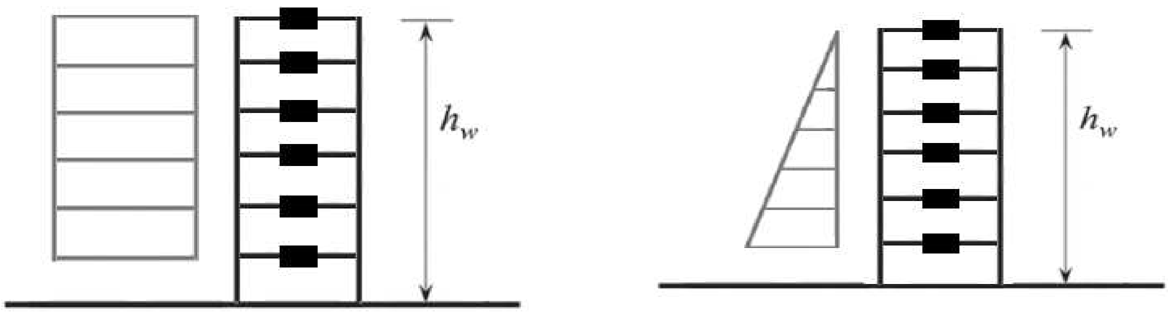
3.1 Selecting Dampers' Types

Two types of friction and viscous dampers were carefully selected, examined, and compared due to their superior performance, widespread availability, and cost-effectiveness. The installation of dampers at the connections between the concrete base structure and the exterior braced frame serves as an effective means of dissipating energy during lateral excitation. In order to determine the appropriate damper types, a comprehensive evaluation and comparison were conducted, considering the crucial parameters for optimal design: the slip force (fs) for friction dampers and the damping coefficient (Cc) for viscous dampers.

The primary criteria for selecting optimal damper parameters are the reduction of maximum roof displacement, base shear, and the enhancement of energy dissipation.

In 2002, Mualla introduced the SPI Index, which represents the square root of the performance indices. Minimizing this index involves optimizing the sliding force and the damping coefficient. The SPI Index is calculated using the ratios (R_d, R_V, R_e) of the maximum displacement of the roof, base shear, and energy dissipation of the structure with a damper to their corresponding values in the base structure. These ratios are defined in Eq. (1, 2, 3, 4).

To determine the optimal sliding force, nonlinear time history analyses were performed for each earthquake record. Both uniform and triangular distributions of sliding forces and damping coefficients were examined for friction and viscous dampers at all stories, as illustrated in Fig. 12. The seismic performance of the uniform scheme outperformed the triangular scheme [8], [9].



a) Uniform Distributions

b) Triangular Distributions

Fig. 12 Schematic view of distributions for sliding forces and damping coefficients for friction and viscous dampers

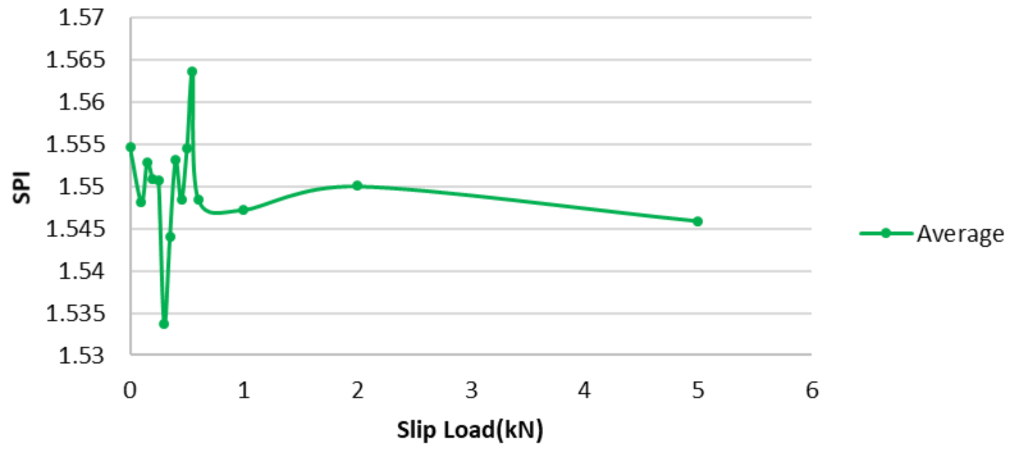
The sliding force (fs) was thoroughly investigated within the range of 0-5 kN. Based on the findings presented in Fig. 13 (a), it was determined that the optimal value for the structure is 0.3 kN. Similarly, the damping coefficient (Cc) was examined over a range of 0-200 kN.s/m. According to the results depicted in Fig. 13 (b), the most optimal value for integration into the structure is 50 kN.s/m.

$$SPI = \sqrt{{R_d}^2 + {R_V}^2 + {R_e}^2} \tag{1}$$

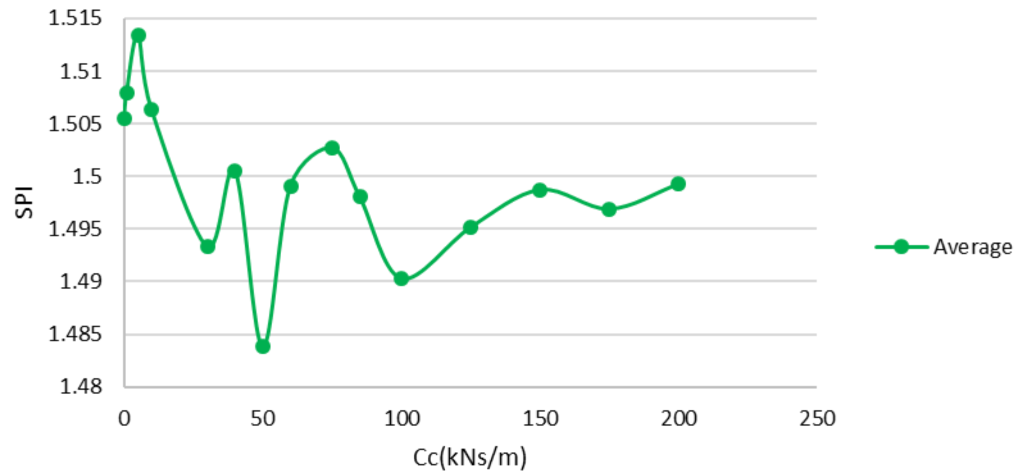
$$R_d = \frac{D_f}{D_p} \tag{2}$$

$$R_V = \frac{V_f}{V_p} \tag{3}$$

$$R_e = \frac{(E_f - E_p)}{E_f} \tag{4}$$



a) Slip force of friction damper



b) Damping coefficient of viscous damper

Fig. 13 Evaluation of the SPI index

3.2 The response modification factors

In seismic design, earthquake design forces can be reduced by utilizing response modification factors (R factors) as permitted by earthquake design codes. The R factor is specific to each structural system and is determined by the structure's capacity for inelastic deformations, energy dissipation (ductility factor), and reserve strength (overstrength factor) under seismic loads. Estimating design earthquake forces in seismic codes relies heavily on the R factor, making it a crucial parameter for structural analysis.

