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SEISMIC PERFORMANCE OF TRADITIONAL BEAM-SLAB AND FLAT SLAB SYSTEMS: AN EXTENSIVE ANALYSIS

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Abstract

The seismicity of slab systems is significant in the overall safety, stability, and resilience of the reinforced concrete constructions erected on the earthquake-prone areas. The conventional beam slab systems have been known to possess a sound load transfer mechanism, increased lateral stiffness, increased ductility, and improved energy dissipation capacity all which lead to increased seismic resistance and controlled deformation during the movement of the ground. On the other hand, the growing use of flat slab systems, as a result of building flexibility, lower floor height, and efficiency in constructions, has cast serious structural concerns, because of their lower rigidity, amplified drift response, stress concentration at slab-column interface and their vulnerability to punching shear failure in seismic conditions. The review is based on the results of large scale experimental studies, advanced numerical modeling, and real life case studies of earthquakes in the attempt to offer a conclusive comparative assessment of the two slab systems. The research draws important behavioral variations in terms of stiffness deterioration, strength ability, ductility variables, load transfer proficiency, deflection character, and collapse mechanisms. Moreover, it reinforces the significance of performance based seismic design, the use of reinforcement details and the use of strong reinforcing details, drop panels, column capitals, shear reinforcements, and even integration with shear walls, to improve the seismic reliability of flat slab structures. In general, the review highlights that, although beam slab systems are usually more predictable and resilient with regard to seismic performance beam slabs, flat slab systems can be made to reach satisfactory levels of safety through effective design improvements, which is why informed system selection and detailing are the key to resilient and sustainable structural design.

Keywords: Beam–slab system, Flat slab system, Seismic performance, Punching shear, Ductility, Lateral stiffness, Earthquake-resistant design

1. Introduction

Earthquake resistance has turned out to be a major issue in the contemporary structural engineering, especially in areas that are often vulnerable to seismic waves. Slab systems are some of the structural components among others that are critical in the maintenance of the structural integrity and stability [1]. Reinforced concrete beam-slab traditional systems have long been popular over decades because their behavior is well understood, their load transfer mechanism is reliable, and they are highly ductile. Nevertheless, the rising need to have architectural flexibility, lower floor height, quicker construction, and better use of functional space have contributed greatly to the use of flat slab systems in residential, commercial buildings and institutions. This construction practice change has brought up valuable concerns about their relative seismic performance, safety and their appropriateness in earthquake-prone areas[2].

Conventional beam slab system provides a separate load path using beam and columns, which increases the stiffness and resistance to lateral loads caused by earthquakes. Conversely, flat slab systems move the slab loads to columns without the intermediate beam making them to be economical in carrying weight but may be susceptible to seismic forces. The non-presence of beams can result in substandard lateral rigidity and vulnerability to punching shearing collapsing, progressive collapsing and undue deformation of the ground with intense ground vibrations. The attributes require a thorough study of their seismic behavior in order to design them safely and efficiently.

In recent decades, analytical studies, various experimental studies, and actual earthquake damage studies have been conducted with the aim of assessing the performance of both systems during seismic loading. Such investigations have identified variations in the dissipation capacity of energy, inter-storey drift management, pattern of crack propagation, and the general collapse process. Simultaneously, the developments in the design guidelines, retrofitting methods, and performance-based seismic design techniques have created the possibility of improving the behavior of flat slab systems and their application in high seismic areas became more practical [3].

Considering the growing topicality of the issue, this review paper is intended to provide a massive comparative study of the seismic performances of the classical beam-slab and flat slab structural systems. The discussion generalizes the results of experimental studies, numeric modeling, actual case studies, and code-based views to show strength, weaknesses, vulnerability, and how they can be improved. In this overall overview, the paper aims at assisting the designers, researchers and policymakers in making sound judgments on the right choice, design and use of slab systems in seismic prone areas.

