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STRUCTURAL CONTROL SYSTEMS: EXPERIMENTAL VALIDATION AND IZIIS EXPERIENCE

Abstract:

This paper presents a critical review of passive and semi-active structural control systems for improving seismic performance and resilience. It synthesizes fundamental control principles with recent advances in energy dissipation technologies. Emphasis is placed on experimental validation to bridge the gap between analytical models and real structural behaviour. A key contribution is the integration of extensive experimental results from IZIIS. These include shake table tests on bridges, steel frames, and retrofit solutions. Overall, the results confirm the effectiveness of both individual and hybrid control strategies.

Keywords: structural control, passive energy dissipation systems, shake table testing

УПРАВЉАНЕ КОНСТРУКЦИЈЕ: ЕКСПЕРИМЕНТАЛНА ВАЛИДАЦИЈА И ИСКУСТВА ИЗИИС-а

Сажетак:

Овај рад представља критички преглед пасивних и полуактивних система управљања конструкцијама у циљу унапређења сеизмичких перформанси и отпорности. Синтетише основне принципе управљања са савременим достигнућима у технологијама дисипације енергије. Посебан нагласак стављен је на експерименталну верификацију као кључни елемент за превазилажење јаза између аналитичких модела и стварног понашања конструкција. Кључни допринос рада огледа се у интеграцији обимних експерименталних резултата из ИЗИИС-а (Институт за земљотресно инжењерство и инжењерску сеизмологију). Они обухватају испитивања на потресним столовима на мостовима, челичним оквирима и решењима за санацију. У целини, резултати потврђују ефикасност како појединачних, тако и хибридних стратегија управљања.

Кључне ријечи: управљане конструкције, пасивни системи, испитивање на сеизмичкој платформи.

1. INTRODUCTION

1.1. EVOLUTION OF STRUCTURAL CONTROL SYSTEMS

The concept of structural control has undergone significant evolution over the past decades, shifting from traditional strength-based design toward performance-oriented approaches focused on response mitigation. Early structural systems relied primarily on strength and ductility to resist dynamic loads; however, severe earthquake events revealed the limitations of such approaches, particularly in terms of damage control and post-event functionality [1], [2]. Structural control was formally introduced as an interdisciplinary field combining civil engineering, mechanical systems, and control theory. Initial developments focused on active control systems, which utilize external energy to counteract structural response. Despite their effectiveness, these systems are limited by high cost, complexity, and dependence on power supply. As a result, research gradually shifted toward more practical and reliable alternatives such as passive and semi-active systems [3]. In recent years, the evolution of structural control has been driven by the increasing demand for resilient infrastructure and sustainable design. Contemporary studies highlight the transition toward hybrid and adaptive systems capable of addressing uncertainties in seismic loading [4], [5]. These developments reflect a broader trend in engineering practice, where structural systems are designed not only to resist loads but also to actively manage and control their dynamic response.

1.2. CLASSIFICATION OF STRUCTURAL CONTROL SYSTEMS

Structural control systems are commonly categorized into passive, active, semi-active, and hybrid systems based on their operational mechanisms and energy requirements [3]. Passive systems, which do not require external energy, remain the most widely adopted due to their simplicity and robustness. Recent studies emphasize the increasing importance of hybrid systems, which combine different control strategies to enhance performance under complex loading conditions [6]. These systems are particularly relevant for modern high-rise buildings, where structural response is influenced by multiple dynamic factors, including wind and seismic excitations. Active and semi-active systems continue to be investigated, particularly in the context of smart structures and real-time control. However, their application is still limited in practice due to implementation challenges. Consequently, passive and hybrid systems remain the primary focus of current research and engineering applications [7].

1.3. PASSIVE ENERGY DISSIPATION SYSTEMS

Passive energy dissipation systems play a central role in modern structural control strategies. These systems function by absorbing and dissipating seismic energy, thereby reducing the demand on primary structural components. They are generally classified into rate-dependent and rate-independent devices. Rate-dependent devices, such as fluid viscous dampers (FVDs), generate forces proportional to velocity, while rate-independent devices, such as friction and metallic dampers, rely on displacement and hysteretic behaviour [8].

Fluid viscous dampers have received considerable attention due to their high efficiency and adaptability. Recent experimental and numerical studies demonstrate their effectiveness in reducing structural response, particularly in high-rise buildings [12], [14]. Additionally, research has shown that damper performance is influenced by parameters such as piston configuration, fluid properties, and orifice design [13]. Despite their advantages, individual passive devices may exhibit limitations under varying loading conditions. This has led to increased interest in optimizing damper properties and placement within structures to achieve maximum performance.