To estimate the R factor, the ATC-34 [10] method is employed in this study. According to this method, pushover analysis was conducted separately in the X and Y directions. The analyses were carried out until the roof displacement reached the target displacement, which was determined based on Eq. (5). Specifically, the target displacements were estimated as 0.1884 meters and 0.282 meters in the X and Y directions, respectively.

$$\delta_t = C_0 C_1 C_2 S_a \frac{T_e^{\,2}}{4\pi^2} \qquad (5)$$

where,

C_0= The ratio of the roof displacement of the building to the maximum displacement of an equivalent SDOF system

C_1= The ratio of the maximum inelastic displacements of a bilinear elasto-perfectly plastic of an equivalent SDOF system to the displacements calculated for the linear elastic response of the same SDOF system

C_2= Represents the effect of pinched hysteretic shape, stiffness degradation, and strength deterioration on maximum displacement response.

S_a= Response spectrum acceleration

T_a= Elastic fundamental period for substituted bilinear approximation

g = Gravitational acceleration

To idealize the computed nonlinear pushover curve, the Uang method was employed, which represents the curve using a bilinear elasto-perfectly plastic relation (as shown in Fig. 14).

Fig. 15 and Fig. 16 compare the pushover curves in the longitudinal and transverse directions for four structures: the base structure, structure redesigned by the proposed method, applied retrofitted structure, and structure retrofitted by the proposed method. Additionally, Fig. 17 provides a comparison of the energy absorption levels based on the derived pushover curves for these four structures.

The analysis reveals that the base structure exhibits the most ductile behavior. However, due to its low base shear, the energy absorption is relatively low in both directions. In the X-direction, the applied retrofitted-structure demonstrates the best behavior and energy absorption. Conversely, in the Y-direction, the structure redesigned by the proposed method exhibits superior behavior and energy absorption.

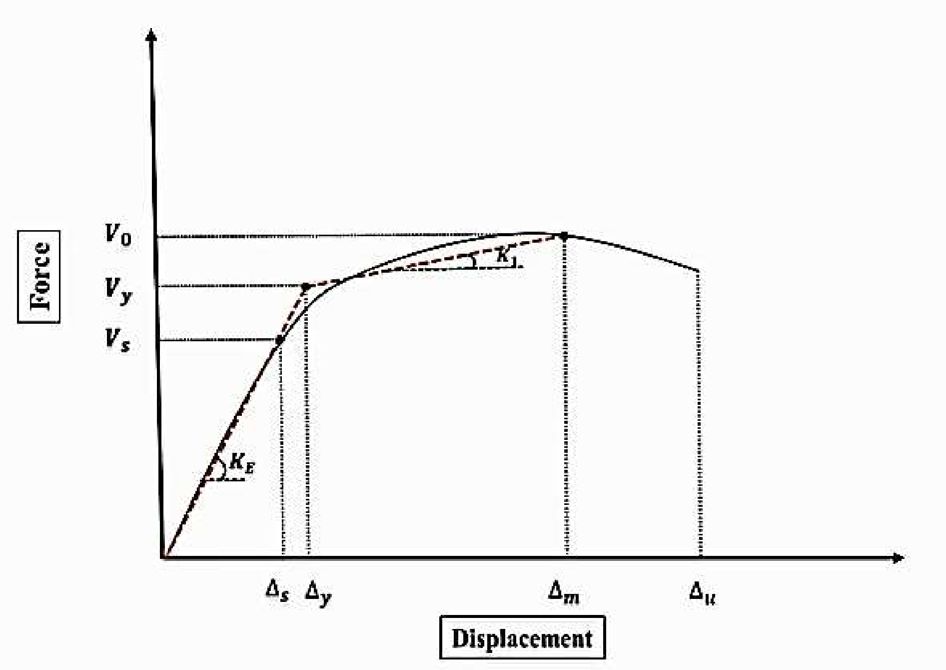


Fig. 14 Bilinear approximation of computed pushover curve graph according to Uang method

ATC-34 proposed Eq. (**Error! Reference source not found.**) to estimate the R factor:

$$R = R_\mu * R_s * R_r \qquad (6)$$

In which, R_μ, R_s, and R_r are the ductility, overstrength, and redundancy factor, respectively.

R_μ can be calculated using the Miranda method according to Eq. (**Error! Reference source not found.**):

$$R_\mu = \frac{\mu - 1}{\emptyset} + 1 \qquad (7)$$

In the above relation, Ø is a function of μ, the period of the structure T, and the soil conditions of the site, which for different soil types can be calculated in Eq. (8, 9, 10) as follows:

For rocky lands
$$\emptyset = 1 + \frac{1}{10 * T - \mu * T} - \frac{1}{2T} e^{-105(\ln(T) - 0,6)^2} \qquad (8)$$

For sedimentary soils
$$\emptyset = 1 + \frac{1}{12 * T - \mu * T} - \frac{2}{5T} e^{-2(\ln(T) - 0,2),^2} \qquad (9)$$

For soft soils
$$\emptyset = 1 + \frac{Tg}{3T} - \frac{3Tg}{4T} e^{3(\ln T/Tg - 0,25)^2} \qquad (10)$$

R_s is computed as

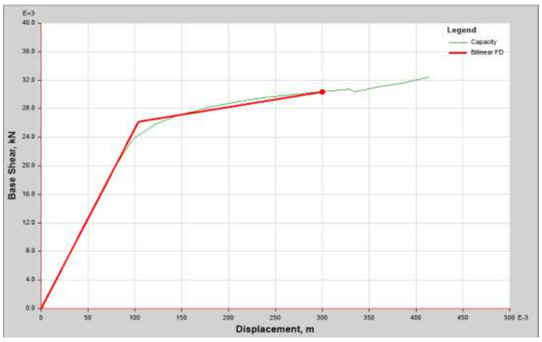
$$R_s = \frac{V_0}{V_d} \tag{11}$$

Where V_0 is the maximum base shear strength, and V_d is the design base shear. The R factors are calculated and depicted in Table 8 for the four structures.

