CONTEMPORARY STRUCTURES IN THE ERA OF DIGITAL AND SUSTAINABLE CONSTRUCTION

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Abstract

Digitalization of design, growing sustainability requirements and the growing need for functional resilience of buildings after earthquakes are changing the paradigm of modern construction. This paper provides a critical overview of modern seismically resistant structural systems (frame systems, wall/core systems, dual systems, additional energy dissipation systems and basic seismic isolation), with a mathematical foundation of basic principles (spectral calculation, control of interfloor displacements, energy dissipation and effective attenuation). The analysis is complemented by five representative case studies from recent practice: (i) Başakşehir Çam & Sakura City Hospital (Istanbul) – large-scale base isolation, (ii) Apple Park (Cupertino) – base isolation of a large corporate campus, (iii) SFO International Terminal (San Francisco) – an early example of a friction pendulum, (iv) Tokyo Skytree (Tokyo) – a central pillared vibration control system inspired by the concept of "shinbashir", and (v) Wilshire Grand Center (Los Angeles) – a high-rise building with Stiffening System and Dissipative Elements (BRB). A comparative table of performance, key technologies and project frameworks is provided, as well as a critical discussion in the context of Eurocode 8 and ASCE 7/41. In conclusion, an integrated framework for performance-based design with BIM/digital twin and LCA metrics is proposed, with a focus on preserving the functionality of buildings and reducing overall lifecycle losses.

Keywords: *seismically resistant structure, ram constructive systems, basic seismic isolation, energy dissipation, performance design, BIM; digital twin, Eurocode 8, ASCE 7, sustainability.*

JEL classification: P01, P56, O33, L74, R33

1. INTRODUCTION

Modern construction is at a turning point in its development, conditioned by the simultaneous action of accelerated urbanization, climate change, increasingly stringent requirements in terms of sustainability and intensive digital transformation of engineering practice [10, 21]. In this context, the design and implementation of seismically resistant structures occupy a central place, especially in regions with pronounced seismic activity, because earthquakes dominate the risk of sudden collapse and large indirect losses. A modern approach to seismic safety goes beyond minimal collapse prevention and includes damage control, preservation of functionality (e.g., hospitals, airports, management centers), reduction of economic losses, and accelerated community recovery [5, 12].

The concept of performance-based design (PBSD) relies on nonlinear analysis and clearly defined objectives (drift, plastic rotations, damage to non-load-bearing elements), applying the principles of capacitive design and detailing for ductile behavior [7, 17, 18]. At the same time, the development of numerical methods (FEM) and nonlinear dynamics algorithms has allowed for more realistic modeling of stiffness and strength degradation, cyclic behavior, and cumulative damage [3, 9]. The connection of BIM, digital twins and SHM systems enables the closing of the loop between the project, the as-built state and the exploitation, which is especially important for critical infrastructure facilities [4, 10].

The aim of this paper is to systematize modern seismically resistant constructive systems, mathematical and engineering foundation of basic response parameters, processing of five case studies from recent practice and critical linking with Eurocode 8 and ASCE 7/41 for the transferability of conclusions.

The paper is based on an analytical-synthetic review of literature and project practice. For case studies, publicly available technical descriptions and expert reviews of investors, designers and relevant professional publications (e.g. ENR, SOM), as well as expert reviews on specific systems (e.g. base insulation, BRB, vibration control) were used. The comparison was made through: system type, performance targets, dominant energy dissipation mechanisms, expected drift/acceleration reduction, execution complexity, and compatibility with Eurocode 8 and ASCE frameworks.

2. MODERN SEISMIC RESISTANT STRUCTURAL SYSTEMS

The design of seismically resistant structures in modern engineering practice is based on a clearly defined hierarchy of load-bearing capacity, control of fracture mechanisms and rational management of seismic energy (Figure 1). Unlike traditional approaches, which mainly relied on increasing rigidity and strength, modern systems tend to optimize ductility, energy dissipation, and controlled damage to load-bearing elements [7, 17, 18].

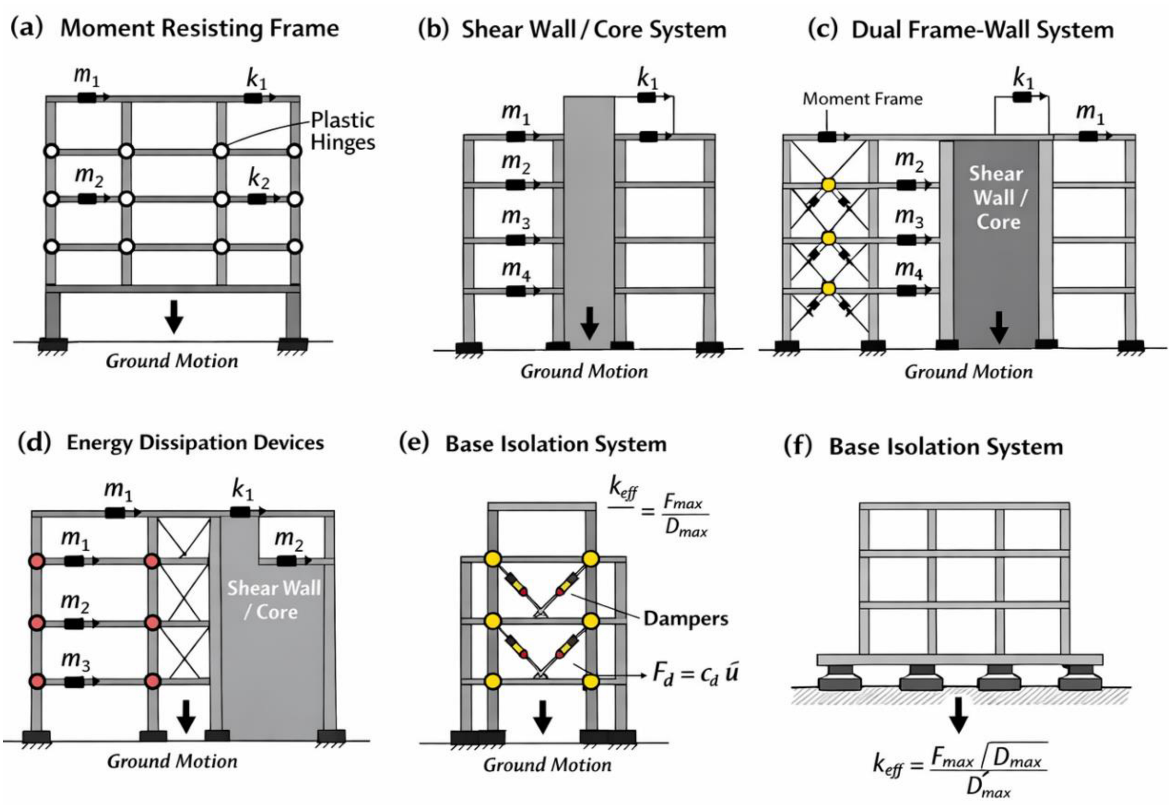

Figure 1: *Seismic-Resistant Structural Systems*

2.1. Ram (ram) constructive systems

Structural frame systems (Figure 1a), especially reinforced concrete and steel frames, continue to be the basis of seismic design in a large number of buildings. Their seismic resistance is based on the formation of plastic joints in predefined zones, whereby the energy of the earthquake is dissipated through the hysteresis behavior of the material [5, 16]. Modern approaches insist on the principle of "strong pillar – weak beam", which provides a stable mechanism of behavior and prevents progressive collapse [11, 17, 18].

