SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I8P121

Volume 13 Issue 8, 342-361, August 2026

Original Article

Seismic Vulnerability of Waffle Slab Systems: Nonlinear Dynamic Assessment and Development of a Slab Seismic Fragility Index (SSFI)

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Received: 14 May 2026 Revised: 16 July 2026 Accepted: 27 July 2026 Published: 31 August 2026

Abstract *- Waffle slabs are widely used in modern construction because they can span large distances while reducing material consumption and overall structural weight. Despite these advantages, their relatively low lateral stiffness can become a major source of seismic vulnerability, especially when simplified assumptions such as the rigid diaphragm model are adopted in structural analysis. This study examines the seismic response of waffle slab systems, with particular attention to the influence of diaphragm flexibility on displacement amplification and damage concentration around slab–column connections. The findings indicate that inadequate in-plane stiffness can generate excessive interstory drift, dynamic amplification effects, and progressive deterioration of slab–column interfaces, ultimately reducing the overall seismic performance of the structure. The research combines previous literature, post-earthquake observations, and advanced numerical simulations to identify the main mechanisms responsible for seismic vulnerability in waffle slab structures. Reported damage patterns include extensive cracking, formation of plastic hinges, bond degradation, and progressive punching shear failure, which in severe cases may result in partial or complete collapse. To better evaluate these effects, an advanced numerical framework is proposed to assess the seismic capacity of waffle slabs and investigate the causes of their reduced lateral stiffness. In addition, a Seismic Fragility Index for Slabs (SSFI) is introduced to quantify vulnerability and classify waffle slab systems according to regional seismic hazard levels. The adopted methodology integrates modal analysis, nonlinear static (pushover) analysis, and nonlinear time-history simulations. A comparison between rigid and flexible diaphragm models highlights the significant influence of slab flexibility on both the overall seismic response and the distribution of structural damage. The findings show that adopting the rigid diaphragm assumption can substantially underestimate displacement demands and overlook critical failure mechanisms, resulting in unconservative seismic evaluations and an increased probability of structural failure.*

Keywords *- Waffle slabs, Seismic performance, Diaphragm flexibility, Lateral drift, Punching shear, Nonlinear analysis, Structural vulnerability, Stiffness degradation, Energy dissipation.*

1. Introduction

Floor systems are important components in determining the seismic response of buildings since they convey gravity loads and engage with vertical structural elements to transfer lateral forces. Today, there are different systems of slabs. The most favourable and also widely used slab system is waffle slabs, which decrease total weight of whole structure by allowing large spans with lesser material consumption. The latter provides greater freedom for architecture and space planning in residential, commercial and public buildings with their beamless configuration that is another reason for their widespread use [1, 2, 7]. Waffle slabs perform very well under gravity loads, but their seismic response remains unclear. In earthquake conditions, their relatively flexible behavior may produce larger floor displacements and higher inter-story drifts than expected. This can affect the overall response of the building, especially in structures where lateral stiffness is already limited. In many cases, the most vulnerable areas are located around slab-column connections, where stress concentration can progressively damage the concrete and eventually trigger brittle mechanisms such as punching shear or local diaphragm failure [1-5, 15, 18, 22].

In earthquake design, floor slabs are usually assumed to act as rigid diaphragms. For waffle slabs, however, this simplification can be misleading because their structural behavior is influenced by their ribbed geometry and relatively low in-plane stiffness. Studies carried out over the last few years have shown that slab flexibility may increase horizontal displacements and inter-story drifts, while also concentrating damage near slab-column connections [2-6, 15, 18, 22]. Despite these findings, most previous research has been limited to particular structural cases, without establishing a broader approach for evaluating the seismic vulnerability of waffle slab buildings [1-8].

Field observations following recent earthquakes have shown that buildings incorporating waffle slabs exhibit similar patterns of damage. Most noticeable are the vertical and inclined cracks that occur near the junctions of the slab and columns. Punching shear cracking was observed in many locations near these areas. Other damage includes early-onset yielding of the columns, which leads to progressive loss of stiffness of the story and eventually the entire structure. In the worse cases, it contributes to loss of diaphragm continuity and ultimately, collapse of part or the entire building [9-12, 15, 16].

Waffle slab systems under dynamic loading behave differently from the assumptions often used in conventional design codes; therefore, engineers need to evaluate these systems with more realistic seismic analyses [2-8, 18-21].

Although some studies have investigated the seismic behavior of waffle slabs, their overall seismic vulnerability is still not fully understood. To bridge this gap, the present study aims to describe the cracking behavior of waffle slabs, identify the physical mechanisms responsible for crack development, evaluate their intrinsic seismic vulnerability, and propose practical indicators for earthquake-resistant design and seismic assessment [1-8, 13, 14].

This study is based on the hypothesis that the slabs' ability to deform in-plane, governed by their horizontal shear stiffness, dictates the amplification of seismic response under cyclic loading, the redistribution of loads across the slab, and the evolution of structural damage.

The paper's primary contribution is the formulation of a quantitative index, called the Slab Seismic Fragility Index (SSFI), to evaluate the seismic vulnerability and seismic performance of waffle slab structures for varying hazard levels. The index offers the advantage that, unlike any of the previously introduced models in the literature, it incorporates into a single value the original elastic stiffness, ultimate lateral displacement, available ductility in terms of displacements and forces, and loss of seismic performance with the increase in drift ratios (in terms of restoring forces and initial stiffness.

The methodology used in this study combines different analysis techniques to better capture the seismic behavior of waffle slab systems. Modal analysis is first employed to determine the dynamic characteristics and vibration modes of the structure. Nonlinear static (pushover) analysis is then carried out to estimate the structural capacity and identify possible yielding and collapse mechanisms. In addition, nonlinear time-history analysis is used to simulate damage progression, stiffness degradation, and the gradual development of plastic hinges during seismic loading.

This study aims to provide a more reliable analytical framework for understanding and assessing the seismic behavior of waffle slab systems. It also emphasizes the limitations of conventional design approaches, which are generally more focused on gravity-load resistance than on seismic performance. To address these limitations, the study proposes an advanced Nonlinear Time-History Analysis (NLTHA) framework adapted to waffle slab structures, together with a seismic classification approach that can be applied to regions with different seismic hazard levels.

The remainder of this paper is organized as follows. First, a review of previous studies and post-earthquake observations is presented. The numerical methodology is then described, including modal analysis, nonlinear static (pushover) analysis, nonlinear dynamic time-history analysis, and the formulation of the proposed Slab Seismic Fragility Index (SSFI). The following sections present and discuss the obtained results. Finally, the paper concludes with the main findings and their implications for the seismic assessment and design of waffle slab systems.

2. Experimental Studies on the Seismic Behavior of Waffle Slab Systems

Experimental studies carried out in recent years have pointed out the seismic vulnerability of structures using waffle slab systems. This vulnerability is mainly related to their relatively low lateral stiffness and flexible diaphragm behavior, which may amplify structural displacements during earthquakes. From a structural point of view, three main factors appear to control this behavior: the reduction in global stiffness leading to longer vibration periods, the limited capacity for energy dissipation when stable ductile mechanisms are not fully developed, and the concentration of stresses around slab–column connections, especially in relation to punching shear. Both experimental and analytical investigations indicate that these characteristics can significantly increase the seismic sensitivity of waffle slab systems when subjected to strong ground motions.

2.1. Early Experimental Investigations and Evidence of Seismic Vulnerability

The experimental work conducted by Rodríguez, Santiago, and Meli (1995) represents one of the earliest and most influential references regarding the seismic performance of Waffle Flat-Plate (WFP) structural systems [1]. In their study, the authors subjected a two-story structural model to cyclic loading intended to simulate the effects of a severe earthquake, with the objective of characterizing the lateral response and the progression of structural damage. A key conclusion of this investigation is that such structural systems may exhibit relatively large lateral displacements and limited energy dissipation capacity when compared with structural systems specifically designed to ensure ductile behavior. This study played an important role in highlighting the need to explicitly consider inter-story drift demands and local degradation mechanisms at slab–column connections when evaluating the seismic safety of waffle slab structures.

A complementary line of investigation focuses on the vulnerability of older Waffle Flat-Plate (WFP) buildings that were designed without strict seismic design provisions. In this context, Goñi (WCEE, 2008) discussed the seismic vulnerability of existing waffle–flat plate structural typologies, emphasizing that their seismic performance may be governed by insufficient lateral stiffness and by design details that are not compatible with cyclic structural behavior. This perspective is particularly relevant for the seismic assessment of existing building stocks, as it demonstrates that structural risk is not solely associated with strength capacity but is often controlled by displacement demand and the absence of reliable energy dissipation mechanisms [7].

2.2. Punching Shear Failure in Waffle Slab Systems: Critical Mechanisms and Experimental Evidence

In addition to global lateral stiffness and energy dissipation, the seismic performance of Waffle Flat-Plate (WFP) structures is strongly influenced by the punching shear behavior at slab–column connections. Under cyclic seismic loading, repeated plastic rotations can progressively damage the concrete around the connection zone, increasing the risk of brittle punching failure and, in some cases, progressive collapse. Experimental work by showed that punching failure may occur suddenly once the shear demand exceeds the connection resistance, often without significant prior flexural yielding. Later studies by also reported that cyclic loading reduces punching shear capacity compared with monotonic loading, with noticeable strength degradation appearing at drift ratios of about 1.5% to 2.0%, values that can easily be reached in WFP structures during moderate or strong earthquakes.

More recent work by showed that many existing waffle flat-plate buildings do not contain enough punching shear reinforcement [14]. Their study also revealed that local punching failures may appear even when the global lateral response of the structure remains relatively moderate. Similar damage was later observed after earthquakes such as Mexico (1985), Lorca (2011), and Kahramanmaraş (2023), where slab–column connection failures contributed to severe structural deterioration. These observations clearly show that punching shear effects should be directly considered in seismic assessment. In general, previous studies suggest that the seismic performance of waffle slab systems should be evaluated through both global and local behavior. Parameters such as stiffness, drift, and energy dissipation are important, but they are not sufficient on their own. The local response of slab–column connections, especially punching resistance and cyclic degradation, must also be included in the assessment. This idea forms the basis of the enhanced Slab Seismic Fragility Index (SSFI) proposed in this study.

