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Assessment and Retrofitting Of a Multi-Storey Reinforced Concrete Building

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Abstract - Due to safety issues, many of the existing reinforced concrete structures in Cyprus, built 50 years ago, require immediate retrofitting. In general, a great number of structures have issues with reinforcement corrosion and damaged concrete, and in some instances, they are unsafe even under dead loads. Considering the high seismicity of the area, the retrofitting of buildings is crucial. This research work presents the seismic assessment of an existing multi-storey reinforced concrete building, considered to have been built with the prevailing construction practices in Cyprus in the 1970s. Furthermore, it examines various retrofitting strategies that meet the seismic requirements of the region where it is located. Specifically, strengthening with reinforced concrete walls, and concrete jacketing of various layouts and combinations are investigated to compare their contribution towards the seismic upgrade of the structure. Both the assessment and the retrofitting are conducted using non-linear static (pushover) analysis. The results show that the optimal seismic upgrade of the structure in terms of structural response to anticipated earthquakes in the area is achieved by integrating infill walls and concrete jacketing strategically in critical locations. Summing up, the present work investigates the seismic behaviour of a reinforced concrete building before and after strengthened with different combinations of concrete jacketing and reinforced concrete walls.

***Keywords*:** Concrete jacketing, Infill walls, Pushover Analysis, Seismic Assessment, Retrofitting RC buildings

1. Introduction

Due to the geographical location of Cyprus (bordering the Eurasian Plate with the African Plate), there is pronounced seismic activity. This is reflected in existing reinforced concrete structures, which exhibit damages and structural weaknesses both in their foundations and the load-bearing structure. Common problems observed in these structures are mainly in the columns and beam-column joints, where extensive cracking and spalling of concrete are evident.

The causes leading to these deficiencies are mainly due to the lack of implementation of necessary measures for reinforcement detailing in accordance to a seismic code. In particular, the absence of sufficient longitudinal reinforcement, lack of transverse reinforcement, inadequate anchoring length of bars, short reinforced concrete elements, and poor concrete conditions such as compaction are making vulnerable the structure to develop premature damages or plastic hinges.

Therefore, the issue of the physical aging of existing reinforced concrete structures, primarily attributed to corrosion mechanisms (carbonation of concrete, chloride exposure, cracks), combined with the above-mentioned causes, creates significant problems related to the structural integrity and durability of the structures. Consequently, the improvement of the seismic resilience of existing structures is deemed necessary, utilizing various retrofitting methods which are available in modern engineering. Guidelines regarding seismic assessment and retrofitting of concrete structures in accordance to **EN 1998-3:2005 [1]**, are described in **Fardis (2009) [2]**. Numerous researchers are investigating retrofitting methodologies of existing reinforced concrete structures (**Altin et al.,1992 [3]; Kahn et al.,1979 [4], Thermou & Pantazopoulou, 2007 [5], Tastani & Pantazopoulou, 2006 [6]**)

Initially, in this work, the seismic vulnerability level of an existing 5-storey reinforced concrete structure is identified through seismic assessment according to **EN 1998-3:2005 [1]**. Subsequently, once the upgrade level of the structure is determined, where in this specific study the seismic assessment level is "Damage Limitation" (DL), two different strengthening techniques are combined aiming to achieve the appropriate performance level. The first strategy includes the use of reinforced concrete jackets on different structural elements as shown in **Figure 1**. The second technique focuses to the use of R.C. infill walls, within selected frames, to enhance the strength, stiffness and ductility of the structural system as depicted in **Figure 2**. These two retrofitting approaches were primarily applied at the exterior of the building's plan. Non-linear static analysis (pushover) was employed for both the assessment and reinforcement stage of this work.

Altin et al. (1992) [3], who investigated the behaviour and load-carrying capacity of reinforced concrete frames with added infill walls through experiments, demonstrated that frame reinforcement method leads to a desired upgraded structure. Considering the study **by Kahn et al. (1979) [4]** who explored the retrofitting of frames with infill walls, it indicated that for achieving greater resistance to anticipated seismic excitations, it is necessary to strengthen both the frames and the columns comprising the frame with a reinforced concrete jacketing.

The results, in this work, revealed that the combination of reinforced concrete infill walls and concrete jacketing of columns played a decisive role in improving the behaviour of the structure, as they provide significant resistance to horizontal seismic forces.