Base isolation remains one of the most effective passive control strategies for seismic protection. By decoupling the structure from ground motion, base isolation systems significantly reduce the transmission of seismic forces to the superstructure [22]. Recent advancements in base isolation technologies include the development of friction pendulum systems and high-damping rubber bearings, which provide improved energy dissipation and stability. These systems are increasingly used in both new construction and retrofitting applications.

In parallel, energy transfer mechanisms such as tuned mass dampers (TMDs) have been widely implemented in high-rise buildings. TMDs function by transferring vibration energy from the main structure to a secondary mass, thereby reducing overall response. Recent research has focused on advanced configurations, such as distributed and multiple TMD systems, which offer enhanced performance under multi-hazard conditions [6], [17]. These developments highlight the growing complexity and sophistication of modern vibration control strategies.

The rapid increase in the construction of high-rise buildings has intensified the need for effective vibration control strategies. Due to their flexibility and low inherent damping, high-rise structures are particularly susceptible to dynamic excitations. Recent studies have demonstrated the effectiveness of energy dissipation systems in improving the seismic resilience of tall buildings [9]. These systems not only reduce structural response but also enhance occupant comfort and structural serviceability. Furthermore, the integration of damping technologies into high-rise buildings has been significantly advanced through modern design approaches and materials. Developments in damping systems, including viscous and viscoelastic devices, have contributed to improved performance under both wind and seismic loading [10].

Japan has played a leading role in the development and implementation of structural control systems. Large-scale experimental studies, particularly shake-table testing, have provided valuable insights into the performance of controlled structures. Full-scale tests conducted at facilities such as E-Defence have demonstrated the effectiveness of passive control systems in reducing structural response and damage [23]. These studies have also contributed to the development of design guidelines and standards for structural control systems. The success of structural control technologies in Japan can be attributed to strong collaboration between academia, industry, and government, as well as the integration of experimental research with practical applications [24].

Hybrid passive control systems represent one of the most promising directions in structural control research. By combining multiple damping mechanisms, these systems aim to provide consistent performance under a wide range of loading conditions. Recent studies have demonstrated that hybrid systems can significantly improve energy dissipation capacity and reduce structural response compared to single-type devices [8]. Additionally, emerging technologies such as tuned mass damper inerters (TMDI) offer new possibilities for enhancing vibration control performance [17]. Future research is expected to focus on the integration of hybrid control systems with advanced digital technologies, including artificial intelligence and digital twins. These developments will enable more efficient design, optimization, and real-time control of structural systems.

Despite significant advances in structural control technologies, a clear gap remains between theoretical developments and experimentally validated performance under realistic seismic conditions. In particular, the integration of large-scale experimental evidence into design-oriented frameworks is still limited. This paper aims to address this gap by combining a critical review of control systems with extensive experimental results obtained at IZIIS, providing insight into real structural behaviour and practical implementation of passive and hybrid control strategies.

2. EXPERIENCE OF IZIIS IN STRUCTURAL CONTROL-SELECTED SHAKE TABLE TESTS

2.1. SEISMIC ISOLATION OF BRIDGES

Figure 1. EPS systems implemented on the bridge model and tested on shake table (photography by author).

During the period of February to April 2026 experimental campaign on bridge structure was conducted in the Dynamic Testing Laboratory (DynLab) in IZIIS, where advanced seismic protection systems have been investigated under realistic earthquake conditions. These tests represent a benchmark study aimed at evaluating the performance of different devices under controlled and repeatable conditions. The experimental program involved a scaled bridge model (approximately 1:1.5 scale, with a total mass of about 35 tons) tested on the 5-DOF shake table at IZIIS, allowing the simulation of horizontal seismic excitation. The input motions included real earthquake records, such as Kobe, Ecuador, Jiashi, and the recent Türkiye–Syria earthquakes appropriately scaled to satisfy the physical limitations of the testing facility while preserving dynamic similitude.