2.3. Shake Table Experiments: Lateral Flexibility and Drift Demand

Shake table testing represents a particularly reliable experimental approach for investigating the global dynamic response of structural systems subjected to realistic seismic records. Benavent-Climent (2016) conducted shake table experiments on a reduced-scale Waffle Flat-Plate (WFP) structure designed according to modern engineering practice [2]. The experimental protocol consisted of a sequence of earthquake simulations with progressively increasing intensity, allowing the progressive degradation of the structural system to be observed. The results show that, even though the structure satisfied current design requirements, it still exhibited a relatively flexible behavior, resulting in significant inter-story drift demands during seismic loading. The study also demonstrates that seismic vulnerability is largely controlled by the lateral stiffness of the structure and by its capacity to limit and redistribute displacement demands effectively.

2.4. Energy-based Perspective: Limited Energy Dissipation and Damage Accumulation

Beyond displacement-based observations, several recent studies have focused on an energy-based interpretation of seismic behavior. Benavent-Climent, Galé-Lamuela, and Donaire-Ávila (2019) experimentally investigated the energy capacity and seismic performance of Waffle Flat-Plate (WFP) structures subjected to simultaneous bidirectional horizontal excitations [3]. Their results indicate that bidirectional seismic loading significantly increases the global demand and may intensify structural damage, as the system is required to dissipate a larger amount of input energy without possessing a stable and efficient energy dissipation mechanism. This study provides important evidence that purely unidirectional assessments may underestimate the actual seismic vulnerability of WFP structural systems.

Following the same line of investigation, Donaire-Ávila, and Galé-Lamuela (2020) proposed a detailed evaluation of the energy capacity of WFP structures using numerical modeling and energy-based concepts to characterize seismic performance [5]. This shows that the flexible structure may be able to accommodate a lot of energy from an earthquake, but does not have enough capacity to dissipate the energy effectively. This will result in permanent deformation and deterioration of the structure due to the energy that cannot be absorbed. It is quite advantageous for understanding the behavior of earthquakes since it clearly links energy dissipation to structural collapse through inter-story drift.

2.5. Towards Collapse: Failure Tests and the Role of Structural Irregularities

Galé-Lamuela, Donaire-Ávila, and Benavent-Climent (2021) investigated the energy dissipation capacity of Waffle Flat-Plate (WFP) structures with irregular column layouts by conducting bidirectional shake table tests up to collapse [4].

The results provide important insights into the seismic behavior of such systems. Structural irregularity combined with limited lateral stiffness was found to significantly amplify displacement demands, while the structural system may reach collapse after progressive damage accumulation when energy dissipation capacity remains insufficient.

This study reinforces the idea that seismic vulnerability is not governed solely by local structural properties, but also by the global configuration and the distribution of stiffness within the structural system. In a subsequent contribution, Benavent-Climent (2025) performed bidirectional near-fault shake table tests up to ultimate limit states. Near-fault ground motions are known to generate particularly severe displacement demands on structural systems [8].

The experimental results confirm that WFP structures may experience significant drift demands and rapid structural degradation when adequate lateral stiffness and energy dissipation mechanisms are not available. The current paper brings the discussion to bear on the subject of extreme but realistic seismic events, which are crucial for assessing the adequacy of the system's safety and robustness. To conclude, both the existing experimental data and energy-based considerations lead to one and the same result: WFP structural systems show substantial deformability, which is not always considered in global seismic modeling. As a result, their seismic vulnerability is largely governed by the combined effects of:

- Relatively low lateral stiffness;
- Limited energy dissipation capacity;
- High displacement demands, particularly under Bidirectional seismic excitation.

These factors result in increased demands for drift between stories, leading to degradation in stiffness and causing failure modes such as "pancake-type" collapse in extreme cases. In terms of practical solutions to deal with these issues, some of the approaches that can be followed include:

a) Revisiting the assumption regarding the rigid diaphragm hypothesis;
b) Stiffening the building structure by the addition of shear walls or rigid cores;
c) Using hysteretic or viscoelastic damping devices; and
d) Strengthening of critical slab-column connections.

2.6. Recent Advances in the Seismic Assessment of Ribbed and Waffle Slab Systems

Recent studies have further highlighted the importance of considering the in-plane flexibility of ribbed and waffle slab systems in seismic analysis. Baldassi et al. (2024) demonstrated that the in-plane deformability of reinforced concrete floor diaphragms may significantly influence the lateral response of buildings, particularly in structures incorporating waffle slab systems [22]. Their work emphasized that conventional rigid diaphragm assumptions may not always provide an accurate representation of the actual seismic behaviour, especially for buildings with flexible floor systems.

More recently, Kırtel and Çelebi (2025) investigated the seismic performance of reinforced concrete buildings with ribbed slab systems following the 2023 Kahramanmaraş earthquakes [15]. Their findings showed that buildings with ribbed slabs may experience increased lateral displacements and greater seismic vulnerability due to their relatively low in-plane stiffness. The authors recommended that these structural systems should be evaluated using more realistic nonlinear seismic analyses instead of relying solely on conventional design assumptions.

The studies reviewed consistently demonstrate that the seismic vulnerability of waffle slab (WFS) systems is closely related to their structural configuration and dynamic response. Previous investigations have primarily focused on specific aspects of their behaviour, including slab–column connections, diaphragm flexibility, punching shear, or the seismic response of individual structural configurations. Experimental and numerical studies have shown that beamless slab systems may exhibit limited lateral stiffness and ductility, leading to increased inter-story drifts and localized damage under seismic loading.

However, these studies generally remain limited to the assessment of particular failure mechanisms or case-specific structural responses and do not provide a unified framework for quantifying the overall seismic vulnerability of waffle slab buildings. In contrast, the present study integrates nonlinear dynamic assessment with the proposed Slab Seismic Fragility Index (SSFI), providing a practical and quantitative framework for evaluating the seismic performance and vulnerability of waffle slab structures under different seismic hazard levels.

3. Seismic Vulnerability of Beamless Waffle Slab Systems: Evidence from Post-Earthquake Observations

The following part focuses on the analysis of data from actual earthquake scenarios for recognizing and describing the primary modes of failure of beamless floors with special attention to two-way waffle slabs.

3.1. The Famous 1985 Mexico Earthquake

In the year 1985, Mexico City had a destructive earthquake (Mw ≈ 8.0–8.1), a lot of reinforced concrete building was damages. One of the causes is the effects of the soft soils of the Valley of Mexico, which amplified intensitie. Structures that have comparatively lower lateral stiffness, especially those with long natural periods, were significantly affected.

Field observations after the earthquake showed that several damaged or collapsed buildings used waffle slab or flat-plate systems. In many of these structures, failures developed around slab–column connections because of insufficient punching shear resistance [9-12].

With the onset of local failure, mechanisms for progressive collapse would propagate quickly through the structure. Such findings played an very important role in the development of earthquake design codes and provided insights into the seismic deficiencies of beamless floors.

Fig. 1 Progressive collapse of a reinforced concrete waffle slab building (1985 Mexico earthquake.)

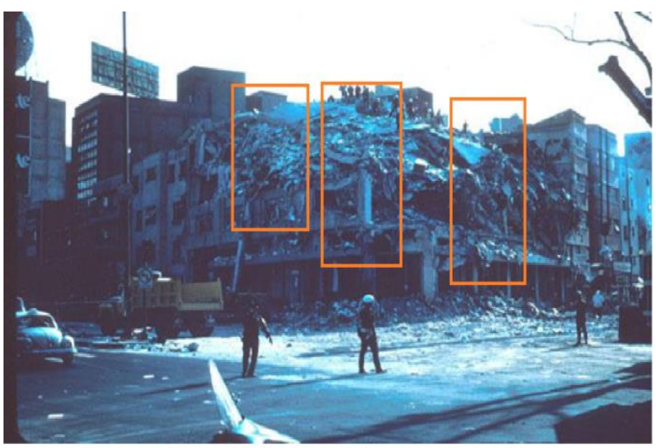


Fig. 2 Seismic punching shear failure at a slab-column connection following the 1985 Mexico earthquake

A lot of the collapsed buildings were constructed using this structural configuration.These illustrations highlight the characteristic vulnerability modes of beamless floor systems observed in the field, including in relatively low-rise buildings. The identified failure mechanisms are primarily governed by punching shear failures at slab–column connections, frequently followed by progressive collapse of the upper floors. Insufficient global lateral stiffness, the absence of effective energy dissipation mechanisms, and the lack of adequate lateral load-resisting systems played a decisive role in the initiation and propagation of these structural failures.

3.2. Evidences from Spain and Other Moderate-Seismicity Events

Lorca (Spain) had a moderate earthquake that occurred on May 11, 2011 (Mw ≈ 5.1). The epicentral distance was less than 10 km away from the city, and a focal depth of about 5 km. The short source-to-site distance, despite being a moderate earthquake, caused high-frequency shaking and hence large lateral drift loads on buildings. Post-earthquake investigations revealed that buildings relying on beamless floor systems, including waffle slab structures, experienced a rapid degradation of their lateral load-resisting capacity, with damage concentrated primarily in the lower stories. Slab–column connections were identified as critical zones, confirming the sensitivity of these systems to soft-story-type mechanisms, even under moderate seismic excitation when the overall seismic design is insufficient.

