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SEISMIC VULNERABILITY AND REHABILITATION STRATEGIES FOR INDUSTRIAL RC STRUCTURES

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Abstract

The catastrophic impact of building collapses or severe structural damage during significant earthquakes has led to considerable economic losses, serious injuries, and tragic loss of life. Retrofitting has emerged as a globally recognized solution, particularly for critical structures such as historical buildings and aging constructions that have experienced degradation over time. Unlike traditional repair and rehabilitation methods, retrofitting offers a more effective and practical approach, markedly enhancing the strength, resilience, and overall lifespan of structures. This paper provides a detailed investigation of seismic retrofitting techniques, with a particular focus on reinforced concrete (RC) industrial buildings, which constitute a substantial portion of the existing built environment. The study delves into various retrofitting methods, categorized primarily into two groups: concrete column jacketing, which bolsters the durability and load-bearing capacity of columns, and steel bracing, which enhances structural performance against lateral loads. These techniques are essential for maintaining the safety and integrity of structures, especially in regions prone to seismic activity. By addressing structural vulnerabilities, these retrofitting strategies significantly reduce the risk of catastrophic failures and bolster community resilience. This research offers valuable insights into the field of structural engineering and disaster resilience planning, highlighting the importance of understanding and applying these strategies. Through informed implementation, engineers and policymakers can improve the seismic resilience of existing buildings, thereby mitigating the detrimental effects of earthquakes on both human life and infrastructure.

Keywords: seismic retrofitting, steel bracing, concrete jacketing, structural vulnerabilities, seismic assessment

1. INTRODUCTION

Reinforced concrete (RC) is extensively utilized in the construction industry due to its cost-effectiveness and robust structural properties, particularly in low-rise, multi-story buildings [1]. In the past five years, Bangladesh has experienced eight minor earthquakes, according to the Richter scale. Even a moderately strong seismic event can cause significant damage without warning, especially in densely populated areas like Dhaka [2]. A large number of existing buildings in Dhaka and across Bangladesh were

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constructed without adhering to proper seismic design and detailing standards [3]. Retrofitting these structures is essential to reduce the risks associated with seismic events. Among the various retrofitting techniques, steel bracing is particularly effective [4]. The choice of reinforcement method depends on the structural design and the types of loads it encounters. For structures subjected to primarily static loads, the focus is on enhancing bending and axial compressive strength, while for those subjected to dynamic loads, improving bending and shear strength becomes a priority [5]. Damage to RC columns can present in several forms, such as minor cracks without reinforcement failure, surface damage to concrete without reinforcement failure, concrete crushing, and buckling of reinforcement or tie rupture. The nature and extent of damage depend on the severity of the failure. Addressing these issues involves various techniques, including injections, removal, replacement, or jacketing [6]. During construction, RC columns are commonly reinforced using jacketing techniques, such as Concrete jacketing, Steel Jacketing, Composite materials like Carbon Fiber Reinforced Polymer (CFRP) Jacketing, Precast Concrete Jacketing, and External Pre-stressing Jacketing using Steel Strands [5]. The effectiveness of steel-braced RC frames is highly dependent on the bracing pattern employed [7]. There are three primary methods for integrating steel bracing into an existing RC frame: (i) externally affixing the bracing to the frame, (ii) positioning the bracing within a single frame unit and connecting it via an intermediary steel frame, or (iii) inserting the brace directly into the frame and establishing a direct connection with the RC frame [8, 9, 10]. The first approach has several limitations, including architectural constraints, uneven load transfer from the brace to the RC frame, and challenges in securing the brace-frame connection [11]. The second method, while feasible, is more expensive and poses difficulties in connecting the intermediary steel frame to the RC frame. However, the third method, known as "direct internal bracing," overcomes these drawbacks and has become widely adopted for retrofitting RC frames. This approach was initially introduced by Maheri and Sahebi [12], whose research demonstrated significant improvements in the shear strength of RC frames retrofitted with X steel bracing directly attached to the frames. In another study, Hao Wang *et al.* emphasized the importance of seismic performance and practical retrofitting techniques, highlighting the role of retrofitting and seismic risk assessment in mitigating earthquake risks [13]. Eduardo *et al.* investigated the seismic vulnerability of RCC structures in earthquake-prone areas, revealing that vulnerable columns could suffer significant damage or sudden collapse when subjected to lateral loads [14]. Several conventional methods for structural enhancement have been proposed and implemented, including shear walls, reinforcing columns with steel or concrete jackets, and incorporating advanced materials like fiber-reinforced polymers (FRP) [15]. Ramírez’s study on eleven rehabilitation approaches revealed that concrete jackets are highly effective, economical, and relatively easy to construct compared to other methods [16]. Vandoros and Dritsos, through experimental investigations, demonstrated that using CFRPs and RC jacketing resulted in notable improvements in both the strength and ductility of columns [17]. Research by Natraj *et al.* on the use of CFRP for reinforcing structural elements showed that retrofitting with CFRP could significantly enhance the load-bearing capacity of columns [18]. Krainskyi *et al.* found that concrete jacketing of ten reinforced RC columns led to a doubling of their cross-sections, which in turn increased their capacity by nearly 290% using the same design procedure and loads [19]. This approach enhances the axial strength, bending capacity, and overall rigidity of the original column [14]. Stelios Antoniou, in his comprehensive book, delves into the complexities and challenges of upgrading building infrastructure, providing a thorough analysis of various strengthening methods along with their advantages and disadvantages [20]. Rahimi and Maheri’s study on the seismic impact of retrofitting RC frames with steel X-braces highlighted the widespread use of steel X-braces in retrofitting RC frames. The introduction of steel braces into an existing RC frame results in substantial changes to the load pathways responsible for transferring lateral forces, thereby altering the demands on the frame and its components. The integration of steel X-braces improves the seismic response of an RC frame by reducing maximum displacement, inter-story drifts, and the base shear demand [21]. Pasha Javadi *et al.* conducted a study on retrofitting RC structures using vertical shear links and hybrid connections, emphasizing the importance of the perimeter steel frame in achieving a stable hysteretic response. The hybrid connection also demonstrated significant strength in resisting shear forces between the RC frame and the steel frame [22]. Despite the wealth of research on concrete column jacketing and vertical steel bracing, studies on the combined retrofitting method using X steel bracing and concrete column jacketing in existing RC buildings remain limited. Most research has focused on simulation and experimental testing, with relatively few applications in practical engineering [23, 24, 25, 26, 27]. Numerous studies have focused on structural risk assessment, progressive collapse evaluation, and retrofitting of buildings, employing Extended Three-Dimensional Analysis of Building System (ETABS) as a primary computational tool [28, 29, 30].

