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Seismic Retrofitting of Unreinforced Masonry School Structures Using External Cable Bracing and Displacement-Based Analysis: A Case Study from Tabriz, Iran

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Abstract: Unreinforced masonry (URM) school buildings are particularly vulnerable to seismic events, especially in seismically active regions such as Tabriz, Iran. This study investigates a practical and effective retrofitting technique that employs external cable bracing in conjunction with displacement-based analysis to enhance the seismic resilience of URM school structures. The methodology includes a case study of a representative URM school in Tabriz. Analytical modeling and performance-based assessments demonstrate that optimally placed external cable bracing systems can significantly reduce inter-story drifts and improve overall structural stability. The paper concludes with recommendations for broader implementation in Iran's seismic retrofitting programs. The aim of this research is to analyze the seismic behavior of a three-story school building based on Iranian Code, standard no. 2800 in Tabriz city. The building consists of brick walls and brick slabs with steel I-beams. Seismic loads should be carried by the brick walls and transferred to the strip concrete foundation. The building is calculated according to Iranian Code for type II soil. And the results show that in small displacements, the building behaves elastically or with small cracks (IO). In larger displacements, the building will have larger cracks (LS). In very large displacements, the entire building will behave as cracked (CP).

Keywords: Unreinforced Masonry (URM), Seismic Retrofitting, External Cable Bracing, Displacement-Based Analysis, School Safety.

1 INTRODUCTION

Adobe and brick have long been traditional building materials in many parts of the world, particularly in regions with abundant clay and limited access to modern construction materials. These materials continue to be utilized in various countries for constructing schools, especially in rural and low-income areas. Unreinforced masonry (URM) school buildings are particularly vulnerable to seismic damage due to their inherent structural deficiencies (Yılmaz, Tama & Bilgin, 2013). URM buildings are characterized by their heavy mass and brittle materials. Their seismic vulnerability arises from the inability to dissipate energy during ground motion, often resulting in out-of-plane wall failures, corner collapses, and connection failures between diaphragms and walls (Decanini et al., 2004; Kadam, Singh, & Bing, 2020). Schools constructed with adobe or unreinforced brick are especially at risk during seismic events. These materials lack the ductility and reinforcement necessary to withstand earthquakes, posing significant risks to occupants (Sarabi, et al. 2023). Determining the exact number of schools constructed from adobe or brick, specifically unreinforced masonry (URM), worldwide is challenging due to limited global data.

However, regional studies and reports provide insights into the prevalence and risks associated with such structures. For example, in Utah alone, a significant number of public schools were historically constructed using unreinforced masonry. A 2022 report identified 119 school campuses with buildings vulnerable to earthquakes due to their URM construction. Sixty years ago, approximately 95% of schools in Utah were URMs; today, that number has decreased to around 12% due to retrofitting and rebuilding efforts (FEMA, 2009). The Seismic Retrofit Grant Program, which provides federal funding to assist property owners in covering retrofit costs, exemplifies how financial mechanisms can support community safety initiatives. This program not only addresses immediate structural concerns but also alleviates the financial burden faced by school districts, allowing for enhanced safety measures to be implemented without straining resources.

Iran is located in a seismically active region, making earthquake preparedness a critical concern. A significant number of school buildings in the country are constructed using unreinforced masonry (URM) techniques, which lack the necessary ductility and strength to withstand seismic forces (Abrams, et al. 2015). Although exact statistics are no exact statistics, it is estimated that over 50% of school buildings in Iran are either URM or non-engineered structures (Yekrangnia et al., 2016). Consequently, unreinforced masonry school buildings in Iran constitute a significant portion of the nation's educational infrastructure. Given Iran's high seismic activity, these structures pose considerable risks to student safety.

Tabriz, situated along the active North Tabriz Fault, has historically experienced devastating seismic events (Berberian & Yeats, 2001). Retrofitting these structures is essential for safeguarding lives, particularly in schools, which are highly vulnerable to seismic activity due to their brittle nature and lack of ductile load paths (D'Ayala & Speranza, 2003). The earthquakes of 1780 and 2012 near Tabriz highlight the urgent need for effective retrofitting strategies (Sarabi, Norouzian & Karimimansoob, 2023). In Tabriz, a city renowned for its rich architectural heritage and historical masonry structures, seismic retrofitting has become a focal point due to the region's susceptibility to earthquakes. The addition of diagonal cross bracing and the strengthening of concrete elements have been shown to enhance structural performance under seismic conditions, particularly for beam-column joints (Vatandoost & Nateghi, 2019).