Table 1: Summary of Key Literature on Reinforcement and Performance of Slab Systems

Author & Year	Study Title / Source	Focus Area	Methodology / Approach	Key Findings	Relevance to Present Review
Hsu et al. (2019) [4]	Discussion on the Reinforcement of Reinforced Concrete Slab Structures (Sustainability)	Improvement of reinforcement strategies in RC slabs	Analytical discussion supported by design evaluations and performance analysis	Highlighted the significance of appropriate reinforcement detailing for enhancing strength, crack control, and serviceability of RC slabs	Supports understanding of reinforcement importance in seismic performance of slab systems
Kassem (2015) [5]	Reliability of Reinforced Concrete Structures: Case of Slabs Subjected to Impact (PhD Thesis, INSA de Lyon)**	Structural reliability and behavior of slabs under extreme impact conditions	Experimental and numerical investigation on RC slabs under impact loading	Demonstrated that slab behavior is highly dependent on reinforcement configuration, thickness, and material properties	Provides insight into structural reliability and resilience concepts relevant to seismic loading
Isufi & Ramos (2021) [6]	Review of Tests on Slab–Column Connections with Advanced Concrete Materials (Structures, Elsevier)	Performance of slab–column connections, especially with innovative concrete materials	Comprehensive literature review of experimental tests	Showed that use of high-performance and advanced concrete materials significantly improves punching shear resistance and connection strength	Directly relevant to improving the seismic safety of flat slab systems
Mohamed et al. (2023) [7]	Shear and Flexure of FRP-Reinforced Concrete Beams and Slabs – A Review (Materials Today: Proceedings)	Behavior of FRP-reinforced slabs and beams in shear and flexure	Review of past experimental and analytical studies	Found FRP reinforcement enhances corrosion resistance and flexural performance but requires careful design for shear	Useful in exploring advanced reinforcement techniques for seismic strengthening
Evstratova et al. (2021) [8]	Design of Prefabricated Reinforced	Comparison and analysis of	Comparative analytical study and	Demonstrated structural efficiency,	Relevant in understanding modern slab

	Concrete Structures (IOP Conference Series)	prefabricated RC slab systems	design evaluation	reduced weight, and improved performance of prefabricated slab systems with proper design considerations	construction alternatives and their potential seismic behavior

1.1 Overview of Slab Systems in Reinforced Concrete Structures

Slab systems are considered one of the most vital structural elements in reinforced concrete constructions, which will mainly be used as a way of supporting and loading weight to the supporting beams and columns, and eventually the foundation. Not only do they bear the gravity loads of the weight of the structure, occupants, and furnishings but are also instrumental in the overall lateral load resistance when the forces are dynamic, i.e., wind, earthquake, etc. The slab system design, configuration, and type taken in a building have a great impact on the structural performance, stiffness, ductility, and safety of the building under various loading conditions.

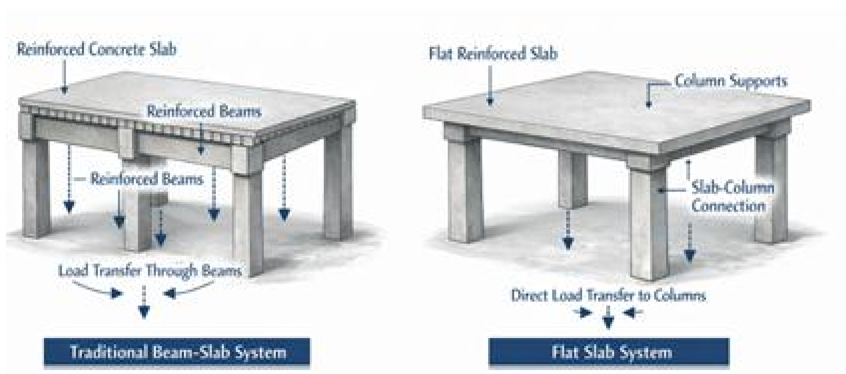

Figure 1: Comparison between Traditional Beam–Slab System and Flat Slab System

Source: https://gharpedia.com/blog/difference-between-flat-slab-conventional-slab-beam-system/

In a normal reinforced concrete building, the traditional beam and slab arrangement and a flat slab arrangement are the most typical slab arrangements. Beam-slab system This system is a combination of slabs and beams, with the latter carrying the loads to columns and providing a clear load path and increased structural stiffness. Flat slab systems, on the other hand, do not use intermediate beams, and instead the slab is supported by columns, which gives it architectural freedom, lower floor height, and accelerated construction. Nonetheless, there are various behavioral properties of this simplified structure, particularly in the case of seismic loading.