Advances in numerical modeling have made it possible to accurately simulate the nonlinear behavior of frame systems, including stiffness and strength degradation, as well as cumulative damage due to cyclic loading [3, 7, 9]. Particular attention is paid to the detailing of nodes, which represent critical zones from the point of view of seismic reliability [1, 5].

Figure 1a shows a classic frame system (torque frame) without walls/stiffeners, where columns and beams are connected to transmit torques.

- *m_1, m_2:* a lot of floors.
- *k_1, k_2:* floor stiffness (the sum of the stiffness of the columns and frame fields).
- *Plastic Hinges:* marked zones where plasticity is intentionally expected (usually in beams at the ends), as part of capacity design ("strong column-weak beam").

MRF achieves seismic resistance through ductility and hysteresis energy dissipation in plastic joints. The advantage is the robustness and distribution of damage, and the disadvantage is the relatively higher drift if there is not enough stiffness.

2.2. Stiffening walls and core

Stiffening walls, whether in the form of classical seismic walls or central cores, play a key role in controlling horizontal displacements and limiting interfloor displacements [17, 18]. In modern multi-storey buildings, these elements are often

combined with frame systems, thereby forming the so-called dual systems [2, 11].
Modern research points to the importance of proper arrangement of walls in the floor plan, in order to minimize torsional effects and uneven seismic behavior [7, 34]. Particular attention is paid to the nonlinear behavior of the walls, the appearance of sliding and bending fracture mechanisms, as well as the interaction with the foundation structure [18, 35].
Figure 1b shows the dominance of the reinforced concrete wall/core as the main lateral resistance.

- The wall/core significantly increases the K (lateral stiffness).
- I've got a lot of stiffness and stiffness that is now "under control" of the wall.

The system gives high rigidity → less drift, but requires attention to:

- layout in the floor plan (torsion),
- nonlinear wall mechanisms (bending/sliding shear),
- interaction between the foundation and the wall.

2.3. Dual Systems and Hybrid Solutions

Dual systems are a combination of framework systems and stiffening walls, with both subsystems actively participating in the assumption of seismic effects. Such solutions allow for optimal distribution of internal forces, increased redundancy and a higher level of seismic reliability [2, 11, 36].
Hybrid solutions, which include a combination of different materials (reinforced concrete-steel, steel-wood), are increasingly being used in modern construction. Their advantage is reflected in the ability to adjust the seismic response of the structure, while improving sustainability and reducing the mass of the object [20, 32].
Figure 1c shows the combination:

- frames (distributed ductility and redundancy),
- wall/core (stiffness and drift control).

In the panel, you can see the Shear Wall/Core as the central rigid element + frames with stiffeners.
The dual system is often the "golden mean":

- the wall carries a large part of the lateral shear and controls the drift,
- RAM contributes to ductility and redistribution of forces.

It is important to properly "adjust" the ratio of stiffness and load-bearing capacity (so that one subsystem does not "suffocate" the other or does not take over everything).

2.4. Energy dissipation systems

Systems with additional energy dissipation are one of the most important innovations in the field of seismic engineering. These systems include viscous, viscoelastic, and metal dampers, which are designed to absorb a significant portion of seismic energy and reduce the demands on the primary load-bearing elements [6, 19].
The application of energy dissipation systems enables the design of structures with reduced damage, which increases their functionality after earthquakes [12, 20, 32]. Modern approaches integrate these systems into digital models of structures, which allows them to be optimized in the early stages of design [33].
Figure 1d shows additional elements (dampers, metal fuse-zones, BRB, viscous dampers) that "subtract" the energy of the system.

- The red dots in the panel symbolize the locations of the dissipative elements.
- The essence is to increase **C** (effective attenuation) without a large increase in K.

Instead of wasting energy on damaging the primary elements, "sacrificial" or dissipative elements are introduced:

- Reduce drift and/or acceleration.
- They can be very suitable for repairs and extensions,
- It is possible to design for "low-damage" concepts.

2.5. Base seismic isolation

Baseline seismic isolation is one of the most effective approaches to protecting structures from earthquakes. By installing insulating elements between the structure and the ground, a significant reduction in the transmission of seismic forces is achieved, as well as an extension of the object's own oscillation period [3, 15].

Modern insulation systems, such as lead-rubber bearings and friction-controlled sliding insulators, provide high reliability and predictable behavior[]. These systems are particularly suitable for facilities of strategic importance, such as hospitals, bridges and critical infrastructure facilities [20, 32].

The development of basic insulation is closely related to advances in experimental research and numerical simulations, which allow detailed examination of the long-term behavior of insulating elements, including the impact of aging and repeated seismic events [8, 15].

Figure 1e shows the insulation at the foundation level that is changing global dynamics. Insulation increases the effective period of construction (T increases), reduces spectral accelerations in the superstructure, "displaces" most of the displacement to the insulation plane. That is why it is great for hospitals, terminals, bridges, critical infrastructure facilities.

Figure 1f shows the emphasis on the physical layer of the insulator. This panel is a "clean" representation of a building standing on insulators (bearings). Panel f serves as a visual "summary" of the insulation: the main constructive concept is the separation of the superstructure from the movement of the ground and the control of the transmission of forces.

2.6. Comparative analysis of the system

Eurocode 8 and ASCE 7 are clearly defined (Table 1):

- the hierarchy of load-bearing capacity,
- permissible deformities,
- requirements for ductility,
- I'm using isolation and dissipators.

The modern constructions presented in this paper are fully compliant with these standards, but also upgrade them with the use of digital technologies and sustainable materials.

Table 1: *Comparative analysis of the system*

System	Ductility	Cruelty	Damage	Cost	Standards
Ramovski	high	Medium	Controlled	Medium	EC8 / ASCE 7
Dual	high	high	small	Medium	EC8 / ASCE 7
Dissipation	very high	Medium	very small	Higher	FEMA
Base insulation	very high	Low	Minimum	high	EC8 / ASCE 7

3. DIGITAL TOOLS AND NUMERICAL MODELING OF SEISMIC BEHAVIOR

Modern structures are designed using BIM, nonlinear FEM analyses and digital twins. These tools make it possible to optimize structures in terms of weight, material consumption and seismic performance, which directly contributes to sustainability [33].

