Seismic Performance of Steel Braced Frames: Comparing Buckling Restrained Braces, Friction Braces, and Braces with Resilient Slip Friction Joint Dampers

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ABSTRACT

Recent earthquakes have highlighted the importance of having robust structural systems capable of minimizing permanent damage. This paradigm shift has led designers to explore innovative Lateral Load Resisting Systems (LLRS) that offer improved energy dissipation and ductility, ensuring the protection of both structural and non-structural components. This study presents a comparative analysis of three (3) advanced bracing systems, Buckling Restrained Braces (BRBs), braces with Friction Dampers (FD), and braces with Resilient Slip Friction Joint (RSFJ) dampers, implemented in a 4-story and 8-story steel braced framed structures designed in accordance with NZS1170.5. Numerical models of the 4-story and 8-story steel braced frames were developed in ETABS, and the seismic performance of each of the LLRS was evaluated using the Capacity Spectrum Method and verified using Non-linear Time History Analysis (NLTHA) under Design Level Earthquake (DLE). Numerical Analyses revealed that both BRB and RSFJ LLRS yielded ductility factors ranging from 2.6 to 3.1 under DLE while maintaining inter-story drifts within 1.5%.

On the other hand, braces with FDs exhibited higher ductility factors of 3.5 to 3.8, without exceeding the drift limit. Notably, both RSFJ and FD systems offer flexibility in performance optimization through inherent calibration properties, enabling enhanced ductility while maintaining drift control under DLE. Overall, all three (3) configurations demonstrated enhanced seismic performance through reduced base shear, floor accelerations, and inter-story drifts, with RSFJs displaying inherent self-centering capability. The findings suggest that while all three (3) systems offer robust solutions for seismic protection, the system should be carefully selected based on project requirements, including post-event functionality and economic considerations.

1 INTRODUCTION

The devastating consequences of recent major earthquakes have underscored the critical need for innovative structural systems that can effectively protect buildings and their occupants. Traditional seismic design approaches often accept significant structural damage under severe earthquakes, leading to substantial economic losses and prolonged recovery periods. This paradigm has prompted structural engineers to develop and implement advanced Lateral Load Resisting Systems (LLRS) that not only ensure life safety but also minimize post-earthquake damage and maintain building functionality. Among these innovative solutions, advanced bracing systems have emerged as promising alternatives, offering enhanced energy dissipation capabilities, improved ductility, and better control of structural response during seismic events. These systems represent a significant evolution in seismic design philosophy, moving beyond conventional approaches to address both immediate safety concerns and long-term resilience objectives.

Dampers in seismically active regions function analogously to automotive shock absorbers, protecting buildings during intense earthquake events. The fundamental principle of damping involves energy dissipation from an oscillating system (Crandall, 1970), directly influencing the transition between stable and unstable structural response. Under severe seismic loading, dampers are designed to undergo controlled deformation or yielding to protect the primary structure. This behavior is typically characterized through hysteretic load-deformation relationships, as illustrated in Figure. 1, where nonlinear deformation occurs beyond specific load thresholds, effectively limiting force transmission to the structure. While traditional seismic design relies on designated structural elements to undergo plastic deformation, modern approaches increasingly utilize specialized damping devices to concentrate energy dissipation and preserve the integrity of the main load-bearing system. Damping devices serve as crucial components in seismic resistance, with experimental studies demonstrating their capacity to absorb and dissipate over 90% of the total earthquake-induced energy input into the structure (Soong & Dargush, 1999).

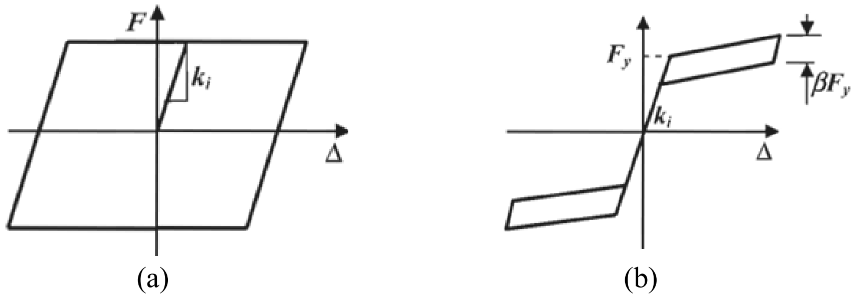


Figure 1. Load-deformation (Hysteresis) curve: (a) Elasto- plastic (EPP), and (b) Flag- shape (FS) (Calvi et al., 2007).

This study examines the seismic performance of 4-story and 8-story steel-framed structures by incorporating three different types of lateral load-resisting systems (LLRS) in the transverse direction: Buckling Restrained Braces (BRBs), Concentrically Braced Frames (CBFs) with Resilient Slip Friction Joints (RSFJs), and Concentrically Braced Frames (CBFs) with Friction Dampers (FD). The load-deformation curves for BRBs and CBFs with Friction Dampers (FD) are illustrated in Fig.1 (a), while Fig 1 (b) shows the flag-shape load-deformation response of the CBFs with RSFJs. In the longitudinal direction, the LLRS consists of Steel Moment Resisting Frames (SMRF). The seismic performance is evaluated in accordance with the provisions outlined in New Zealand's Earthquake Design code (NZS1170.5:, 2004) under the Design Level Earthquake (DLE).

2 ADVANCED LLRS FOR STEEL FRAME STRUCTURES

2.1 Buckling Restrained Braces (BRBs)

Buckling-Restrained Braces (BRBs) represent a significant advancement in seismic-resistant structural systems, emerging as an innovative solution for both new construction and retrofitting applications (Zhou et al., 2021). These specialized structural elements effectively combine strength, stiffness, and energy absorption capabilities to enhance building performance during seismic events. Unlike conventional bracing systems, BRBs are designed to prevent buckling under compression while maintaining consistent behaviour in both tension and compression, thereby providing stable hysteretic performance and reliable energy dissipation (Fahnestock et al., 2007).