Choosing an appropriate slab system requires consideration of several factors that include functional requirements, span length, architectural requirement, seismic zone, economic consideration and the technology available in constructing the slab. As the structural design practice evolved and focus started shifting to performance-based design, the knowledge of structural performance and role of the slab system is of paramount importance. Their nature, strengths as well as weaknesses therefore need to be well understood by engineers to achieve efficiency and safety in the modern reinforced concrete structures.

1.2 Need for Seismic Performance Evaluation in Modern Construction

In recent decades witnessed the occurrence of rapid urbanization, population growth, and the demand to construct multi-storey reinforced concrete buildings in high numbers to ensure the construction industry changed drastically in the modern world order. A lot of these buildings lie in areas which face a high risk of earthquakes and the effects of structural collapse, in this case, are devastating in matters of human fatalities, economic damages, and social upheavals. Consequently, this has necessitated the assessment of seismic performance of building systems as a necessity and not a design consideration. The current construction theory should therefore be in such a way that the structural systems should be able to sustain the seismic forces without any functional instability and safety [9].

The motions that are produced by the earthquakes cause dynamic, lateral loads on the buildings and thus make them deform, they crack, their strength is destroyed and in the worst case, a building may collapse entirely. The behaviour of a structure in relation to such seismic forces is mainly influenced by its arrangement, stiffness, ductility, energy elimination capability and generally load resisting mechanism. As slab systems constitute a substantial load-bearing element, and because they greatly determine the allocation of seismic forces, their overall behavior has a direct impact on the overall structural performance of structures. This explains why it is important to evaluate and compare various slab systems with regard to their capacity to endure the demands of earthquakes.

Furthermore, the emergence of performance-based seismic design philosophies and the fact that building codes are always being revised with more and more realistic evaluation of the performance of structures in strong ground motions point to the necessity of realistic evaluation of such performance. Conventional methods of design which mainly emphasized on the gravity loads are not viable in the contemporary environments of high-risk seismic activities. Individual engineers and scientists are thus required to study the behavior of different slab structures to different seismic intensities, building structures, and design circumstances. Not only such evaluation improves safety but also leads to more cost-effective and dependable construction, which in the end promotes sustainable and resilient development of the city.

2. Structural Behaviour and Seismic Response Characteristics

Slab system seismic performance is an important aspect that determines the safety and stability of the building during any earthquake of reinforced concrete buildings. The beam-slab systems of the traditional type tend to work better since the load-transfer mechanism is clear, and includes beams and columns, which increases the rigidity in the lateral direction, energy dissipation, and controllable deformation [10]. This causes increased resilience and predictable seismic behaviour. Conversely, flat slab construction directly supports the columns and has architectural and construction benefits, but tends to be less rigid, more storey drift and prone to punching shear failure at slabs column connections during intense seismic events. Nevertheless, they can be carefully reinforced to enhance their performance with regard to detailing of drop panels, column capitals and incorporation with lateral load-resisting elements like shear walls or cores. In general, these behavioural differences need to be understood to provide safe and efficient seismic design of reinforced concrete buildings.