3.1. The Role of Digital Technologies in Seismic Design

Digital technologies are a key segment of the modern engineering approach to seismic design. The integration of advanced software tools enables engineers to analyze in detail the behavior of structures under seismic loading conditions, simulate complex interactions, and optimize structural solutions already in the conceptual design phases.

The use of Building Information Modeling (BIM) platforms enables the unification of geometric, material and functional data on the structure into a single digital model, which significantly improves the coordination of project teams and the accuracy of seismic analyses [10].

3.2. Numerical modelling methods

Although linear seismic analyses remain part of standard design practice due to their simplicity and lower computational requirements, their application is limited in structures subject to large deformations. Therefore, modern approaches rely on non-linear static (pushover) and dynamic analyses that allow more accurate prediction of the behavior of the structure in phases close to plastic fracture [38].
Nonlinear models include detailed modeling of material properties, degradation of stiffness and strength, as well as simulation of cyclic effects and cumulative damage [7].
The finite element method is a basic tool for simulating the seismic behavior of complex structures. Models can range in varying levels of complexity — from simplified macromodels for preliminary analyses to detailed micromodels involving material heterogeneity and complex contacts between elements [3].
The use of adaptive networks and parallel computational techniques allows for simulations of large models with high accuracy in a reasonable time frame.

3.3. BIM and digital twins

The integration of BIM technologies with seismic analysis enables the automatic exchange of data between building models and numerical software. This approach reduces data transfer errors, speeds up iterative design processes, and enables real-time visualization of deformation and failure [39].
Digital twins are dynamic digital representations of physical objects that are updated with data collected through sensors and structural health monitoring (SHM) systems. The application of digital twins in seismic engineering makes it possible to monitor the actual behavior of objects over time, predict potential damage, and make informed decisions about maintenance and repair [40].

3.4. Structural Health Monitoring (SHM) systems

SHM systems use sensors to measure vibration, displacement, and other parameters, allowing for continuous assessment of the condition of the structure. These systems are especially important for facilities exposed to frequent seismic events, where timely detection of damage can prevent catastrophic consequences [41].
The integration of SHM with digital twins and BIM platforms represents a promising direction in the development of smart and sustainable seismically resistant structures.

4. SUSTAINABLE ASPECTS AND LIFE CYCLE OF SEISMICALLY RESISTANT STRUCTURES

4.1. Sustainable construction in seismically active areas

The development of sustainable construction is one of the key challenges of modern engineering, especially in regions prone to seismic effects. Sustainable concepts include not only energy efficiency and the reduction of the carbon footprint during the construction phase, but also the long-term resilience and functionality of buildings [42].
Seismically resistant structures that successfully survive earthquakes have a direct impact on reducing the consumption of resources needed for rehabilitation and reconstruction, which contributes to the overall sustainability of the system. This promotes the concept of "resilience through sustainability," where the key goal is not only to survive a disaster, but also to quickly restore functionality [5].

4.2. Materials with a reduced environmental footprint

The use of materials with a low carbon footprint and high durability is one of the main directions of sustainable seismic design. These include:

- the use of recycled steel and concrete,
- application of innovative composite materials with fibers,
- development of concrete with the addition of industrial by-products (flyer, ash from thermal power plants),
- Research in the field of bio-based and carbon-neutral building materials [43].

These materials not only reduce greenhouse gas emissions, but often have better mechanical properties, which further contributes to seismic resistance.

4.3. Design for long service life and easy renewal

The design of seismically resistant structures should enable not only resistance to the immediate consequences of earthquakes, but also simple and fast restoration and maintenance procedures. This includes:

- modular structural elements with easily replaceable parts,
- design approaches with the possibility of repositioning or adapting the energy dissipation system,
- Implementation of structural health monitoring systems that enable timely identification of damage and planning of interventions.

This approach contributes to the reduction of overall maintenance costs throughout the life cycle of the building and increases its economic and environmental sustainability.

4.4. Life Cycle Assessment (LCA) and Seismic Resistance

Life Cycle Assessment (LCA) is a quantitative tool for evaluating the environmental impacts of buildings throughout their life cycle, including the stages of construction, exploitation, rehabilitation and recycling.

The integration of LCA with performance-based seismic design allows for design optimization not only in terms of safety and functionality, but also in terms of minimizing negative environmental effects [44]. This represents a new direction in research, where design is done through a holistic approach to sustainability.

4.5. Examples of good practice and standards

Standards and recommendations for sustainable seismic design increasingly include requirements to reduce the environmental footprint and increase the resilience of buildings. Examples of such documents are:

- Eurocode 8 in combination with EN 15804 (standard for LCA of construction products),
- FEMA P-58 (USA) that integrates performance and life cycle,
- Sustainability Assessment Frameworks in Earthquake-Prone Areas Developed in Pacific Countries.

The implementation of these standards in practice significantly contributes to the integration of safety and sustainability, which is the foundation of modern seismic construction.

5. CASE STUDIES OF MODERN SEISMICALLY RESISTANT STRUCTURES

5.1. Taipei 101 (Taiwan) – frame system with TMD

The Taipei 101 skyscraper is one of the most famous examples of the integration of frame systems and vibration control systems. The structure uses a massive TMD (tuned mass damper) weighing about 660 tons, which significantly reduces seismic and wind oscillations. This system makes it possible to preserve the usability of the building even during strong earthquakes [20].

The Taipei 101 uses one of the most famous tuned mass damper (TMD) systems in the world (weight ≈ 660 t), located at the top of the facility. The structure is a combination of steel frames and reinforced concrete cores.

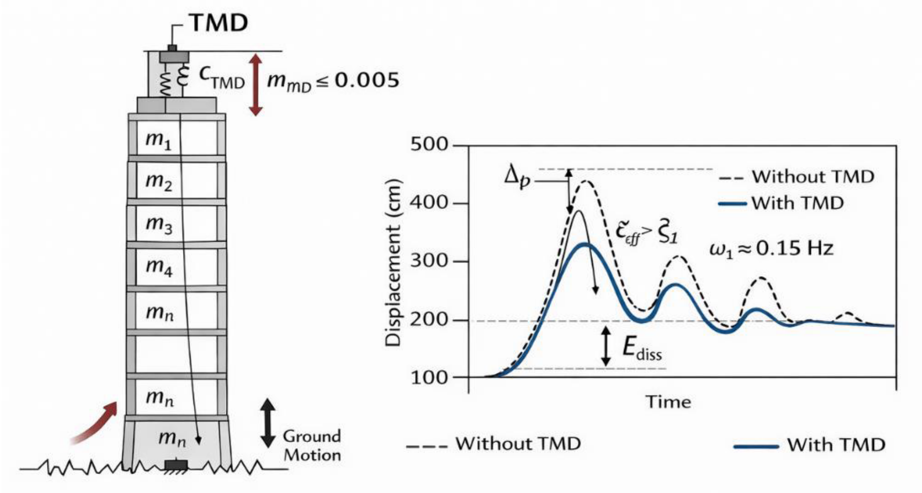

Figure 2: *Idealized dynamic model of the Taipei 101 skyscraper*

Figure 2 shows an idealized dynamic model of the Taipei 101 skyscraper, designed as a frame (torque-resistant) structural system with an additional vibration control system - a tuned mass damper (TMD), located on top of the object. TMD does not significantly change the payload capacity of the system, but it does drastically reduce the dynamic response, especially in long-term excitations.