The evolution of BRB technology over recent decades has led to various configurations and design approaches, from traditional concrete-filled steel tubes to more recent innovations such as all-steel designs (Hoveidae & Radpour, 2021). Research has consistently demonstrated their effectiveness in controlling structural response during earthquakes, with studies showing their capability to dissipate more than 75% of seismic input energy (Tan et al., 2021) while maintaining story drifts within acceptable limits. However, a conventional BRB system may experience significant residual deformations following a major event. Thus, large deformations can reach levels that can make post-earthquake repair work challenging (Chen et al., 2019).

2.2 Resilient Slip Friction Joint (RSFJs)

Resilient Slip Friction Joints (RSFJs) are classified under passive dampers, representing an innovative advancement in seismic-resistant bracing systems that combines effective energy dissipation with inherent self-centering capabilities, offering a solution to the residual drift challenges commonly associated with traditional buckling-restrained braces while maintaining comparable structural performance.

In RSFJs, energy dissipation occurs through the frictional sliding of plates coated with a proprietary material. The ridged sliding surfaces and disc springs enable self-centering behavior. When an applied force exceeds the resistance between the clamped plates, the middle plates begin to slide while the cap plates move outward. This continues until the joint reaches its design deflection (ultimate displacement), at which point the disc springs flatten. RSFJs provide effective energy dissipation, full self-centering capability, and enhanced force and displacement capacity by engaging a secondary fuse mechanism, ensuring life safety during major earthquakes. These joints can accommodate 1.75 to 2 times their displacement capacity due to the built-in secondary fuse mechanism. Additionally, the reserve force capacity beyond the design displacement is approximately 1.35, accounting for the strain hardening of bolts after yielding (Hashemi et al., 2018; Hashemi, Zarnani, et al., 2020).

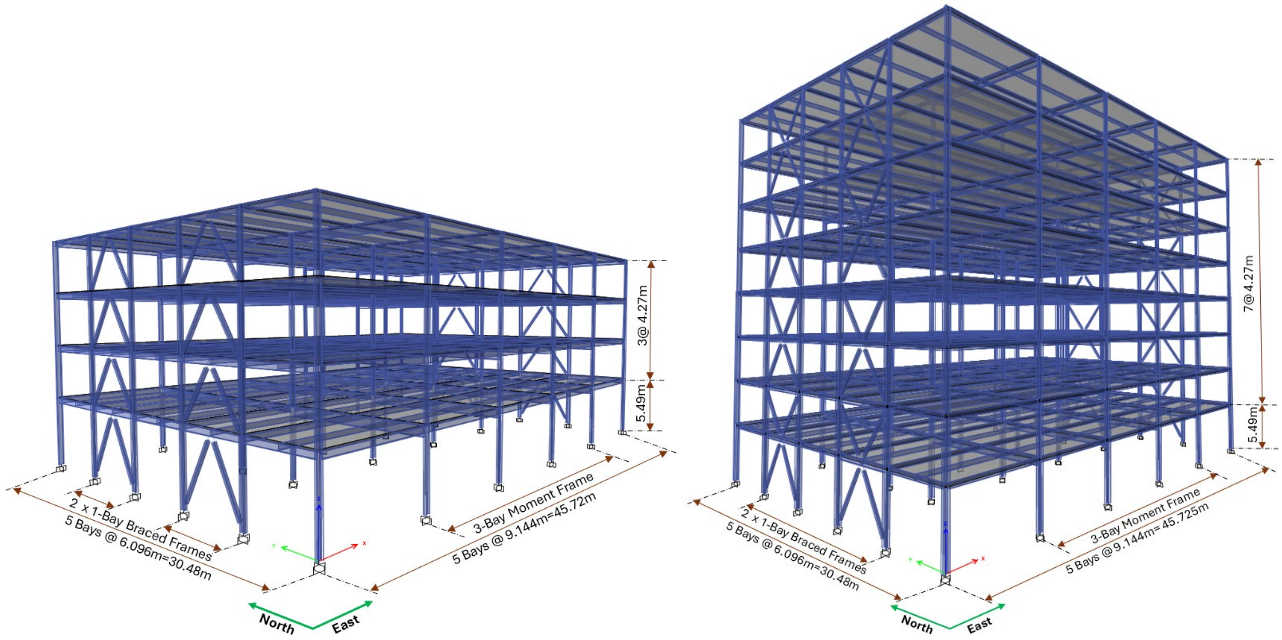
2.3 Friction Dampers (FD)

Friction dampers represent an innovative passive energy dissipation system that utilizes the mechanism of solid friction to dissipate seismic energy through relative sliding between metallic surfaces under normal pressure. When incorporated into Concentrically Braced Frames (CBFs), these devices are typically installed at the brace-to-frame connections or within the bracing members themselves. During a seismic event, as the structure deforms laterally, the relative movement between the connected surfaces of the friction damper activates the friction mechanism, converting kinetic energy into heat through controlled sliding, thereby reducing the overall structural response. Unlike conventional bracing systems where energy dissipation occurs through inelastic deformation of the brace members, friction dampers provide stable and predictable Elasto-plastic (EPP) hysteretic behavior (Calvi et al., 2007) without causing permanent damage to the primary structural elements. This characteristic makes them particularly attractive for seismic applications, as they can be easily inspected and, if necessary, retightened after a major seismic event without requiring replacement.