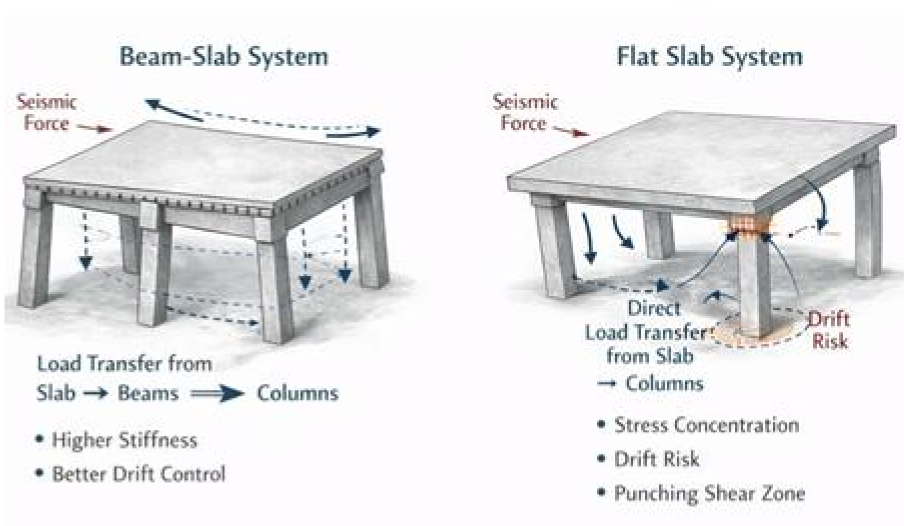

Figure 2: Seismic Behaviour Comparison of Beam–Slab and Flat Slab Systems

Source: https://gharpedia.com/blog/difference-between-flat-slab-conventional-slab-beam-system/

2.1 Load Transfer Mechanism in Beam–Slab and Flat Slab Systems

Load transfer mechanism is an important aspect that defines the structural performance, and seismic performance of reinforced concrete slab systems. With the conventional beamslab structure, the slab initially supports the loads which are subsequently distributed to the beams then the beams on columns and the foundation. This multiple step direction of transfer is designed to enhance the distribution of stress, increase the stiffness and resistance to both the gravitational and the lateral load and make the structural performance during the seismic events safer and more stable [11].

In contrast, flat slab systems are designed to pass the load through the slab onto the supporting columns, without the use of intermediate beams, which provides the flexibility of architecture and efficiency in construction. Nevertheless, this direct load transfer causes stress concentration on the slab-column connections, and thus these areas are critical during seismic loading and the possibility of punching shear and localized failure is enhanced. Thus, these differences should be learned about and appropriate design considerations should be made in terms of proper reinforcement, drop panels, or capitals on columns, to make the structures of flat slabs safe, reliable, and seismically resilient.

2.2 Stiffness, Strength, And Ductility Parameters

Three important parameters that determine the seismic performance of structural systems include stiffness, strength and ductility. The parameters define the behavior of a structure to lateral earthquake forces, the amount of deformation that a structure can experience and the effectiveness of the structure to sustain collapse. The characteristics are important in assessing and comparing the performance of beam-slabs and flat slabs in the presence of seismic loading conditions.

- **Stiffness:** Stiffness can be defined as the capacity of a structure to withstand deformation when external forces are applied on them. In seismic, lateral stiffness gives more assistance in lowering storey drift, regulating movement, and lessening the possible structural damage. The traditional beam-slab systems are usually stiffer because it contains beams that increase the rigidity of the floor system and also helps in improving lateral stability. Conversely, flat slab systems have no intermediary beams, and as a result tend to be less laterally stiff, and more prone to greater displacement and inter-storey drifts in case of an earthquake. Thus, the sufficient level of stiffness is essential to achieve the structural safety and serviceability of buildings made of reinforced concrete in seismic regions.

- **Strength:** Strength is the ability of a structural system to sustain loads put on it without failing. When the structure is subjected to seismic loading, the strength defines the capacity of the structure to withstand the lateral forces and collapse as well as the stability of the structure in general. Beam-slab systems are typically stronger in flexural and shear because they have supporting beams which have an efficient way of distribution. Flat slab, though efficient structurally when it comes to gravity loads, can exhibit a lower strength at slab column connections when subjected to the forces of earthquakes and therefore become susceptible to punching shear and local failure when not designed efficiently. It is therefore necessary to ensure that the strength is sufficient by means of proper detailing and reinforcement to have trustworthy seismic performance.