The left side of Figure 2 shows a building modeled as a multi-stage system with discrete masses:

- The masses m_1, m_2, ..., mn represent the effective masses of the individual floors,
- interfloor stiffness (implicitly) comes from a frame system with rigidly bonded beams and columns, which provides resistance to bending and shearing,
- The seismic effect is shown as ground motion, which induces inertial forces in the masses of the floors.

This representation corresponds to the MDOF (multi-degree-of-freedom) model, standard in seismic dynamics of structures.

The right side of Figure 2 shows the comparative time response of the movement of the top of the building.

5.2. Seismically Resistant Buildings in Japan

Japan is one of the most active seismic areas in the world and is an example of cutting-edge engineering expertise in the field of seismically resistant design. Buildings in urban centers such as Tokyo and Osaka are designed using advanced construction systems that integrate:

- Base seismic insulation with rubber-lead bearings that reduce force transmission by up to 70% [45],
- high ductile steel frames with dissipative connections,
- Sophisticated vibration control systems that include active and passive dampers.

In addition to technical solutions, Japan uses developed digital tools and SHM systems to monitor the condition of objects in real time, enabling timely assessment of safety after the earthquake [46].

5.2.1. Tokyo Skytree (Tokyo) – central column vibration control system (shinbashira concept)

Tokyo Skytree integrates a vibration control system inspired by traditional pagodas ("shinbashira"), where the central pillar and outer frame oscillate with different phases, effectively reducing global response. Expert descriptions state that the concept can significantly reduce wobble (e.g., up to ~50% in certain regimes) [25]. Although it is primarily a vibration control system, it conceptually belongs to the class of "response modification systems" that are complementary to capacitive design.

Figure 3 clearly demonstrates that the Tokyo Skytree uses an advanced seismic concept based on the interaction of two dynamically distinct systems, with the central pillar acting as:

- internal mass damper,
- system for the redistribution of seismic energy,
- and a key element in reducing the global response.

This approach is a prime example of modern seismic engineering, with strong potential for application in future super-tall structures.

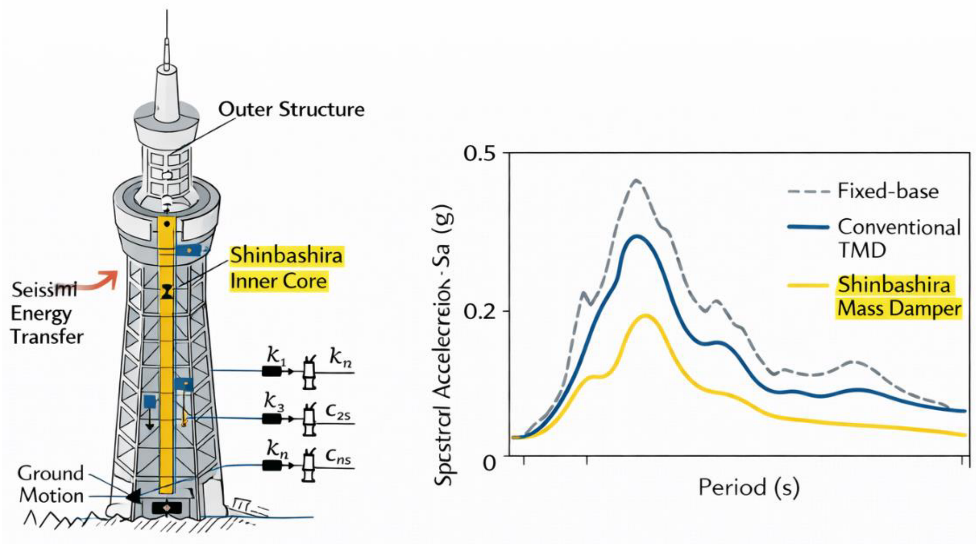

***Figure 3:** Seismic performance of Tokyo Skytree utilizing a central mass damper (shinbashira)*

Figure 3 shows the constructive-dynamic concept of the Tokyo Skytree, based on a central column vibration control system, known as *the shinbashira* concept, which originates from traditional Japanese wooden architecture (pagodas). Left part of Figure 3 (constructive and dynamic model) - The tower's outer structure (designated as *the Outer Structure*) represents the main load-bearing system of the steel frame-truss type, which takes on vertical loads and part of the seismic forces. In its interior there is a central pillar – shinbashira, clearly marked and highlighted in yellow (*Shinbashira Inner Core*).

The graph on the right side of Figure 3 shows *the Spectral Acceleration (Sa)* spectra as a function of the oscillation period for three cases: Fixed-base (dashed line), Conventional TMD (blue line) and Shinbashira Mass Damper (yellow line). The Shinbashira concept reduces maximum acceleration, works efficiently in multiple oscillation modes, and provides more robust behavior compared to classic TMD systems.

5.2.2. Sendai Mediatheque (Japan) — Innovative Ram System

The facility uses a unique spatial frame system with large-diameter steel pipes, enabling exceptional ductility and energy dissipation. This example illustrates the combination of architectural freedom and seismic safety.

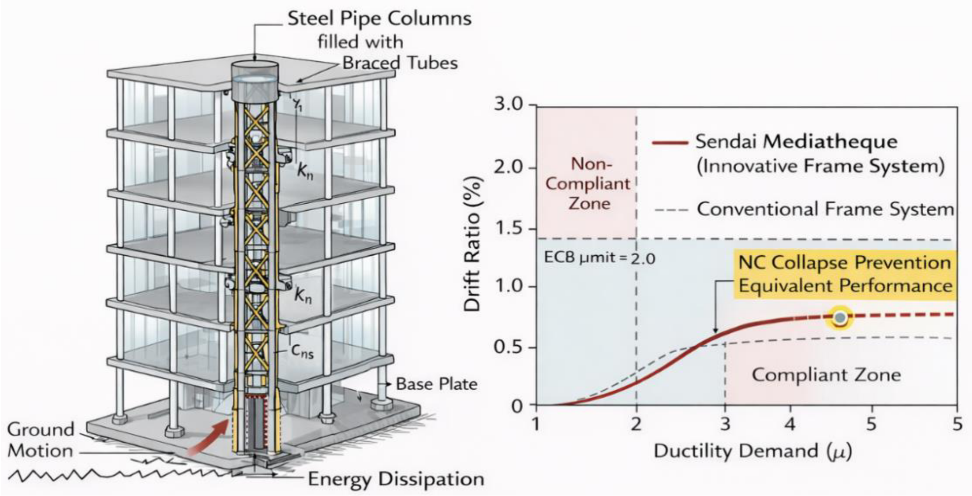

Figure 4: *Sendai Mediatheque – an innovative frame system*

The essence of Figure 4 is that Sendai Mediatheque is an example of an unconventional but high-ductile frame system, where the load-bearing elements are also energy dissipators. This approach shows how architectural freedom and high seismic capacity can be integrated into a single structural solution, in accordance with the modern principles of performance-based design.