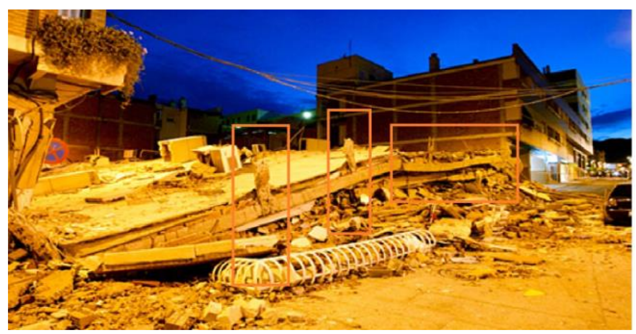


Fig. 3 Slab–column connection damage and observed in waffle slab buildings during the 2011 Lorca earthquake (Spain)

Fig. 4 Pancake-type collapse observed in waffle slab buildings during the 2011 Lorca earthquake (Spain)

3.3. The 2023 Kahramanmaraş Earthquakes (Türkiye): New Insights

The earthquakes in Kahramanmaraş, Türkiye, on February 6, 2023, were really devastating, hitting around magnitudes of 7.7 and 7.6. They caused a lot of structural damage, mainly because of their proximity to the fault line, long shaking durations, and some pretty intense vertical ground movements. Buildings that were near the fault got hit hard, experiencing huge displacement pulses and significant demands on how much they could sway between floors. This led to repeated failures in the reinforced concrete systems that lacked beams, like soft-story issues and problems with the connections between slabs and columns. Field observations further indicate that insufficient lateral load-resisting systems and pronounced second-order (P–Δ) effects significantly increased the likelihood of pancake-type collapses.

Fig. 5 Pancake-type collapse of a beamless reinforced concrete building observed after the 2023 Kahramanmaraş earthquakes (Türkiye)

The two earthquakes have shown that several reinforced concrete structures with slab-on-grade foundations were vulnerable to seismic hazards due to the use of the beamless slab-on-grade system, usually in combination with a central core frame arrangement. It has been noted that the mere use of a central core framework cannot be considered enough to guarantee proper seismic response. This problem was further compounded by the absence of perimeter shear walls and low stiffness of the slab-on-grade system [15].

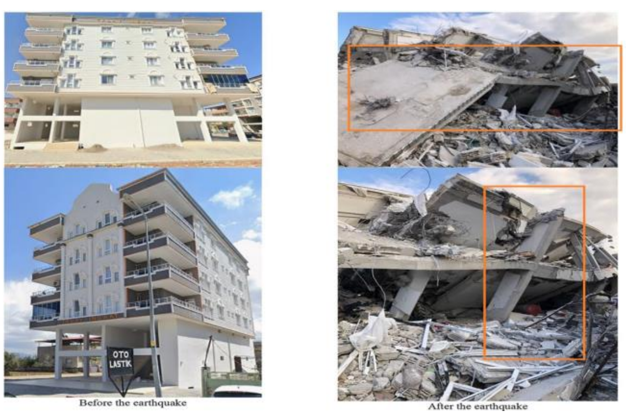


Fig. 6 Total structural collapse of a reinforced concrete beamless building with a central core observed after the 2023 Kahramanmaraş earthquakes (Türkiye)

3.4. The 1986 Kalamata Earthquake (Greece)

The September 13, 1986, earthquake in Kalamata, Greece (magnitude 6.2), illustrated that the structural deficiencies of relatively young structures using reinforced concrete beamless floor slabs could lead to seismic vulnerability. Studies showed that failure of the connection between the floor slab and columns was often the initiating point for progressive collapses, mainly owing to punching shear failure under the effects of earthquakes. It became clear that the mere presence of ribs cannot ensure seismic safety and the importance of having lateral load-carrying elements like shear walls and ductile frames [16, 17].

Fig. 7 Progressive collapse of a waffle slab-column system observed after the 1986 Kalamata earthquake (Greece)

3.5. Synthesis of Failure Modes and Partial Conclusion

It is well observed that reinforced-concrete buildings that use waffle slab flooring systems without beams have considerable vulnerability to earthquake effects. This conclusion is drawn from previous earthquake experiences in countries such as Mexico (1985), Spain and Türkiye more recently.

Structural failures frequently initiate at slab–column connections due to limited ductility and insufficient punching shear resistance. These weaknesses are often aggravated by insufficient lateral load-resisting systems and by the relatively low global lateral stiffness of such buildings, which increases fundamental periods and amplifies inter-story drift demands. Soft-story effects, vertical components of ground motion, and second-order (P–Δ) effects may further intensify damage and contribute to progressive collapse mechanisms [13, 14].

Field evidence confirms the failure mechanisms previously identified in experimental investigations and highlights the importance of rigorous seismic design. Such a design should incorporate adequate lateral load-resisting systems, localized strengthening of critical regions, and sufficient energy dissipation capacity.

These observations also call into question the rigid diaphragm assumption, which is widely adopted in structural analysis software. In structures with flexible floor systems, this simplification may lead to inaccurate predictions of seismic response and potentially severe consequences during strong earthquakes.

4. Numerical Methodology for Advanced Seismic Analysis

Based on the experimental investigations and the previously presented field observations, which clarified the fragility mechanisms associated with waffle slab systems and revealed the limitations of commonly used simplifying assumptions, advanced numerical analyses are carried out to accurately characterize their real seismic behavior. The observations further revealed that the rigid diaphragm assumption-widely adopted in modeling practices and implemented by default in many structural analysis tools-may introduce significant bias in the evaluation of the global structural response, as it neglects the actual in-plane deformability of floor systems as well as the progressive degradation mechanisms associated with severe seismic loading. This situation highlights the limitations of simplified modeling approaches for structures with beamless waffle slab systems.

Specifically, the assumption of the rigid diaphragm can result in overestimation of the slab's strength while causing a conservative evaluation of the demand on displacements and inter-story drifts, hence making the predictions unreliable and posing a greater risk of structural collapse.

In order to account for all these characteristics of the structure, a sophisticated numerical technique has to be applied, which will properly model nonlinear behavior, such as lateral flexibility, stiffness deterioration, cracking, yielding, and force redistribution. The employed analysis approach integrates three separate analyses: spectral modal analysis, which focuses on identifying the dynamic characteristics of the system; nonlinear static analysis, which is pushover analysis used to determine the strength and deformation capacity of the building; and nonlinear time-history analysis.

A comparison is performed between rigid and flexible diaphragm assumptions to assess their influence on natural periods, global displacements, and drift demands. The main objective is to determine the conditions under which the rigid diaphragm assumption becomes non-conservative and leads to an underestimation of seismic effects.

4.1. Numerical Modeling and General Assumptions

4.1.1. Calculation Assumptions and Design Standards

The design assumptions are defined in accordance with current codes to ensure consistency between numerical modeling and seismic design requirements, using ACI 318-19 for reinforced concrete design and ASCE/SEI 7 for loading definitions. The model includes self-weight, additional permanent loads (4kN/m²), and live loads (2.5KN/m²) based on residential building occupancy [19]. Seismic action is defined according to ASCE/SEI 7-22 using an elastic response spectrum characterized by key parameters such as ground acceleration, soil type (D stiff soil), Response mod factor R initial (3.0), Ss (1.0g), S1 (0.4g), importance factor (1.0), and damping ratio (5%). Load combinations follow ultimate limit state principles by combining gravity and seismic effects. For nonlinear analyses, gravity loads are applied first, and ground motions are selected and scaled to match the target response spectrum [20].

The nonlinear behavior of the structural system is simulated using concentrated plastic hinges assigned to critical regions of columns and slab elements. The modeling approach follows the guidelines of ASCE/SEI 41-17 (Seismic Evaluation and Retrofit of Existing Buildings), which provides standardized definitions for plastic hinge properties and acceptance criteria.

For reinforced concrete columns, plastic hinges are defined using the P-M2-M3 interaction hinge type, which accounts for the interaction between axial load and biaxial bending. The moment-curvature relationships are derived from fiber section analysis, considering.

For slab elements, flexural plastic hinges are assigned at the slab-column connection regions, where the highest stress concentrations occur. The hinge properties are defined based on the flexural reinforcement ratio and the slab effective width, in accordance with ASCE 41-17 provisions for flat slab systems [20].

In practice, a damping ratio of $\xi = 5\%$ is commonly adopted in linear modal analysis (as it corresponds to the reference value used for response spectra), whereas in nonlinear time history analysis, damping is generally modeled using Rayleigh damping ($C = \alpha M + \beta K$ based on the initial stiffness), calibrated to about 2% in order to avoid double counting with hysteretic energy dissipation.

4.1.2. Adopted Numerical Modeling

The structure is modeled using a three-dimensional numerical model developed in the ETABS software environment. Linear analysis is performed for modal analysis, whereas nonlinear analyses are carried out for pushover and nonlinear Time-History Analyses (THA). Nonlinear behavior is represented by assigning concentrated plastic hinges to the structural elements in order to simulate inelastic deformation under seismic loading.

This modeling approach allows for an explicit representation of the physical mechanisms governing the seismic response of waffle slab systems. The investigated structure represents a typical reinforced concrete building (G+8) commonly encountered in engineering practice, with bay spans ranging from 7 m to 8 m.

A regular structural configuration was deliberately selected to isolate the influence of the waffle slab system on the overall seismic response, without the additional effects of structural irregularities or significant torsional behaviour. The objective was to evaluate the intrinsic seismic vulnerability of waffle slab buildings under representative design conditions. Demonstrating significant seismic vulnerability in such a regular and commonly used structural configuration highlights that waffle slab systems may require particular attention in seismic design. These findings also suggest that buildings incorporating waffle slab systems with plan or vertical irregularities and significant torsional effects may exhibit an even more critical seismic response.

The structural characteristics of the investigated building are summarized in Table 1.

Table 1. Dimensions and reinforcement details

Element	Dimensions (cm)	Concrete (fck)	Longitudinal reinforcement	Transverse reinforcement
Columns	65 × 65	30 MPa	22 bars of 16 mm (Grade 60)	10 mm ties at 12 cm
Waffle slab (total depth)	30 cm	30 MPa	14 mm bars at 15 cm (top & bottom mesh)	–
Ribs	12 cm (width) × 25 cm (depth)	30 MPa	2 bars of 12 mm (top and bottom)	8 mm stirrups at 20 cm
Perimeter beam	30 × 30	30 MPa	4 bars of 14 mm (top and bottom)	8 mm stirrups at 12 cm

The dimensions and reinforcement of the structural elements are determined from static analysis and the equivalent lateral force Method -EFL, and serve as basis for dynamic analysis.