This study evaluates structural safety by analysing data from laboratory tests and Finite Element Method (FEM) simulations, alongside practical applications, to explore the challenges and solutions encountered during the retrofitting of buildings. The focus is on the impact of concrete column jacketing and steel X-bracing in existing RC buildings, discussing complications that arise during the retrofitting process. The stability of existing structural elements is assessed based on the current structure, taking into account BNBC-2020 load and load combination criteria during structural analysis. Serviceability is determined by comparing developed deflection and floor drift with lateral loads. Time history analysis is conducted to accurately assess seismic effects, comparing base shear against the time period for the structure before and after retrofitting.

2. METHODOLOGY

2.1. Project details

The research focuses on a five-story reinforced concrete (RC) industrial building located in Bangladesh. The building, designed as a moment-resisting frame (MRF), comprises RC slabs, beams, and columns as the primary load-bearing elements. Notably, it lacks shear walls or other lateral load-resisting structures. Coarse aggregates consist of a combination of brick chips and stone chips, while local sand and Sylheti sand are used as fine aggregates, with PCC cement employed during construction. Deformed 60-grade steel bars were used for reinforcement. Importantly, the structure was not designed in accordance with seismic guidelines and was built by a local contractor. There remains uncertainty regarding whether the original design considered seismic factors. A preliminary evaluation was conducted to assess the condition of the building, leading to several recommendations based on the findings. Multiple visual inspections were carried out to gather precise structural and architectural as-built data. Information was collected on all structural components, including those supporting lateral and vertical loads, as well as equipment that contributes to machine load, dead load, and live load, in their original built condition. An excavation was undertaken to determine the foundation type, revealing the use of isolated footing systems along with a moment-resisting frame as the structural system. Several material tests were conducted to assess the strength of the concrete and reinforcement bars. The structural analysis was performed using Computers and Structures (CSI), ETABS software to verify the adequacy of the building's components. The framework consists of a moment-resisting frame system with RCC load-bearing columns and two-way beam-supported slabs. Specifics regarding the structure are as follows: the building measures 44.05 meters in length, 12.46 meters in width, and 12.78 meters in height. The column dimensions vary, with corner columns measuring 375 mm x 375 mm, side columns at 400 mm x 400 mm, and inner columns at 350 mm x 450 mm. The slab thickness is 150 mm, while the beam dimensions are 375 mm x 350 mm and 400 mm x 375 mm. The stair slab thickness is

185 mm. The building has two staircases, though no elevator is provided. The foundation system consists of isolated shallow footings. The building's layout serves various functions: the first floor houses the security guard room, generator room, and storage area, ensuring operational efficiency. The second and third floors accommodate the equipment room, office space, and a doctor’s room, providing a comprehensive work environment. The fourth and fifth floors are allocated to the cutting, sewing, and ironing sections, facilitating streamlined production processes. The building is situated in a congested and high-risk area of Bangladesh. Figure 1 provides a typical floor plan of the industrial building, while Figure 2 illustrates the typical layout of the slabs, beams, and columns.