Fig. 1: Retrofitting method: a) Concrete jacketing of Columns, Source: (**Thermou & Elnashai, 2006 [7]**).

Fig. 2: Retrofitting method: b) Concrete Reinforced Infill Walls, Source: (**Thermou & Elnashai, 2006 [7]**).

2. Methodology

2.1. Description of Selected Building

The building was constructed in Paphos, Cyprus, during the 1970s according to the current **British Standards BS CP 110-1 (1977) [8]** and is located in close proximity to the sea. It is a multi-storey building consisting of a ground floor (Pilotis) and 4 additional floors. For illustration purposes, the 3D model of the existing structure and the typical floor plan is depicted in **Figure 3**. The structural elements of the initial model are summarized in **Table 1** and **Table 2**.

Since there were no seismic code regulations in place, all the buildings were hastily constructed with insufficient construction details, inadequate supervision of construction works, and poor-quality control. However, it is highlighted that it was a common phenomenon that the available structural analysis in many cases were not implemented on site.

The mechanical properties of existing structure's materials are summarized in **Table 3**. Focusing solely on the current compressive strength of concrete which is very low, the need of immediate seismic upgrading of the structure is unavoidable. In accordance to available structural analysis of the existing structure, the dead and live load considered for the existing structure are outlined in **Table 4**.

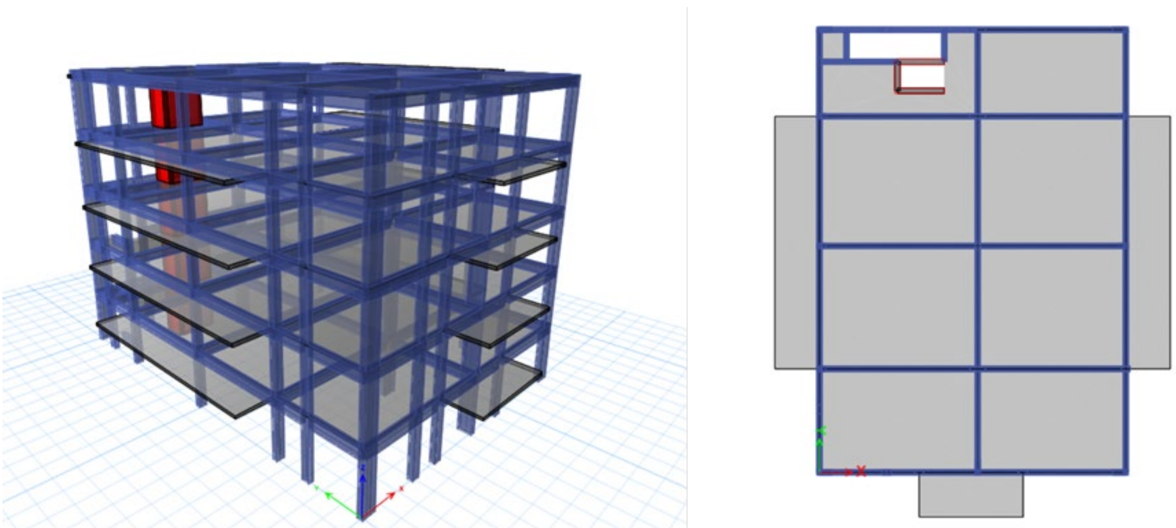

Fig. 3: Reference Building for Geometry: a) 3D view of the frame structure, b) Typical floor plan.

Table 1: Beam sections and reinforcement details of existing structure

Floor	Beam	Section (mm)	Rebars
Ground floor	All	200*500	2ø12 top & 3ø16 bottom
1st Floor – 4th Floor	All	200*500	2ø12 top & 3ø16 bottom

Table 2: Column sections and reinforcement details of existing structure

Columns	Section (mm)	Rebars	Transverse
1	250*400	4ø20+2ø16	ø6/20
2	250*700	4ø20+2ø16	ø6/20

Table 3: Mechanical properties of existing structure's materials

Concrete	B160 → C12/15
Elasticity modulus	27 GPa
Concrete Compressive Strength of Concrete	12/15 MPa
Longitudinal Reinforcement Steel	StIII
Elasticity modulus	200 GPa
Average Yield Strength (f_{yl})	400 MPa
Stirrups Reinforcement Steel	StI
Elasticity modulus	200 GPa
Average Yield Strength ($f_{y,tr}$)	220 MPa