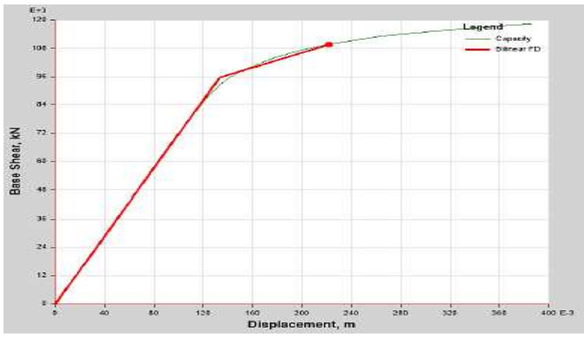
Table *8* Calculated R factor

Structure	X-Axis	Y-Axis
Base Structure	3	3.84
Structure Redesigned by Proposed Method	2.69	2.73
Structure Retrofitted by Proposed Method	1.84	3.7
Applied Retrofitted Structure	1.47	3.31

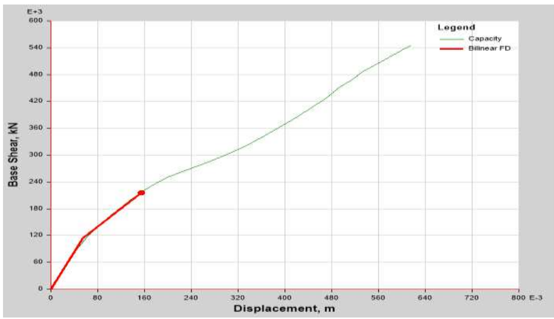
X-Axis



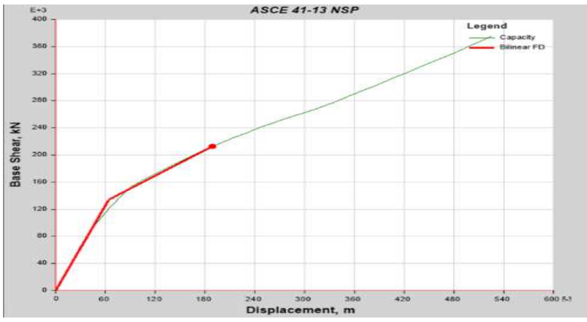
Base structure



Structure Redesigned by Proposed Method

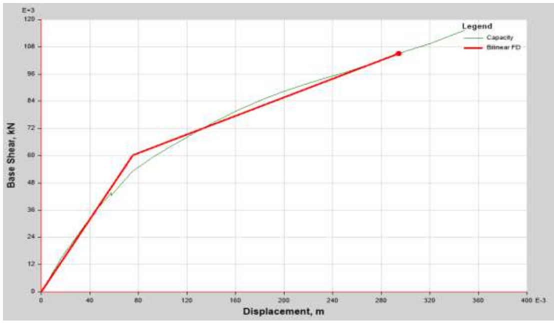


Applied-retrofitted structure

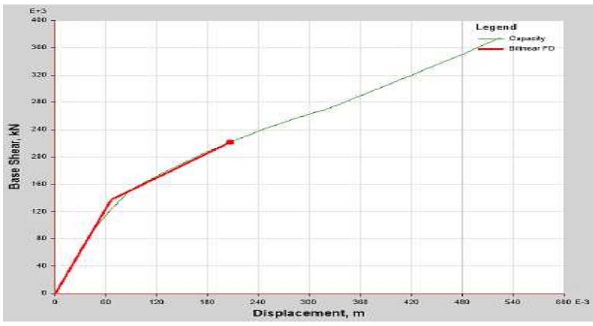


Structure Retrofitted by Proposed Method

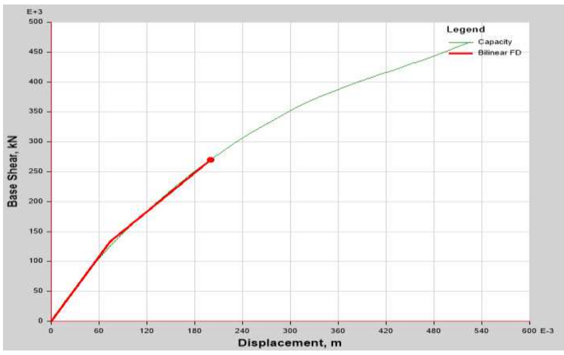
Y-Axis



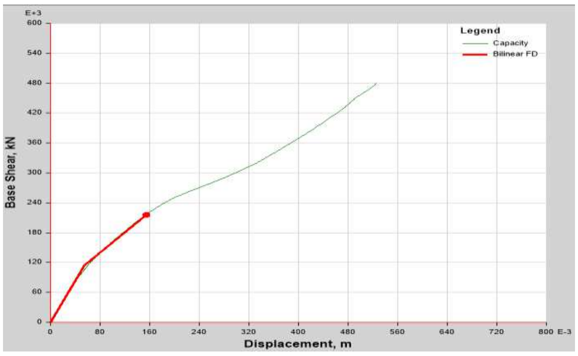
Base Structure



Structure Redesigned by Proposed Method

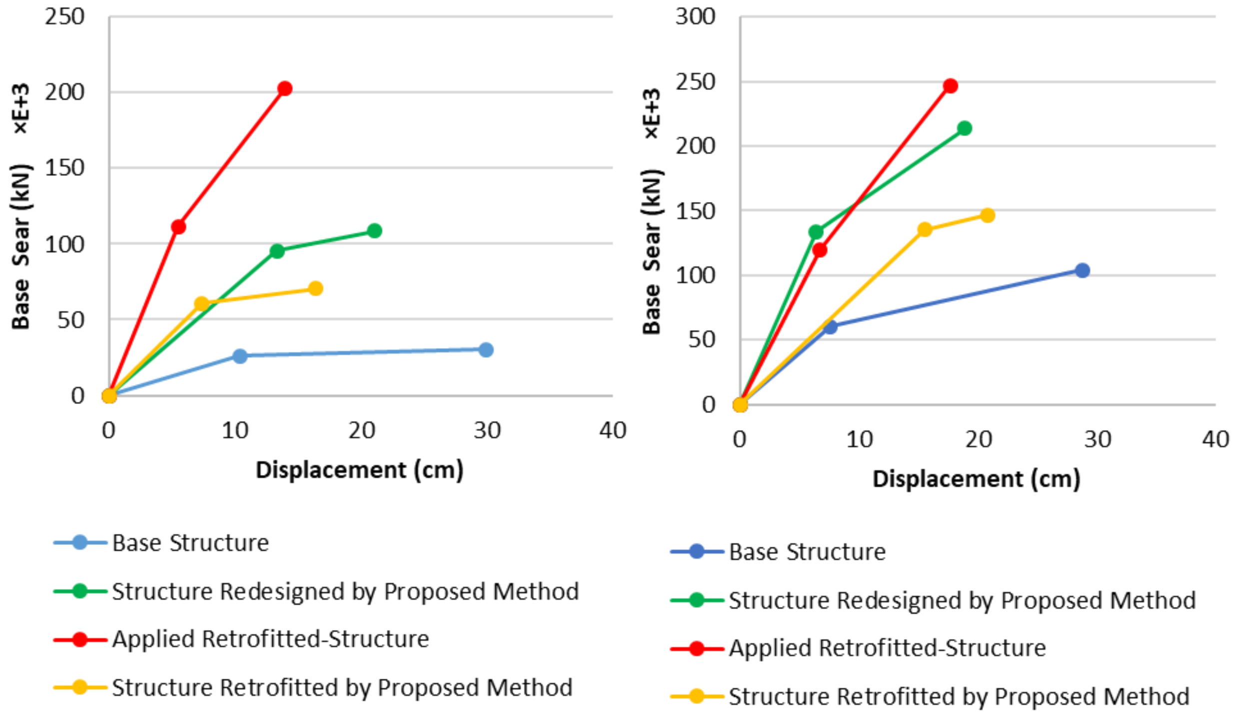


Applied-Retrofitted Structure



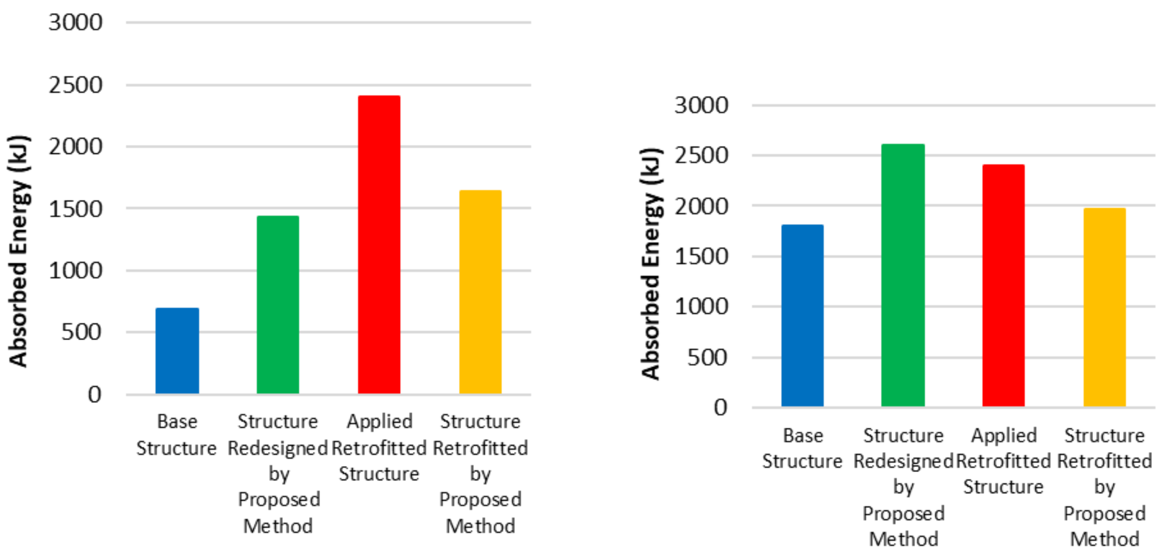
Structure Retrofitted by Proposed Method