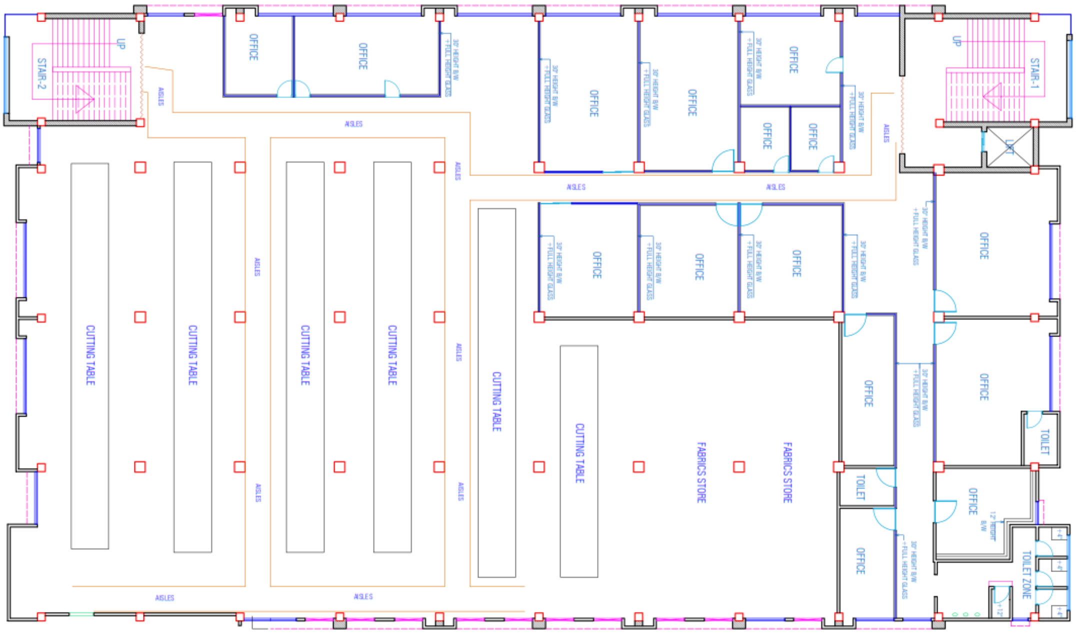


Fig. 1. Typical floor plan of the building

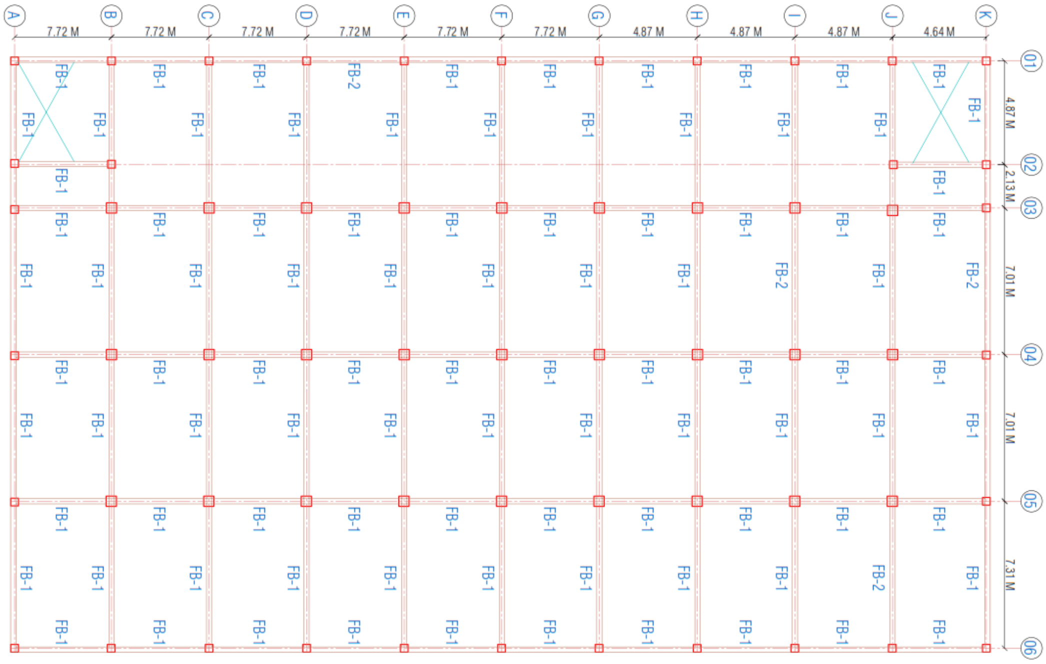


Fig. 2. Typical column, beam and slab layout plan of the building

2.2. Assessment of loads

The building was subjected to a comprehensive inspection covering various areas, including floors, workspaces, offices, cutting and sewing sections, machine rooms, storage areas, water tanks, restroom facilities, furniture, and both interior and exterior walls. These inspections were essential for accurately calculating both live and dead loads. Each load-contributing element was assessed individually to determine dead loads. For live loads, an average of 3.014 kilopascal (kPa) was calculated for the working floors, while dead loads of 2.010 kPa and 5.015 kPa were identified for the roof and stair areas, respectively.

2.3. Evaluation of material strength

Concrete strength and reinforcing bar strength were evaluated through a series of laboratory tests using drilled concrete cores. Core tests were performed to determine the compressive strength of the concrete, while a ferroscan was used to verify the presence and arrangement of reinforcements within the RC elements. Based on the ACI-562 [31] guidelines, the concrete was found to have a compressive strength of 19310 kPa, and the tensile strength of the reinforcing bars was determined to be 413685 kPa.

FEM simulation of the structure:

This study involves the modelling and analysis of reinforced concrete (RC) framed structures using ETABS-2016 software. After gathering as-built architectural and structural data, alongside material strength test reports, a comprehensive structural model was developed and assessed. The analysis accounts for a site class of soil type C and is conducted within earthquake zone II, incorporating an importance factor (I) of 1.2 and assuming a five percent damping ratio. The structural model employs pinned support at the base. The dead load includes the self-weight of all structural components, built-up areas in toilet zones, floor finish loads, and other elements contributing to permanent loads. Live load considerations are based on the latest guidelines from the Bangladesh National Building Code (BNBC-

2020) [32]. Wind and seismic loads, along with their combinations, are also determined according to BNBC-2020 standards.

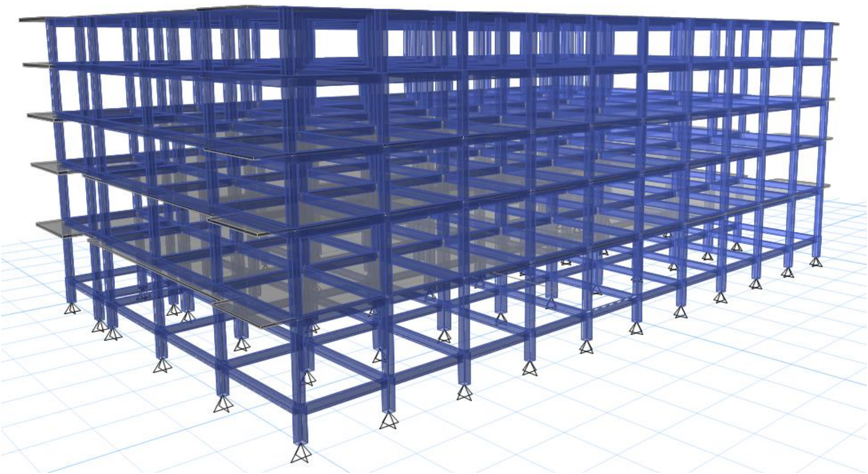


Fig. 3. 3D structural model of the building

Design and analysis software ETABS [33] has been used in this study. In the FEM model, beams and columns are represented as frame elements, while slabs and stairs are modelled as shell elements and treated as semi-rigid diaphragms. The model integrates both RCC and steel components, applying appropriate load combinations for each. Figure 3 illustrates the 3D structural model of the building as generated by ETABS. To calculate seismic forces according to BNBC 2020, the base shear (V), design spectral acceleration (Sa), normalized acceleration response spectrum (Cs), and vertical distribution of lateral forces are expressed using the following equations.