Despite significant progress, several challenges hinder the widespread implementation of retrofitting programs. Limited funding hampers these initiatives, while a shortage of skilled professionals affects the quality and consistency of retrofitting work. Additionally, ensuring compliance with seismic design codes remains a significant hurdle (Yaghfoori, Miri & Yaghfoori, 2021). Although retrofitting methods show promising outcomes, challenges persist in terms of funding, community awareness, and the urgent need to address existing vulnerabilities.

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Despite significant progress, several challenges hinder the widespread implementation of retrofitting programs. Limited funding hampers these initiatives, while a shortage of skilled professionals impacts the quality and consistency of retrofitting work. Additionally, ensuring compliance with seismic design codes remains a substantial obstacle (Yaghfoori, Miri & Yaghfoori, 2021). Although retrofitting methods demonstrate promising outcomes, challenges persist regarding funding, community awareness, and the urgent need to address existing vulnerabilities.

2 MATERIALS AND METHODS

The methodology incorporates field inspections, analytical modeling, and experimental testing of a representative unreinforced masonry (URM) school building retrofitted with external cable bracing. Displacement-based seismic analysis (DBA) was employed to establish performance objectives and assess structural enhancements (Iravani & Dehghan,2022). Nonlinear time-history analysis was conducted using SAP2000. Field measurements were collected from the Tabriz region utilizing accelerometers and strain gauges.

A full-scale wall segment retrofitted with external cable bracing was subjected to quasi-static cyclic lateral loading. Instruments measured horizontal displacement and wall rotation. A comparison between the retrofitted and control walls demonstrated a 40–60% reduction in lateral displacement, along with increased ductility.

2.1 Seismic Retrofitting Techniques

Seismic retrofitting techniques aim to improve the seismic performance of structures, particularly unreinforced masonry (URM) buildings, which are especially susceptible to earthquake-induced damage. These techniques are designed to provide additional strength and stability, enabling buildings to better withstand seismic forces. Common retrofitting techniques include:

Base Isolation: Base isolation involves the installation of isolation bearings or seismic isolation systems at the base of a building. This technique separates the structure from ground motion, effectively reducing the seismic energy transmitted to the building during an earthquake.

Bracing and Anchoring: Bracing techniques involve the incorporation of diagonal or vertical steel braces, as well as horizontal anchors, into walls, floors, and roofs. These components enhance the overall stability of the structure against lateral forces, significantly improving its capacity to withstand seismic loads. Various configurations of braces, including X-braces and eccentric braces, have been analyzed for their effectiveness in enhancing strength and ductility.

Concrete Shear Walls: The addition of concrete shear walls is a widely used retrofitting method for unreinforced masonry (URM) structures. These walls provide essential lateral support, which is crucial for minimizing movement and potential damage during seismic events. Their implementation can significantly enhance the overall seismic performance of the building.

Jacketing of Columns and Beams: Jacketing involves encasing existing columns and beams with additional layers of concrete or other reinforcing materials to increase their load-bearing capacity. This technique aims to enhance the strength of critical structural elements that are essential for maintaining the integrity of the building under seismic loads.

Shear Wall Infill: Filling frame bays with shear walls can also bolster a building's structural resilience. This technique involves incorporating shear walls within the existing frame, which not only increases stiffness but also helps in energy dissipation during seismic events.

This case study focuses on the implementation of external cable bracing and displacement-based analysis as effective methods for strengthening unreinforced masonry (URM) school structures in Tabriz. The integration of diagonal bracing systems has demonstrated significant improvements in structural performance, including enhanced load-carrying capacity, energy dissipation, and overall stability under seismic loads. These techniques are particularly crucial given the region's historical experiences with devastating earthquakes, which have necessitated a reevaluation of building standards and retrofitting practices. This approach emphasizes the importance of cost-effective and context-specific solutions to safeguard educational facilities and their occupants, as the analysis reveals a pressing need for comprehensive retrofitting initiatives across the city's school infrastructure.

Displacement-Based Design (DBD) evaluates structural performance by estimating the expected displacement under seismic loads, rather than focusing solely on strength. This approach is particularly suitable for unreinforced masonry (URM) buildings, where excessive displacement is a significant failure mode (Priestley, 2007). Performance objectives are established based on acceptable drift limits and damage states (Calvi et al., 2002). External cable bracing involves the installation of steel cables anchored to the foundations and the roof corners or mid-walls of the structure. These cables function in tension to restrain out-of-plane wall movements and control lateral displacements (Klingner & Abrams, 1994). The key advantages of this method include minimal disruption to building use, ease of installation, Cost-effectiveness.