The central focus of the experimental campaign was the investigation of base isolation and energy dissipation devices, including:

- Triple friction pendulum (TFP) isolators, developed by Earthquake Protection Systems (EPS, USA), providing multi-stage friction-based isolation behavior
- Fiber-reinforced elastomeric bearings, supplied by Italgum S.r.l., designed to combine flexibility and durability
- Fluid viscous dampers, developed by DAHT Limited, offering velocity-dependent energy dissipation
- Metallic yielding dissipators (SOMMA AIOS devices), classified as displacement-dependent dissipative devices (DDDs), designed to dissipate energy through controlled plastic deformation

The experimental configurations included multiple combinations of these devices, enabling a comparative assessment of different seismic protection strategies, including:

- pure isolation systems
- hybrid isolation–dissipation systems
- systems combining elastomeric bearings with supplemental damping

The results of the shake-table tests demonstrated significant improvements in structural performance when control systems were applied. In particular:

- reduction of deck displacements and inter-story drifts, indicating improved deformation control
- decrease in acceleration levels, contributing to improved serviceability and reduced demand on non-structural components
- reduction of base shear forces, confirming the effectiveness of isolation systems in decoupling the structure from ground motion
- improved energy dissipation capacity, particularly in hybrid configurations combining isolation and damping devices

Figure 2. Somma device (left), EPS systems (right), Viscous dampers and Rubber Bearings (photography by author).

An important aspect of the experimental campaign was the application of time scaling (SFT ≈ 1.22) and amplitude scaling (SFA) to ensure compatibility with the shake-table displacement limits (maximum allowable displacement of approximately 100 mm). These scaling strategies preserved the dynamic characteristics of the input motions while enabling safe and accurate experimental execution. The bridge tests also provided valuable insight into the interaction between different control devices, highlighting the advantages of hybrid systems. For example, while isolation systems effectively reduced transmitted forces, the addition of viscous dampers improved response control under higher intensity excitations, particularly by limiting excessive displacements. Furthermore, the experimental results contributed to the validation of numerical models, enabling improved calibration of analytical tools used in performance-based seismic design. This is particularly important for bridge structures, where accurate prediction of nonlinear behaviour and device interaction is essential. These results confirm that hybrid isolation–dissipation systems provide a more stable and robust response across different seismic intensities compared to single-device configurations. Viscous dampers effectively compensate for the displacement amplification typically associated with pure isolation systems under near-fault excitations. These findings have direct implications for performance-based seismic design, where the selection and combination of control devices can be optimized depending on target performance objectives.

2.2. ERIES-RESUME

A significant recent experimental contribution in the field of integrated seismic retrofit strategies is provided by the ERIES-RESUME project, which investigates the performance of a hybrid timber–aluminium exoskeleton system applied to non-ductile reinforced concrete (RC) frame structures. The experimental campaign was conducted at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) using shaking table testing, representing one of the few large-scale, data-rich investigations addressing both seismic resilience and energy-efficiency upgrading within a unified framework. The study focused on two geometrically scaled (1:3) two-storey RC frame models representative of pre-code construction typologies characterized by low ductility and high seismic vulnerability. A multi-phase testing protocol was implemented, comprising a total of 66 dynamic tests performed under progressively increasing seismic excitation, including both real and spectrum-compatible ground motion records. The experimental programme was structured to enable direct comparison between different structural conditions, including the as-built configuration, the damaged state, the retrofit condition with the exoskeleton applied after damage, and a pre-strengthened configuration in which the exoskeleton was installed prior to seismic loading.

Figure 3. RESUME project models, model without exosceleton (left), model with damages from shake table tests (right) (photography by author).

The exoskeleton system itself consists of an external load-bearing frame composed of laminated timber elements connected through steel joints, combined with thin aluminium shear panels acting as dissipative components. This hybrid configuration provides a dual function: on one hand, it enhances global stiffness and load redistribution capacity, and on the other, it introduces additional energy dissipation through the nonlinear behaviour of the aluminium panels. Furthermore, the system integrates façade elements with thermal insulation layers, highlighting its potential as a combined structural and energy retrofit solution.

Figure 4. Model strengthened with exoskeleton (left), damages from shake table tests(right) (photography by author).

The experimental results demonstrated a clear improvement in the global seismic response of the retrofitted structures compared to the unstrengthen configuration. In particular, the exoskeleton contributed to increased lateral stiffness, reduction of inter-storey drift demands, and more favourable damage distribution mechanisms, effectively delaying the onset of critical structural damage. Differences between post-damage retrofitting and pre-strengthening configurations also provided valuable insight into the timing and effectiveness of intervention strategies. An important outcome of the campaign is the generation of a comprehensive experimental dataset, including synchronized time-history records of accelerations, displacements, and strains, together with detailed information on geometry, materials, instrumentation layout, and testing sequence. Such high-resolution data enable advanced system identification, calibration of nonlinear numerical models, and validation of innovative retrofit concepts under realistic dynamic conditions. Moreover, the multi-phase nature of the testing programme, combined with consistent boundary conditions and input motions, allows for rigorous comparative assessment of structural performance across different configurations. Overall, the ERIES–RESUME experimental study represents a benchmark contribution in the field of structural control and retrofit, demonstrating the effectiveness of exoskeleton-based solutions and providing a valuable foundation for the development of next-generation performance-based seismic design and integrated resilience strategies. This study demonstrates that exoskeleton-based retrofit systems can simultaneously enhance structural performance and energy efficiency, representing a promising solution for integrated seismic and sustainability-oriented design.