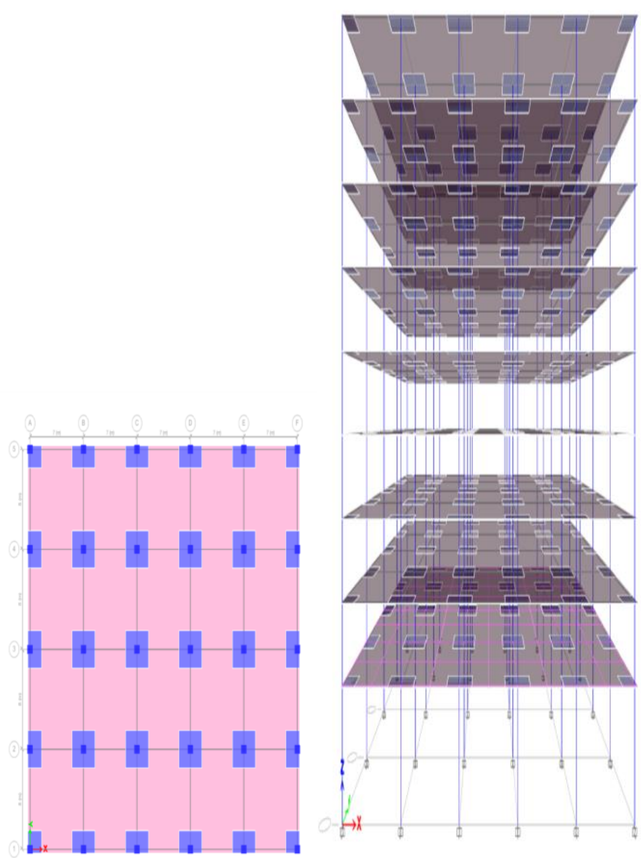


Fig. 8 Plan and elevation views of the studied structure

These dimensions are representative of common construction practices, ensuring realistic and applicable results.

The numerical model incorporates key nonlinear behaviors, including concrete cracking and crushing, plasticity in columns with confinement effects, and coupled flexure–shear response in slab–column connections to capture potential punching failure mechanisms.

Additionally, a cumulative damage model is used to simulate stiffness and strength degradation under cyclic loading.

The waffle slabs are modeled with a refined mesh to accurately represent rib geometry and stiffness, with particular focus on slab–column connections due to their critical influence on drift capacity and failure modes.

Table 2. Two analysis regimes are considered

Analysis phase	Objective
Linear elastic analysis	Determination of natural frequencies, fundamental periods, and dominant vibration modes
Nonlinear post-elastic analysis	Investigation of plasticization mechanisms, global ductility, and progressive stiffness degradation

This dual approach establishes a consistent link between the initial vibrational characteristics of the structure and the evolution of damage mechanisms under severe seismic loading, thereby enabling a performance-oriented evaluation of the studied structure.

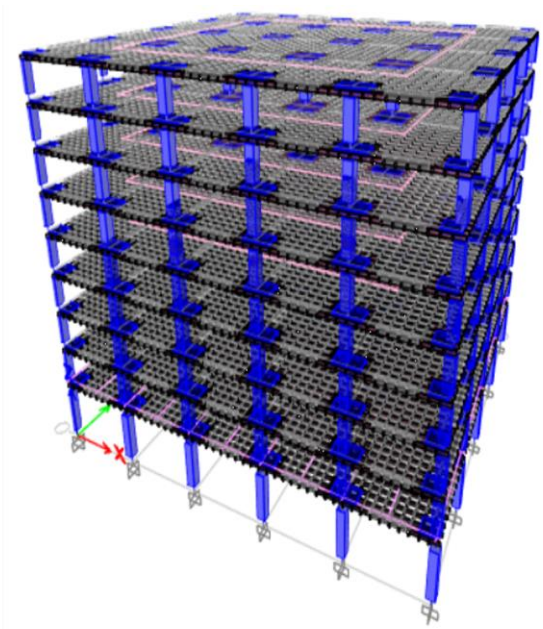


Fig. 9 Three-dimensional model and numerical discretization of the studied structure

4.2. Modal Spectral Analysis (Vibrational Characteristics)

Modal analysis is the first step used to identify the fundamental dynamic properties of waffle slab systems, including natural periods, mode shapes, and modal participation in translation and torsion. It is performed using a linear elastic 3D finite-element model in ETABS, where the structural response is obtained through modal decomposition of the equation of motion. (Linear model) :

$$M\ddot{u}(t)+C\dot{u}(t)+Ku(t)=-M\Gamma a_g(t)$$

Where M, C, and K are the global mass, damping, and stiffness matrices, respectively; u(t) is the vector of relative displacements; Γ is the influence vector; and $a_g(t)$ represents the ground acceleration. Under the assumption of linear behavior, the solution is obtained through modal decomposition by solving the eigenvalue problem:

$$(K-\omega_i^2 M)\phi_i=0$$

Which yields the natural circular frequencies $\boldsymbol{\omega_i}$ and the associated mode shapes $\boldsymbol{\varphi_i}$. The structural displacement vector can then be expressed as a linear combination of the eigenmodes:

$$u(t)=\sum_{i=1}^{n}\phi_i q_i(t)$$

This formulation leads to a series of uncoupled single-degree-of-freedom equations for each generalized coordinate $q_i(t)$:

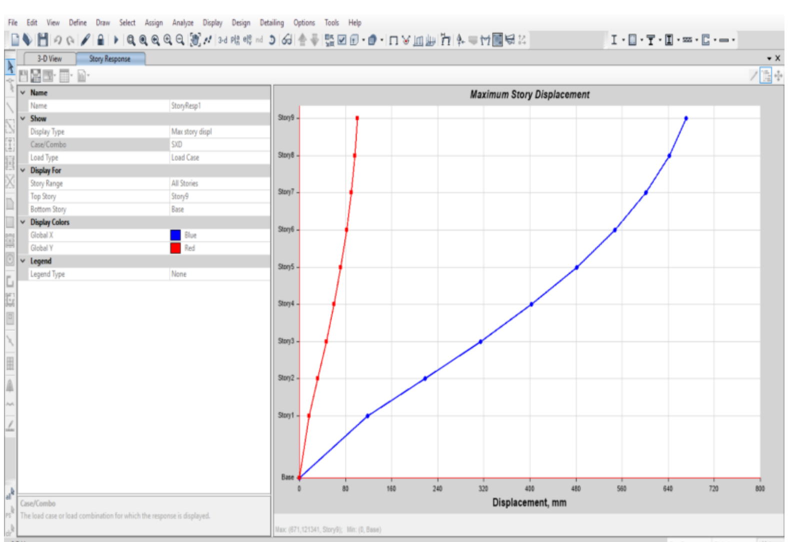
$$\ddot{q}_i(t)+2\xi_i\omega_i\dot{q}_i(t)+\omega_i^2 q_i(t)=-\Gamma_i a_g(t)$$

Where Γ_i denotes the modal participation factor. The maximum response of each mode is evaluated from the elastic response spectrum using the spectral acceleration $S_a(T_i)$ corresponding to the natural period T_i.

The modal contributions are subsequently combined using an appropriate statistical rule, such as the Square Root of the Sum of Squares (SRSS) or the Complete Quadratic Combination (CQC) method, to obtain the global structural response in terms of displacements, interstory drifts, and internal forces.

It should be noted that the modal spectral analysis implemented in ETABS is strictly linear. Structural nonlinear effects are accounted for indirectly through the use of a design response spectrum reduced by a behavior factor R (or q), in accordance with the applicable seismic design provisions.

After completing the calculations, the following results are obtained under the rigid diaphragm assumption:



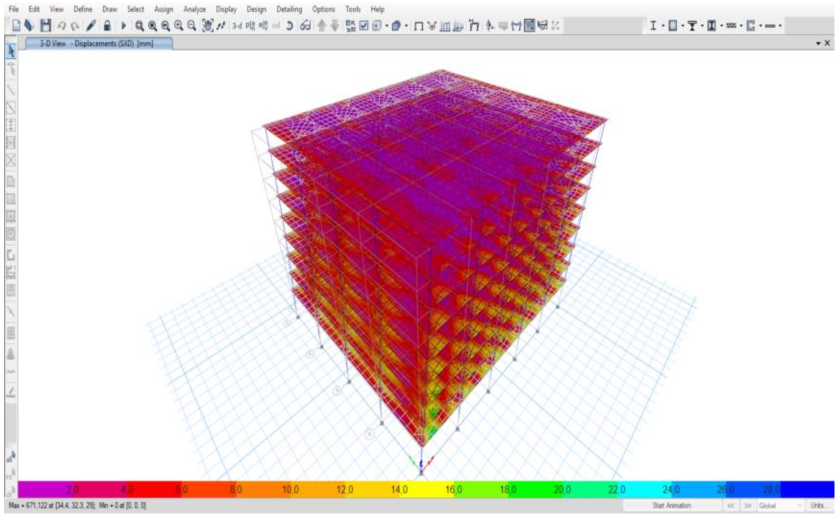


Fig. 10 Interstory drift profiles derived from modal spectral analysis assuming a rigid diaphragm & Structural displacement response obtained from modal spectral analysis under the rigid diaphragm assumption in the X direction. Dmax=685.86mm et Tmax=2.452s

After completing the calculations, the following results are obtained under the flexible diaphragm assumption:

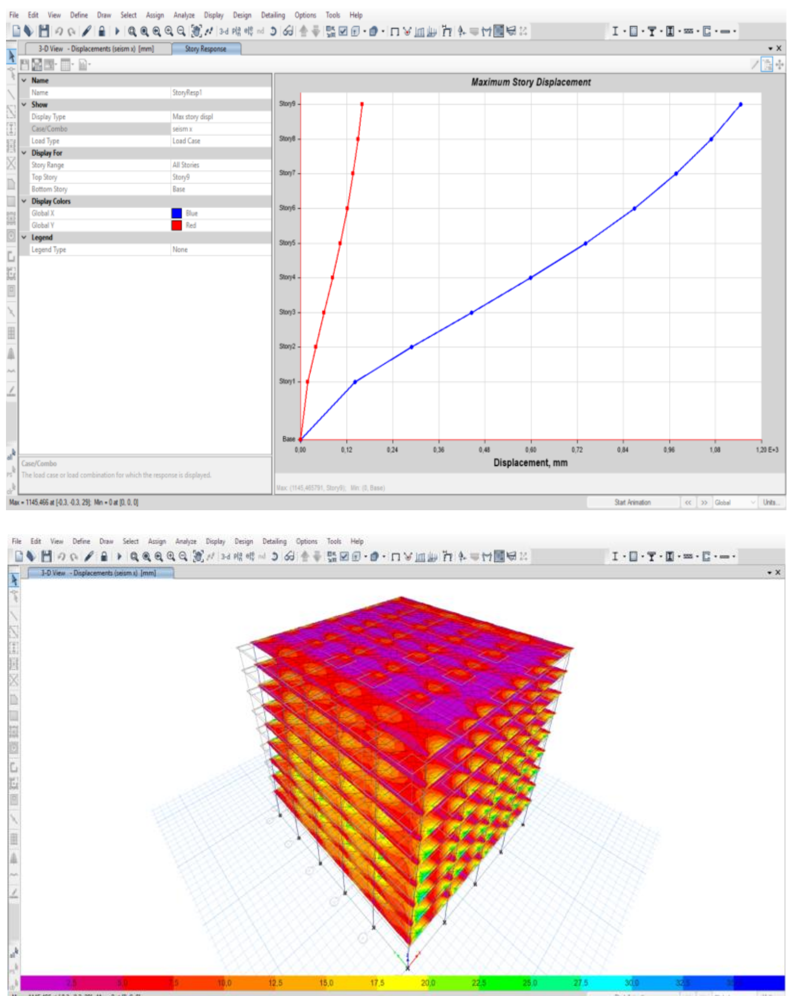


Fig. 11 Interstory drift profiles derived from modal spectral analysis assuming a flexible diaphragm & Structural displacement response obtained from modal spectral analysis under the rigid diaphragm assumption in the X directions. Dmax=1151.01mm et Tmax=4.004s

Two of the modeling assumptions-rigid and flexible diaphragm-were analyzed, revealing a strong influence on the global structural response. The flexible diaphragm significantly increases the fundamental period (from 2.45 s to 4.00 s) and nearly doubles lateral displacements (686mm to 1151mm), reflecting a reduction in effective lateral stiffness due to in-plane slab deformability.

This behavior leads to a redistribution of forces and reduced efficiency in transferring loads to vertical elements, while the rigid diaphragm assumption tends to overestimate stiffness and underestimate displacement demands.

From a seismic standpoint, the period elongation shifts the structure toward higher displacement demands in the response spectrum, increasing vulnerability to second-order (P–Δ) effects and damage, particularly at slab–column connections.

The results suggest that the structure may reach the post-elastic range, which cannot be captured by linear modal analysis. Therefore, a nonlinear pushover analysis is performed to better assess inelastic capacity and identify potential plastic mechanisms.

4.3. Nonlinear Static Pushover Analysis

For determining explicitly the inelastic capacity of the structure, as well and to analyze the progressive formation of plastic hinges, a nonlinear static pushover analysis was carried out using ETABS. In contrast to dynamic analysis, which is based on the complete equation of motion:

$$M\ddot{u}(t)+C\dot{u}(t)+Rint(u,\alpha)=Rext(t),$$

The pushover approach relies on a quasi-static assumption in which inertia and damping effects are neglected. By eliminating the dynamic terms $M\ddot{u}$ et $C\dot{u}$, the equation reduces to a nonlinear static equilibrium condition:

$$Rint(u,\alpha)=Rext.$$

Within the framework of the incremental analysis, the vector of external forces is expressed as:

$$Rext=\lambda Rpat+Rgrav,$$

Where λ denotes the load amplification factor applied to the lateral load pattern Rpat, while que Rgrav represents the gravitational loads maintained constant throughout the analysis. The nonlinearity of the problem arises from the dependence of the internal forces Rint on the displacement vector u and on the internal state variables α (plasticity, stiffness degradation, and geometric effects).

The equilibrium equations are solved incrementally and iteratively using a Newton–Raphson procedure, which updates the tangent stiffness matrix at each loading step.

This formulation leads to the derivation of the capacity curve, expressed in terms of base shear as a function of the control displacement, thereby providing an explicit estimate of the structural performance beyond the elastic range.

Given the strong sensitivity observed with respect to the diaphragm modeling assumption in the modal analysis, two pushover analyses were performed (rigid diaphragm and flexible diaphragm) in order to quantify the influence of in-plane floor stiffness on the global capacity, drift distribution, and hierarchy of plastic mechanisms.

After performing the analysis, the following results are obtained under the rigid diaphragm assumption:

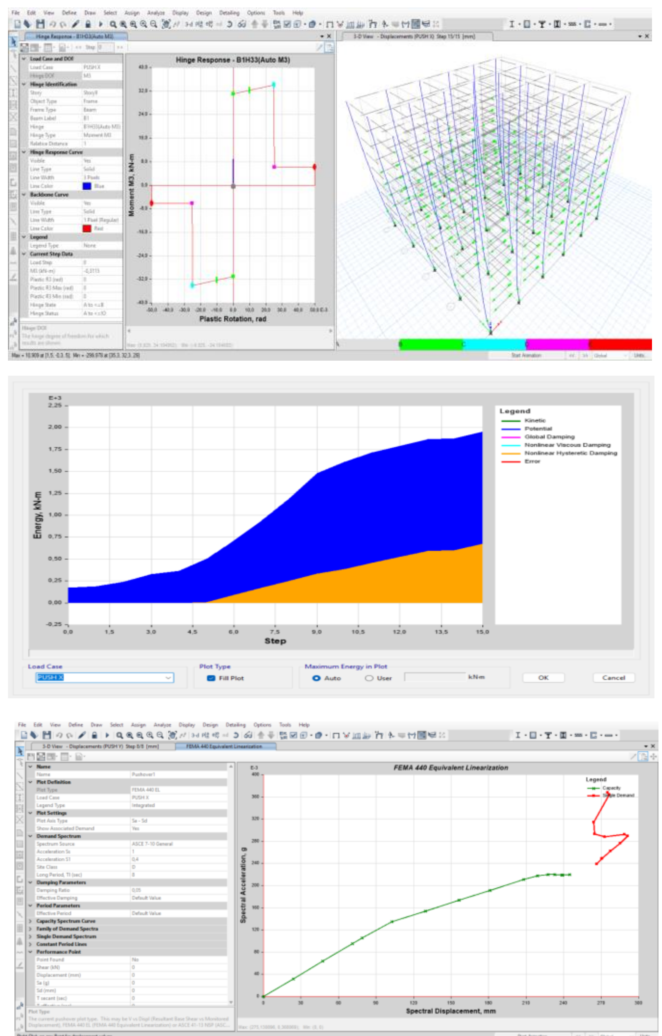


Fig. 12 Development of plastic hinges, plastic energy dissipation from pushover analysis and structural capacity curve (according to FEMA 440) derived from pushover analysis in the X direction

The following observations can be made:

- Plastic hinges develop primarily in the columns, with a strong concentration at the ground story (LS performance level);

- Slab ribs remain mostly within the A–B performance range;
- No significant energy dissipation is observed within the slab. system;
- The displacement capacity remains insufficient relative to the seismic demand.

So the obtained results indicate that, even when the rigid diaphragm assumption is adopted, plastic deformations do not significantly develop within the slab system itself but are mainly concentrated in the columns.

This behavior suggests that the structure has limited displacement capacity and reflects the seismic vulnerability of beamless waffle slab systems. The problem becomes more pronounced when lateral stiffness is insufficient and post-elastic energy dissipation mechanisms are not effectively mobilized during seismic loading.

After performing the analysis, the following results are obtained under the flexible diaphragm assumption:

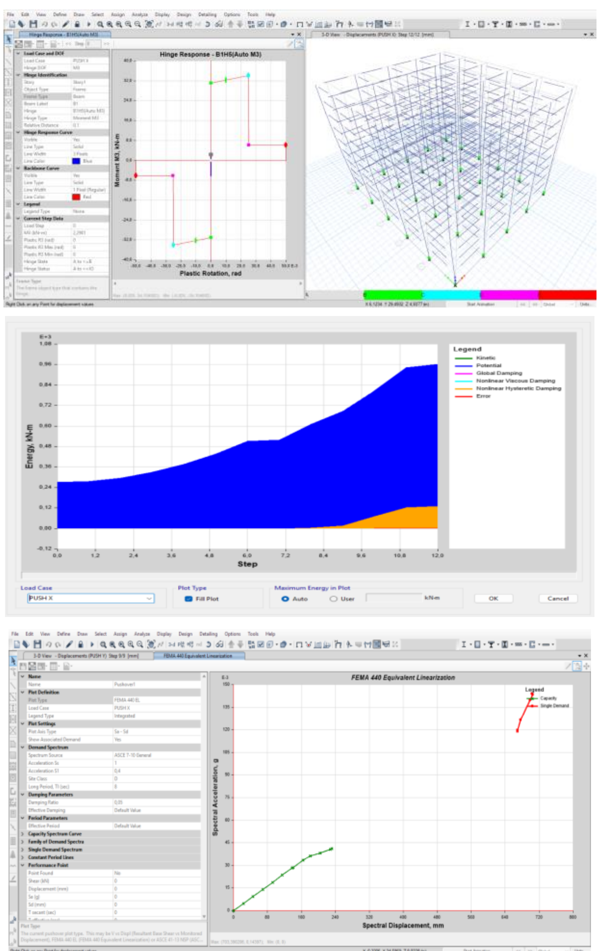


Fig. 13 Development of plastic hinges, energy dissipation due to plasticity from pushover analysis and structural capacity curve (according to FEMA 440) derived from pushover analysis in the X direction

The following observations can be made:

- Plastic hinges develop primarily in the columns, with a strong concentration at the ground story (LS performance level);
- Slab ribs remain mostly within the A–B performance range;
- No significant energy dissipation is observed within the slab system, indicating limited ductility;
- The displacement capacity remains insufficient relative to the seismic demand;
- A potential soft-story mechanism may develop at the ground level;
- The flexible diaphragm assumption further accentuates the vulnerability by revealing even larger displacement demands.