5.3. Friction Pendulum, Dissipative Stiffening and Base Insulation in the USA

California faces a constant threat of powerful earthquakes, so seismic reinforcement measures are key to keeping existing structures safe. Renovation projects include:

- installation of base insulators in old reinforced concrete buildings,
- implementation of metal frames for energy dissipation in combination with original structures,
- Digital monitoring of the performance of reconstructed objects.

An example of a successful renovation is the San Francisco School Complex, where a combination of seismic isolation and SHM was used, significantly increasing the safety of children and faculty [47].

5.3.1. SFO International Terminal (San Francisco) – steel ball isolators

The San Francisco International Terminal is a classic example of base insulation in public infrastructure, with insulators that allow the superstructure to slide/swing independently of the ground. Expert reviews list 267 steel insulators (steel ball / friction pendulum concept), with a conceptual reduction of seismic forces of approximately ~70% compared to the fixed foundation [14, 22-24].

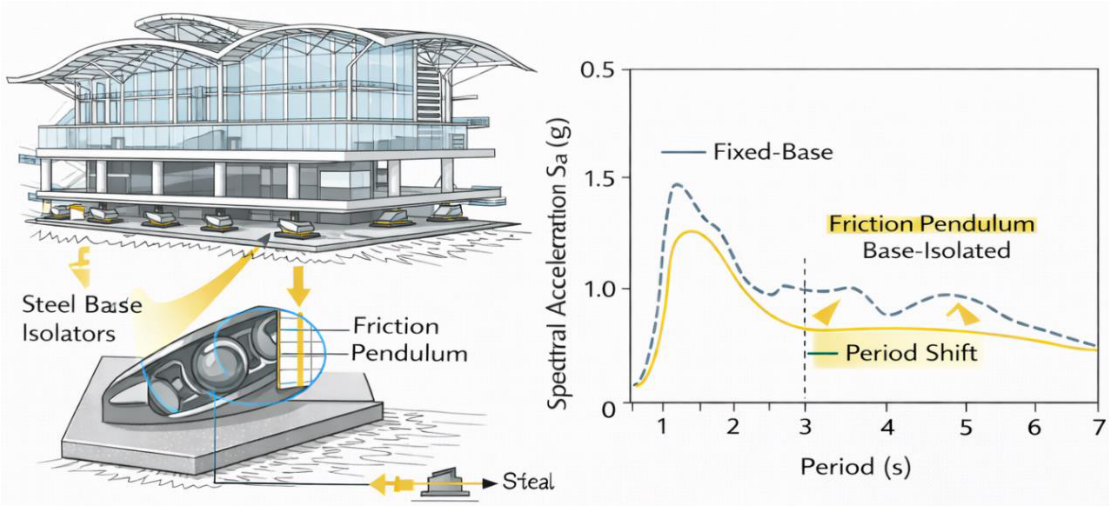

***Figure 5:** SFO International Terminal (San Francisco) – steel ball isolators*

The left part of Figure 5 shows an airport terminal that is base-insulated by steel ball/friction pendulum insulators placed between the superstructure and the foundation. Insulators allow the superstructure to move and slide over a curved surface in a controlled manner during an earthquake, whereby seismic energy is dissipated by friction. This achieves a separation of the movement of the ground and the structure, so the seismic forces acting on the object are significantly reduced. The bottom detail shows the principle of operation of the insulator: a steel pendulum ball moves along the concave surface and automatically returns the structure to its starting position.

The right-hand diagram (response spectrum) compares a fixed-based object (higher spectral accelerations) and a base-isolated object (lower accelerations). The key effect is the "period shift" – the extension of its own oscillation period, which moves the object to a more favorable part of the seismic spectrum.

Base insulation with a friction pendulum enables a drastic reduction of seismic forces and damage, which is crucial for the functionality of the airport after an earthquake and makes this facility one of the reference examples of modern seismic protection in the world.

5.3.2. Wilshire Grand Center (Los Angeles) – high-rise building with dissipative stiffening (BRB)

The Wilshire Grand Center is an example of a high-rise building designed for high seismic exposure, with the use of stiffening systems and dissipative elements (Figure 6). Expert reviews indicate the use of buckling-restrained braces (BRBs) in significant numbers (e.g., hundreds of pieces), thus providing stable hysteresis energy dissipation and drift control [28, 29]. This concept is compatible with the PBSD approach that is common in high-rise buildings on the West Coast.

Construction concept: The high-rise building uses BRB type steel dissipative couplings embedded in the core and peripheral frame, thus ensuring high ductility and stable behavior under cyclic seismic loading.

BRBs are designed to equally carry tension and pressure without buckling, allowing for reproducible hysteresis behavior and efficient dissipation of seismic energy.

Seismic forces are taken over the frames and cores, and plastic deformation is intentionally localized in the BRB elements, while the primary load-bearing elements are protected.

Graphical representation (right): The diagram shows that the system with BRB achieves less interfloor drift for the same level of ductility compared to conventional couplings, while meeting the Collapse Prevention (CP) criteria according to modern standards.

Engineering significance: This system is a typical example of performance-based design (PBSD) for high-rise buildings in zones of high seismicity and is in line with ASCE7/ASCE41 practice, and conceptually with dissipative systems in Eurocode 8.

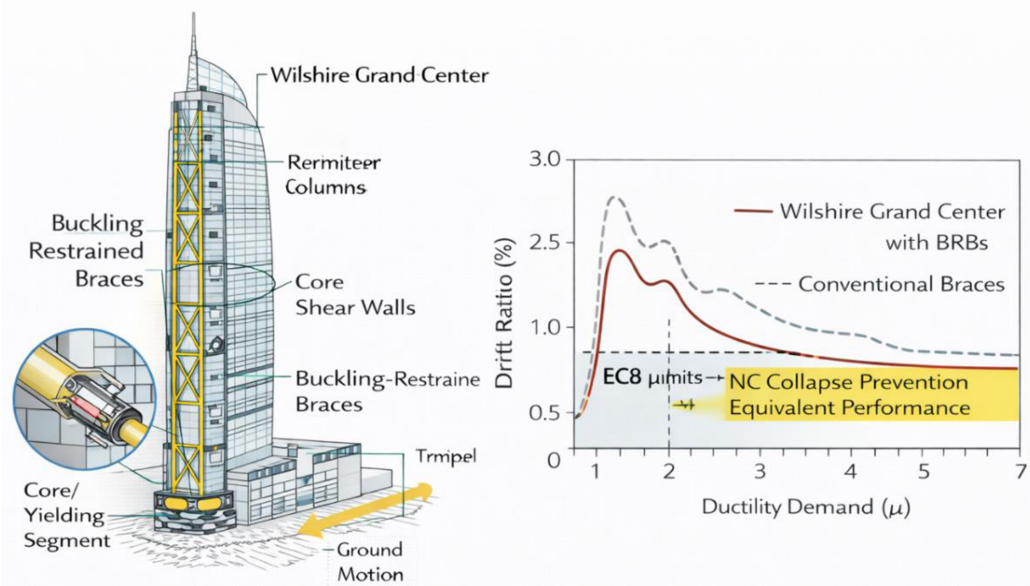

Figure 6: *Wilshire Grand Center (Los Angeles) – tall building with dissipative stiffening (BRB)*