For the calculation of shear and moment, the 3MURI software developed by Professor S. Lagomarsino was utilized. To determine soil stiffness (Dizaji & Aydin,2025), the CONAN program provided by Professor John P. Wolf from ETH Lausanne was employed. The displacement method was used to calculate the earthquake effects, and the building was modeled in 3D.

3 RESULTS

3.1 Unreinforced Masonry (URM):

Unreinforced masonry (URM) refers to structures constructed using masonry units—such as bricks, stones, and adobe blocks—bonded together with mortar, without any embedded reinforcement like steel bars or mesh. These structures are commonly found in residential, religious, and public buildings worldwide due to their low cost, availability of local materials, and thermal insulation properties (Drysdale et al., 1999). However, their inadequate performance during earthquakes and other dynamic loads poses significant challenges for structural engineers and policymakers. URM buildings are characterized by:

- **Brittleness**: Unreinforced masonry (URM) structures have a limited capacity for plastic deformation, rendering them susceptible to sudden collapse when subjected to stress.
- **High compressive strength, low tensile strength**: While masonry excels under compressive loads, it is prone to failure when subjected to tension or shear (Kaushik et al., 2007).
- **Material heterogeneity**: The variability in the quality of masonry units, the composition of mortar, and construction practices results in inconsistent performance.

These properties render unreinforced masonry (URM) particularly susceptible to dynamic loading conditions, such as earthquakes and high winds (Paulay & Priestley, 1992). URM buildings are among the most hazardous structures during seismic events. They inherently lack the structural integrity necessary to withstand seismic forces due to their brittle composition and the absence of reinforcement. Common failure modes observed during earthquakes include:

Out-of-plane wall failures: Walls collapsing perpendicular to their plane due to insufficient anchorage.

- **In-plane shear failures:** Cracking and sliding happen along mortar joints due to lateral loads.

- **Connection failures:** Separation between walls, roofs, or floors can lead to partial or total collapse.

These vulnerabilities have been observed in previous seismic events, highlighting the necessity for targeted retrofitting strategies. In response to the identified risks, Iran has initiated extensive retrofitting programs designed to enhance the seismic resilience of unreinforced masonry (URM) school buildings. Key measures include:

- **Structural reinforcement:** Incorporating steel frames, reinforced concrete elements, or fiber-reinforced polymers to enhance load-bearing capacity (Iravani, & Liel, 2021).
- **Wall anchorage:** Installing ties and anchors to secure walls to floors and roofs.
- **Foundation strengthening:** Enhancing the connection between the building and its foundation to prevent sliding or overturning (Dizaji, 2024).

These interventions have been implemented in numerous schools, yielding varying degrees of success (Abrams, et al. 2015). To mitigate the seismic risk associated with unreinforced masonry (URM) structures, several strategies have been developed.

- **Steel ties and anchors** for connecting walls and floors.
- **Shotcrete overlays** for Enhanced Strength and Stiffness
- **Fiber-reinforced polymer (FRP) wrapping** to Enhance Ductility
- **Infill walls and bracing** to improve lateral load resistance
- **Reinforced concrete jacketing**
- **Steel bracing systems**
- **Base isolation**

Building codes, such as the International Existing Building Code (IEBC), and guidelines like FEMA 547 (2006) provide frameworks for retrofitting. However, these methods can be cost-prohibitive or intrusive in school environments. External cable bracing offers a low-cost, non-invasive, and reversible alternative (Inel et al., 2008). This method typically involves the application of various techniques to enhance the load-carrying capacity, energy dissipation, and overall ductility of buildings without the necessity for complete reconstruction (Maheri & Ghaffarzadeh,2008).