- **Ductility:** Ductility is the capability of a structure to experience significant deformations without its abrupt failure that can take place, allowing it to release seismic energy. High ductility structures have the ability to take up and re-distribute energy during ground shaking, and this reduces the chances of brittle failure. The ductility of beam-slab systems is usually superior due to the fact that beams can smoothly yield and manage cracking and this plays a role in safer structural behavior. The flat slabs systems however are less ductile as a result of no beams and concentration of stress at the slab-column joints. In order to enhance the ductility of flat slabs, the design (additional reinforcement, drop panels, column capitals, and combination with elements resisting sideways loads) are usually necessary.

3. Review of Experimental, Numerical, and Case Study Findings

This part is aimed at the synthesis of the results obtained with the help of different experimental studies, numerical modeling, and real-life examples to comprehend the comparative seismic performance of the traditional beam-slab and flat-slab systems. With laboratory scale experiments, shake-table tests over the years and full-scale structural tests, many researchers have been undertaking the behavior of these systems under cyclic and dynamic loads. The investigations conducted using these experimental studies have given the wealth of knowledge on crack formation and failure, stiffness decaying, load distribution patterns, and the entire structural response under seismic excitation [13].

In addition to experimental research, the numerical and finite element modelling methods have been important in enhancing the knowledge on slab behaviour under seismic loading. High level analytical tools allow the modeling of complex loading conditions, nonlinear material behavior and realistic structural behaviors that can be challenging to measure using physical testing only. These models assist in assessing the parameters of inter-storey drift, pattern of displacement, locus of stress concentration and capacity of dissipation of energy in the two slab systems. They also enable the researcher to examine the role of design modifications, reinforcement detailing and strengthening methods towards enhancing seismic resistance.

Practical evidence of structural performance under the real seismic conditions is further justified by real-world case studies of past earthquake occurrences that experimentally and analytically confirm the findings. The damaged buildings have also been observed to have severe weak points like punching shear failure in flat slabs and ductile benefits in beam-slabs. The combination of experimental, numerical and case study results provides a thorough body of knowledge which assists engineers and researchers in determining the reliability, safety and appropriateness of slab systems in the areas with earthquakes. These lessons could be vital in refining design principles, enhance construction habits as well as in enriching the strength of today reinforced concrete.

3.1 Overview of Existing Research Approaches

The currently available studies concerning the seismic performance of both beam-slab and flat slab systems have come about as a result of experimental studies, analytical functions and practical performance evaluations. Initial researches mainly concerned with the basic behavior of these structural systems when they are subjected to gravity loads, though, as the frequency and the intensity of the earthquakes increased, the interest slowly tended to be directed to assessing their seismic behavior. Various methodologies have been used to investigate elements like stiffness loss, ductility, energy dissipation ability, punching shear susceptibility and general collapse processes.

Experimental studies that have been conducted in the laboratory have been important in providing direct evidence on structural behavior when subjected to simulated seismic loading. These involve small scale models, full scale structural elements and shake table experiments that imitate the effects of the ground motions. These investigations can be used to see the pattern of cracks, gauge the nature of deformation, and designate the key areas of failures in both beam slab and flat slabs. In addition to these experiments, numerical simulations based on finite element methods and nonlinear dynamic analysis methods allow researchers to examine a wide range of complex structural responses that cannot be readily measured in the laboratory.

Additionally, a number of studies derive post-earthquake damage assessment and real-life building performance evaluation to confirm experimental and analytical results. Such field-based observations offer field experience in how various systems of slabs would act during real seismic events and their strengths and weaknesses. On the whole, the use of experimental testing, numerical modelling, and analysis of case studies makes it a comprehensive research structure, thanks to which one can better understand seismic behaviour of traditional beam slab and flat slab structures.

3.2 Experimental Investigations on Beam–Slab Systems

Experimental studies on beam slab have also contributed significantly to the structural behavior of beam slab systems in seismic loading conditions. A variety of laboratory-based tests such as component testing, full-scale prototyping, and shake-table experiments have been taken to evaluate the behaviour of these types of systems under cyclic and dynamic load. The essential seismic parameters that are usually assessed during these investigations include the lateral stiffness, strength, ductility, maximum drift and energy dissipation properties [14].