5.3.3. Apple Park (Cupertino) – base isolation of the corporate complex

Apple Park ("Ring") is widely publicized as a complex with a large-scale base insulation system, which allows for significant relative displacements while preserving the functionality of the facility [26, 29]. The role of isolation is twofold: reducing spectral accelerations and protecting equipment and finishing systems, which is crucial for a quick return to service.

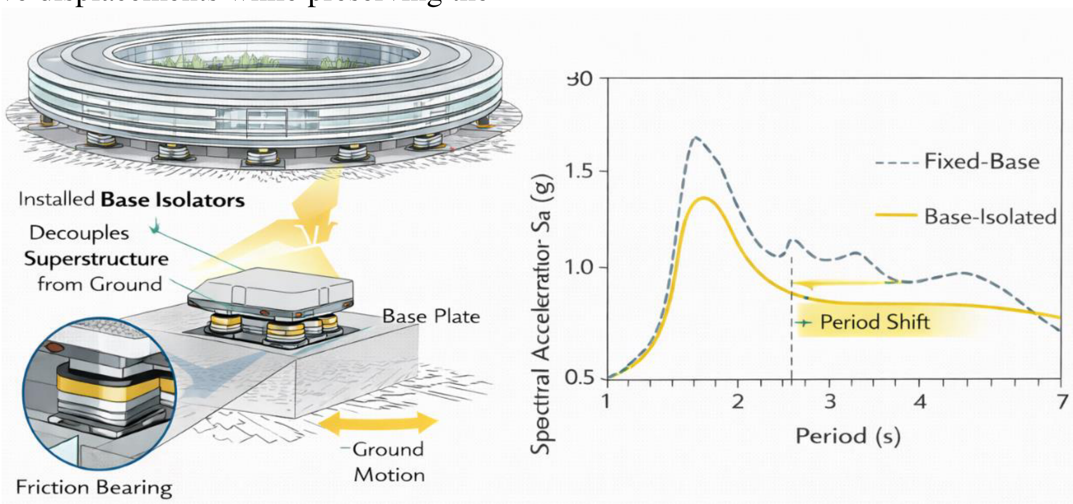

Figure 7: *Apple Park (Cupertino) – base isolation of the corporate complex*

Base insulators are placed between the foundation and the superstructure, mechanically separating (decouples) the object from the movement of the ground during an earthquake (Figure 7).

The earthquake movement of the ground is mostly "absorbed" in the plane of the insulation, while the superstructure remains much calmer.
The details in Figure 7 show the base insulators that allow for controlled movement and dissipation of energy.
The diagram on the right in Figure 7 shows the period shift:
- A fixed object has higher spectral accelerations.
- A base-isolated object has significantly reduced accelerations over the relevant period range.

The key effect of the system is to reduce seismic forces, damage to the structure and non-structural elements, while preserving the functionality of the complex after an earthquake.

5.4. Torre Mayor, Mexico City – Energy Dissipators

Torre Mayor uses more than 90 viscous silencers integrated into the frame system. During strong earthquakes, the structure showed minimal damage, confirming the efficiency of the system with additional energy dissipation [19].
A tall building with peripheral steel stiffening is shown, in which fluid (viscous) energy dissipators are installed (Figure 8). Dissipators are placed between oblique/perimeter couplings and convert some of the kinetic energy into heat (damping) during an earthquake. This reduces seismic accelerations, forces, and interfloor displacements of the structure.
The diagram on the right in Figure 8 compares the response with and without the dissipator and shows clearly lower spectral accelerations in energy-dissipated systems.
The concept allows for ductile, controlled behavior without significant damage to the primary load-bearing elements, which is crucial for objects in strong seismic zones such as Mexico City.

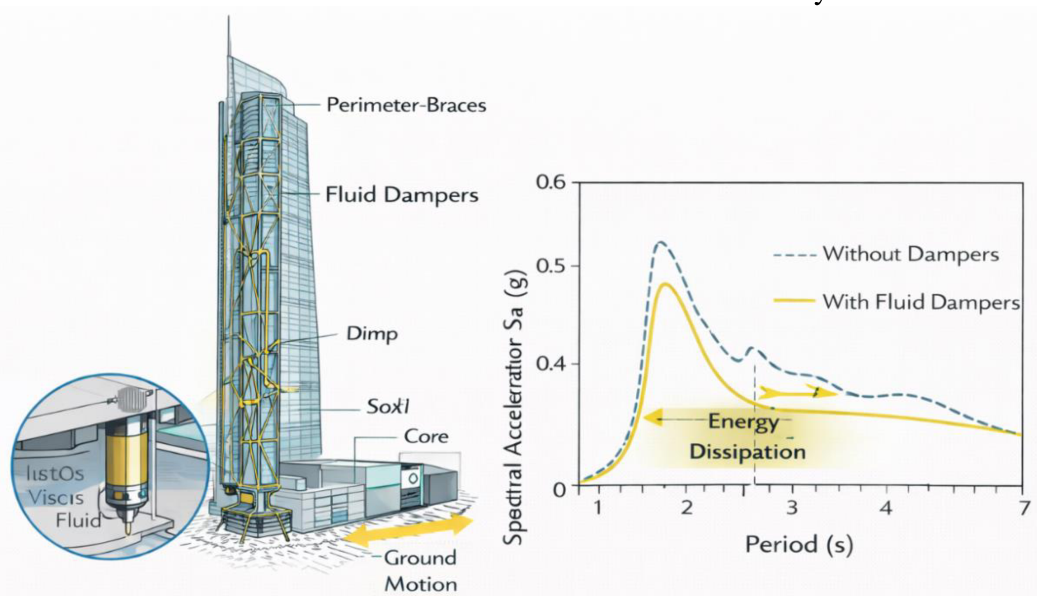

Figure 8: *Torre Mayor, Mexico City – energy dissipators*

5.5. Base Insulation and Hybrid Systems in Turkey

5.5.1. Başakşehir Çam & Sakura City Hospital (Istanbul) – Large-Scale Base Isolation

This complex is cited in expert sources as one of the largest (often the largest) seismically isolated buildings, with about ~2,000+ isolators in the main hospital building, with the aim of ensuring uninterrupted operability during and after strong earthquakes (nky.com.tr; Daily Sabah, 2025) (Figure 9). The dominant concept is the reduction of acceleration and damage to non-load-bearing elements, with displacement control at the level of insulation. For hospital-grade facilities, this approach directly supports the operational performance targets in PBSD Frameworks [12, 30, 31].