Table 4: Structure's Loads

Dead Loads	Live Loads
Specific Gravity of Concrete: 2.4 tn/m^3	Floor: 2 kN/m^2
Dead Loads of Slab: 1 kN/m^2	Cantilever: 5 kN/m^2
External Walls: 3.6 kN/m^2	Stairs: 3.5 kN/m^2
Internal Walls: 2.1 kN/m^2	

2.2. Investigation Methodology

In the present work, the seismic assessment of the model was conducted employing non-linear static analysis (pushover). In European assessment regulations **(EN-1998:3, 2005 [1]),** static and dynamic analyses are recommended for the assessment of a structure. The calculation of the resistance curve *Base Shear – Displacement* was carried out using as a reference point the displacement of the structure's top.

Specifically, a total displacement of 450 mm was applied at the top of the 5th floor. This ensures greater accuracy in determining the seismic response of the structure and estimates the magnitude of structural deformations. The envelope resistance curve of the existing structure was determined in accordance to **EN-1998:3, 2005 [1]**. The response spectrum used according to **EN-1998:3, 2005 [1]** is the elastic spectrum Type 1 (q=1), allowing for the non-linear analysis to represent the behaviour of the structure under worst-case conditions and identify its vulnerability.

Subsequently, following the regulations of **EN-1998:3, 2005 [1]** particular strategies of seismic upgrading of the building were applied. At this stage, particular emphasis was placed on the seismic shear demand that the existing structure can withstand and considering the available displacement ductility in both longitudinal and transverse direction. In order to achieve the desired upgrade of the structure, three structural analyses were conducted.

During the first attempt of retrofitting model, reinforced concrete infill walls were added in combination with concrete jacketing at locations of the perimeter of the structure as depicted in **Figure 4**. In the second reinforcement model, the sections of the walls were modified. Specifically, their width was increased, additional walls were added, and additional columns were reinforced as illustrated in **Figure 5**. In the third reinforcement model, the sections of the first model were used, but the arrangement of the reinforced concrete infill walls was modified to attain the desired retrofitting of the structure. The combination of these two reinforcement methods, which is shown in **Figure 6** leads to a significant upgrade of the structure, enabling it to withstand expected seismic events in the region satisfactorily, according to **EN-1998:3, 2005 [1]**.

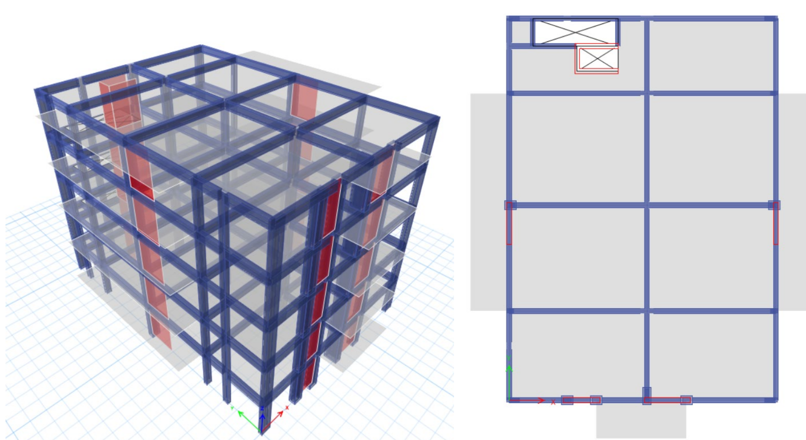

Fig. 4: First Retrofitting Model-Combination of Infill Walls and Concrete Jacketing

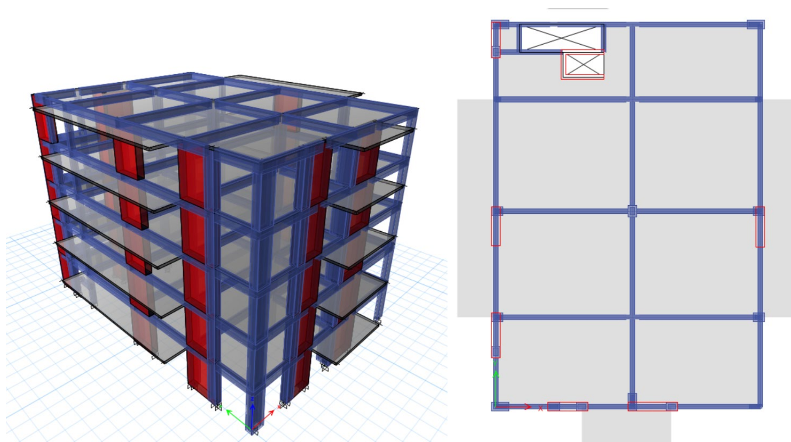

Fig. 5: Second Retrofitting Model-Combination of Infill Walls and Concrete Jacketing