3 METHODOLOGY

3.1 Overview of 4-Storey and 8-Storey Steel Framed Building

This study examines two steel-framed office buildings, one with four (4) storeys and the other with eight (8) storeys as shown in Figure 2. The building archetypes for this case study are adopted from the NIST TN 1863-4: Assessment of First-Generation Performance-Based Design Methods for New Steel Buildings, Volume 4: Buckling- Restrained Braced Frames (Speicher & Harris, 2019). Advanced bracing systems, including Buckling Restrained Braces (BRBs), CBF with Resilient Slip Friction Joints (RSFJs), and Friction Dampers, are implemented in the N-S direction (Transverse), and their seismic performance is assessed it terms of base shear, drift, and acceleration response. All LLRS frames are symmetrically positioned along the building's perimeter. Meanwhile, Special Moment Resisting Frames (SMRFs) in the East-west (longitudinal) direction provide structural stability and resistance to environmental loads. While the SMRFs are designed to ensure stability in the longitudinal direction, their seismic performance evaluation is outside the scope of this study.



(a) (b)

Figure 2. Case study archetypes: (a) 4-story structure and (b) 8- story structure.

Both buildings have a rectangular floor plan, consisting of five 9.144 m bays in the east-west direction and five 6.096 m bays in the north-south direction. The overall floor dimensions are 45.72 m in the E-W direction and 30.48 m in the N-S direction. In both structures, the first story has a height of 5.49 m, while all subsequent stories are 4.27 m tall. The 4-storey building features a chevron bracing configuration, whereas the 8-storey building utilizes X-bracing (refer to Fig. 2). Table 1 summarizes the roof and floor loads. The total seismic weight is 22,864 kN for the 4-storey building and 46,862 kN for the 8-storey building. For simplicity, the buildings are assumed to have no elevators or stairwell diaphragm openings.

Table 1. Gravity loads on respective levels of the buildings

Load	Type	Magnitude
Dead, D	Dead	2.20 kPa
Floor Superimposed Dead, SD	Dead	0.72 kPa
Roof Superimposed Dead, SD	Dead	0.48 kPa
Façade Dead (Curtain Wall), SD	Dead	3.65 kN/m
Unreduced Design Floor Live, Lo	Floor Live	2.40 kPa
Unreduced Design Roof Live, Lo	Roof Live	1.44 kPa

3.2 Seismic Analysis

Numerical models were developed in ETABS (Computers and Structures Inc, 2021) to assess the seismic performance of different bracing configurations in the 4-storey and 8-storey building archetypes. A Nonlinear Static Pushover (NSP) analysis was conducted alongside the Capacity Spectrum Method (CSM). The system's performance was evaluated using both CSM and Nonlinear Time History Analysis (NLTHA) to account for suitable variability in this analytical study. The hysteretic behavior of the Friction Damper and Resilient Slip Friction Joint (RSFJ) was modeled in ETABS using the "Plastic Wen" and "Damper - Friction Spring" link elements. The modeling of RSFJ as "Damper Friction Springs" in ETABS (Computers and Structures Inc, 2021) has been verified through research conducted in various numerical-based studies (Assadi et al., 2023; Hashemi, Bagheri, et al., 2020; Hashemi, Zarnani, et al., 2020).

All case study structures are assumed to be located on Soil Class D in Christchurch and classified as Importance Level 2 buildings, meaning they are standard structures where large crowds do not gather, with an Ultimate Limit State (ULS) annual probability of exceedance of 1/500. A near-fault factor of 1.0 was applied in this analysis, with a maximum allowable drift limit of 1.5% for ULS. For SLS design considerations, an annual probability of exceedance of 1/25 years and a maximum allowable drift limit of 0.33% were used. The case study structures are summarized in Table 2. A structural performance factor (Sp) of 0.85 was conservatively adopted for this study, as it falls within the typical range of 0.7 to 1.0.

Table 2. Overview of the case study buildings

No.	Case Study	LLRS Configuration	No. of connections	Direction
1	4 story-steel Frame Structure	BRB	32	N-S
2		RSFJ	32	N-S
3		FD	32	N-S
4	8 story-steel Frame Structure	BRB	64	N-S
5		RSFJ	64	N-S
6		FD	64	N-S

3.3 Selection of ground motion records and scaling

A set of nine ground motion records (comprising 18 horizontal components) was used to assess the seismic performance of the case study building archetypes. These ground motions were selected to represent a subset of Zone South C records for the South Island of New Zealand (Burlotos et al., 2022). The records were scaled in accordance with NZS 1170.5 (NZS1170.5:, 2004), ensuring consistency with local seismic design requirements. Nonlinear Time History Analysis (Direct Integration) was then conducted on the six case study-building archetypes to evaluate the effectiveness of different lateral load-resisting systems (LLRS). The performance of each system was compared based on base shear, inter-story drift, residual drift, and floor acceleration. The details of the selected ground motions used in this study are described in Table 3.

Table 3. Selected ground motion records for NLTHA

Event	Country	Year	M	Fault Mechanism
ChiChi-TCU051	Taiwan	1999	7.6	Reverse Oblique
Christchurch-CBGS	New Zealand	2011	6.2	Reverse oblique
Christchurch-RicartonHschool	New Zealand	2011	6.2	Reverse oblique
ImperialValley-02	USA	1940	6.9	Strike-slip
ImperialValley-06	USA	1979	6.5	Strike-slip
ImperialValley-ElCentroArray#9	USA	1979	6.5	Strike-slip
Kobe-PortIsland	Japan	1995	6.9	Strike-slip
Valparaiso-Llolleo	Chile	1985	7.8	Reverse/Thrust
Victoria-Chihuahua	Mexico	1980	6.3	Strike-slip

4 RESULTS AND DISCUSSION

4.1 Capacity Spectrum Method (CSM)

CSM was first standardized in FEMA 356 and ATC 40 (as the Coefficient Method) and later refined in FEMA 440. In New Zealand, a similar yet more simplified approach to seismic assessment of existing buildings is outlined in C2: Assessment Procedures and Analysis Techniques by the Ministry of Business, Innovation, and Employment (2018).