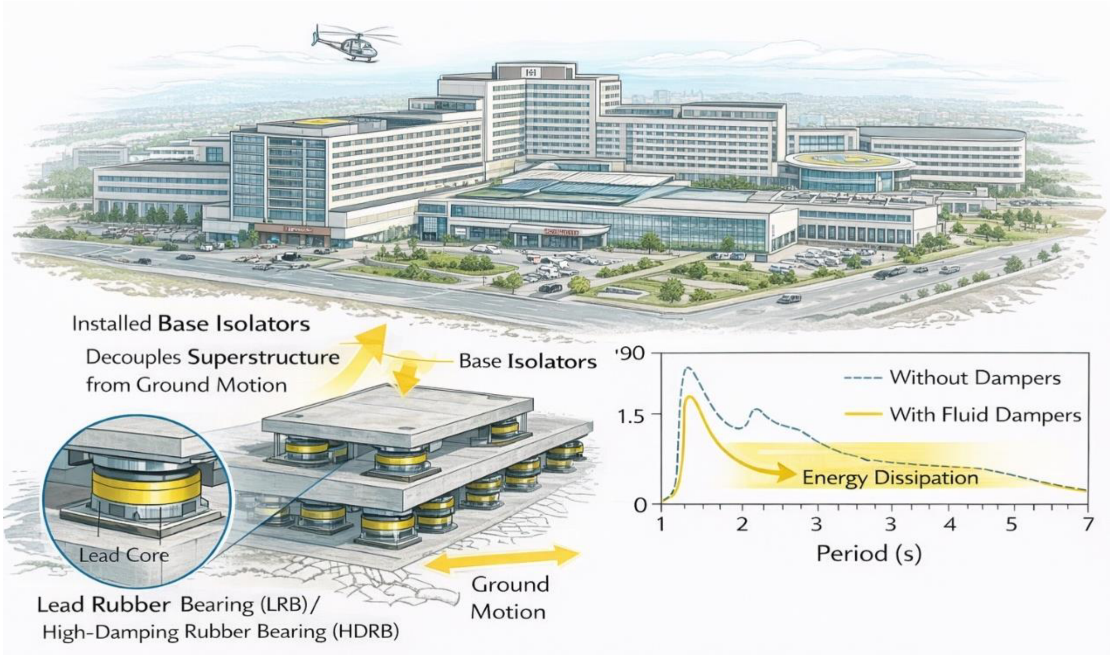

__Image 9:__ Başakşehir Çam & Sakura City Hospital (Istanbul)

5.5.2. Bosphorus Bridge Retrofit (Turkey) — Hybrid Systems

The Bosphorus Bridge is an example of hybrid seismic reinforcement that combines base insulation, dissipators, and local element reinforcement. The project is in line with modern seismic regulations and is a reference for infrastructure facilities [20].

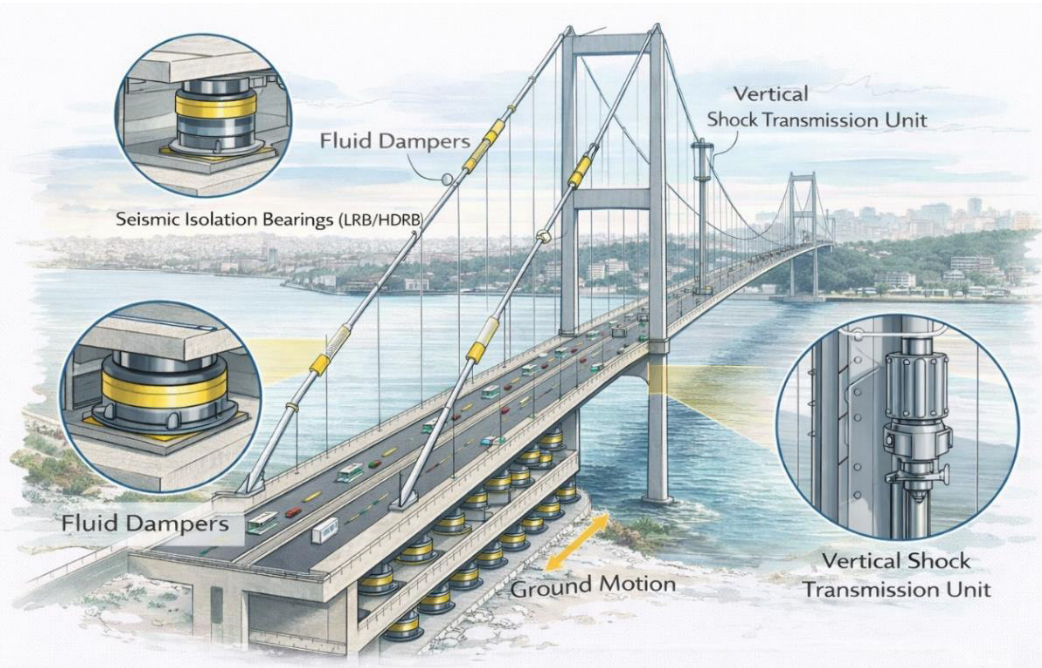

__Figure 10:__ Bosphorus Bridge Retrofit (Turkey) – hybrid systems

Figure 10 shows the seismic reinforcement (retrofit) of the Bosphorus Bridge using a hybrid protection system, which combines basic seismic isolation, energy dissipation, and displacement control. Elastomeric seismic bearings (LRB/HDRB) are installed on the bridge abutments to reduce the transfer of seismic forces from the ground to the structure, while fluid dampers are installed along the cables and span structure to dissipate energy during earthquakes and limit relative displacements. In addition, vertical shock transmission units provide a rigid response under slow loads (e.g. temperature, traffic) and a flexible and dissipative response under rapid seismic action. This combination of systems allows for a significant reduction in seismic demands, control of deformation and increase the reliability of the bridge without compromising its functionality and aerodynamic behavior.