Fig. 15 Pushover curves in both longitudinal and transverse directions.



X-Axis Y-Axis

Fig. 16 Comparison of pushover curves in both longitudinal and transverse directions



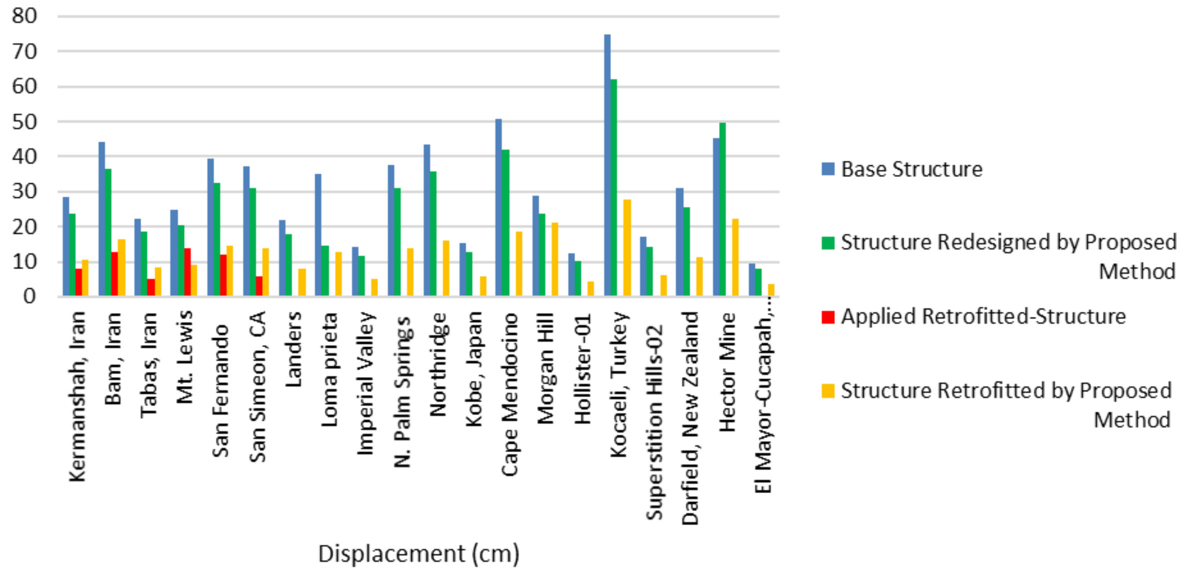
X-Axis Y-Axis

Fig. 17 Energy absorption rate

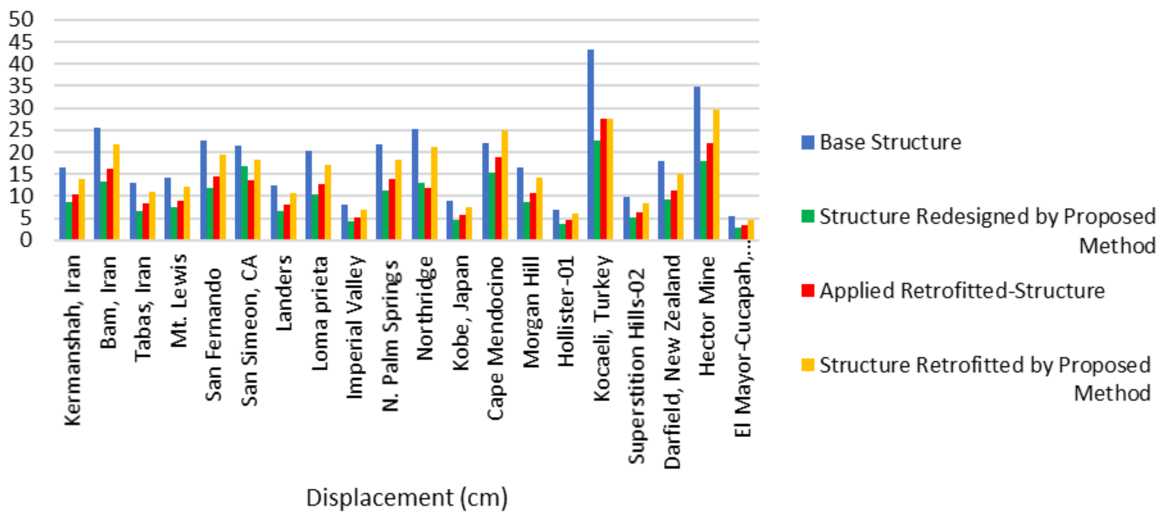
3.3 Nonlinear time history analyses:

A series of nonlinear time history analyses were conducted using a set of 20 earthquake records, as outlined in Table 7. All earthquake records were scaled according to the ASCE/SEI 7–16 [11] approach, where both components were scaled by the same factor. To ensure compliance with the target spectrum, the average of the square-root-of-sum-of-squares (SRSS) response spectra across all records should not fall below the target spectrum within a specific period range, which varies depending on the fundamental period of the structure.