Lateral stiffness is one of the most important factors that are analyzed during the experiments and that define the ability of the structure to resist under the influence of seismic forces. The relationship is commonly used in determining stiffness:

$$k = \frac{F}{\delta}$$

where k represents stiffness, F L is the lateral load acting and δ is the lateral displacement. Increased stiffness of beam slab systems contributes to reduction of inter-storey drift which contributes to structural and stability.

The other critical parameter that is being evaluated is that of strength which is usually determined in terms of ultimate load-carrying capacity under cyclic loading. The use of structural weight is often associated with seismic base shear demand:

$$V = A_h \times W$$

where V is the base shear, A_h is the design horizontal seismic coefficient and W is the seismic weight of the structure. Beam-slab structures tend to be more resistant because load transfer by means of beams is effective.

Ductility is also discussed in great detail because it also indicates how the system can be deformed without collapsing abruptly. It is typically expressed as:

$$\mu = \frac{\Delta_u}{\Delta_y}$$

where μ is ductility ratio, Δ_u is ultimate displacement, and Δ_y is yield displacement. It has been experimentally determined that beam–slab systems are more ductile because beams can progressively yield more enabling them to absorb more energy.

Similarly, drift capacity is evaluated using:

$$\text{Drift Ratio} = \frac{\Delta}{\text{h}}$$

where Δ is lateral displacement and h is storey height. Experimental behavior of controlled drift proves the lateral performance to be improved in beam-slab systems.

All in all, experimental studies have consistently identified that conventional beam-slab systems have been found to be more stiff, stable in strength, better ductile and more efficient in dissipation of energy when subjected to seismic loads. Their discovery supports their appropriateness as a structurally resilient choice when the buildings are built in the areas characterized by earthquakes.

3.3 Experimental Investigations on Flat Slab Systems

Laboratory studies on flat slab systems have given essential information on the seismic performance of such systems especially their stiffness, drift characteristics, punching shear strength, and general stability to loading during earthquakes. Many laboratory tests such as slab-column connection tests, cyclic loading tests and shake-table tests have been performed to investigate their behavior in the presence of the lateral and combined lateral and vertical forces. The studies assess some of the main seismic performance parameters that include the lateral stiffness, the displacement capacity, the ductility, and the efficiency of the energy dissipation.

The punching shear capacity is one of the most significant areas of experimental study because it is one of the most important failure modes in the flat slab systems because the load is transferred to the columns directly through the slab. Punching shear stress is usually measured with the help of:

$$v = \frac{V_u}{b_0 d}$$

Expressions that can be used to compare design strength include:

$$V_c = 0.75\sqrt{f'_c}\, b_0 d$$

Flat slabs also have a lower lateral stiffness that is usually calculated as:

$$k = \frac{F}{\delta}$$

Reduced stiffness means increased lateral movements, determined by storey drift ratio:

$$\text{Drift Ratio} = \frac{\Delta}{h}$$

The experiment results have shown higher ratios of drift, which means that it is more flexible and may not be stable during intense earthquakes.

Ductility is another major parameter that is experimentally measured and this is a measure of the ability to deform before failure:

$$\mu = \frac{\Delta_u}{\Delta_y}$$

Studies that usually tend to demonstrate that flat slab systems have a relatively lower ductility unless they are reinforced with appropriate detailing.

Energy dissipation is measured by the area of the hysteresis loop in the case of cyclic loading with the larger the area enclosed considered that the seismic performance is better. Findings indicate that flat slabs that are insufficiently detailed have low dissipation of energy, but systems reinforced with drop panels, column capitals, shear reinforcement or shear walls have much better hysteretic behavior.

Overall, experimental research establishes that despite the benefits of flat slab systems on the architectural dimension and structural effectiveness in the context of gravity loads, the seismic behavior should be meticulously designed. To promote safe and reliable behavior in earthquake prone regions, the slab-column connection, enhancing of the punching shear resistance, and incorporation of the lateral load-resisting elements are required.