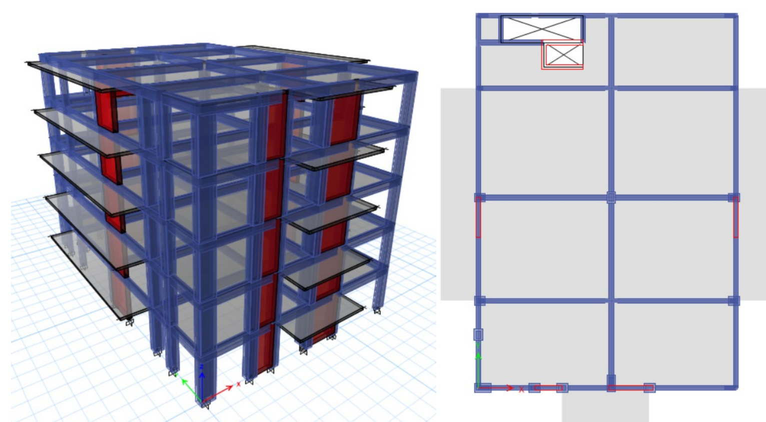

Fig. 6: Third Retrofitting Model-Combination of Infill Walls and Concrete Jacketing

Retrofit 1 and 3 have infill wall sections of 2.10/2.15/2.35m x 0.25 m, whilst retrofit 2 has 2.10/2.15/2.35m x 0.45 m. The columns of all the models have sections of 0.6m x 0.45 m and 0.9 m x 0.45 m. Concrete C20/25 was utilized in all the retrofitted sections. The infill walls of all retrofitted models have longitudinal and transverse rebars ⌀10/150 The transverse rebars of columns are ⌀10/200. Columns of 0.6x0.45 m and 0.9 x 0.45 m have 8⌀20 and 16⌀20 respectively.

3. Results and Discussion

The results of the nonlinear pushover analysis of the initial model and the three reinforced models for both horizontal and transverse direction in terms of base shear vs drift is depicted in **Figure 7a.** Regarding the response in the longitudinal direction, the difference in response of the reinforced models and the initial model, is noticeable both in the level of the deformation limit that the structure can reach and in the horizontal seismic forces it can withstand. As shown in this **Figure 7a**, the third retrofitted model exhibits the best results in terms of base shear force and ductility.

Focusing on the response in the transverse direction, as shown in **Figure 7b**, it is evident that the proposed reinforcements result in an upgraded structure that yields better response under seismic loading. Similarly, to the horizontal direction, the third model yields again the most optimum seismic behaviour both in terms of base shear force that it can undertake and ductility.

The final displacements experienced by the structure, as well as the total base shears for all examined analysis models, are summarized in **Table 5**. As shown in **Table 5**, for the horizontal direction, in all three retrofit models, there is an increase in the maximum base shear by 35.98%, 46.97% & 61.59% of the first, second and third retrofitted model compared to the initial model respectively. Additionally, the retrofits led to an increase in the final displacement of the structure by 30.59%, 18.99%, 65.59% of the first, second and third retrofitted model compared to the initial model respectively. Similarly, for the transverse direction, there is an increase in the maximum base shear by 42.94%, 37.25%, 74.30% of the first, second and third retrofitted model compared to the initial model respectively. Furthermore, for the transverse direction, only in the third retrofitted model, there is an increase in the final displacement by 14.77% compared to the initial model.

In order to assess the contribution of reinforcements to the existing structure, the Spectral Acceleration (Sa) vs the Spectral Displacement (Sd) for the initial model and the three retrofit models for both horizontal and transverse direction, are illustrated in **Figure 8a** and **Figure 8b** respectively. The demand curve according to **EN-1998:3,2005 [1]** for the location of Paphos in Cyprus, is also included in both figures, to aid the assessment of initial and retrofitted models.