$$Base\ shear, V = S_a W \tag{2.1}$$

Where,
Sa = Design spectral accelerating
W = Total seismic weight

$$F = V \frac{W_x h_x^k}{\sum_i^n W_i h_i^k} \tag{2.2}$$

Where,
Wx = Total dead load
hx = Height above the ground

$$S_a = \frac{2}{3} \frac{ZI}{R} C_S \tag{2.3}$$

Where,
Z = Zone coefficient, 0.20.
I = Importance coefficient
R = Response reduction factor
CS = Normalized acceleration response spectrum

$$C_s = 2.5S\eta, for\ T_B \leq T \leq T_C \tag{2.4}$$

Where,
S = Site class
T = Period
TB = Lower limit of the period
TC = Upper limit of the period
DCF = Damping correction factor

Occupancy and exposure category 3 and B respectively, basic wind speed has been considered as 65.6 m/s. Wind load has been calculated according to BNBC-2020 that can be expressed by below equation 2.5:

$$q_z \frac{kN}{m^2} = 0.000613K_zK_{zt}K_dIGC_fV^2 \tag{2.5}$$

Whereas,
V = Wind velocity at 10.0 m above low ground in m/s
Kzt = Topographic factor
Cf = Force coefficient
Kz = Velocity pressure exposure coefficient
Kd = Wind directionality factor
G = Gust effect factor

3. RESULT AND DISCUSSION

The initial phase involved a comprehensive analysis of the existing structure, with a focus on evaluating the structural safety of all members. Detailed assessments were conducted to examine maximum displacements, story drift, story stiffness, and base shear under time history analysis. The findings revealed that several reinforced concrete (RCC) columns were under excessive stress, resulting in inadequate performance against lateral loads. However, the footing foundations, beams, and slabs were found to be structurally sound. Considering these findings, significant modifications were made to the structural model, transitioning it into a retrofitted design. The retrofitting strategy included jacketing the overstressed columns using the concrete column jacketing technique and introducing steel I-section vertical cross bracing to enhance lateral stability. Post-retrofitting evaluations confirmed that all columns were now within safe stress limits, and the overall structural stability against lateral loads had substantially improved, meeting the required standards. Notably, the excessive deflection observed in the original structure was reduced to within permissible limits, and story displacements were also brought within acceptable bounds. The addition of vertical cross bracing and the retrofitting of overstressed columns led to an increase in story base shear, indicating a significant improvement in structural performance following the retrofitting measures.

3.1. Evaluation od demand capacity ratio

Demand-capacity ratios (DCR) or Strength Capacity Ratios (SCR) are utilized to identify structural elements that have exceeded their load-carrying capacity, potentially leading to progressive collapse [34]. DCRs are calculated according to various international structural standards using linear static analyses, where the applied maximum moments are compared to the expected moment capacities. The maximum moments are derived from ETABS' frame analysis and are always presented as absolute values. DCR values, calculated using Equation 3.1, should not exceed specified limits, which are used in linear elastic static analysis to determine DCR values and dictate whether the structure is acceptable. If the SCR exceeds these limits, the elements are considered severely damaged or at risk of collapse [35, 36]. A DCR value greater than 1.00 indicates that the structural member is overstressed, while a DCR value less than 1.00 indicates that the member is safe.

$$SCR = M_{max} \,/\, M_p \tag{3.1}$$

Where,
M_{max} = the moment demand is determined through linear elastic static analysis conducted in ETABS,
Mp = the ultimate moment capacity, also known as the plastic moment, can be calculated for each structural member.

$$Mp = F_y\left(\frac{A}{2}\right)\alpha = F_y Z \tag{3.2}$$

Where,
Mp = plastic moment
A = total cross-sectional area
α = distance between the resultant tension and compression forces
Z = $\left(\frac{A}{2}\right)\alpha$ = plastic section modulus of the cross section