2.3. GERB-PDDS

To evaluate the effectiveness of Prestressed Damping Devices (PDDs) developed by GERB Schwingungsisolierungen GmbH & Co. KG, Germany, in controlling the structural response to seismic excitations, and to develop an optimal design and placement procedure for these or similar devices in earthquake-resistant structural design, a research program was undertaken.

Figure 5. Tested models with PDDs on the shake table (photography by author).

A hypothetical 5-story steel frame structure was designed in accordance with Eurocode3 and Eurocode 8 requirements for design response spectrum calculated for soil type B, PGA=0.20 g, and behaviour factor q=4. The structure was subjected to simulated real earthquake time histories with varying intensities under two conditions: a) structure without PDDs and b) four configurations of the same structure with PDDs placed in different positions through the bays and along its height. Seventeen different time history records of real earthquakes were used in the experimental testing.

An extensive experimental campaign was conducted to evaluate the effectiveness of PDDs. Simulations of various, seventeen different earthquake time histories were conducted on a model structure both with and without PDDs, revealing that this system can substantially reduce responses depending on the frequency content of the seismic input and the corresponding sensitivity of the structure. More than 270 runs were performed on the shaking table and the recorded response histories, totalling over 19400, provide a strong foundation for developing appropriate analytical models for the tested structure with and without PDDs.

Results from frequency response function curves of resonant search tests showed that the bare frame model, has very low equivalent viscous damping (0.65-0.85 %) in its fundamental mode of vibration and as consequence of this exhibits very unfavourable dynamic behaviour during earthquake simulation tests compared to the other model structures with PDDs. Although, the added viscous damping of approx. 6.5% by PDDs is not as much as high as it should be generated by conventional viscous dampers in sealed containers, it was quite enough substantially to dampen the structural response and to enable the structure to withstand the seismic excitation having peak ground acceleration of almost twice than design one without visible damage and significant changes in natural frequencies.

The effectiveness of the PDDs have been estimated based on the comparison of response histories of the tested models in terms of accelerations, storey displacements (absolute, relative), inter-storey drifts and strain measurements for identification of axial loads and bending moments, for all tested structural models.

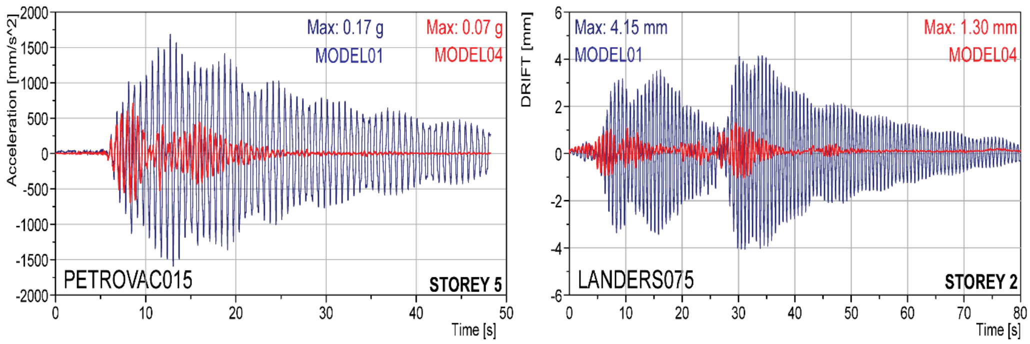

Figure 6. Response histories of the tested models in terms of acceleration and inter-storey drift (creates by author).

The analytical model of PDDs was further utilized in subsequent phases of the research program, including analytical estimation of the effectiveness of PDDs on various steel frame structures subjected to different seismic excitations, improving PDD characteristics, and practical procedures for optimal design and placement of these and similar devices in the earthquake-resistant design of structures.

2.4. TMD-GERB

Within the experimental research program conducted at the Dynamic Testing Laboratory of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), a five-storey steel frame structure equipped with a tuned mass damper (TMD), manufactured by GERB (Germany), was subjected to comprehensive dynamic testing. The primary objective of the experimental campaign was to evaluate the effectiveness of the passive control system in modifying the dynamic response of the structure under seismic excitation.