The results highlight the following key observations:

- The rigid diaphragm assumption may partially mask the actual magnitude of structural displacements.
- Beamless waffle slab systems exhibit limited post-elastic capacity when the lateral load-resisting system is insufficient.
- An explicit nonlinear modeling approach is essential for accurately assessing seismic performance.
- Particular attention must be given to local slab–column mechanisms (punching shear), which are not fully captured by flexure-only modeling approaches.

The comparative analysis indicates that, regardless of the diaphragm stiffness assumption adopted, the investigated waffle slab system does not develop a favorable post-elastic energy dissipation mechanism. This behavior is primarily attributed to the absence of beams and the lack of a strong-column–weak-beam mechanism capable of promoting stable plastic redistribution.

The concentration of nonlinearities in the ground-story columns, combined with the absence of a clear capacity–demand intersection, reveals a significant structural vulnerability under severe seismic loading. These vulnerabilities are further aggravated by pronounced second-order (P–Δ) effects and the potential development of a soft-story mechanism at the ground level, which amplify lateral displacements and accelerates structural degradation.

Although nonlinear static pushover analysis provides useful insight into the global inelastic capacity of structures, its applicability remains limited for complex systems such as beamless waffle slab buildings. The pushover procedure is fundamentally based on a quasi-static loading process and typically assumes that the structural response is dominated by the first vibration mode. Consequently, the contribution of higher modes, modal interaction effects, and the evolution of dynamic inertia forces during seismic excitation are not explicitly captured.

These limitations become particularly significant in multi-story buildings where higher vibration modes may considerably influence the distribution of inter-story drifts and internal forces. As a solution to all these problems, Nonlinear Time-History Analysis (NLTHA) is carried out in the current study. This method allows the exact simulation of the response of the structure subjected to the earthquake loading, taking into account the effect of inertia, cyclic loading conditions, gradual deterioration of stiffness, and the effects associated with multi-mode vibrations. NLTHA thus becomes an effective method of assessing the demand on displacement and inter-story drift along with the nonlinear damage mechanism in structures, especially those having flexible floor diaphragms such as Waffle slab buildings.

4.4. Nonlinear Dynamic Time-History Analysis

To evaluate the seismic performance of the structure under realistic ground motion excitation, an Incremental Dynamic Analysis (IDA) is performed. This approach enables a detailed representation of the structural response under progressively increasing seismic intensity levels and provides a more realistic assessment of structural behavior under cyclic loading conditions.

Specifically, the analysis allows:

- Capturing the effects of repeated loading cycles during earthquake excitation;
- Monitoring the evolution of inter-story drift ratios over time;
- Identifying phases of stiffness degradation and modal amplification;
- Assessing the potential risk of progressive collapse and dynamic punching failure.

A set of real or artificially generated seismic records is applied to the structural model at increasing intensity levels within the framework of the incremental dynamic analysis procedure. The structural responses are recorded and evaluated through several key performance indicators, summarized as follows:

Table 3. Structural Performance indicators

Parameter	Structural meaning
Maximum inter-story drift ratio	Primary performance indicator
Hysteretic energy dissipation	Measure of cumulative structural damage
Residual stiffness during loading cycles	Indicator of post-peak structural capacity
Distribution of column rotations	Indicator of plastic hinge formation

The simultaneous evolution of drift demand, structural stiffness degradation, and plasticity development enables the construction of seismic fragility curves. These curves provide a probabilistic representation of structural damage for a given level of seismic intensity and constitute a key tool for evaluating the seismic vulnerability of waffle slab structural systems. The El Centro ground motion record is selected as a representative seismic input (EW component applied in the X-direction) to evaluate the structural response under moderate to strong seismic excitations and to investigate the formation of plastic hinges and the associated structural degradation mechanisms.

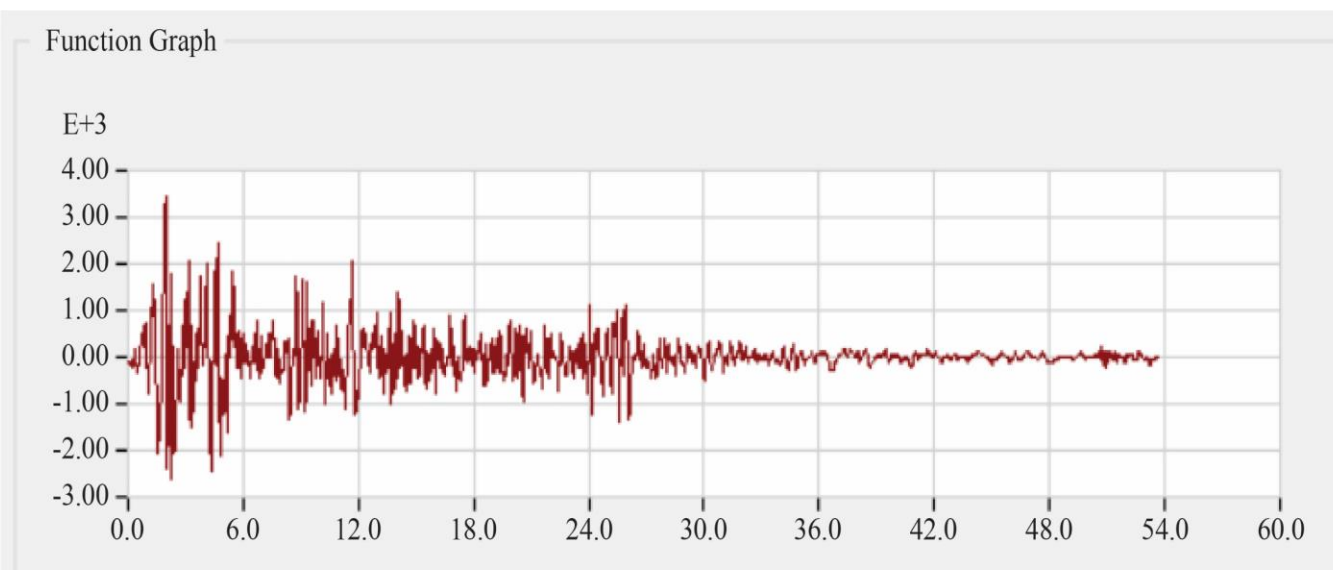


Fig. 14 Acceleration time history used in analysis: El Centro earthquake

After performing the analysis, the following results are obtained under the rigid diaphragm assumption:

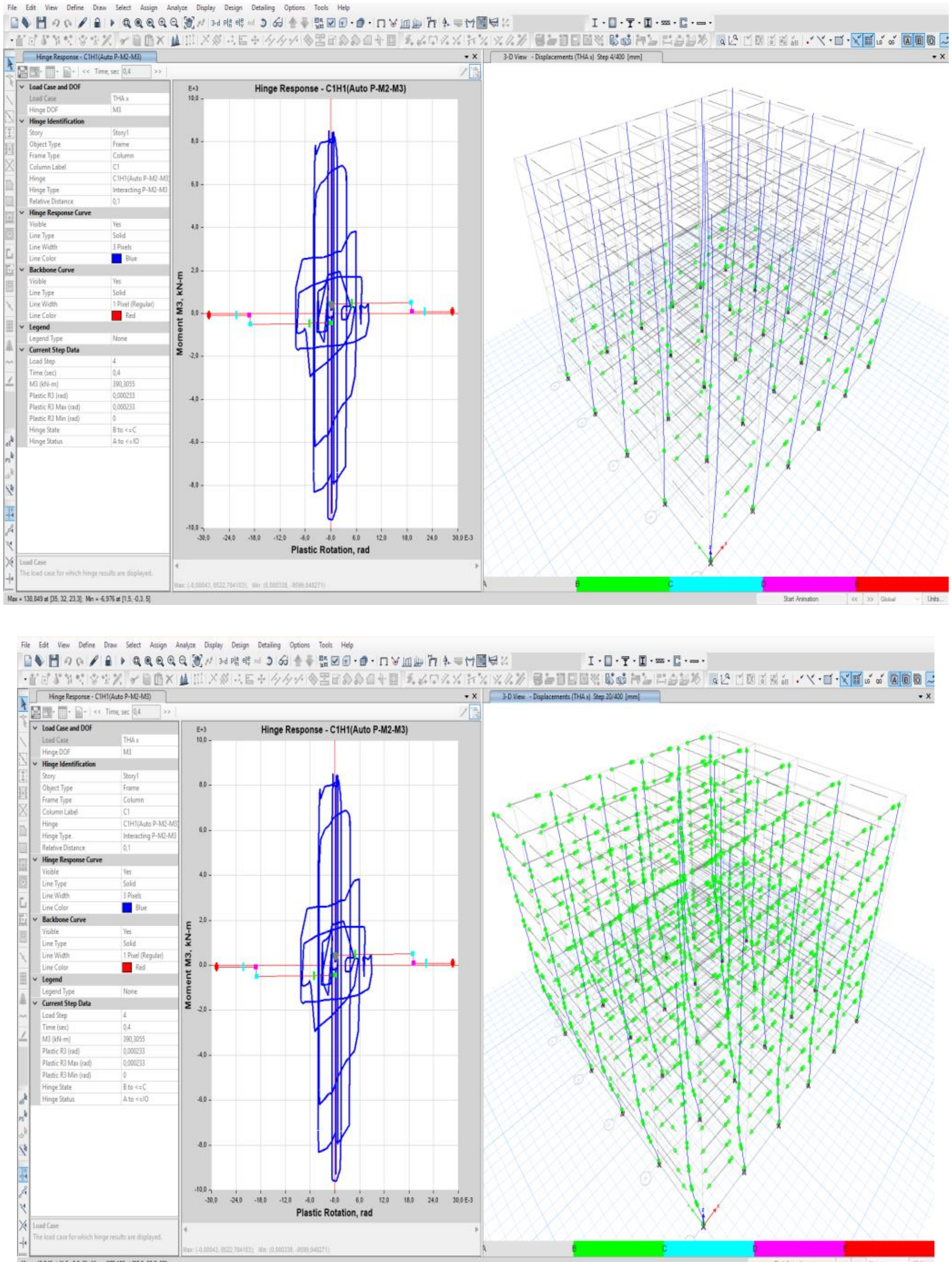


Fig. 15 Hysteretic moment-plastic rotation curves of column plastic hinges (P-M2-M3) and spatial distribution of plastic hinges within the structure obtained from nonlinear dynamic time-history analysis under the rigid diaphragm assumption