CSM is performed by plotting the backbone curve obtained from a nonlinear pushover analysis (NPA) against the modified Acceleration-Displacement Response Spectrum (ADRS), which is reduced from 5% damping for both the Serviceability Limit State (SLS) and Ultimate Limit State (ULS) (refer to Figure 3). An optimal system should have its minimum yield point (representing device or fuse activation) positioned just above the SLS ADRS curve while intersecting the ULS ADRS curve (performance point) at force and displacement levels exceeding the design values. According to FEMA 440 and C2, higher mode effects are considered negligible if the square root of the sum of the squares (SRSS) of shear in any given storey—accounting for modes contributing at least 90% of the mass—does not exceed 130% of the storey shear derived from a first mode-only analysis (Assadi et al., 2023). Figure 3 illustrates an idealized Single Degree of Freedom (SDOF) structure, represented by a pushover curve intersecting with the damped spectra to indicate the performance point.

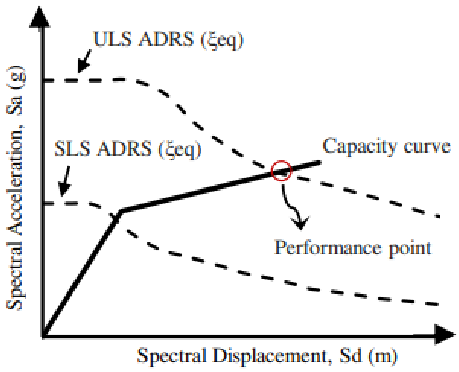


Figure 3. Idealized Capacity Spectrum Approach (Assadi et al., 2023).

The Acceleration Displacement Response Spectrum (ADRS) curves in Figures 4 and 5 illustrate the performance points for three Lateral Load Resisting Systems (LLRS) - Buckling Restrained Braces (BRBs), Resilient Slip Friction Joints (RSFJs), and Friction Dampers (FDs) - implemented in 4-storey and 8-storey steel-framed structures along the N-S (transverse) direction. The structures were analyzed at 1.5% drift to evaluate the effectiveness of these advanced bracing systems. The performance point, defined as the intersection of the pushover curve with the damped spectra, was determined using the Capacity Spectrum Method (CSM) for each LLRS configuration. For the 4-storey structure, the analysis yielded base shears of 4316 kN, 4655 kN, and 3708 kN for BRB, RSFJ, and FD systems, respectively, with corresponding inter-storey drifts of 1.2%, 1.0%, and 1.2% (refer to Fig. 4). The 8-storey structure exhibited base shears of 4900 kN, 5564 kN, and 3800 kN for BRB, RSFJ, and FD systems respectively, all maintaining a consistent drift ratio of 1.0% (refer to Fig. 5).

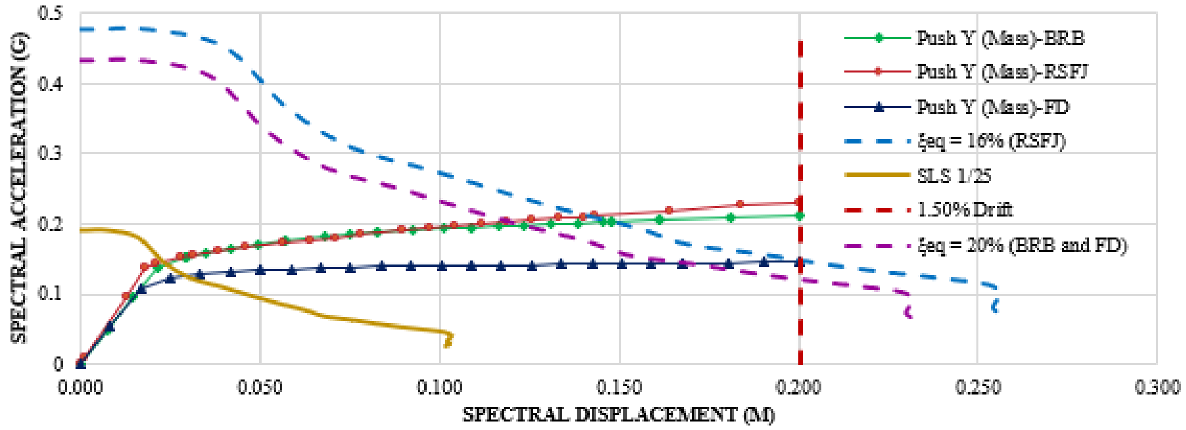


Figure 4. ADRS Performance point for 4-storey LLRS configuration with BRB, RSFJ, and FD _ULS