In Fig. 18, a comparison is presented for the maximum displacements of the roof's mass center in both directions of the structure for the four considered structures. It can be observed that compared to the base structure, the redesigned structure shows an average reduction of 23% and 48% in the maximum displacement of the roof's mass center in the longitudinal and transverse directions, respectively. Likewise, the proposed method and the applied method demonstrate average reductions of 63% and 15%, and 57% and 36%, respectively, in the same displacement values.



X-Axis



Y-Axis

Fig. 18 Maximum displacement of the roof's mass center in the studied structures in both longitudinal and transverse directions

The same set of 20 earthquake records was utilized to conduct Incremental Dynamic Analysis (IDA). IDA curves take into account the record-to-record variability, capturing variations in the amplitude, frequency content, and duration of probable future ground motion, thereby providing a comprehensive understanding of a structure's seismic response. Each IDA curve represents engineering demand parameters, such as inter-story drift, plotted against intensity parameters, such as spectral acceleration. These curves are obtained from a series of nonlinear dynamic analyses that subject the structure to increasing scaled intensities of specific ground motion.

Based on the IDA curves, the Immediate Occupancy (IO) limit state is defined when the inter-story drift reaches $\theta_{max} = 2\%$. The collapse capacity of the structure (CP) is determined as the last point on the IDA curve where dynamic instability occurs or when the slope of the IDA curve exceeds 20% of its initial tangent slope, up to the limit of $\theta_{max} = 10\%$.

For brevity, the IDA curves are represented by their percentile curves, as depicted in Fig. 19. IDA is commonly used to estimate fragility curves for different limit states, considering uncertainties in future earthquake characteristics [12], [13].

Fragility curves provide a cumulative probability distribution of damages and are essential for assessing the performance of structures.

In order to compare the performance of the concrete base structure retrofitted with friction dampers and viscous dampers as connection elements, fragility curves were computed and compared, as illustrated in Fig. 20. The fragility function is expressed by Eq. (12), where R represents the response of the building, LSi corresponds to damage levels associated with R, IM denotes the intensity measure, and S denotes the considered intensity value. These fragility curves provide valuable insights into the cumulative probability distribution of damages.

$$Fragility = P[R > LS_i | IM = S] \qquad (12)$$

In this particular study, the parameter R represents the maximum total drift ratio of the walls, while LSi corresponds to the performance levels defined in ASCE/SEI41-17(2017). The fragility curve, in mathematical terms, represents the conditional probability of exceeding or reaching a specific limit state. In this context, the fragility curves express the probability that the maximum total drift ratio of the walls will surpass the defined performance levels under various earthquake intensities.

The study's findings revealed that the selection of viscous dampers is favorable due to their lower probability of exceeding the performance levels at both the Immediate Occupancy (IO) and collapse capacity (CP) levels across a wide range of earthquake intensities. This indicates that the viscous dampers exhibit better performance in terms of mitigating drift and reducing the risk of reaching or surpassing the specified performance thresholds.

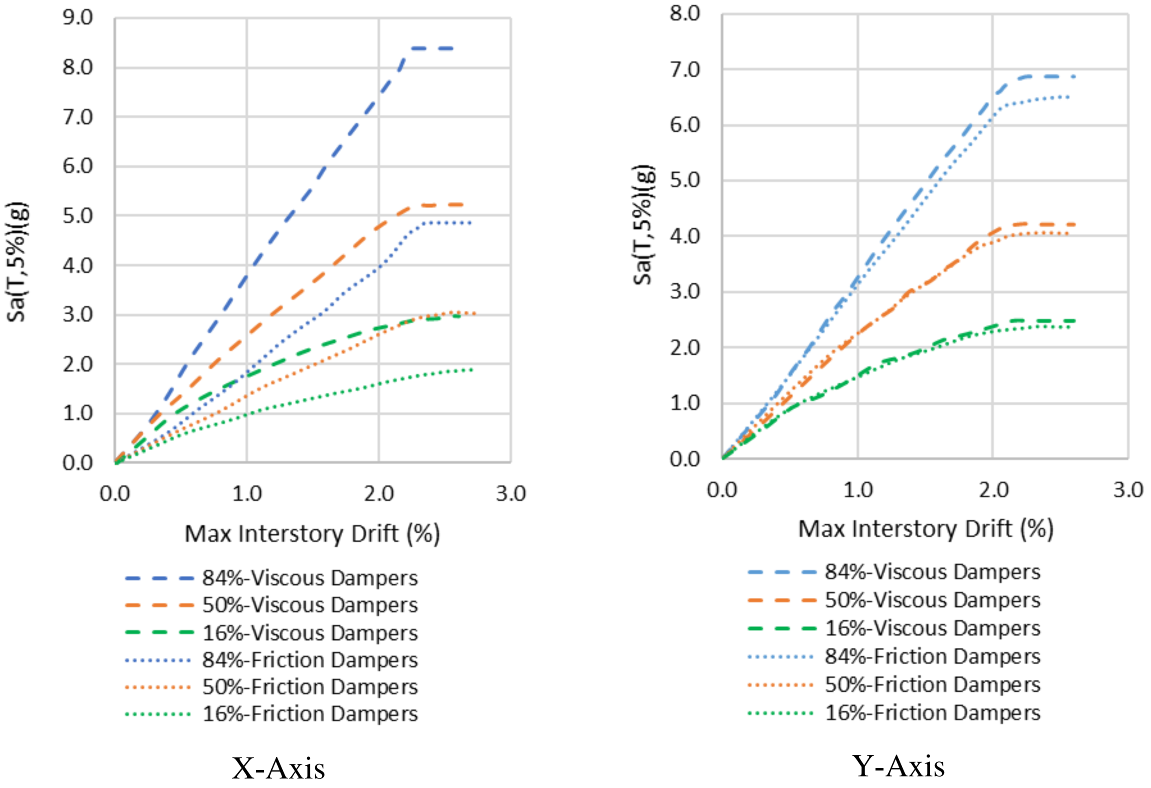


Fig. 19 16th, 50th, and 84th percentiles of IDA curves for Structure Retrofitted by Proposed Method with viscous and friction dampers