3.2 URM Schools

While comprehensive global statistics are lacking, regional data indicate that a substantial number of schools constructed from adobe or unreinforced brick remain in use, particularly in areas with limited resources. Given their vulnerability to seismic events, it is crucial for authorities to assess these structures and implement necessary safety measures to protect students and staff. Approximately 400,000 classrooms are constructed using unreinforced clay-unit masonry. Many of these structures are single-story buildings located in regions with high seismicity. Notably, two-thirds of these schools were built before the implementation of seismic design requirements, rendering them particularly susceptible to earthquake damage (Abrams, et al. 2015). Empirical studies have been conducted to evaluate the effectiveness of retrofitting measures. For instance, a survey of school buildings in Yazd province utilized an index-based damage assessment method to derive empirical fragility curves, aiding in the prioritization of retrofitting efforts (Azizi-Bondarabadi, et al. 2016). While retrofitting initiatives have yielded positive outcomes, ongoing efforts are essential to safeguard students and educational infrastructure. A concerted approach involving resource allocation, technical training, and policy enforcement is vital to enhance the seismic resilience of these critical structures (Sadeghi, et al. 2020).

3.3 Earthquakes in Tabriz/Iran

Iran is located in a seismically active region, making earthquake preparedness a critical concern. Tabriz, situated in northwestern Iran, has a long history of devastating earthquakes due to its position along the active North Tabriz Fault. Below is a chronological list of major earthquakes that have impacted the city (Melville,1981).

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Location	Zone	ag [m/s۲]
Tabriz	۱	۳,۵

Tab.1- Tabriz city's risk level against earthquakes. (up).(Iran Code 2800)

Hijra date	Christian date
—	634*
—	694*
—	746*
—	838*
244	858
249	864 January
—	868*
—	949*
411	1020*
434	1042 November 4
671	1273 January 18
704	1304 November 7
746	1345
—	1441*
863	1459
908	1503
—	1522, 1527*
957	1550
1050	1641 February 5
1060	1650*
—	1657*
1074	1664
—	1717 March 12
—	1720
1133	1721 April 26
1139	1727*
1193–4	1780 January 7–8
1201	1786

Tab.2- Major earthquakes in Tabriz city. (Left) (Melville,1981).

4 DISCUSSION

The analysis conducted on the seismic retrofitting of unreinforced masonry school structures utilizing external cable bracing has yielded significant findings regarding the effectiveness of different bracing systems in enhancing structural performance during seismic events. The study focused on various parameters, including lateral displacement, storey drift, axial forces in columns, and base shear, which are critical for evaluating the seismic resilience of buildings.

4.1 Current condition of the building

Location	Soil Type	Soil Class
Tabriz	Silt, Sand and Moraine	II

Tab.3 Characteristics and composition of Tabriz soil

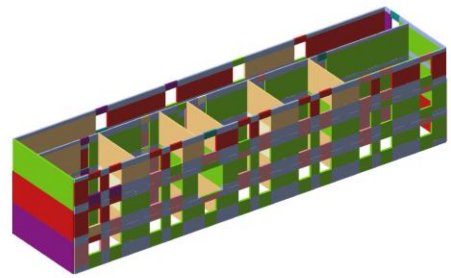
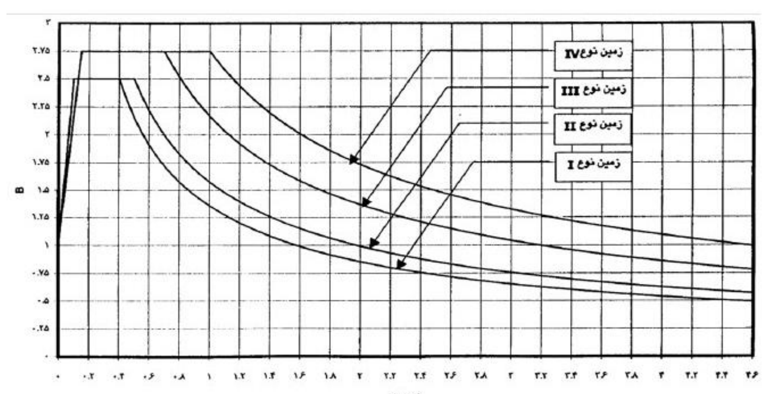


Fig.1- 3D model of the school under study

The perimeter brick walls contain numerous openings that compromise the building's structural integrity during an earthquake, resulting in insufficient resistance.
Since the plan of all three floors is similar, the load path remains continuous.
Compared to the transverse direction, the building's capacity in the longitudinal direction is significantly greater.
The perimeter facade and central brick walls transfer earthquake loads from the upper floor to the foundation.
The building plan is consistent on every floor, resulting in a continuous load path throughout the structure.
Compared to the longitudinal direction, the building's capacity in the transverse direction is significantly lower.
The compressive strength of the brick was 10 N/mm², while the compressive strength of the mortar was 1.1 N/mm² in the tests.