4. Comparative Seismic Performance, Vulnerabilities, and Strengthening Strategies

The relative evaluation of beam slab and flat slab structures subjected to earthquake loading is necessary to know the comparative benefits and shortcomings of the systems and the reliability of their safety in seismic prone areas. Conventional beam-slab structures tend to be more seismically stable because their loads are clearly defined, increased in stiffness and ductility because of the beam availability. These properties make them efficient in combating the lateral forces, inter-storey drift, and dissipation of seismic energy and hence the chance of sudden collapse is minimized. Their mechanisms of failure are predictable and add to safer structural behavior during strong ground motions [15].

On the other hand, flat slab systems, despite their efficiency in architecture and structural advantages during gravity, have relatively high susceptibility during seismic forces. The immediate transfer of loads between slab and columns leads to an accumulation of stress at slab to column connections and therefore they are prone to punching shear and localized brittle failures. Also, less lateral stiffness would result in greater lateral movements and instability in case of major earthquakes. Nevertheless, the seismic practice ability of flat slab systems has been strongly achieved because of the contemporary design method, enhanced reinforcement detailing, and connection to other objects resistant to lateral loads.

To mitigate vulnerabilities, several strengthening measures are suggested and tested in research. To improve stiffness and punching shear resistance, some of the measures that are usually suggested in relation to flat slab systems include the fortification of the slab thickness, dropping panels or capital of columns, the use of shear reinforcement, and the application of post-tensioning. Additional enhancement of the lateral stability is done by the use of shear walls, core systems, and moment-resisting frames. In the case of beam slab, minimized reinforcement detailing, confinement reinforcement and ductile design practices can be used to achieve better seismic performance. Therefore, suitable selection and strengthening plan, on the basis of the structural needs and seismic loads, is an essential part of the realization of the safe and stable building.

Table 2: Seismic Performance of Beam–Slab vs Flat Slab Systems

Parameter	Beam–Slab System	Flat Slab System
Load Transfer Mechanism	Load transferred from slab → beams → columns; well-defined load path	Direct load transfer from slab to columns; concentrated stress at joints
Lateral Stiffness	Generally high due to beam support	Comparatively lower, leading to higher displacement
Ductility	High ductility with progressive yielding behavior	Generally lower ductility unless strengthened
Energy Dissipation	Efficient energy dissipation under cyclic loading	Limited unless reinforced with supplemental systems
Seismic Drift Control	Better control over storey drift	Higher drift tendency
Punching Shear Vulnerability	Minimal; beams reduce concentration of shear	High; critical at slab–column connections
Failure Mode	More predictable and ductile failure	Often brittle punching failure if not strengthened
Construction & Architectural Flexibility	Moderate flexibility; deeper floor systems	High architectural flexibility; reduced floor height
Strengthening Requirements	Mainly reinforcement optimization and ductility enhancement	Requires drop panels, column capitals, shear reinforcement, shear walls, or cores
Suitability for Seismic Zones	Highly suitable for moderate to high seismic zones	Suitable with advanced detailing and strengthening in moderate to high seismic zones

Conclusion

This review gives a detailed comparison evaluation of the seismic efficiency of the conventional beam-slab and flat slab systems with respect to their behavioral characteristics, weaknesses, and strengthening needs, during earthquake loading. The beam-slab systems tend to be more stiff, strong, ductile and provide better energy dissipation because of their clear mechanism of load transfer, which leads to better drift control and predictable seismic behavior, hence the level of moderately high to high seismic zones. Despite the benefits of a flat slab system like the ability to provide architectural flexibility, lowering the height of the floor, accelerating construction speed, flat slab systems are characterized by lower lateral stiffness and heightened susceptibility to punching shear and localized brittle failures, especially at the slab column intersections. Their performance can however be greatly enhanced by the proper description of reinforcement, the use of drop panels, column capitals, shear reinforcement, combinability with shear walls or core systems facilitated by the progress of performance-based design and modification of codes. Hence selection of slab systems in seismic areas must be influenced by the structural safety factor than by architectural convenience alone so that the practice can be resilient, reliable and sustainable.

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