5.6. A Comparative Review of Five Case Studies and Dominant Seismic Systems

A comparative tabular overview (Table 2) of five case studies systematizes different contemporary approaches to seismic protection through clearly observable differences in the dominant structural system, energy dissipation mechanism, and performance targets. The Taipei 101 and Tokyo Skytree are vibration control systems (TMD and shinbashira) in which seismic energy is reduced through phase shift and additional mass, predominantly to reduce the acceleration and oscillation of tall objects. Sendai Mediatheque and the Wilshire Grand Center rely on the ductile and dissipative behavior of the primary structure, through innovative frame systems, steel tubular columns and buckling-restrained braces (BRBs), thus achieving high ductility and reliable protection against collapse. SFO International Terminal and Apple Park are examples of baseline seismic isolation, where the superstructure effectively separates from the ground, shifts its own period, and drastically reduces seismic forces and damage, which is especially suitable for facilities that need to remain operational. Finally, the Bosphorus Bridge retrofit demonstrates a hybrid approach, in which insulators, shock absorbers and shock transmission devices are combined, thereby simultaneously controlling displacements, forces and shock effects. The table clearly shows that modern practice is moving from universal solutions to purposefully designed systems, where the choice of seismic concept depends on the type of object, the requirements of functionality and the acceptable level of risk, in accordance with the principles of Eurocode 8 and ASCE 7/41.

Table 2: *Comparative review of five case studies and dominant seismic systems*

Object	The dominant system.	Key implementation	Performance target	Binding with codes
Başakşehir Çam & Sakura City Hospital (TR)	Base Insulation (LRB/HDRB)	~2000+ insulators	The hospital's operability; Acceleration reduction	EC8: insulation (EN 1998-1) + national annexation; ASCE: Insulation (ASCE 7/41)
Apple Park (U.S.)	Base insulation (sliding/bearings)	A large number of insulators (public announcement)	Functionality and protection of equipment	ASCE frames; Conceptually analogous to EC8 solutions.
SFO International Terminal (US)	Friction pendulum/steel ball isolators	267 insulators	Reduction requirement ~70% (sources)	ASCE; An Early Reference Example of Isolation
Tokyo Skytree (JP)	Vibration control (central pillar + frame)	The Shinbashira Concept	Reduction of wobble (sources say up to ~50%)	It is not directly codified as isolation; It is connected to vibration control.
Wilshire Grand Center (US)	Dissipative stiffening (BRB)	320 BRB (case study)	Drift control and energy dissipation	ASCE; Compatible with the EC8 dissipative element concept.

5.4. Seismic resilience in the Balkans – examples and challenges

Seismically active areas of the Balkans face a number of challenges, including outdated infrastructure and limited resources for modernization. Examples of successful projects include:

- reconstruction and reinforcement of public buildings in Belgrade and Zagreb using composite materials (e.g. CFRP tapes) to increase ductility [48],
- application of traditional reinforced concrete wall systems with modern detailing of reinforcement in new buildings,
- the introduction of digital technologies in the planning and monitoring of the construction of new infrastructure facilities.

The main challenges remain in harmonizing standards and raising awareness of the importance of seismic resilience, which is necessary to reduce the catastrophic consequences of future earthquakes.

6. ADVANTAGES AND LIMITATIONS OF MODERN APPROACHES TO SEISMIC DESIGN

The Advantages of Modern Construction Systems

Modern systems, including base insulation, energy dissipators and hybrid designs, allow for a significant reduction in seismic damage and increase user safety. Performance-based design leads to structures that can better withstand extreme seismic events, reducing the risk of collapse [49].

The use of recycled and innovative materials in structures reduces the carbon footprint, while longevity and renewability increase, contributing to the overall sustainability of the construction sector [43].

Digital tools and BIM models enable more efficient coordination, reduce errors in the design and construction phases, as well as better control over the quality and performance of structures [10].

Limitations and challenges

The implementation of advanced systems such as base insulation and energy dissipators increases construction costs and requires a high level of expertise in design and construction. This can be a barrier in countries with limited budgets [15].

While international and regional standards exist, the harmonisation of regulations on advanced technologies and sustainability is still under development, making it difficult to apply them widely [12].

Numerical models depend on the accuracy of input data and assumptions, and their application in complex buildings requires significant computational time and expert interpretation of the results [7].

The effectiveness of SHM systems and digital twins depends on proper maintenance and continuous calibration of the sensors, which can pose an operational challenge throughout the lifetime of the facility [41].

Prospects for future development

The improvement of seismic engineering is expected through further integration of artificial intelligence in analysis and decision-making, the development of new sustainable materials with improved properties, as well as the wider application of smart systems for monitoring and adaptation of structures in real time. Also, interdisciplinary approaches that combine seismic resilience with urban planning and crisis management will become key to increasing the overall resilience of societies to earthquakes [5].

7. CRITICAL DISCUSSION AND LINKING WITH EUROCODE 8 AND ASCE 7/41

Eurocode 8 (EN 1998-1) and ASCE 7 use related logic, but different terminology and reduction coefficients. In EC8, the reduction of requirements is introduced through the behavior factor q and ductility class (DCL/DCM/DCH), with strictly prescribed rules of capacitive design and detailing, while ASCE 7 uses R (reduction), Cd (drift amplification) and Ω0 (overstrength), with the categorization of seismic risk and detailing requirements through accompanying standards (e.g. ACI/AISC). In both frameworks, for PBSD and non-linear procedures, it often relies on additional documents (e.g., FEMA P-58; ASCE 41).

For base insulation, both systems require explicit consideration of displacement in the insulation plane and verification of the load-bearing capacity and stability of the insulator, with special requirements for objects of importance. Case studies (hospitals in Istanbul; Apple Park; The SFO terminal confirms that the insulation is moving from a "special" technology to a standard solution for facilities with an operability requirement. For dissipative systems (BRBs), ASCE practice is highly developed, while EC8 formally supports dissipative behavior with detailed classification and rules, but implementation depends on national appendices and industry practice.

In tall objects, the critical point is the control of drift and secondary effects (P–Δ), as well as the interaction of the core, frame, and dissipative elements. Therefore, the PBSD, along with model validation and robust detailing, represents a practically indispensable framework [7, 18].

CONCLUSION

Modern structures in the era of digital and sustainable construction are integrated systems that combine advanced construction concepts, digital tools and sustainable principles. The analyzed examples confirm that seismic resilience today does not only mean preventing collapses, but also preserving functionality, reducing economic losses and long-term sustainability of buildings. Future developments will be geared towards even greater integration of digital technologies and adaptive constructions.

The analysis of modern seismically resistant structural systems shows that global practice is shifting towards solutions that ensure not only the prevention of demolition but also the preservation of functionality, especially for critical infrastructure facilities. Base insulation demonstrates the highest potential for reducing acceleration and damage in non-load-bearing systems, while dissipative systems (dampers/BRB) allow for economical control of drift and demands on primary elements. For tall buildings, combining cores, frames, and dissipative elements remains the most common path to robust performance.

Digital tools (BIM, digital twins and SHM) enable the transition to "life-cycle" seismic risk management, while sustainability requires that seismic resilience be seen as a key component of reducing overall emissions and resource expenditure through the avoidance of reconstructions. Coupling with Eurocode 8 and ASCE 7/41 demonstrates conceptual compatibility, with the need for careful translation of coefficients and detailing requirements depending on standards and local conditions.

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