Figure 7. Tested structure with TMD (photography by author).

The tested structural model represents a three-dimensional steel moment-resisting frame with five storeys, designed to simulate realistic structural behaviour. Each node of the structure was modelled with six degrees of freedom, allowing accurate representation of spatial dynamic response. To ensure dynamic similitude and realistic inertial properties, additional masses in the form of steel ingots were placed at each floor level, resulting in a total structural mass of approximately 16.5 tons. This approach enabled the reproduction of realistic vibration characteristics and dynamic behaviour under earthquake loading. The experimental program included dynamic excitation of the structure using a shaking table, where the model was subjected to a series of real earthquake records with different frequency content and intensity levels. Among the applied ground motions were well-known earthquakes such as El Centro, Kobe, Northridge, Petrovac, and Izmit, appropriately scaled to match the testing conditions. These tests allowed evaluation of structural response under a wide range of seismic scenarios. A key aspect of the investigation was the comparison between structural response with and without the TMD system. The dynamic absorber was installed at the upper level of the structure and designed to reduce vibrations through energy dissipation and dynamic interaction with the primary system. Measurements were collected using an extensive instrumentation setup, including accelerometers, displacement transducers, and sensors for monitoring internal forces. This enabled detailed tracking of time histories of displacements, accelerations, and force distribution throughout the structure.

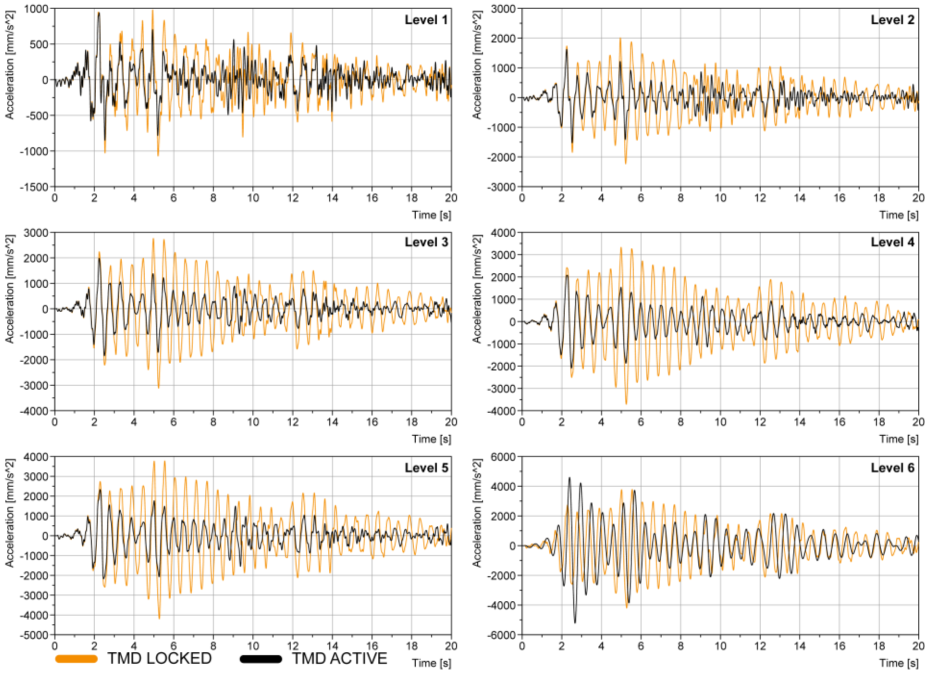

Figure 8. Comparisons of accelerations for structure with and without TMDs for ELCENTRO earthquakes at different levels (created by author).

The results of the experimental investigation clearly demonstrated the effectiveness of the tuned mass damper in reducing the dynamic response of the structure. Significant reductions in displacement and acceleration amplitudes were observed when the TMD was active, with response reductions reaching up to approximately 50% compared to the uncontrolled configuration. Furthermore, the study enabled detailed analysis of the influence of key parameters such as damping ratio, mass ratio, and damper location along the height of the structure.