The structural standards utilized in this research are:

- Iran Code 2800
- Norm SIA 261 2003
- Norm SIA 262 2003
- Norm SIA 266 2003
- Merkblatt 2018 2004
- Euro Code 8 EC 8



Tab.4 Response spectrum (Iran Code 2800)

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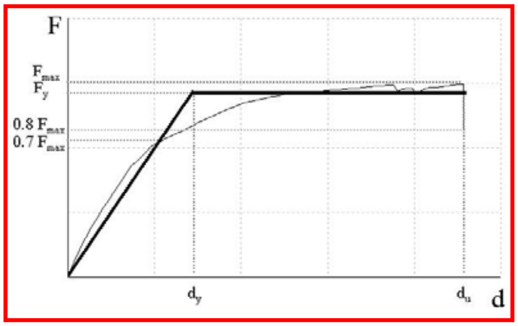
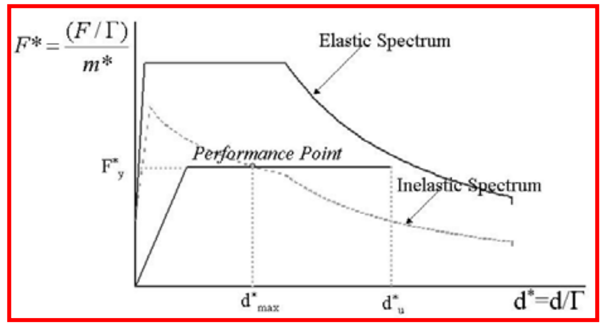
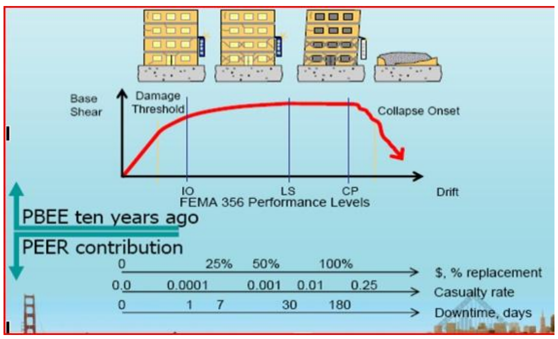


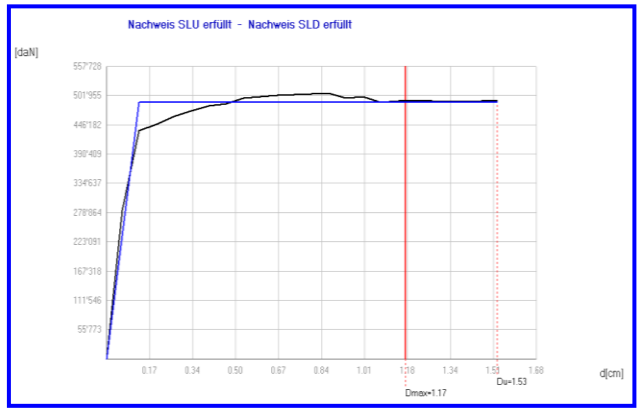
Tab.5- Push-Over diagram



Tab.6- Performance Point Determination



Tab.7-Displacement function for damage degree determination



Tab.8- Push-Over diagram

The behavior of the building and the seismic loads are represented by a force-displacement diagram

The design spectrum values can be obtained by reducing the elastic spectrum values by the ductility q factor.

According to Euro Code8(EC8) and Swiss Code SIA 262, the structure is able to dissipate seismic forces through ductility. This is defined by q factor.

Seismic force direction	*q Factor*
X	**1/5q_x =**
Y	**1/5q_y =**

Tab.9- The coefficients of the q factor

Soil-Structure Interaction:

$$\bar{s} = \frac{\omega_s h}{c_s}$$

$$\bar{h} = \frac{h}{a}$$

$$\overline{m} = \frac{m}{\rho a^3}$$

$$\frac{\widetilde{\omega}^2}{\omega_s^2} = \frac{1}{1 + \frac{\overline{m}\overline{s}^2}{8}\left[\frac{2-\nu}{\overline{h}^2} + 3(1-\nu)\right]}$$