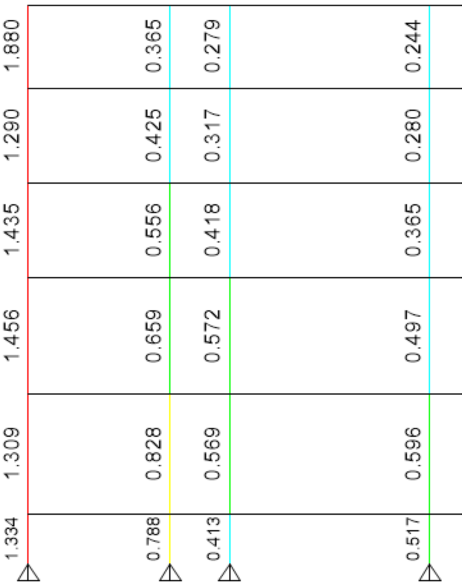


Fig. 4. DCR value of critical columns in existing condition

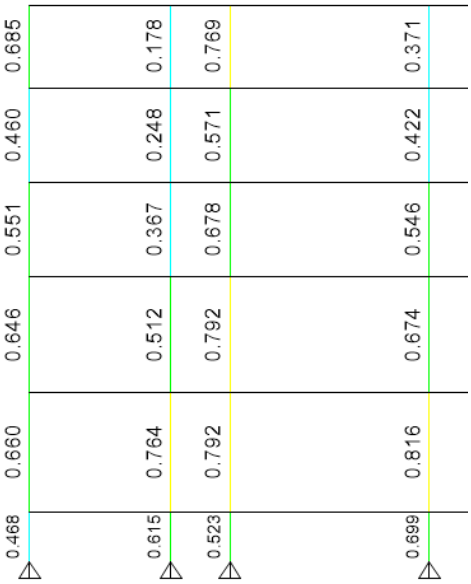


Fig. 5. DCR value of critical columns in retrofitting condition

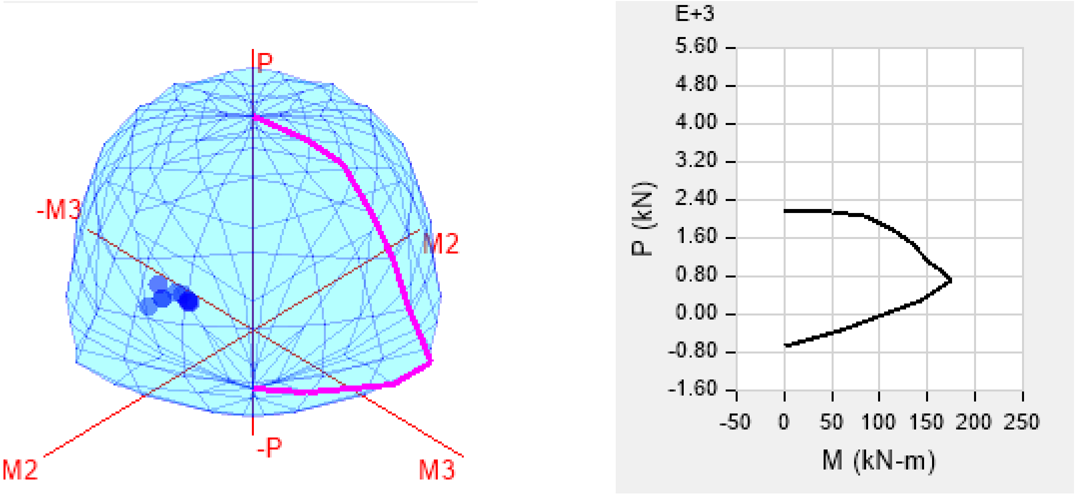


Fig. 6. 3D interaction surface and interaction curve of the critical column (existing)

Figure 4 shows the DCR of specific columns, while Figure 6 illustrates the interaction surface and curve of the critical column under axial and bending forces in the building's existing condition. In the initial analysis, columns with a DCR exceeding 1.00 are marked in red, indicating overstressed conditions. After the retrofitting process, Figure 5 displays the DCR of selected columns, and Figure 7 presents the interaction surface and curve of the critical column in the retrofitted structure for axial and bending forces. The results clearly indicate that, post-retrofitting, all columns are within safe limits, with DCR values below 1.00.

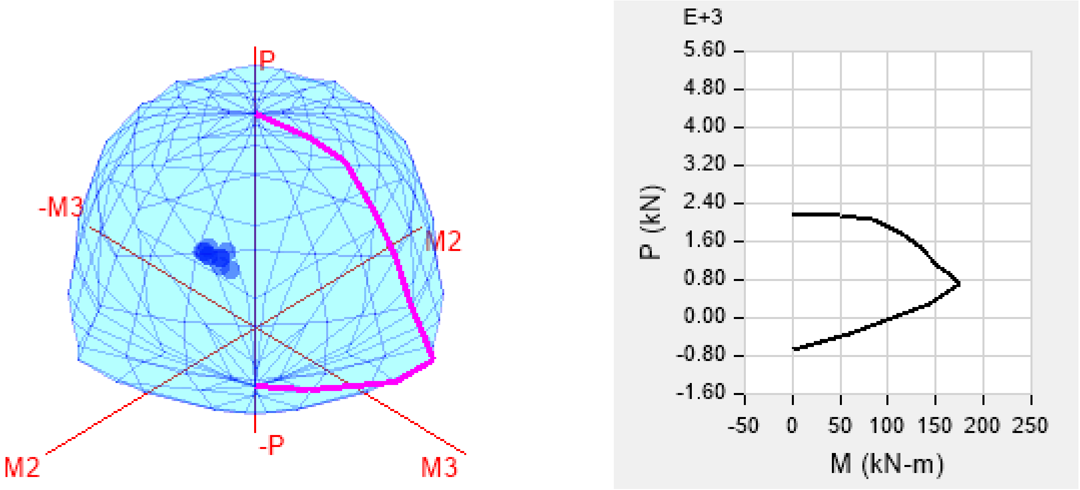
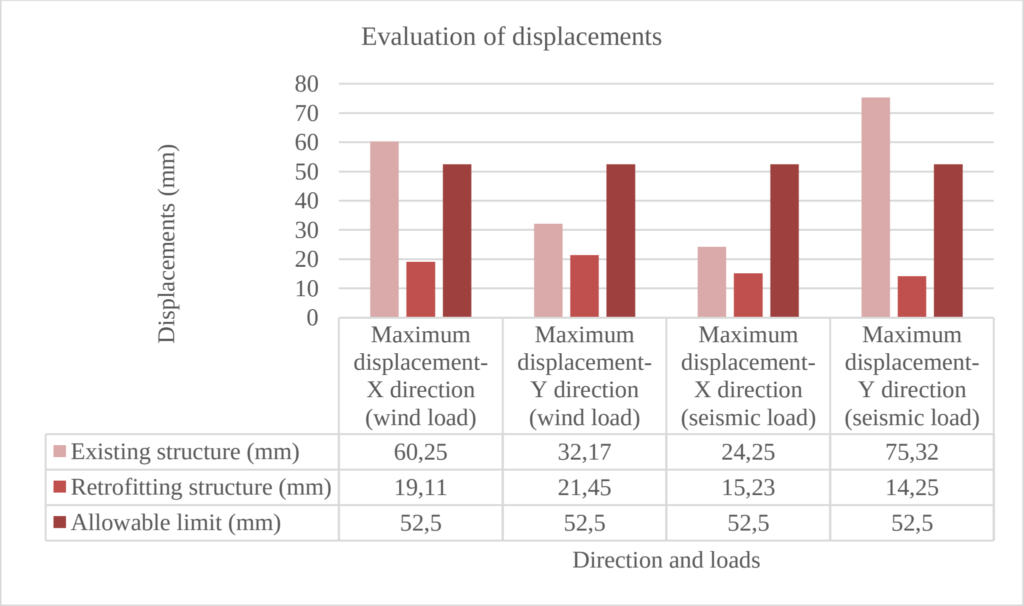