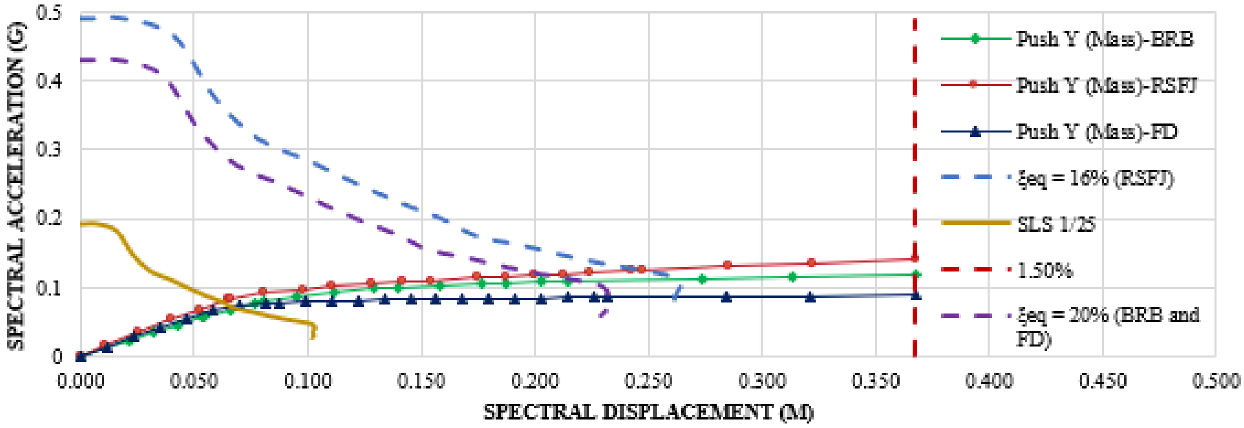
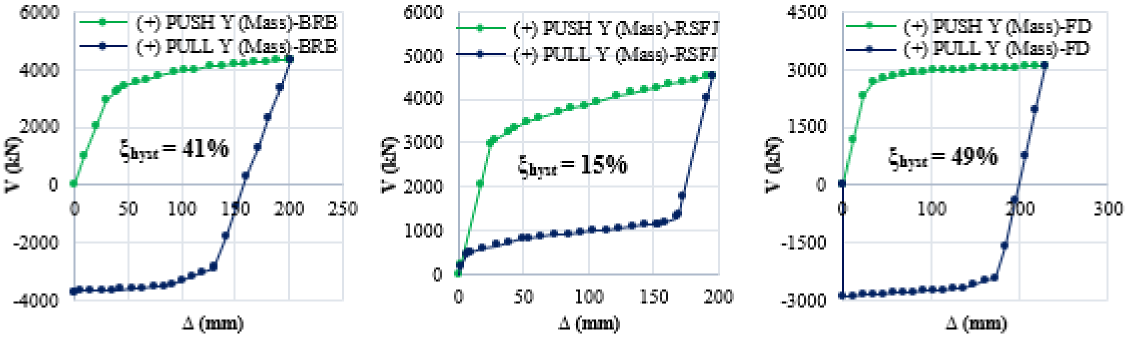


Figure 5. ADRS Performance point for 8-storey LLRS configuration with BRB, RSFJ, and FD _ULS

4.2 Nonlinear Static Pushover (NSP) analysis

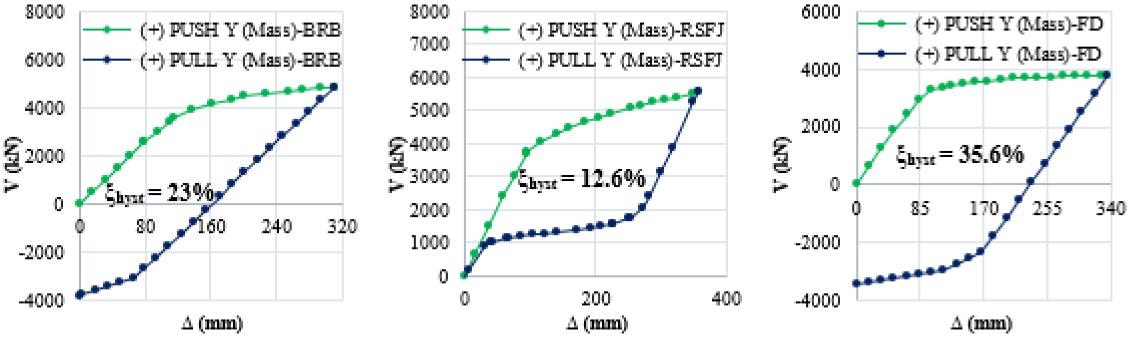
The NSP cyclic curves are plotted at respective drifts obtained from ADRS, and the area-based damping is calculated using Jacobsen's method (Chan et al., 2021). NSP identifies potential hinge locations and defines the backbone curve of the structure, illustrating the relationship between lateral force and deformation (displacement) under cyclic loading, typical in seismic events. Initially, the structure exhibits elastic behaviour, followed by a significant yield point on the backbone curve, marking the transition from elastic to inelastic response as the structure undergoes plastic deformation. Figures 6 and 7 present the half-cycle (+Y-direction) NSP curve of the three different advanced bracing systems (BRBs, RSFJs, and FDs) implemented in the N-S (transverse) direction of the 4- storey and 8- storey steel framed structures. In both 4-storey and 8-storey structures, the FD system demonstrates superior energy dissipation capabilities with the system exhibiting area-based damping (ξ_{hyst}) of 49% and 35.6%, respectively (refer to Fig 6c and 7c). On the other hand, the BRB system shows moderate performance with noticeable reduction in effectiveness when scaled to 8 stories with area-based damping (ξ_{hyst}) decreasing from 41% to 21% (refer to Fig 6a and 7a). The RSFJ system consistently exhibits the lowest energy dissipation (ξ_{hyst}) of 15% and 12.6% when implemented in the 4-storey and 8-storey structure. However, the RSFJ system showed full self-centring capability and post-earthquake functionality (refer to Fig. 6b and 7b).

All systems show decreased energy dissipation capacity in taller structures, indicating that building height significantly impacts seismic performance regardless of the chosen system. This suggests additional design considerations may be necessary for taller buildings to achieve comparable seismic resistance.