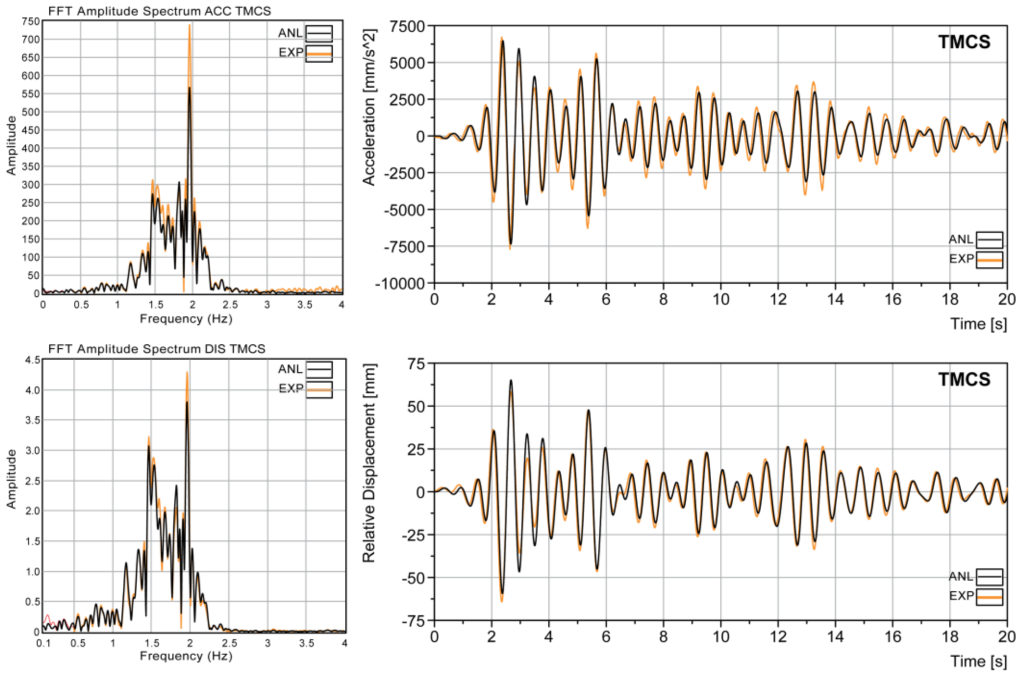

Figure 9. Comparisons of Analytical and Experimental results for accelerations and displacement for ELCENTRO earthquake (created by author).

Overall, the experimental campaign provided a comprehensive dataset for understanding the behaviour of steel frame structures equipped with passive control devices. The findings confirm that tuned mass dampers represent an effective and practical solution for reducing seismic response and improving structural performance, while also providing a reliable basis for the development and validation of analytical and numerical models for controlled structures.

2.5. GERB-BSC

The experimental model was equipped with a comprehensive and carefully designed instrumentation system to capture the dynamic response of the structure with high accuracy during shaking table testing. The model, representing a multi-storey steel frame structure with an integrated base control system (BCS), was installed on a biaxial seismic shaking table and instrumented using a combination of accelerometers, displacement transducers, and strain gauges distributed along the height of the structure and at critical structural components.

Figure 10. Model on shake table with GERB-BSC system (photography by author).

A total of 29 transducers were used for the BCS configuration, allowing simultaneous acquisition of multiple response parameters. The instrumentation included 12 accelerometers, positioned both on the shaking table and at each floor level, enabling detailed measurement of global and local accelerations, as well as torsional effects at the top level. Additional vertical accelerometers were installed above the spring elements of the base control system to capture vertical response components. Displacement measurements were obtained using linear potentiometers placed at each storey level and at the base, allowing precise determination of absolute and relative displacements, including inter-storey drift demands. Furthermore, strain gauges were installed at the first-storey columns to monitor stress distribution and to enable indirect calculation of internal forces and bending moments in the structural elements. Special attention was given to the instrumentation of the base control system itself, which consists of springs and dashpots located at the foundation level. Due to the complexity of simultaneous vertical and horizontal motion of these elements, additional visual instrumentation was implemented to capture rocking and translational behaviour, including optical tracking of displacement indicators. This approach ensured that critical nonlinear behaviour of the isolation system could be properly observed and analysed. The instrumentation set up demonstrated a dense sensor network with extensive cabling connecting all transducers to a centralized data acquisition system. The system was capable of recording up to 64 channels simultaneously in real time, ensuring synchronized acquisition of acceleration, displacement, and strain data. This high-resolution dataset enabled detailed analysis of both global structural response and local behaviour of individual components, including the interaction between the superstructure and the base control system.