These curves are used to assess the robustness of the structure under the influence of seismic forces expected in the examined area. The evaluation is based on the performance point, i.e. the intersection point of the two curves. Therefore, a decision is made on whether retrofitting is required or not. If retrofitting is deemed necessary, it is then checked whether the results of the upgraded structure satisfy the desired level of resistance to seismic excitations. In other words, the damages caused under seismic excitation in the reinforced structure should be consistent with those selected from the initial study. The seismic assessment levels proposed by **EN-1998:3, 2005 [1]** are "Damage Limitation" (DL), "Significant Damage" (SD), and "Near Collapse" (NC).

As evident in **Figure 8**, the initial model cannot withstand the horizontal seismic forces in both directions. However, it is observed that the performance point, i.e., the point where the demand curve intersects the capacity curve, is located in the third retrofitting model. Therefore, the structure after reinforcement is capable of withstanding the design-level ground accelerations, as the spectral capacity curve, as evident, is within the safe design range. Furthermore, the initial objective that was chosen is also achieved, so that if a seismic event occurs, the seismic assessment level is set to "Damage Limitation" (DL). The performance point of the third retrofit model for the pushover in horizontal direction is at a displacement of 36.58 mm and Base Shear of 5192.88 kN. Similarly, the performance point for transverse direction is at a displacement 31.54 mm and Base Shear of 5451.59 kN.

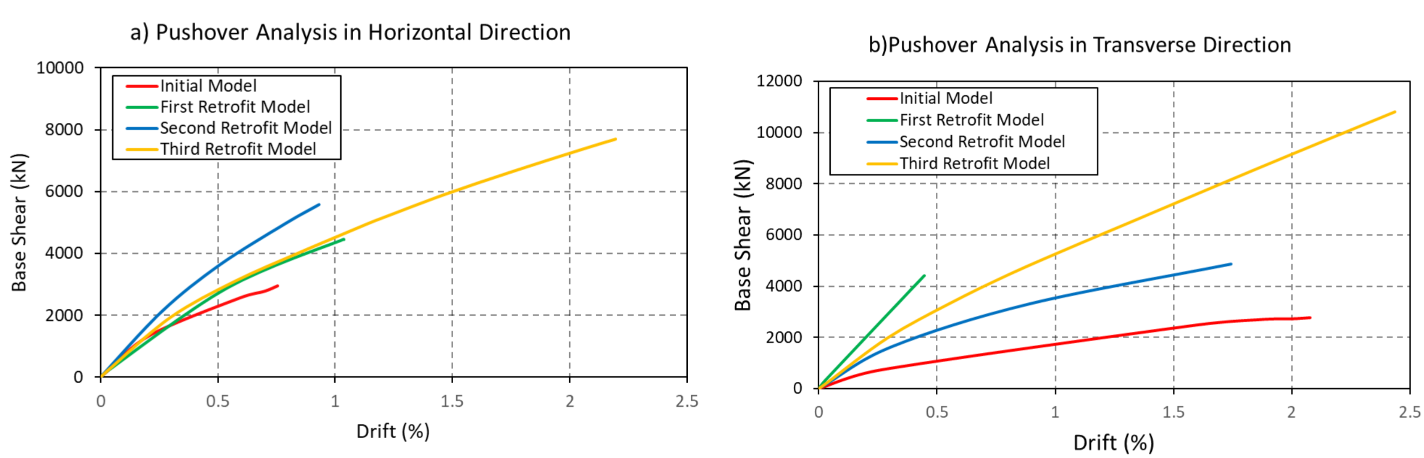

Fig. 7: Base Shear vs Drift of Pushover Analyses in (a) Horizontal, b) Transverse Direction

Table 5: Displacement and base shear at yield and ultimate state of pushover in horizontal direction for all the investigated models