(a) (b) (c)

Figure 6. NSP cyclic curves for 4-storey LLRS : (a) BRB, (b) RSFJ, and (c) FD_ULS



(a) (b) (c)

Figure 7. NSP cyclic curves for 8-storey LLRS : (a) BRB, (b) RSFJ, and (c) FD_ULS

4.3 Nonlinear Time History Analysis (NLTHA)

Non-linear Time-History Analysis (NLTHA) evaluates the structural response to ground shaking. This analysis was conducted to assess the seismic performance of the two buildings with different LLRS when subjected to ground motion records scaled to the Design Level Earthquake (DLE) hazard. A Rayleigh damping model was implemented with 2% inherent damping, applied to the first mode and the mode corresponding to 90% mass participation, both set at the 2% damping level. The analysis indices (base shear, drift, and floor acceleration) for this study are evaluated using the mean of 9 records as suggested in seismic performance criteria based on response history analysis guideline (Bradley, 2014). Although the New Zealand design code (NZS1170.5:, 2004) considers a maximum of three records, the approach adopted in this study captures all the variabilities in dynamic analysis that is within the scope of this analytical study.

4.3.1 Base Shear

The Non-Linear Time History Analysis (NLTHA) results for both the 4-storey and 8-storey steel-framed structures highlight distinct variations in base shear demands among different lateral load-resisting systems (RSFJ, BRB, and FD). For the 4-storey structure, RSFJ consistently exhibited the highest base shear demands, averaging 4655 kN—7.9% higher than BRB (4316 kN) and 25.5% higher than FD (3708 kN) (see Figure 8). A similar trend was observed in the 8-storey structure, where RSFJ recorded the highest average base shear (5554 kN), exceeding BRB (5123 kN) by 8.4% and FD (4616 kN) by 20.3%. Across multiple ground motion records, FD consistently demonstrated the lowest base shear demands, with reductions of up to 26% in the 4-storey structure and 23% in the 8-storey structure compared to RSFJ (see Figure 9).

Overall, while all systems provide effective lateral load resistance, the FD LLRS configuration demonstrated superior force reduction capabilities, making it a more efficient option for minimizing seismic forces on steel-framed structures.

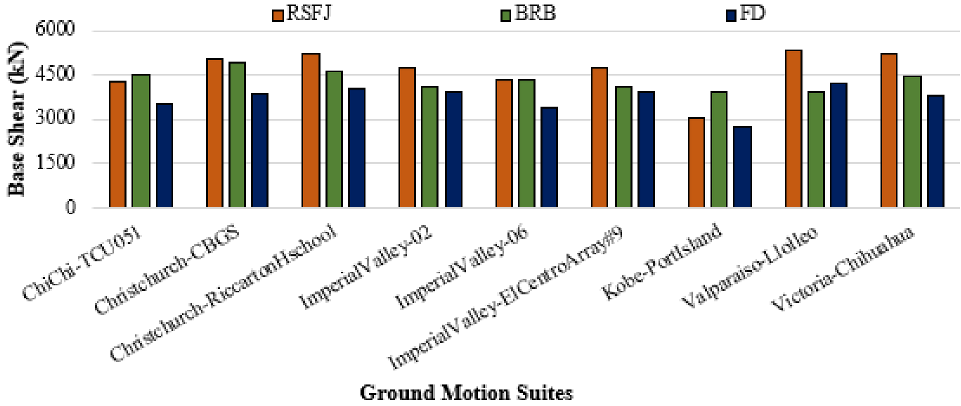


Figure 8. Comparison of ULS Base Shear in N-S direction: 4-Storey archetype.

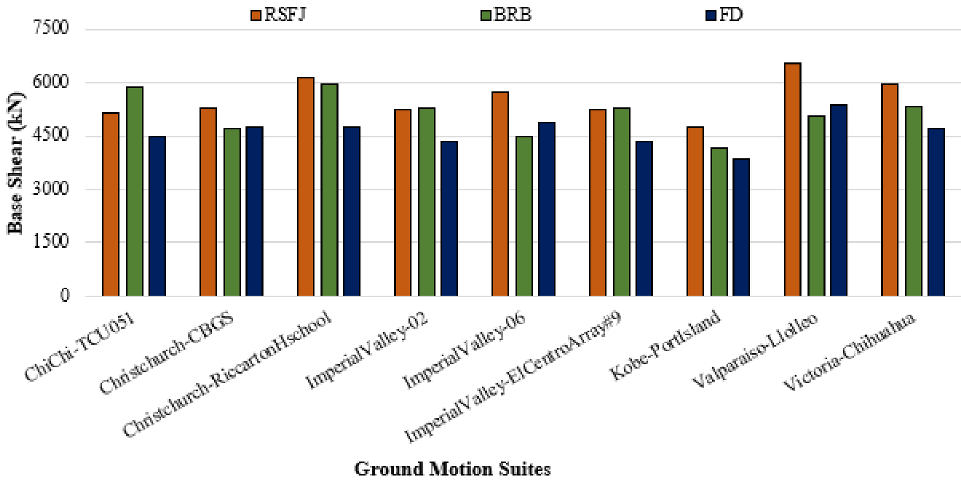
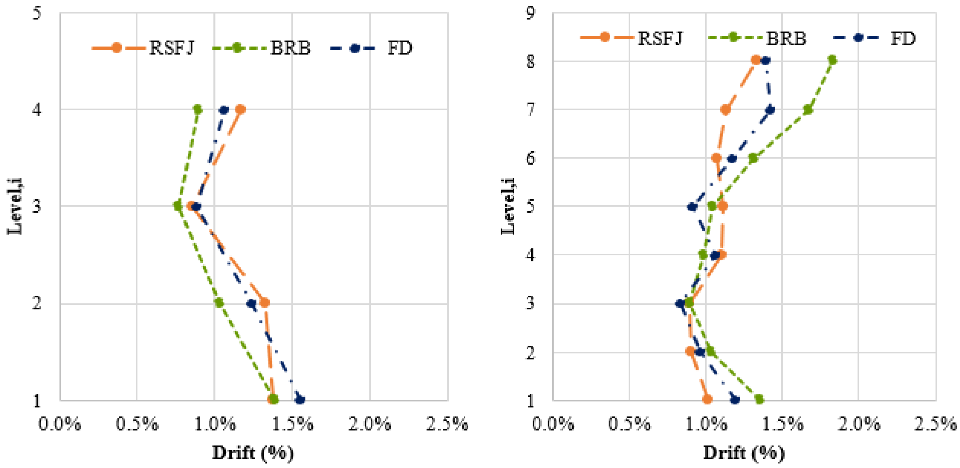


Figure 9. Comparison of ULS Base Shear in N-S direction: 8-Storey archetype.