The results of the nonlinear dynamic analysis of the rigid diaphragm model reveal a significant development of plasticity in the slab elements, while plasticization in the columns occurs at a later stage.

The evolution of hinge behavior can be interpreted with reference to the characteristic points A-B-C-D-E defining the capacity curve of plastic hinges. At first, the response of the structure is limited to the elastic region A to B, during which there are no deformations permanently set up. Then, as more seismic load is applied, the structure yields, and the plastic rotation initiates when the response curve reaches point B.

Under successive loading cycles, the response progresses toward point C, corresponding to the Immediate Occupancy (IO) performance level, characterized by limited inelastic deformations. With further increase in seismic demand, some hinges may evolve toward point D, associated with the Life Safety (LS) performance level, where plastic rotations become more significant, and stiffness degradation becomes more pronounced. In certain cases, the response may approach point E, corresponding to the Collapse Prevention (CP) limit state.

The rigid diaphragm assumption enforces uniform in-plane displacements, leading to a more homogeneous redistribution of seismic forces and a greater participation of the slab in energy dissipation. This results in an apparent increase in ductility and a delay in column plasticization. However, this behavior may overestimate the slab's capacity and mask the actual damage mechanisms, requiring careful interpretation of the results.

After performing the analysis, the following results are obtained under the flexible diaphragm assumption:

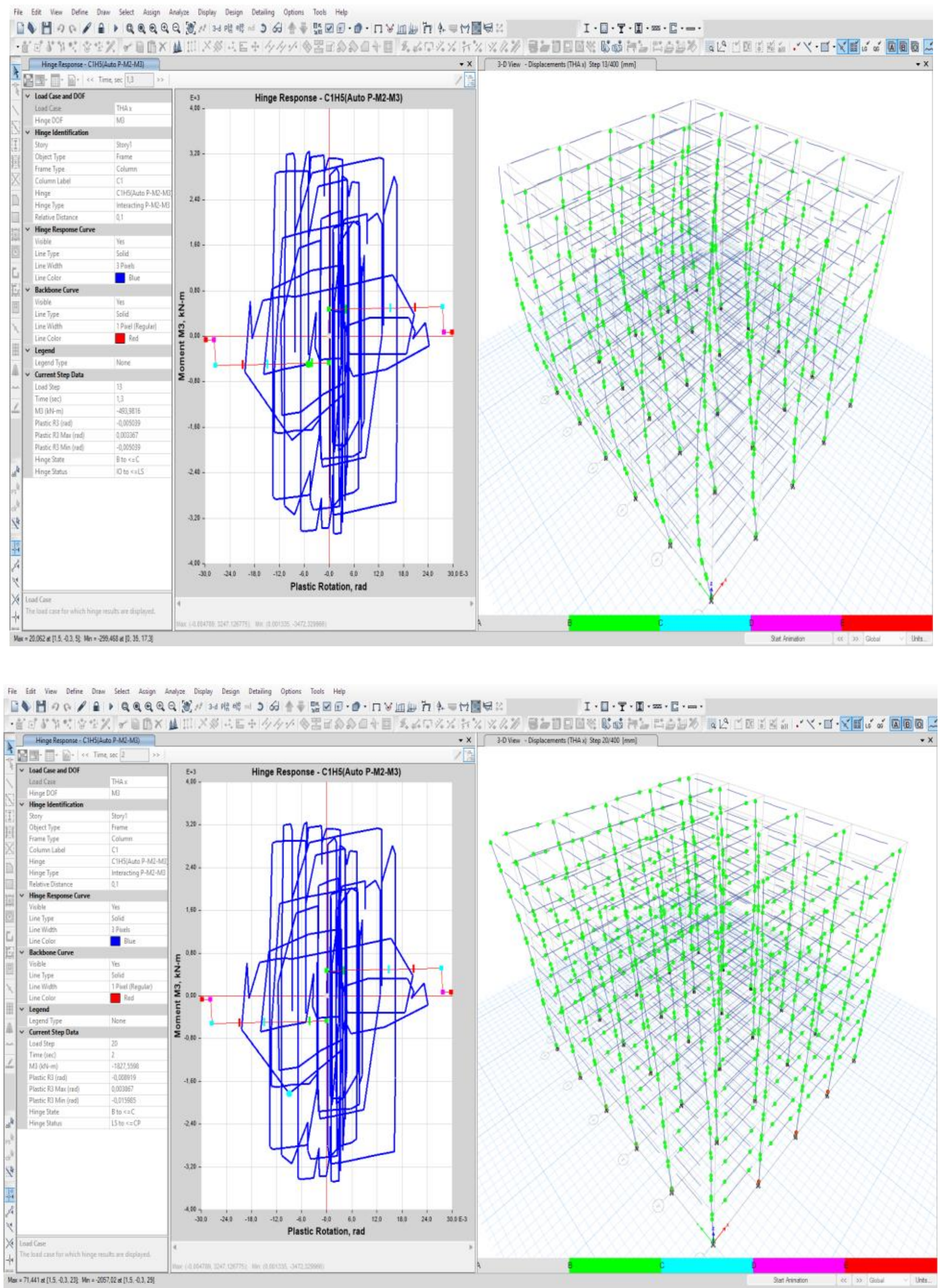


Fig 16 Hysteretic moment–plastic rotation curves of column plastic hinges (P-M2-M3) and spatial distribution of plastic hinges within the structure obtained from nonlinear dynamic time-history analysis under the flexible diaphragm assumption

The hysteretic response of column plastic hinges reveals a strongly nonlinear behavior accompanied by a progressive degradation of stiffness during seismic excitation. The development of hinge actions may be described with reference to the typical points A-B-C-D-E of the capacity curve of plastic hinges.

At first, the reaction is confined to the elastic region between points A and B, during which no yielding takes place. As the seismic load is increased, the reaction attains point B, and the plastic rotations initiate in the columns. Under successive loading cycles, the response then progresses toward point C, corresponding to the Immediate Occupancy (IO) performance level, characterized by limited inelastic deformations.

As the intensity of seismic excitation further increases, the hinge behavior may evolve toward point D, associated with the Life Safety (LS) performance level, where plastic rotations become more significant, and stiffness degradation becomes more pronounced. In some cases, the response may approach point E, corresponding to the Collapse Prevention (CP) limit state, indicating an advanced level of structural damage and a substantial loss of lateral stiffness.

The observed hysteretic loops show that plastic hinges initially develop in the columns and progressively spread throughout the structure. This behavior indicates that the vertical load-resisting system becomes the primary mechanism of energy dissipation. The early development of plasticity in the columns, therefore, leads to a column-dominated failure mechanism.

Such a mechanism is generally considered fragile and undesirable in seismic design, as it may result in a rapid degradation of lateral stiffness and global load-carrying capacity, thereby increasing the risk of instability and structural collapse under severe seismic loading. These results therefore indicate that the rigid diaphragm assumption may lead to a non-realistic representation of the seismic behavior of flat slab structures, artificially delaying column plasticization and masking a more critical failure mechanism.

In contrast, the flexible diaphragm model produces a response that is mechanically closer to the actual behavior of the structure, although it also reveals a higher level of seismic vulnerability. The differences observed between pushover analysis and Nonlinear Time-History Analysis (NLTHA) mainly result from the theoretical assumptions behind each method, which directly influence the formation of plastic hinge mechanisms.

Pushover analysis is based on a monotonic lateral loading pattern generally controlled by the first vibration mode, with a force distribution that remains constant during the analysis. Because of this simplification, phenomena such as cyclic degradation, crack closing, and dynamic redistribution of internal forces cannot be fully reproduced. As a consequence, inelastic deformations tend to concentrate in the most flexible structural elements, especially the ground-story columns, leading to a column-dominated plastic mechanism. On the other hand, nonlinear time-history analysis solves the complete dynamic equations of motion under realistic earthquake excitation. This approach takes into account inertial effects, higher vibration modes, and continuously varying force distributions during seismic loading. Under cyclic actions, these effects progressively reduce the stiffness of slab–column connections.

When the rigid diaphragm assumption is imposed, displacement compatibility forces the slab system to participate more actively in the transfer of lateral loads. This generates additional bending moments in the slab, which may exceed the flexural resistance of the reinforcement and lead to the formation of plastic hinges within the slab before significant plasticization develops in the columns.

Therefore, the column-dominated mechanism obtained from pushover analysis mainly reflects the limitations of a simplified static approach that cannot accurately reproduce cyclic degradation and force redistribution. In contrast, the slab-dominated mechanism observed in NLTHA provides a more realistic representation of the actual seismic response of waffle slab systems.