Fig. 7. 3D interaction surface and interaction curve of the critical column (existing)

3.2. Evaluation of displacements

Considering deflection is essential for satisfying serviceability criteria, ensuring it remains within the permissible range defined by structural standards under operational load conditions [37]. Excessive deflection or cracking in a reinforced concrete (RC) structure can undermine performance and inconvenience users, even if safety regulations are technically met [37]. Thus, evaluating the serviceability of RC structures is critical. The principles of ultimate strength underpin many structural standards, including the widely adopted ACI building code. Since maximum strength design incorporates the ultimate material properties into the design process, it is crucial to assess material serviceability regarding deflection or cracking [38]. The evaluation of narrative drift or lateral displacement limits plays a key role in modern seismic design standards and is vital for obtaining accurate structural analysis results [39].



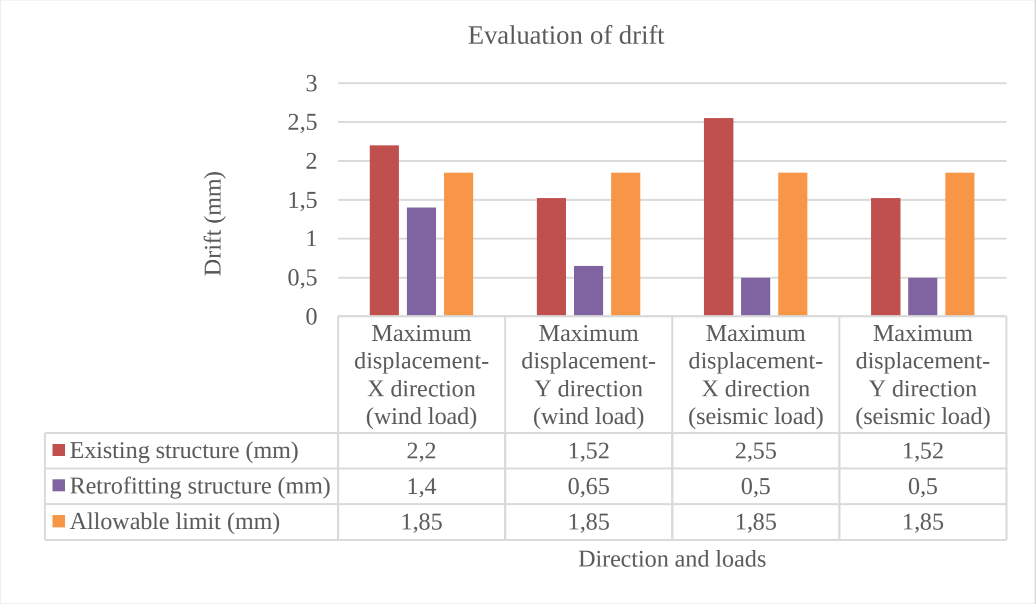
	Maximum displacement-X direction (wind load)	Maximum displacement-Y direction (wind load)	Maximum displacement-X direction (seismic load)	Maximum displacement-Y direction (seismic load)
■ Existing structure (mm)	60,25	32,17	24,25	75,32
■ Retrofitting structure (mm)	19,11	21,45	15,23	14,25
■ Allowable limit (mm)	52,5	52,5	52,5	52,5

Fig. 8. Displacements evaluation

The structure initially exhibited a maximum deflection of 32.17 mm in the Y direction under wind and seismic loads, which exceeded the allowable limit of 52.50 mm. After retrofitting, these deflections were reduced to 21.45 mm and 15.23 mm for wind and seismic loads, respectively, bringing them within the permissible range. Figure 8 visually compares the structure’s deflection in its existing condition with the allowable limit, highlighting the significant improvements achieved post-retrofitting in relation to the permissible deflection threshold.

3.3. Evaluation of study drift

Story drift refers to the change in lateral displacement between two successive stories in a building or structure [40]. During seismic events, structures are subjected to significant lateral forces that impact four key areas: structural elements such as beams and columns, non-structural components, and interactions with neighbouring structures [40]. Neglecting to account for large displacements and drifts during the design phase can adversely affect adjacent buildings, non-structural elements, and the integrity of structural components [40]. Performance-based seismic design (PBSD) evaluates a structure's response and behaviour under potential seismic hazards [41].