$$\widetilde{\zeta} = \frac{\widetilde{\omega}^2}{\omega_s^2}\zeta + \left(1 - \frac{\widetilde{\omega}^2}{\widetilde{\omega}_s^2}\right)\zeta_g + \frac{\widetilde{\omega}^3}{\omega_s^3}\frac{\overline{s}^3\overline{m}}{\overline{h}}\left[0.036\frac{2-\nu}{\overline{h}^2} + 0.028(1-\nu)\right]$$

$$\eta = \sqrt{\frac{1}{0{,}5 + 10\xi}} \geq 0.55$$

$h = 6.7$ Meter

$c_s = 600$ M/Sek

$\omega_s = 2\pi\left(\frac{1}{0.3}\right) = 21$

$\overline{s} = \frac{21 \cdot 6.7}{600} = 0.23$

$a = 12$ Meter

$\overline{h} = \frac{6.7}{12} = 0.56$ Meter

$\rho = 1400$ Kilo/M ^{3}

$m = 1974$ (ton)

$\overline{m} = \frac{1974000}{1400 \cdot 10^3} = 1.4$

$$\frac{\widetilde{\omega}^2}{\omega_s^2} = \frac{1}{1 + \frac{1.4 \cdot 0.23^2}{8}\left[\frac{2-0.25}{0.56^2} + 3(1-0.25)\right]} = 0.93$$

$\widetilde{\omega}^2 = 0.93 \cdot 21^2 = 410$

$$\widetilde{\zeta} = 0.93 \cdot 0.05 + (1-0.93) \cdot 0.05 + \frac{20.2^3}{21^3} \cdot \frac{0.23^3 \cdot 1.4}{0.56} \cdot \left[0.036 \cdot \frac{2-0.25}{0.56^2} + 0.028(1-0.25)\right] = 0.056$$

$\left(2\pi \cdot \widetilde{f}\right)^2 = 410$

$\widetilde{f} = 3.22$

$\widetilde{T} = 0.31$

$T = 0.3$

Reduction due to soil and structure interaction: 8%

Gravity and Earthquake Load Case:

This building is located in a very high seismic hazard area with a significance factor of 2.1 and the soil is classified as type II (Iranian Standard 2800).

$T_B = 0.15 \quad (s)$

$T_C = 0.5 \quad (s)$

$T_D = 3.6 \quad (s)$

For the region with the highest seismic risk in Iran, the horizontal acceleration is = 3.5 m/. Initially, the elastic spectral acceleration was determined using the 2800 standard (Tab 5). The period of the structure can be calculated as follows:

$T_1 = C_t h^{0.75}$

$C_t = 0.05$

$T_1 = 0.05(9.6)^{0.75} = 0.3\, sec$

Or:

$f_1 = 10/\mathrm{n}$

n = Number of floors

$f_1 = \frac{10}{3} = 3.3$ Hz

$T_1 = 0.3\,(S)$

Spectral acceleration is calculated as follows:

$0.15 \leq \mathrm{T} = 0.3 \leq 0.5$

$S_e = a_{gd}\ 2.75\ S\ n$

By assuming 5% damping, a spectral acceleration value of $S^e = 9.6$ is obtained.

S_{ey} *(Longitudinal)*	S_{ex} *Transverse*	T_D	T_C	T_B	S	a_g (m/s^2)
9/6	9/6	3/6	0/5	0/15	1	3/5

Tab.10- Elastic spectral values Sey and Sex in [m/s²]

For the calculation of design values, $0.15 \leq \mathrm{T} = 0.3 \leq 0.5$ we obtain:

$$S_d = 2.75\,\mathrm{I}\,\frac{a_{gd}}{g}\,\frac{S}{q}\cdot\left(T_B \le T \le T_C\right)$$

For an importance factor of **I = 1.2**
Assuming a non-ductile behavior, with **q = 1.5**
We have: $S_d = 7.7$

S_{dy} *(Longitudinal)*	S_{dx} *(transverse)*	T_D	T_C	T_B	S	a_g (m/s2)
7/7	7/7	3/6	0/5	0/15	1	3/5

Tab.11- Design values for accelerations S_{dx} and S_{dy}

Accordingly, the seismic load corresponds to **77%** of the building weight
Therefore, the total base shear force F_d is calculated as follows:

F_d *[kN]*	S_d	M *[t]*	*Direction*
15160	7/7	1974	Transverse
15160	7/7	1974	Longitudinal

Tab.12- Total base shear in [kN]

In the above calculation, the equivalent static load has been used, which results in very conservative design values.
In the **displacement-based method**, the nonlinear energy dissipation capacity of the structure is utilized, which yields much more realistic values. Therefore, the displacement-based method will be used in the design.