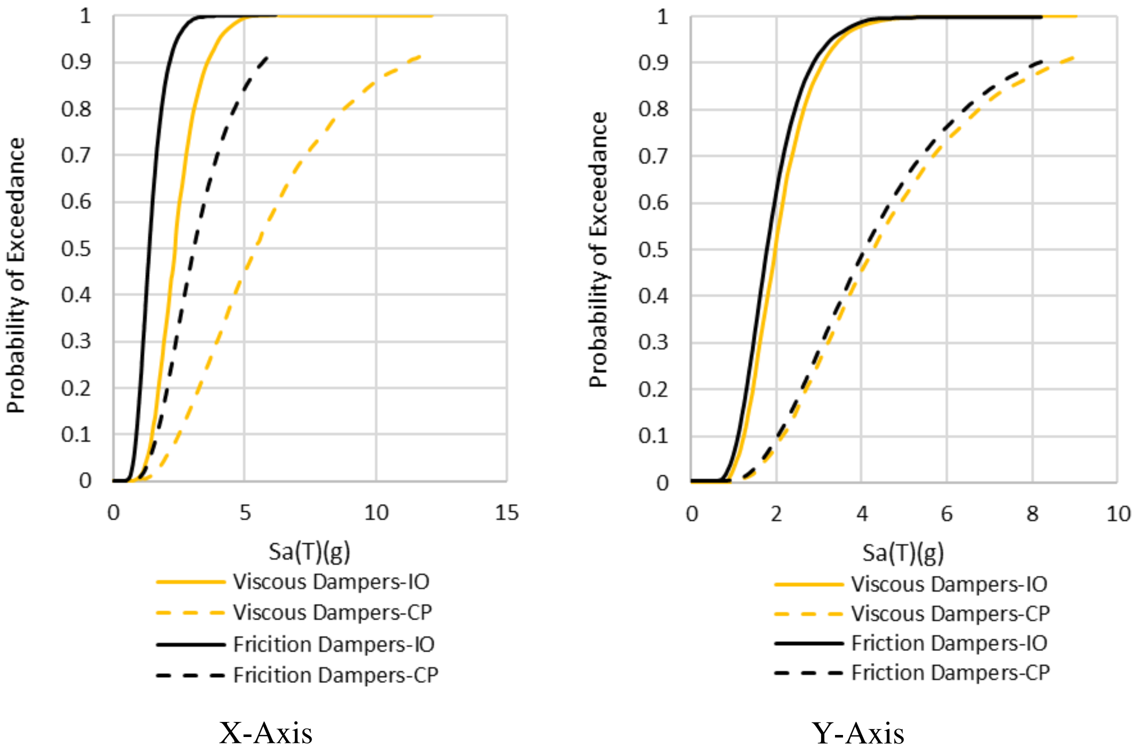


Fig. 20 The fragility curves for Structure Retrofitted by the Proposed Method using friction and viscose dampers

Furthermore, fragility curves were obtained and compared for the base structure, redesigned structure by the proposed method, applied retrofitted structure, and structure retrofitted by the proposed method in both directions of the structure, specifically at the performance levels of Immediate Occupancy (IO) and collapse capacity (CP) (refer to Fig. 21).

It is evident from the analysis that the base structure exhibits the highest probability of exceedance at both IO and CP performance levels, indicating its poorest performance among the four structures. As expected, the retrofitted structure with applied modifications, which offers increased strength, demonstrates a lower probability of exceedance at both performance levels in both directions. Consequently, it exhibits the best performance in the X-axis and the second-best performance in the Y-axis, following the structure redesigned using the proposed method. Overall, these findings reinforce the effectiveness of the retrofitting strategies. The applied retrofitted structure exhibits improved performance due to its enhanced strength, while the structure retrofitted by the proposed method showcases superior performance in both directions, indicating the successful implementation of the proposed retrofitting approach.

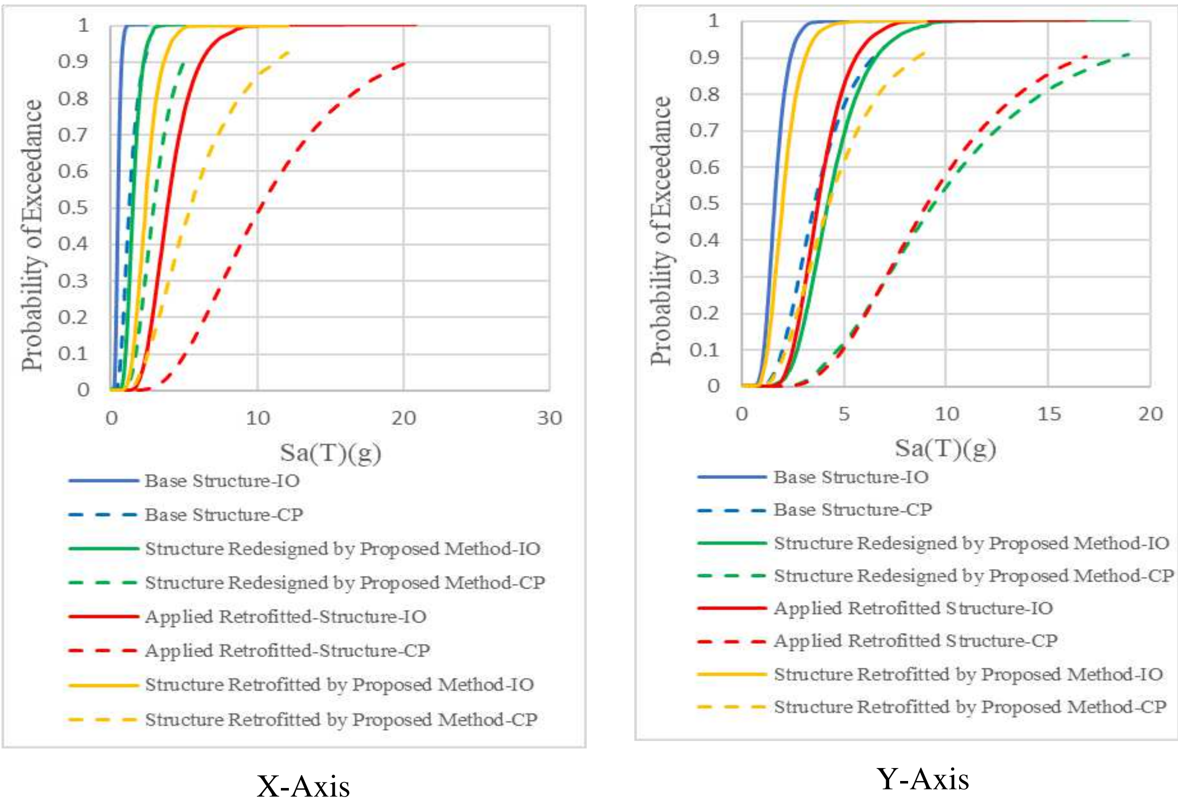


Fig. 21 The fragility curves for four structures in two longitudinal directions X and transverse Y

3.4 Cost Analysis

The estimation of annual monetary loss serves as a crucial factor in the calculation of insurance premiums. It holds significant value as a decision variable within the performance-based seismic assessment framework, offering meaningful insights to decision-makers.

Fig. **22,** Fig. **23,** Fig. **24,** andFig. **25** present the probable annual loss curves for the base structure, structure redesigned by proposed method, applied retrofitted-structure, and the structure retrofitted by proposed method, respectively. The area under each loss curve corresponds to the annual monetary loss: $6094.4632 for the base structure, $5888.6025 for the structure redesigned by proposed method, $5496.029 for the applied retrofitted-structure, and $3393.2542 for the structure retrofitted by proposed method.