	Maximum displacement-X direction (wind load)	Maximum displacement-Y direction (wind load)	Maximum displacement-X direction (seismic load)	Maximum displacement-Y direction (seismic load)
🟥 Existing structure (mm)	2,2	1,52	2,55	1,52
🟪 Retrofitting structure (mm)	1,4	0,65	0,5	0,5
🟧 Allowable limit (mm)	1,85	1,85	1,85	1,85

Fig. 9. Story drift evaluation

Figure 9 illustrates the improvements achieved through retrofitting by graphically comparing the structure's drift before and after retrofitting against the allowable limit. Maximum drift has been found 2.20 mm for wind load and 2.55 mm for seismic load both are within the allowable limit.

3.4. Study on time history analysis

Conducting a time history analysis is essential, whether evaluating a new structure or assessing an existing one. This method is regarded as the most reliable for accurately simulating a structure’s response during an earthquake. It takes into account the elastoplastic deformation of structural elements and uses direct numerical integration of motion differential equations [42].

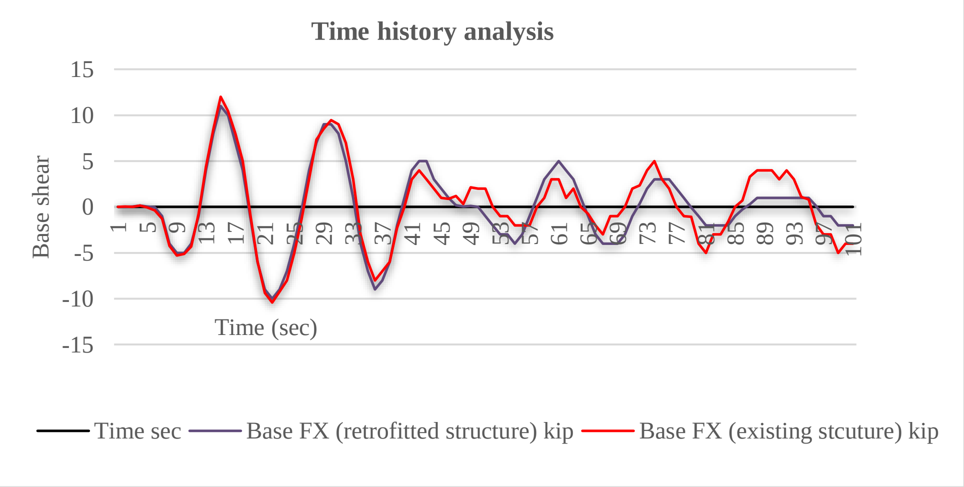
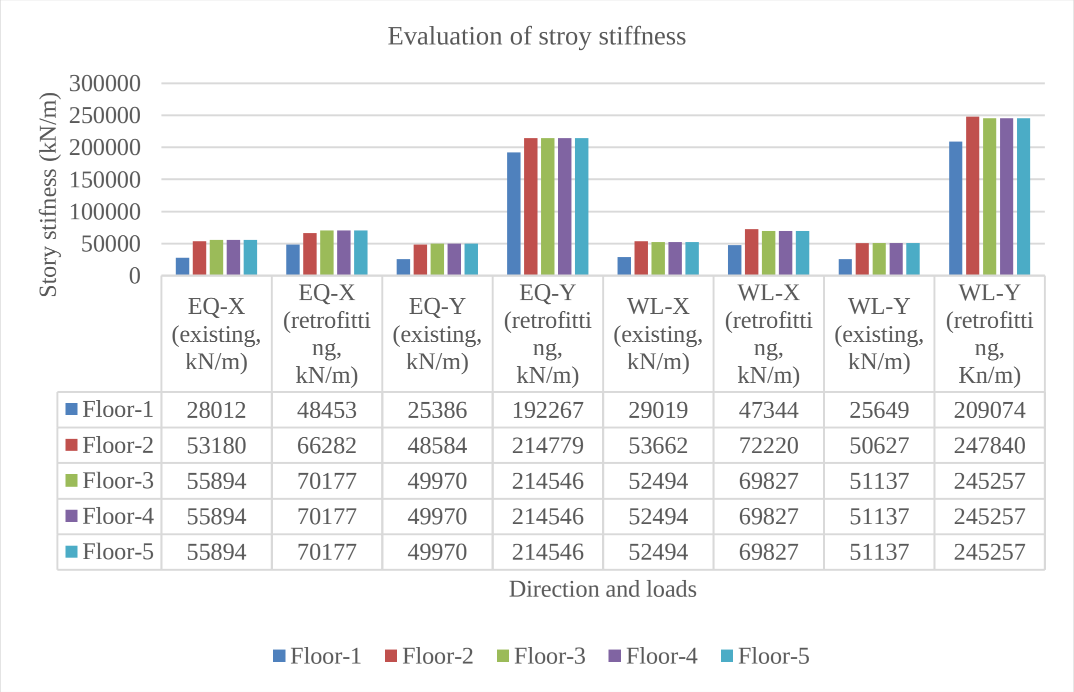


Fig. 10. Time history analysis comparison of existing and retrofitted structure

The time history analysis for this study examined the maximum base shear (FX) and time period (seconds) in both the existing and retrofitted structures. In the existing condition, the maximum base shear was found to be 9.10 kip, while the minimum was 6.80 kip. The maximum time period was 0.004 seconds, with a minimum of -0.004 seconds. After retrofitting, the maximum base shear was recorded at 2.10 kip, and the minimum was 2.30 kip. The maximum time period increased to 0.020 seconds, and the minimum was -0.008 seconds. Figure 10 displays a comparison of the base shear and time period for both the original and retrofitted structures.

3.5. Evaluation of stiffness

The stiffness of a frame structure plays a critical role in determining its response during seismic events. Optimizing the distribution of stiffness can significantly enhance the safety and resilience of the structure against seismic forces [43].