4.3.2 Inter-story drift

The drift distribution analysis of the 4-story and 8-story steel-framed structures reveals distinct behavioral patterns across the three-lateral load-resisting systems. In the 4-storey structure, FD exhibits the highest drift (1.6%) at Level 1, while RSFJ and BRB show similar values (1.4%). At upper levels, drift becomes more uniform, with all systems converging around 0.8–0.9% at Level 3. Average drift values indicate comparable performance for RSFJ and FD (1.2%), while BRB shows a slightly lower drift of 1.0% (see Figure 10a).

For the 8-storey structure, BRB experiences the highest drifts at upper levels, reaching 1.8% at Level 8, whereas RSFJ and FD maintain lower drifts (1.3–1.4%). Across mid-levels, drift remains consistent (1.0–1.3%). Overall, BRB exhibits the highest average drift (1.3%), while RSFJ and FD both average 1.1% (see Figure 10b). FD demonstrates the most consistent performance across both structures, while BRB may require additional drift management in taller buildings.



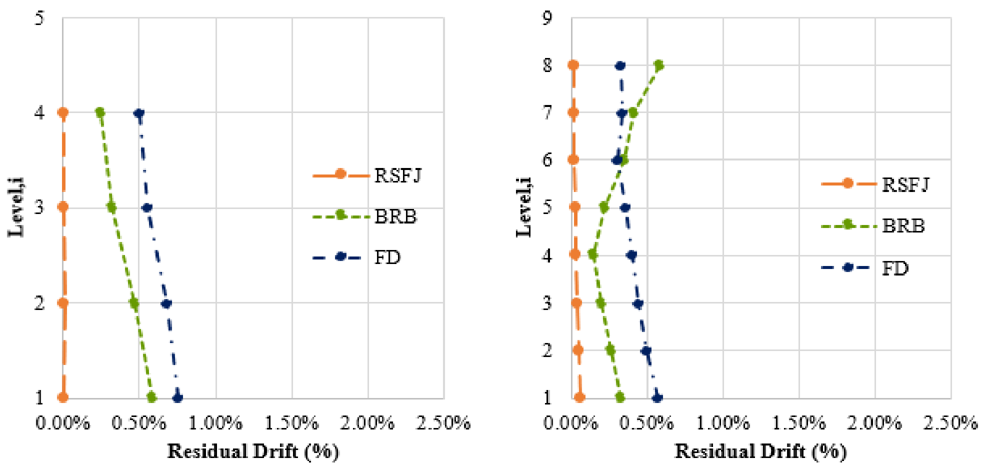
(a) (b)

Figure 10. Comparison of Inter-storey drift in N-S direction: (a) 4-Storey archetype, and (b) 8-Storey archetype_ULS

4.3.3 Residual drift

The comparative analysis of three structural systems across both 4-story and 8-story buildings reveals consistent performance patterns, with the RSFJ system demonstrating superior performance by maintaining near-zero residual drift percentages (approximately 0.000%) throughout all floor levels in both structures (see Figure 11a and 11b). The BRB system shows moderate performance with residual drifts between 0.250-0.500% at lower levels of the 4-story building, while in the 8-story structure, these values increase progressively from 0.250-0.350% at lower floors to 0.600-0.700% at upper levels. The FD system consistently exhibits the highest residual drift values, reaching approximately 0.750% at level 1 in the 4-story structure and showing measurements of 0.500-0.600% at lower levels and 0.600-0.750% at upper levels in the 8-story building structures (see Figure 11a and 11b).

In both structures, while all systems maintain relatively controlled residual drifts, the RSFJ system consistently provides the best self-centering capabilities regardless of building height, with BRB and FD showing more pronounced residual deformations at different locations. The significant benefit of full self-centering capabilities, as demonstrated by the RSFJ system will reduce the post-earthquake repair costs, minimizes building downtime, and enhances overall structural resilience by allowing immediate occupancy following major seismic activities.

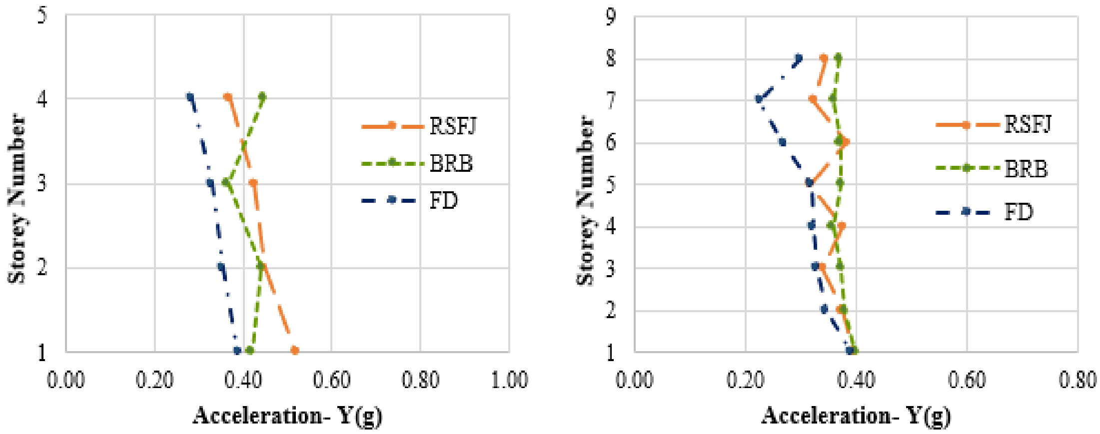


(a) (b)