	Horizontal direction		**Transverse direction**	
	Displacement (mm)	**Base Shear (kN)**	**Displacement (mm)**	**Base Shear (kN)**
		Initial Model		
Yield	d_{y1}=6.39	V_b=1367.38	d_{y1}=8.09	V_b=746.62
Ultimate	d_u=22.60	V_b=2953.18	d_u=62.33	V_b=2775.23
		First Retrofit Model		
Yield	d_{y1}=16.17	V_b=2884.80	d_{y1}=9.30	V_b=1642.24
Ultimate	d_u=32.56	V_b=4613.07	d_u=52.30	V_b=4864.27
		Second Retrofit Model		
Yield	d_{y1}=15.17	V_b=3614.63	d_{y1}=0.88	V_b=336.68
Ultimate	d_u=27.90	V_b=5569.37	d_u=13.41	V_b=4423.30
		Final Retrofit Model		
Yield	d_{y1}=8.90	V_b=1922.75	d_{y1}=16.68	V_b=3334.56
Ultimate	d_u= 65.88	V_b=7690.26	d_u= 73.13	V_b=10802.10

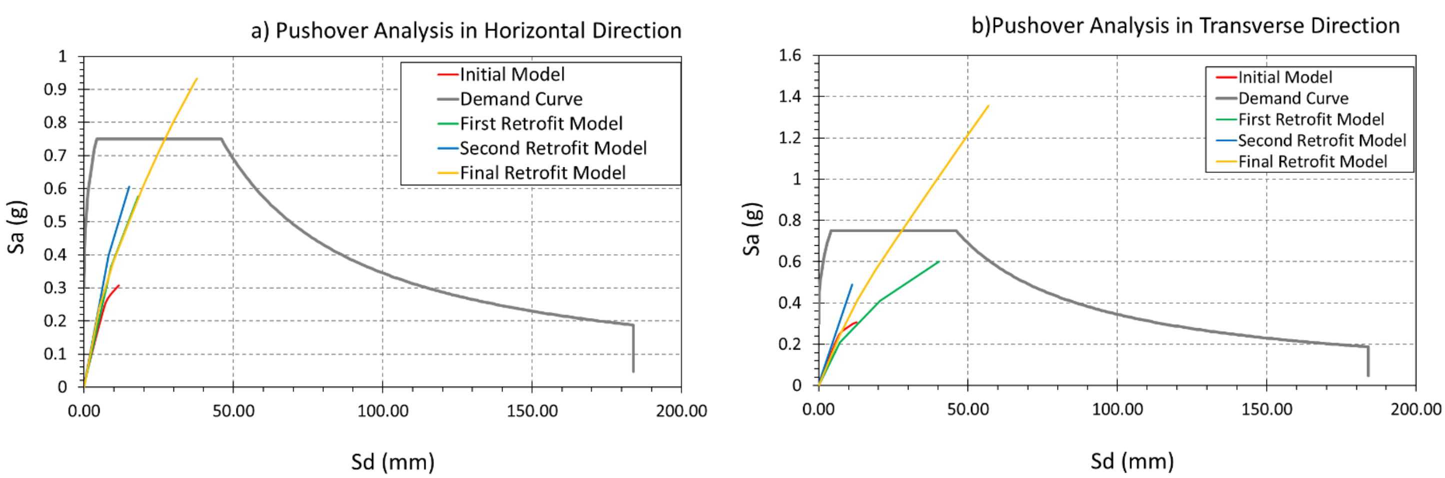

Fig. 8: Sa -Sd of Pushover Analyses in (a) Horizontal, b) Transverse Direction

4. Conclusion

In this article, the seismic vulnerability of a typical existing multi-story structure constructed in the 1970s in Cyprus was investigated. This study confirmed the inability of the structure to withstand ground accelerations according to **EN-1998:3, 2005 [1]**, and the contemporary legislative framework of the region. It also affirmed the urgent need for the immediate upgrading of buildings, especially those constructed during the 1960s, 1970s, and 1980s, as seismic design regulations were not implemented during those periods. Within the scope of this study, an assessment of the existing structure was conducted, along with an exploration of potential reinforcement methods. The study concluded with the optimal reinforcement that imparts the necessary ductility and stiffness to the structure. The ductility of the structure is at low levels, and this is attributed to the placement of infill walls, as these structural elements do not provide ductility to the construction but rather reduce its horizontal displacements. The outcomes demonstrated that a combination of infill walls and concrete jacketing is suitable for upgrading the current structure. The structural strength has significantly increased in both directions, and its load-bearing capacity has been improved to a satisfactory extent, thereby ensuring the desired level "Damage Limitation" (DL) as defined in the case of seismic excitation.

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