Seismic Modeling

To simulate the earthquake, the **displacement-based design method** based on the research by **Prof. M. J. N. Priestley** and **Prof. G. M. Calvi**, titled *Displacement-Based Design*, third edition, published by **Istituto Universitario di Studi Superiori** in Pavia, Italy, was employed.

Displacement-Based Method

In this method, the **standard response spectrum** of **Iran's Code 2800** was used with the following parameters:

- **Seismic hazard level**: Very High
- **Importance factor**: I = 1.2
- **Soil class**: II

The following load case was evaluated:
Gravity + Earthquake
Out-of-Plane Calculations:

The **slenderness ratio** based on **Eurocode** is expressed as:

Seismic hazard of the area	*Building class*
≤ ***17***	Upper Floor
≤ ***18***	First floor
≤ **17**	Other floors

Tab.13- Seismic hazard of the classes

In this building, the slenderness ratio on the first floor is:
960 / 50 = 19
Since this value is greater than 18, the standard requirement is **not satisfied**.
Existing Building Requirements According to SIA 2018 and EC8, Based on the Displacement-Based Method
The **damage-to-capacity ratio** α_{eff} is defined as:

Displacement Method: $\alpha_{eff} = \frac{D_R}{D_{\max}}$

- D_R = Computed displacement for overturning
- $D_{\max}$ = Required displacement according to standards (performance point)

According to **EC8** and **Swiss standards**, the **confidence factor** $\boldsymbol{\alpha_{eff}}$ must be greater than **1**.

5 CONCLUSION

In **Table 8**, building damage is shown as a function of displacement.

- At **small displacements**, the building behaves elastically or with minor cracks (**IO** - Immediate Occupancy).
- At **larger displacements**, wider cracks develop (**LS** - Life Safety).
- At **very large displacements**, the entire building behaves in a cracked manner (**CP** - Collapse Prevention).

In **Figure 2**, the **pushover curve** of the Tabriz school building is shown.

- The **red line** represents displacement
- The **blue line** represents capacity