The adopted methodology combines modal analysis, nonlinear static pushover analysis, and nonlinear dynamic time-history simulations. This integrated approach makes it possible to reproduce the principal damage mechanisms affecting waffle slab systems, evaluate their sensitivity to excessive inter-story drift demands, and establish relevant indicators for seismic fragility assessment.

The results consistently highlight the structural vulnerability of beamless waffle slab systems when their in-plane stiffness contribution is overestimated in structural modeling, in agreement with the damage patterns observed in experimental investigations and post-earthquake field observations. In particular, the analyses emphasize the significant influence of diaphragm flexibility on the global seismic response, leading to increased displacement demands and a higher concentration of nonlinear behavior in critical regions.

These findings, therefore, call for a critical reassessment of the use of such beamless waffle slab systems in regions of high seismic hazard, particularly when they are not integrated within an adequate lateral load-resisting system capable of controlling drift demands and ensuring sufficient energy dissipation capacity.

Definition of the Slab Seismic Fragility Index (SSFI) and Application

The Original Slab Seismic Fragility Index (SSFI) is a global indicator designed to quantify the non-conservative error in displacement demand induced by the rigid diaphragm assumption. Moreover, seismic vulnerability is also dependent upon the ability to withstand deformation without failing.

Thus, a better formulation is suggested by considering the punching shear demand to capacity ratio, which is a crucial aspect of failure. Two strictly identical structural models are considered:

- MR: model with a rigid diaphragm assumption
- MF: model with a flexible diaphragm assumption

The masses, gravity loads, damping ratios, response spectra, and seismic records are kept identical in both models; the only difference lies in the floor modeling approach, in accordance with the adopted methodology.

For a given analysis case (c) and a direction d∈{X, Y}, the following quantities are defined:

$D_{\{c,d\}}^{\{R\}}$: Maximum roof displacement obtained under the rigid diaphragm assumption;

$D_{\{c,d\}}^{\{F\}}$: Maximum roof displacement computed from a flexible diaphragm model that explicitly accounts for the in-plane deformability of the floor system in accordance with its actual geometric configuration.

$V_{\{c,d\}}^{\{ed\}}$: Seismic demand in terms of punching shear force at the slab-column connection.

$V_{\{c,d\}}^{\{rd\}}$: Nominal punching shear capacity.

The directional index is defined as follows:

$$SSFI_{\{c,d\}} = \text{Max}\ [0, \left(1 - \frac{D_{\{c,d\}}^{\{R\}}}{D_{\{c,d\}}^{\{F\}}}\right) \text{x} \left(1 + \max columns \frac{V_{\{c,d\}}^{\{ed\}}}{V_{\{c,d\}}^{\{rd\}}}\right)]$$

With:

$0 \leq$ SSFI c,d < 1

Interpretation:

SSFIc,d≈0: the rigid diaphragm assumption introduces a negligible error in the displacement demand.

SSFIc,d ≈1: The rigid diaphragm assumption significantly underestimates the displacement demand in the considered direction.

The term $\left(1 - \frac{\mathbf{D}_{\{c,d\}}^{\{R\}}}{\mathbf{D}_{\{c,d\}}^{\{F\}}}\right)$ captures the modeling bias introduced by the rigid diaphragm assumption, while the term $\left(1 + \max columns \frac{\mathbf{V}_{\{c,d\}}^{\{ed\}}}{\mathbf{V}_{\{c,d\}}^{\{rd\}}}\right)$ penalizes configurations where the punching shear demand approaches or exceeds the available capacity for the most critical slab column connection.

The improved index offers a more thorough analysis of the seismic vulnerability of buildings by incorporating both the accuracy of the model (displacement demand) and the capability of the structure (punching shear resistance).

It is also a decision-making aid for the improvement of the model through the reduction of this gap and achieving a more accurate representation of the structure. Lowering SSFI results in a higher accuracy of the prediction of seismic demands and, consequently, a safer structure. Otherwise, under strong seismic events, the system cannot be regarded as a rigid diaphragm.

Compared with previous studies, which have mainly investigated individual aspects of waffle slab behaviour, such as diaphragm flexibility, inter-story drift, or punching shear, the present study provides a more comprehensive assessment by integrating these mechanisms into a single engineering framework. The proposed Slab Seismic Fragility Index (SSFI) combines the discrepancy in seismic displacement demand between the conventional rigid diaphragm model and a flexible diaphragm model that explicitly accounts for the in-plane deformability of the waffle slab, together with the punching shear demand-to-capacity ratio at the critical slab–column connections. By simultaneously considering global structural response and local failure mechanisms, the proposed SSFI offers a more realistic and practical tool for evaluating the seismic vulnerability of waffle slab buildings and supports engineering decision-making for seismic assessment and design.

Application of the SSFI to Different Structural Configurations.

To guide engineers on the practical application of the concept, a series of design guidelines has been formulated based on the interaction between the seismic hazard level and the Slab Seismic Fragility Index (SSFI).

The guidelines provide for a step-by-step approach that takes into account the continuum of behavior of structures from low to high seismicity regions.

For low seismicity regions (ag<0.1g), the rigid diaphragm approach can be accepted as long as punching shear reinforcement is incorporated as a minimum.

For moderate seismicity areas (0.1g≤ag<0.3g), the SSFI is used as a tool to make decisions, where an SSFI less than 0.3 implies the use of perimeter beams to improve stiffness and punching shear analysis. For high seismicity areas (ag≥0.3g), a more rigorous approach should be taken, where SSFI greater than 0.3 implies that the rigid diaphragm approach should not be adopted without any analysis, and a lateral load resisting system becomes imperative.

Table 4. Design recommendations according to seismic hazard level and SSFI

Seismicity level	SSFI	Recommendation
Low (ag<0.1g)	<0.1	-Rigid diaphragm acceptable; punching shear reinforcement.
Moderate (0.1g≤ag<0.13g)	<0.2	-Perimeter beams & Hybrid systems with shear walls & seismic punching shear verification required.
High (ag ≥0.13g)	≥0.2	-Rigid diaphragm not acceptable, detailed analysis required.

The proposed threshold values and engineering recommendations for practical retrofit are based on the numerical investigations carried out in the present study. Further comprehensive investigations involving a wider range of structural configurations and seismic scenarios will be conducted to further validate, calibrate, and refine these proposed limits.

As the seismic hazard increases, the limitations of the system become progressively more apparent. A transition zone exists for moderate seismicity, where the SSFI can be used to determine whether the rigid diaphragm assumption remains valid or whether additional measures (perimeter beams, shear walls, hybrid systems (beams on lower stories &waffle slabs upper stories), beams between all columns) are required.

For high seismicity regions, the results of this study indicate that waffle slab systems should not be designed under the rigid diaphragm assumption without explicit verification of in-plane flexibility. The SSFI provides a quantitative criterion to guide this decision, as summarized in Tab.2.

5. Conclusion

The investigations carried out in this study—including the review of experimental studies, post-earthquake observations, and advanced nonlinear numerical analyses—lead to a consistent conclusion: beamless waffle slab systems may exhibit an intrinsic seismic vulnerability when their contribution to the global lateral stiffness of reinforced concrete buildings is overestimated in structural design and modeling.

They confirm that the dominant failure mechanisms are primarily associated with:

- Insufficient lateral stiffness, leading to excessive inter-story drift demands;
- Limited energy dissipation capacity under cyclic seismic loading;
- Concentration of damage at slab–column connections (punching shear);
- Soft-story effects and second-order (P–Δ) effects;
- Progressive pancake-type collapse mechanisms.

The numerical analyses carried out in this study highlight that the rigid diaphragm assumption, commonly adopted in engineering practice, may lead to a significant underestimation of lateral displacements and inter-story drift demands. In the case investigated, the transition from a rigid diaphragm model to a flexible diaphragm model results in:

- A pronounced increase in the fundamental structural period;
- A substantial increase in global lateral displacements;
- An amplification of second-order (P–Δ) effects;
- An increased concentration of nonlinear behavior in the ground-story columns.

These results indicate that the rigid diaphragm assumption may lead to non-conservative predictions of displacement demand in structures whose global response is dominated by slab behavior.

In this context, the proposed Slab Seismic Fragility Index (SSFI) represents a key methodological contribution of this research. This index enables:

- Objective quantification of the discrepancy induced by the rigid diaphragm assumption;
- Identification of structural configurations for which this assumption becomes invalid;
- Classification of slab systems according to their actual diaphragm behavior;
- Guidance of the designer toward an iterative recalibration process involving geometry optimization, stiffness enhancement, and the introduction of adequate lateral load-resisting systems.

The SSFI is not intended to replace conventional code-based verifications; rather, it complements them by introducing an explicit performance-oriented criterion based on displacement demand, directly related to seismic safety.

From a practical perspective, this study shows that the seismic assessment of waffle slab systems cannot be limited to a strength-based verification. Instead, it must explicitly incorporate:

A realistic diaphragm modeling approach based on the actual slab geometry and its in-plane flexibility, rather than relying on the default rigid diaphragm assumption, explicit nonlinear structural analysis, verification of inter-story drift demands and energy dissipation capacity and control of local slab–column failure mechanisms, In conclusion, the observed vulnerability is neither isolated nor incidental; it is structurally related to the low in-plane stiffness and the limited energy dissipation capacity of beamless slab systems when they are not integrated into an appropriate global lateral load-resisting strategy.

The main contribution of this study lies in the quantitative identification of the bias induced by the rigid diaphragm assumption and in the proposal of an operational tool—the Slab Seismic Fragility Index (SSFI)-designed to reduce this bias, improve the reliability of seismic analyses, and ultimately enhance the safety of structures exposed to seismic hazards.

The continued use of rigid diaphragm assumptions without verification—widely adopted in seismic design codes and practice, and implemented as a default option in most structural analysis software—may therefore lead to non-conservative seismic design and increased risk of structural failure in slab-dominated systems.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

Funding Statement

This research received no external funding.

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