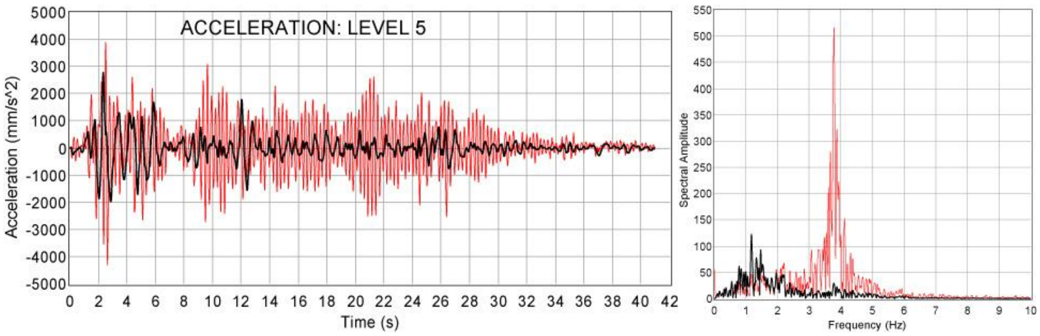

Figure 11. Comparisons for acceleration for the model with and without BSC system for ELCENTRO earthquake-level 5 (created by author).

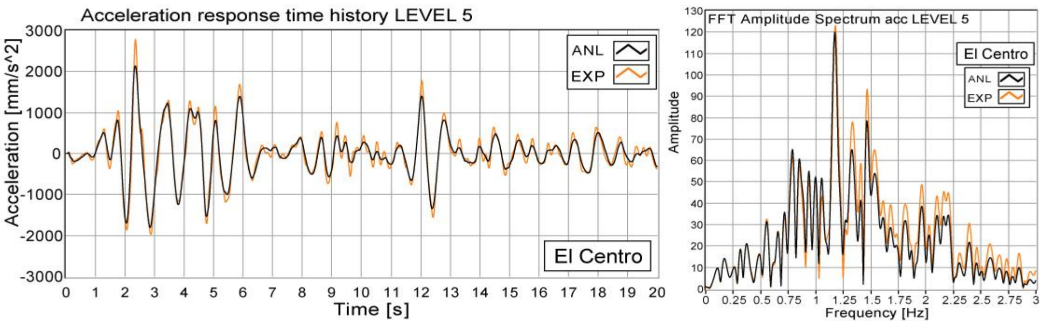

Figure 12. Verification of the numerical model – Analytical and Experimental results comparisons – level 5 for ELCENTRO earthquake (created by author).

Overall, the implemented instrumentation setup provided a robust framework for capturing the complex dynamic behaviour of the tested system under seismic excitation. The combination of global and local measurements, together with advanced data acquisition capabilities, ensured the reliability of the experimental results and supported subsequent validation of numerical models and evaluation of the effectiveness of the control system.

2.6. DEFD - SYSTEM

The DEFD (Disposable Elements Friction Damping) system represents an innovative passive control strategy developed to enhance the seismic performance of frame structures through controlled energy dissipation mechanisms. The concept is based on the integration of two complementary components: friction-based damping devices with limited slip capacity (SBC mechanism) and auxiliary structural elements designed to undergo controlled inelastic deformation. By combining these mechanisms into a unified system, the DEFD concept introduces multiple levels of protection that are activated progressively depending on the intensity of the seismic excitation.

Figure 13. DEFD system on the shake table (photography by author).

The friction mechanism is composed of steel plates connected by high-strength bolts, with sliding surfaces designed to provide a predefined friction force. The activation of this mechanism occurs when the applied force exceeds the friction threshold, which is governed by the level of prestressing in the bolts and the friction coefficient of the contact surfaces. Once activated, the mechanism dissipates a portion of the seismic input energy through controlled sliding, thereby reducing the energy demand transferred to the main structural system. A key feature of this system is the limitation of slip displacement, which prevents excessive deformation and ensures stable hysteretic behaviour during cyclic loading. In addition to the friction mechanism, the DEFD system incorporates auxiliary elements, typically arranged in the form of a closed frame or diagonal bracing system. These elements act as a secondary line of defence and are designed to undergo plastic deformation only after the friction mechanism has been fully activated. This staged activation ensures that energy dissipation begins at relatively low levels of excitation, minimizing damage to both structural and non-structural components, while preserving the integrity of the primary load-bearing system. The overall behaviour of the DEFD system can be described as a multi-level energy dissipation process. During low to moderate seismic events, the friction mechanism is activated first, providing early hysteretic damping and reducing structural response without inducing damage. For stronger ground motions, once the friction capacity is exceeded, the auxiliary elements are engaged and contribute additional energy dissipation through plastic deformation. Only under extreme loading conditions does the primary structural system participate significantly in energy dissipation, thereby acting as a final safety mechanism. This hierarchical response mechanism represents a fundamental advantage of the DEFD system compared to conventional seismic design approaches. In traditional structures, energy dissipation is achieved primarily through damage in the main structural elements, leading to costly repairs and potential loss of functionality. In contrast, the DEFD system shifts the energy dissipation demand to replaceable or repairable components, improving overall structural resilience and post-earthquake performance.