Figure 11. Comparison of residual drift in N-S direction: (a) 4-Storey archetype, and (b) 8-Storey archetype_ULS

4.3.4 Floor Acceleration

The most important aspect of any structure is its ability to safeguard human life. High floor acceleration can result in discomfort, injuries, or even fatalities for the occupants of the building. Keeping floor acceleration low significantly reduces the risk of harm to people during seismic events. At Level 1 of the 4-storey structure, RSFJ recorded the highest acceleration of 0.52g, followed by BRB, which recorded a floor acceleration of 0.42g. In comparison, FD showed the lowest floor acceleration of 0.39g, reducing acceleration by 25% compared to RSFJ. This trend persists throughout the structure, with RSFJ consistently exhibiting higher accelerations (0.37g–0.52g) than BRB (0.37g–0.44g) and FD (0.28g–0.39g), with the largest variation occurring at Level 1 (see Figure 12a). Conversely, for the 8-storey structure, acceleration distribution is more uniform at upper levels, where all systems converge around 0.40g. However, in the lower and middle stories, FD maintains the lowest accelerations (0.27g–0.33g) compared to RSFJ (0.32g–0.38g) and BRB (0.36g–0.37g). These results indicate that while all systems effectively manage accelerations, FD offers the best reduction, particularly in lower stories, benefiting acceleration-sensitive non-structural components and equipment (see Figure 12b).



(a) b)

Figure 12. Comparison of floor acceleration in N-S direction: (a) 4-Storey archetype, and (b) 8-Storey archetype-ULS

4.4 FURTHER DISCUSSION

The study revealed that implementing BRBs, RSFJs, and FDs as LLRS in 4-storey and 8-storey steel-framed structures can significantly reduce force demands. In the 4-storey archetype, RSFJs and FDs achieved equivalent ductility factors of 3.1 and 3.7, respectively, while BRBs yielded 2.7. For the 8-storey archetype, RSFJs and FDs achieved 2.8 and 3.8, respectively, whereas BRBs yielded 2.6. This highlights the robustness of FDs in reducing force demands across both structures.

The findings indicate that as building height increases, the equivalent ductility factor decreases. However, the inherent calibrating properties of RSFJs and FDs can aid in optimizing designs to meet project-specific needs. Moreover, NLTHA results revealed that while BRBs and FDs comply with New Zealand seismic codes, their low post-yield stiffness results in permanent displacements in the 4-storey steel framed structure considered in this study. These permanent displacements were observed to be increasing in the 8-storey archetype, necessitating careful design consideration.

5 CONCLUSION

This study demonstrates the effectiveness of implementing the three (3) advanced bracing systems as Lateral Load Resisting Systems (LLRS) in a 4-storey and 8-storey steel braced framed structure. The findings indicate that these advanced bracing systems with a combination of CBFs and energy dissipating devices can serve as viable alternatives to conventional Concentrically Braced Frames (CBFs) without dampers, enhancing seismic performance by significantly reducing force demands while keeping drifts within code-specified limits at the Ultimate Limit State (ULS).

The study also demonstrates that the Capacity Spectrum Method (CSM) is an efficient tool for evaluating the seismic performance of structures ranging from 4 to 8 storeys, as its results closely align with those obtained from Nonlinear Time History Analysis (NLTHA). Furthermore, all three configurations—Buckling Restrained Braces (BRBs), Resilient Slip Friction Joints (RSFJs), and Friction Dampers (FDs)—achieved equivalent ductility factors between 2.6 and 3.8 when used as LLRS in the examined structures. Among these, the FDs exhibited the highest equivalent ductility factors of 3.7 and 3.8 for the 4-storey and 8-storey archetypes, respectively, indicating potential cost savings in foundation design for new constructions. Additionally, the inter-story drifts for all three systems ranged from 1.0% to 1.3%, demonstrating their ability to minimize damage to non-structural components such as façades, architectural elements, and mechanical, electrical, and plumbing (MEP) systems. Floor accelerations were also comparable across all three configurations in both structural archetypes.

Moreover, results from NLTHA showed that while BRBs and FDs comply with New Zealand's seismic code requirements and exhibit favorable energy dissipation properties, their low post-yield stiffness makes them prone to residual drifts. This limitation could pose challenges for post-disaster structures, where an additional Moment Resisting Frame (MRF) might be necessary to ensure self-centering. In contrast, LLRS configurations incorporating CBFs with RSFJs demonstrated superior performance in controlling residual drifts. Specifically, NLTHA results for structures with RSFJs revealed negligible residual drifts, indicating full self-centering behavior. The self-centering capability of RSFJ-based LLRS in steel-framed buildings ensures minimal maintenance requirements following an earthquake.

Overall, while these LLRS configurations (BRBs, RSFJs, and FDs) demonstrated superior seismic performance by effectively reducing force demands, controlling drifts, and enhancing energy dissipation, their selection should be carefully tailored to meet specific project requirements. Factors such as post-earthquake residual drift, self-centering capability, cost considerations, and maintenance need to be evaluated to ensure optimal performance for the intended application. By strategically selecting the most suitable LLRS, structural resilience and efficiency can be maximized, contributing to safer and more resilient building designs.

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