	EQ-X (existing, kN/m)	EQ-X (retrofitting, kN/m)	EQ-Y (existing, kN/m)	EQ-Y (retrofitting, kN/m)	WL-X (existing, kN/m)	WL-X (retrofitting, kN/m)	WL-Y (existing, kN/m)	WL-Y (retrofitting, Kn/m)
Floor-1	28012	48453	25386	192267	29019	47344	25649	209074
Floor-2	53180	66282	48584	214779	53662	72220	50627	247840
Floor-3	55894	70177	49970	214546	52494	69827	51137	245257
Floor-4	55894	70177	49970	214546	52494	69827	51137	245257
Floor-5	55894	70177	49970	214546	52494	69827	51137	245257

Fig. 11. Evaluation of story stiffness

A detailed assessment and comparison of each floor's performance under seismic and wind loads have been conducted and are illustrated in Figure 11. The analysis of story stiffness shows a marked improvement following the retrofitting of the existing structure, particularly in its capacity to resist seismic and wind loads. Maximum story stiffness has been found in the fifth floor for both existing and retrofitting condition. In the fifth floor existing story stiffness was 51137 kN/m and it has been increased to 245257 kN/m in the retrofitting condition. It has been observed that story stiffness has been increased in every floor after retrofitting of the existing structure.

3.6. Retrofitting of the RCC structure

The retrofitting process for the existing vulnerable structure involved a thorough strategy to enhance its resistance to lateral loads. This approach included enlarging the sections of unsafe columns and incorporating vertical bracing into the design. Additionally, overstressed columns were reinforced through reinforced concrete jacketing, and vertical cross bracing was added using I-section steel. Detailed retrofitting construction drawings were developed based on extensive structural analysis. The construction procedure for concrete column jacketing was meticulously planned: it began with soil excavation around the footing, followed by the removal of plaster from the column's surface. To improve adhesion and structural integrity, the column surface was roughened through sandblasting, and new rebar was added from the footing to the slab as per design specifications. A bonding agent was applied to ensure a strong bond between the old and new concrete. Shuttering was used to support the retrofitting process, and vibration techniques were employed during concrete placement to remove air voids and ensure proper consolidation. The column was then cured for 28 days to achieve optimal strength. Notably, the new concrete had a strength 700 psi higher than the existing concrete, enhancing the structural integrity and load-bearing capacity of the modified elements.

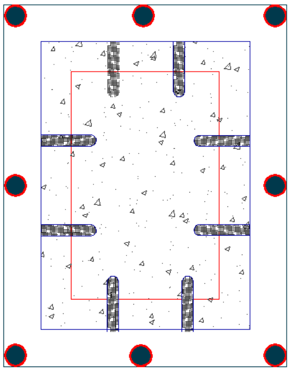


Fig. 12. Structural drawing of concrete column jacketing

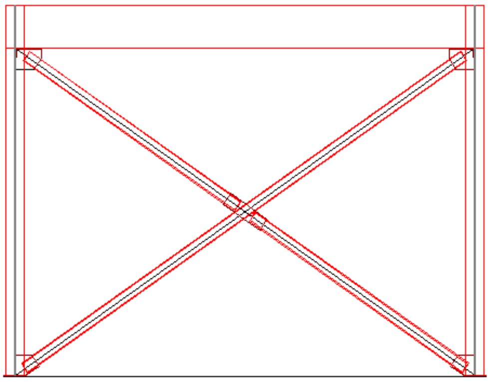


Fig. 13. Structural drawing of vertical X bracing

The study utilized the common force-based approach to design the X-bracing steel system, a method widely used in practice. During the design and analysis phase, the role of the steel diagonal in compression and its impact on the structure's horizontal response were not fully considered. During the retrofitting phase of an existing reinforced concrete (RC) building with steel I-section vertical bracing or X-bracing, the process begins with creating designated access points or openings for the installation of these bracing elements. Steel components are custom-fabricated according to the retrofitting analysis, specifications, and design requirements, ensuring adherence to high quality standards. These bracing elements are carefully positioned and securely attached to the existing structure using welding and bolting methods. Special attention is given to designing the connections between the bracing elements and structural members to ensure effective load transfer and maintain structural stability. Comprehensive inspections and testing procedures are conducted throughout the installation to ensure compliance with safety regulations and industry standards. Figures 12 and 13 present the concrete column jacketing and steel X-bracing drawings, respectively, which are the outcomes of detailed structural analysis and design. The process concludes with a final evaluation to assess the effectiveness of the retrofitting measures in enhancing the building's structural strength and its capacity to resist lateral forces.

4. CONCLUSION

The majority of readymade garments factory buildings in Bangladesh are not designed to withstand earthquakes, underscoring the urgent need for effective seismic retrofitting solutions to address these vulnerabilities.

A comprehensive evaluation of various retrofitting strategies led to the selection of a retrofit system that integrates steel X-bracing with concrete jacketing. This approach has been carefully designed to address and rectify the specific seismic weaknesses identified in the existing structure. The retrofitting measures significantly bolster the building's seismic resilience by reinforcing identified weak points. The analysis emphasizes the critical importance of retrofitting, given the structure's current state, which poses considerable risks during seismic events due to compromised columns and inadequate displacement tolerance. The introduction of steel X-bracing has led to marked improvements in seismic performance, especially for ground floor columns prone to deformation. Additionally, the use of concrete jacketing on upper floors effectively addresses issues associated with short columns, thereby reducing seismic vulnerabilities. These targeted retrofitting interventions enhance the structural robustness and significantly decrease the likelihood of seismic damage. They offer a highly effective solution for improving seismic performance while minimizing disruption to building functionality. This comprehensive approach not only resolves critical structural issues but also exemplifies an optimal strategy for strengthening seismic resilience with minimal impact on the building’s operation.

ADDITIONAL INFORMATION

The authors declare no conflict of interest. This research received no external funding.

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