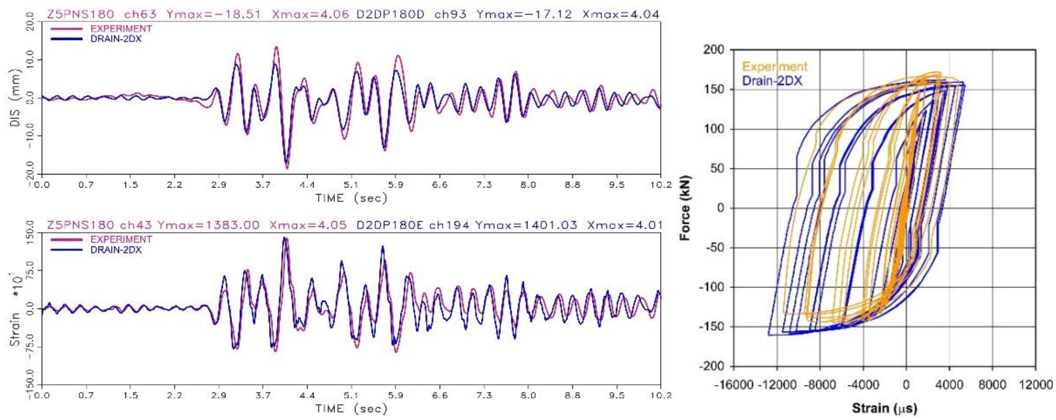

Figure 14. Comparison of experimental and analytical results for strain and displacement(created by author).

Furthermore, the DEFD system introduces hysteretic damping at relatively low excitation levels, which is not typical for many conventional passive systems. This characteristic contributes to improved control of inter-storey drifts and reduction of damage in non-structural elements, which are often critical for maintaining the functionality of buildings. The system also offers flexibility in design, as the friction force, stiffness, and deformation capacity can be adjusted through selection of materials, geometry, and prestressing levels. Overall, the DEFD system represents a robust and efficient passive control solution that enhances both the safety and serviceability of structures subjected to seismic loading. Its ability to provide controlled energy dissipation across different levels of excitation, combined with its practical applicability and adaptability, makes it a promising approach for both new construction and seismic retrofitting of existing structures.

3. CONCLUSIONS

Structural control systems represent one of the most effective approaches for improving seismic performance, resilience, and serviceability of structures. Among the various systems, base isolation, viscous dampers, tuned mass dampers, friction-based devices, and hybrid solutions have shown particularly strong potential, especially when supported by experimental validation. The presented IZIIS experience further demonstrates that large-scale shake-table testing plays a crucial role in verifying device efficiency, understanding complex interaction mechanisms, and validating numerical models for practical design applications. Recent experimental campaigns, including bridge systems, exoskeleton-based retrofit concepts, prestressed damping devices, and tuned mass dampers, confirm that properly designed control systems can substantially enhance seismic safety and structural reliability.

Overall, the results confirm that experimentally validated structural control systems represent a key component of next-generation seismic design. The integration of hybrid control strategies with real-time monitoring and data-driven optimization is expected to significantly advance the field toward adaptive and resilient infrastructure systems.

The practical application of controlled structures is feasible for nearly all types of civil engineering systems, including buildings, bridges, and flexible linear infrastructures. Passive control systems of various categories and types experience increasingly widespread and intensive use, particularly in countries where technical regulations already support their implementation, such as the United States, Japan, and the European Union (with the adoption of 2nd generation of Eurocodes).

Structural engineering, despite its specific characteristics and distinctions from other engineering disciplines, cannot remain unaffected by the advances in structural control technology and the development of new materials. Structural engineers are, and will continue to be, under increasing pressure from emerging technologies, and cannot remain outside these ongoing processes of modern development. However, they must not lose sight of the fundamental responsibility to design and construct structures with service lives spanning decades or even centuries. This implies that safety and economic efficiency must remain constant and uncompromised throughout such extended time periods.

Technological innovations are evolving rapidly across all engineering disciplines, including civil engineering, which has traditionally been regarded as conservative. Owing to these innovations, civil engineering and particularly structural engineering is progressively shedding this conservative label and becoming an integral part of modern technological advancement. Today, and even more so in the future, structural engineering will be intrinsically linked to developments in advanced materials, computer technologies, robotics, and related engineering fields. Controlled structures represent an important component of this broader technological transformation in engineering.

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