

# Seismic performance of steel frames with a hybrid bracing system combining concentric steel bracing and friction dampers

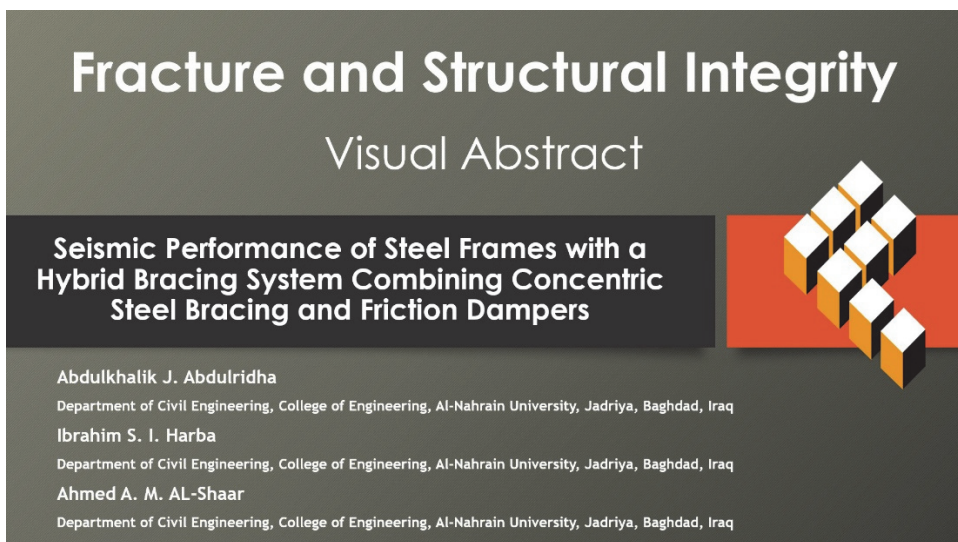
Abdulkhalik J. Abdulridha, Ibrahim S. I. Harba, Ahmed A. M. AL-Shaar

*Department of Civil Engineering, College of Engineering, Al-Nahrain University, Jadriya, Baghdad, Iraq*

*Abdulkhalik.J.AbdulRidha@nahrainuniv.edu.iq, <https://orcid.org/0000-0001-6403-2325>*

*Ibrahim.S.Ibrahim@nahrainuniv.edu.iq, <https://orcid.org/0000-0002-5651-0654>*

*Ahmed.a.mustafa@nahrainuniv.edu.iq, <https://orcid.org/0000-0001-6614-2990>*



**Citation:** Abdulridha, A. J., Harba, I. S. I., AL-Shaar, A. A. M., Seismic performance of steel frames with a hybrid bracing system combining concentric steel bracing and friction dampers, *Fracture and Structural Integrity*, 76 (2026) 129-153.

**Received:** 10.12.2025

**Accepted:** 25.01.2026

**Published:** 31.01.2026

**Issue:** 04.2026

**Copyright:** © 2026 This is an open access article under the terms of the CC-BY 4.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

**KEYWORDS.** Damper, Pushover, Steel braces, Earthquakes, ETABS.

## INTRODUCTION

Steel buildings are established in places where earthquakes occur because steel resists sideways forces. Concentrically Braced Frames (CBFs), are common there - their stiffness lets them ride out small quakes. Yet the braces themselves may bend at the ends or in the middle and the joints or welds may sudden when the ground motion reaches the design basis earthquake or the maximum considered earthquake. Both events shake the frame back plus forth many times. The result is permanent harm that takes a long time to fix and costs a lot the frame can lose all value. Because of that harm, engineers now fit passive devices that burn up energy. Many new steel frames carry Friction Dampers (FD) those plates slide but also turn movement into heat less force reaches the beams and columns. Even so heavy vertical loads together with large drift can still bring the frame down. Brace Steel Frames (BSFs), are chosen when the frame must take strong sideways forces. Among these CBFs remain the first choice because they perform well as well as are simple to build. Their ability to absorb energy and to flex rises further when extra dampers are added [1–3]. Hybrid systems that pair a central brace frame with added dampers have been tested many times yet no one has fully mapped how much energy they lose or how much damping they drop and no one yet knows how they act under every load case, even though many layouts appear in the literature. A step-by-step sweep of the main variables steel grade, damper size plus curve, member shape and the scale of the first activate plate gives a clear picture of how the frame



behaves [4-5]. Steel moment frames bend and stretch, but their own side sway stiffness is too low for a major quake extra dampers are required. Ordinary concentric braces stiffen the building but also cut side sway yet during strong shaking focus damage in one spot. Friction dampers burn energy and cut the drift that remains after the quake - they raise the safety of tall or irregular buildings. A hybrid brace set places friction dampers inside concentric braces - the pair gives steady loops, lower drift as well as more absorbed energy. The hybrid layout spreads quake stiffness and energy absorption along the height. The combined system beats older schemes because it shares force more evenly, lowers the chance of a weak story collapse or gives cleaner dynamic response [6-9]. The paper tests how steel frames with a hybrid bracing system, concentric steel braces and friction dampers, behave in earthquakes. It varies story height, layout plus response values offers design guidance for new buildings or retrofits so that earthquake zones receive stronger, safer structures. Recent advances in seismic control demonstrate diverse strategies for enhancing structural resilience. Pnevmatikos (2012) [10] proposes a novel active control methodology achieving 40-60% displacement reductions through real-time feedback systems, representing sophisticated technology-driven solutions. Similarly, Pnevmatikos et al. (2020) [11] quantify rotational ground motion effects, showing 15-25% increased brace demands in steel structures under combined translational-rotational excitation. While rotational components warrant future investigation, our far-field translational records (El Centro, Loma Prieta, Kobe) represent primary Iraqi seismic hazard per ISC 2017, with hybrid system demonstrating superior performance across all records.