In terms of gross profit for the owner, these translate to $205.85, $598.43, and $2701.209 per year for the structure redesigned by proposed method, applied retrofitted-structure, and structure retrofitted by proposed method, respectively. By utilizing Eq. (13) and assuming a useful life of 50 years for the building, along with a depreciation rate of 3%, it is possible to calculate the total profit that the owner would accrue over the 50-year lifespan of the structure [14], [15].

$$E[B_L] = (EAL_0 - EAL_R) \sum_{t=1}^{T} (1+r)^{-t} \qquad (13)$$

In this context, $E[B_L]$ represents the projected profit that the owner will accumulate over the next 50 years. " EAL_0" and "EAL_R" denote the expected annual losses for the base structure and the retrofitted structure, respectively. The parameter "r" signifies the depreciation rate, while "t" signifies the useful lifetime of the structure. Utilizing this relationship, the projected profit for the structure redesigned by the proposed method amounts to $5294.462, for the applied retrofitted structure it is $15391.62, for Retrofitted Structure by the proposed method it reaches $69475.0955.

Typically, if the ratio of retrofitted cost to profit is less than one, the improvement is considered cost-effective. However, it is important to note that the costs utilized in this study are approximations, and therefore this particular parameter has not been calculated. Our focus will primarily be on comparing the aforementioned parameters.