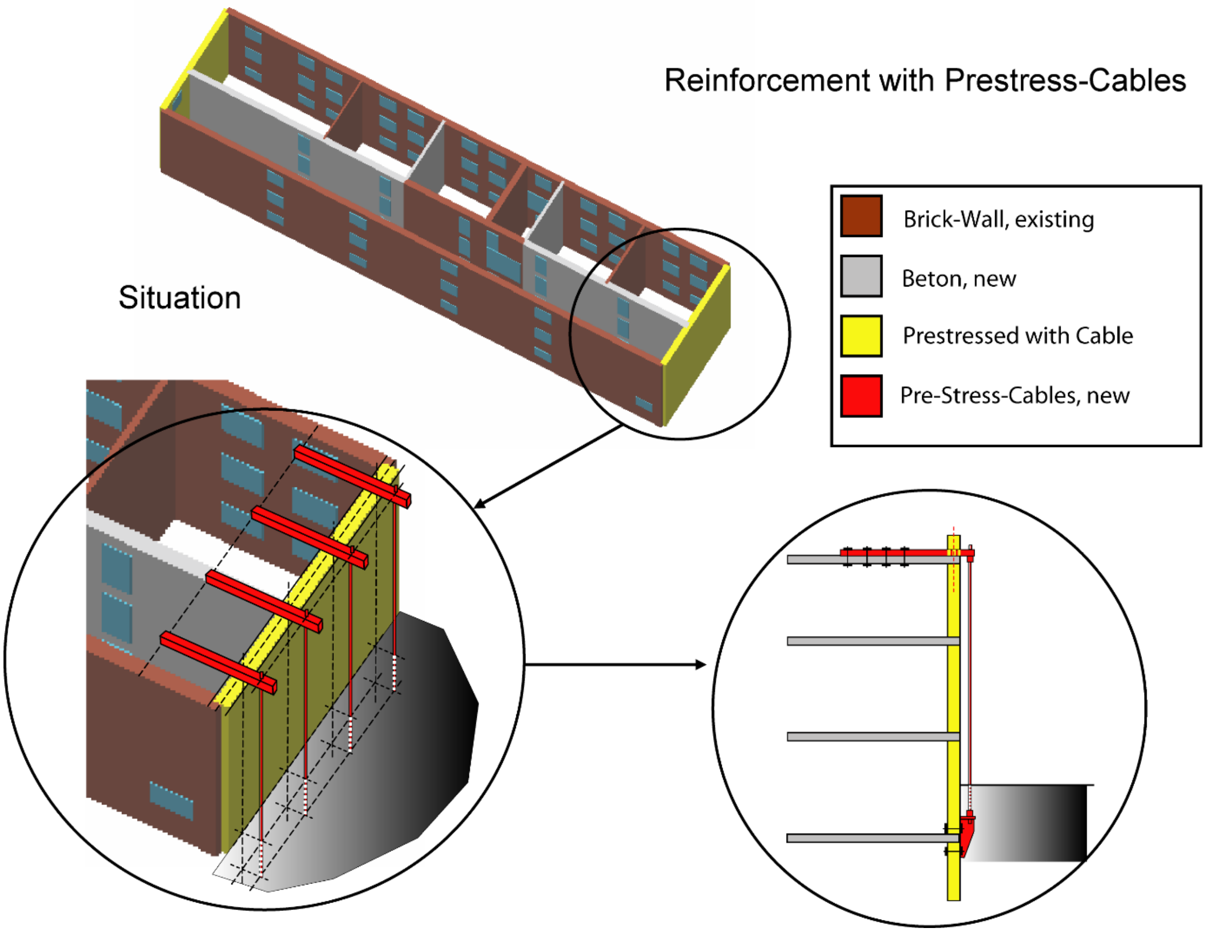


Fig.2- 3D model of the Islamic Revolution School, Tabriz, retrofitting with prestressed cables

The **confidence factor α_eff** is calculated as the **ratio of displacement capacity to the required displacement**.

The confidence factor has been obtained as follows:

Location	*Direction*	***Confidence Factor***
Tabriz	Latitude	1/1
Tabriz	Longitude	1/3

Tab.14- The obtained confidence factor

In the moment and shear calculations, the displacement-based method has been employed. Lateral loads are resisted by a combination of newly added shear walls and existing masonry walls in a composite model.

The location of the shear walls is shown in Figure 9.

In addition to the shear walls, the perimeter walls in the transverse direction have been externally post-tensioned using cables (Figure 9).

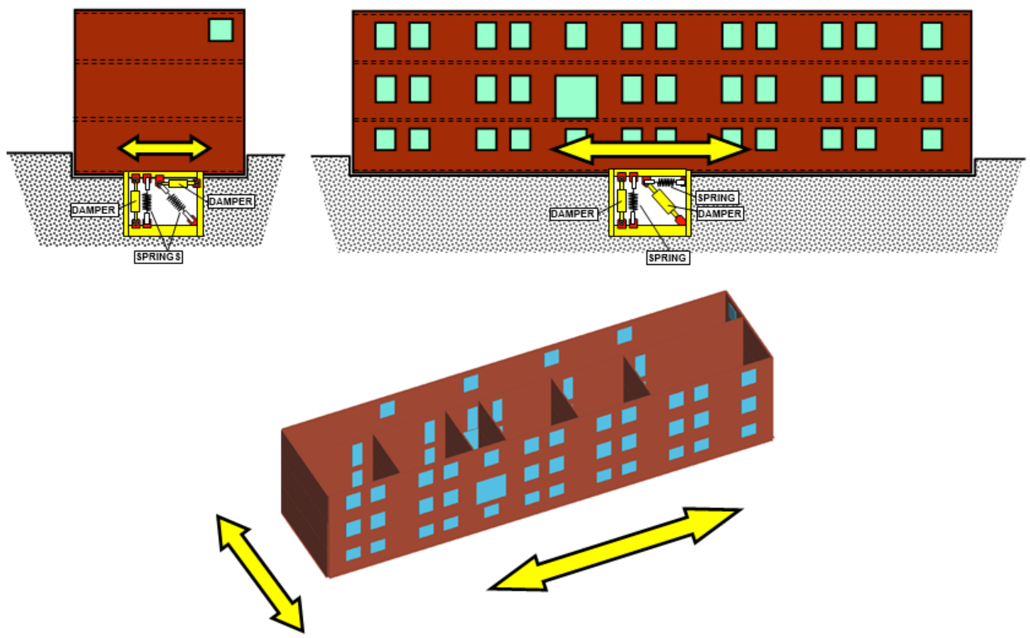


Fig.3- Soil modeled by springs and dampers of the Islamic Revolution School, Tabriz,

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