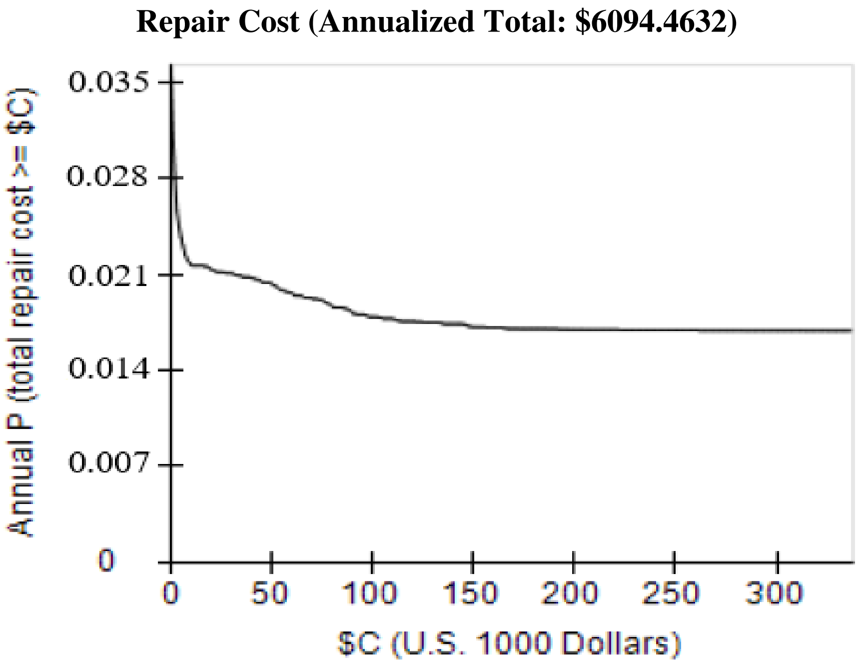


Fig. 22 Probable annual loss for Base Structure

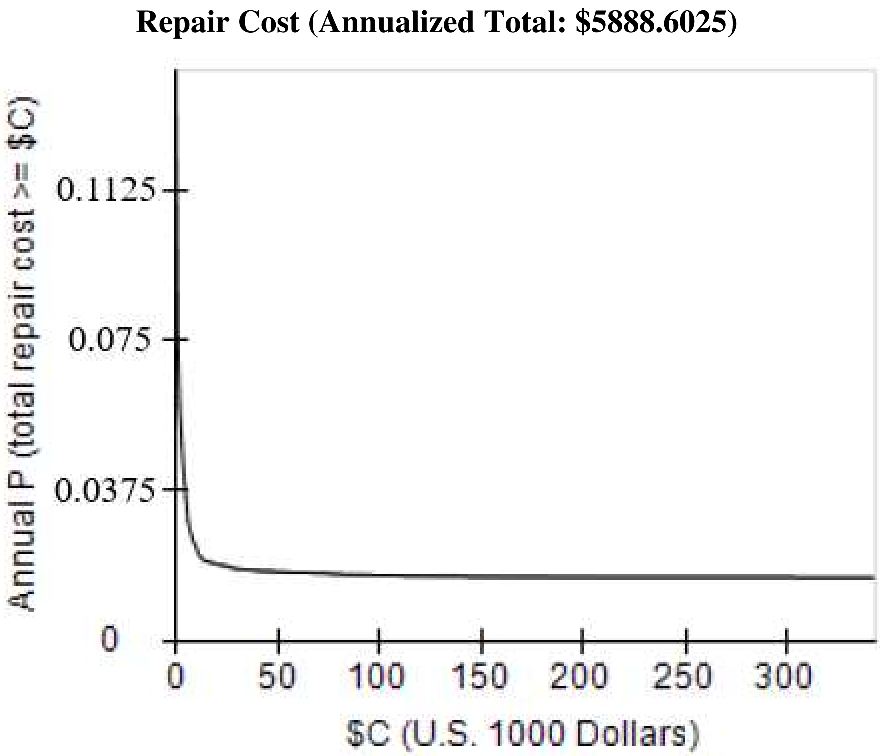


Fig. 23 Probable annual loss for Structure Redesigned by Proposed Method

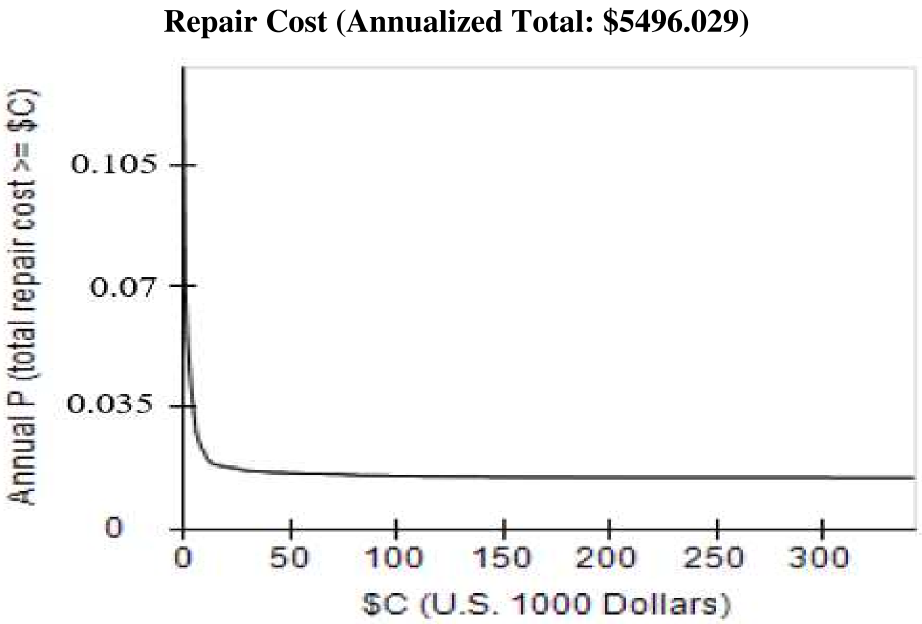


Fig. 24 Probable annual loss for Applied Retrofitted Structure

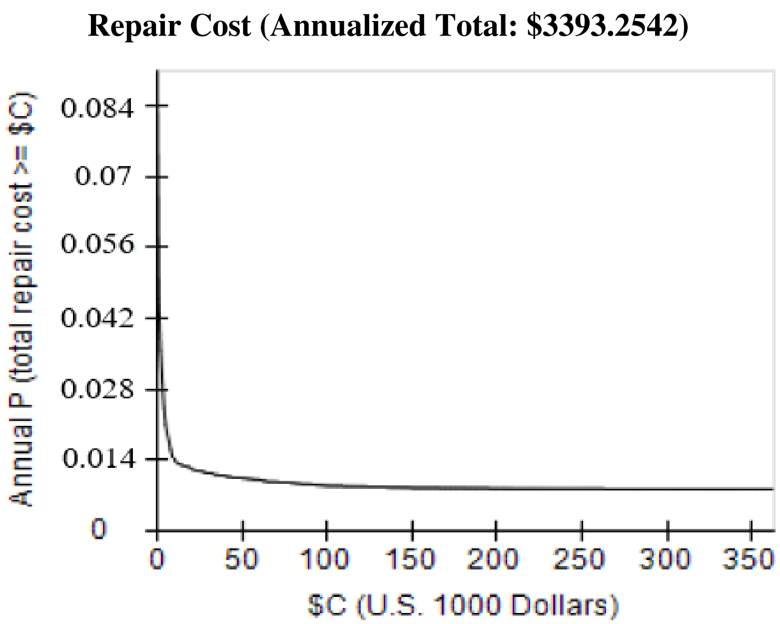


Fig. 25 Probable annual loss for Structure Retrofitted by Proposed Method

Based on the analysis of the aforementioned curves, it can be concluded that while the performance of the retrofitted structure with applied modifications appears to be superior to that of the structure retrofitted using the proposed method, it is important to note that the probable annual loss and repair costs associated with the proposed method are significantly lower compared to the applied retrofitted structure.

In the case of the applied retrofitted structure, which involves an internal retrofitting method, as opposed to the proposed method which is an external method, the retrofitting process took over three years to complete after the 2017 earthquake. Unfortunately, during the midst of the Covid-19 pandemic in 2020, when the community was in desperate need of the hospital's services, the hospital remained closed and unusable. This resulted in irreparable costs to society, highlighting the detrimental consequences of the extended closure and unavailability of the hospital during a critical time.

4 Conclusion:

This study aimed to establish design objectives for new hospital buildings and introduce two retrofitting methods, namely the internal and external schemes. These methods were applied to Imam Khomeini Hospital in Eslamabad-e Gharb, a location in western Iran that experienced significant damage during the recent Kermanshah earthquake in 2017.

To assess the performance of the retrofitted and redesigned methods in comparison to the base structure, which was designed according to the previous seismic code, nonlinear static and dynamic time history analyses were employed as analysis tools.

The internal retrofitting method involved the installation of chevron braces, reinforcement of shear walls with FRP coating, and the use of a metal jacket around wall columns and structural beams. On the other hand, the external retrofitting method utilized two steel-braced frames on the northern and southern perimeters of the structure, along with viscous dampers to connect the steel braced frame to the concrete building. Shear walls were also reinforced with a double layer of CFRP to ensure that the structure remains within the IO performance level.

Additionally, the applied retrofitting method, designed by a consultant company, was examined and compared against the proposed retrofitting and new redesign structure.

In summary, the key findings of this research are as follows:

- Based on the seismic code's requirements for buildings classified as "Very High importance" in high seismic hazard zones, only "special" structural systems are permitted. However, using special structures may not be suitable for critical structures like hospital buildings. This is because the assumption underlying the use of special structures implies that they would sustain damage during a design earthquake, potentially exceeding the performance level of Immediate Occupancy (IO) and possibly reaching the Life Safety level. Essentially, this design assumption allows for undesirable damage in order to maintain the structure's service life after a strong earthquake. As a result, it is recommended to reconsider this design assumption for critical structures, particularly hospital buildings.

- The proposed method for the design of new hospital buildings involves using the R factor adopted for ordinary lateral resisting systems and implementing special reinforcement, reserved strength, and ductility. This design approach ensures that the structure can withstand strong earthquakes and maintain safety and continuous operation even under low to strong ground motions. Although the construction process may require a slightly higher investment due to increased cross sections and the use of special reinforcement, it results in significant improvements in the structural performance. Additionally, it helps avoid additional costs associated with damage to mechanical and electrical equipment, loss of life, and prolonged service interruptions. Overall, adopting this design objective for new hospital buildings provides a reliable and resilient structure.
- The proposed external retrofitting method stands out for its advantages in terms of speed and ease of implementation. Compared to the internal retrofitting method, the external method offers a more efficient and less time-consuming approach. The internal retrofitting method involves labor-intensive tasks such as reinforcing columns with metal jackets, installing various braces within the building spans and walls, and strengthening RC beams and shear walls. These activities require significant time and effort. On the other hand, the external retrofitting method, which includes the use of steel-braced frames and viscous dampers, can be implemented more quickly and with relative ease. This makes it a favorable option for retrofitting critical structures like hospital buildings, where minimizing downtime and ensuring rapid recovery are crucial factors.
- The proposed retrofitting method offers significant advantages over other introduced methods, particularly when considering the probable annual loss as assessed by the FEMA P-58 method. This method demonstrates notably lower levels of potential economic loss, indicating its effectiveness in enhancing the structure's resilience to seismic events. One key advantage of the proposed retrofitting method lies in its ability to ensure continuous operation and serviceability during the reinforcement implementation phase. Unlike alternative methods, this approach allows for the installation of a prefabricated external frame from the exterior of the structure. Consequently, the structure can remain operational and fully functional throughout the retrofitting process, eliminating the need

for any disruptive closures or interruptions. This is particularly advantageous for critical facilities such as hospitals, where uninterrupted operation is vital for delivering uninterrupted medical care and services to patients.

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Data availability: The data that support the findings of this study are not publicly available due to technical reasons. The data are stored in a proprietary format that requires specialized software and hardware to access and process. Data are available from the corresponding author [Seyed Bahram Beheshti Aval] upon reasonable request and with the provision of adequate resources.

Declarations

Conflict of interest: The authors affirm that they have no conflicts of interest to disclose in relation to this work.

Ethical approval: The study did not involve the use of human subjects or any ethical considerations requiring approval. Hence, ethical approval was not applicable to this research.