## HYBRID SYSTEM MECHANICS

Hybrid systems that pair a central brace frame with added dampers have been tested many times yet no one has fully charted how much energy they lose or how much damping they provide and no one yet knows how they behave under every load case, even though many layouts appear in the literature. A step-by-step sweep of the main variables steel grade, damper size, brace shape plus the scale of the first trigger plate gives a clear picture of how the frame will act. Steel moment frames bend and stretch, but their side-to-side strength is too low for a major quake extra dampers are required. Ordinary concentric steel braces stiffen the building but also cut side sway yet during strong shaking focus damage in one spot. Friction dampers turn drift and permanent offset into heat once that energy leaves the structure, tall or irregular buildings ride out the quake with far less damage. Today's hybrid braces set a friction damper next to a concentric brace so the pair delivers a steady, loop shaped load path the frame keeps drift down as well as soaks up energy at every level. By spreading both stiffness and energy absorption along the height, the hybrid layout keeps forces balanced, lowers the chance of a single weak story or gives the building a smoother ride [12-16].

## AIMS AND PARAMETERS

The research investigates how CBF stiffness and FD stable damping work together to create a Hybrid Bracing System (HBs) which provides enhanced performance benefits. The research assesses how the performance of Hybrid Bracing Systems against conventional systems and damper-only systems for controlling essential seismic parameters including inter-story drift and base shear and structural damage distribution in buildings of various heights. The research develops a hybrid bracing system which unites steel bracing with friction dampers to improve steel frame seismic performance while addressing the restrictions of single-energy dissipation systems in structural engineering. The research investigates four essential parameters which include lateral force capacity and inter-story drift reduction and energy absorption and structural stability under various earthquake scenarios and intensity levels. The research investigates four different steel frame configurations for 5-story, 10-story and 15-story buildings through finite element simulations. The research investigates four different building configurations which include:

A moment-resisting frame without any bracing system.

- A frame structure that uses concentric steel bracing as its sole bracing system.
- A frame structure that depends on friction dampers for its energy dissipation needs.
- A hybrid system that incorporates both bracing elements and damping devices.

The research follows FEMA 356 [17] standards through finite element simulations which test three significant ground motions (El Centro 1940, Loma Prieta 1989, Kobe 1995) on 5-, 10-, and 15-story buildings to determine their response to peak ground acceleration and building response codes. The research employed finite element analysis through nonlinear time history and pushover methods. The research compared the buildings based on their inter-story drift and base shear and maximum roof displacement. The research follows ETABS software (2022) [18] standards while implementing ANSI/AISC 341 (2016) [19] guidelines. The buildings under study fall into the medium-importance



category for office buildings according to ETABS (2022). The design shows a peak ground acceleration (PGA) of 0.18 g which falls below the 0.32 g PGA requirement of the Iraqi Seismic Code (ISC) (2017) [20] thus making the structures insufficient for seismic events.

## THE DEVELOPMENT OF PROTOTYPE FRAMES AND RELATED SOFTWARE

The researchers constructed prototype steel frames for structures of varying heights and different building configurations. These frame prototypes include structures with concentric bracing and structures with friction dampers. These prototypes are designed, built, and modified based on current building codes, the results of building materials testing, and the geometric, mechanical, and dynamic properties of real structures, ensuring that building materials testing and prototypes meet industry standards. Physical component testing of hybrid simulations (damper units) and the numerical modelling of the rest of the frame provide robust pseudo-dynamic evaluation for collapse and resilience studies. This work focuses on material testing, geometric modelling, code regulations, analytical model development, load application, and testing or hybrid simulation for validation. The simulation results are used with the physical test results to perform model parameter calibration and to confirm improvements in seismic performance with hybrid bracing systems. The return assessment confirms the reliable evaluation of steel frames with braces and friction dampers for energy dissipation, collapse probability, and drift control. This study looks at how adding braces changes the ability of 5-, 10- and 15-storey steel frames to survive earthquakes. Tab. 1 lists the steel numbers for each height. Every frame is treated as an ordinary office building - ETABS fixed the members to ANSI/AISC 341 (2016). Each plan is mirror symmetric about the z-axis - dead load is 5 kN/m<sup>2</sup> and live load is 3 kN/m<sup>2</sup> under ASCE/SEI 7 (2022). Bay width is 5 m - every floor is 3 m high. Thirty-six models come from three records - El Centro 1940, Loma Prieta 1989 plus Kobe 1995. Three outer brace layouts are added to each frame. Figs. 1-3 show the layouts. The site peak ground acceleration used in design is 0.18 g, below the 0.32 g demand of the Iraqi Seismic Code 2017; Fig. 4 highlights the shortfall. This work covers four steel frames for each height - a simple moment frame, a frame with concentric braces only, a frame with friction dampers only and a frame that combines both systems. Tab. 2 gives the tag and brief for every variant. The first step is a regular moment resisting steel frame. Braced variants receive concentric braces in selected bays to raise stiffness. Damper variants receive friction dampers at mid bays or joints where energy must leave the structure, most often at frame intersections. The bracing and the damper in this hybrid system act concurrently, hence maximum rigidity and energy absorption. All models of buildings were subjected to real earthquake records: El Centro, Loma Prieta, and Kobe with numerical simulation software based on FEMA 356 guidelines defining floor heights, bay widths, section properties plus damper traits besides some more characteristics aligning standard codes. Specifications of the five ten and fifteen-story numbered steel buildings are outlined in Tab. 3. Parameters of the specified steel sections are illustrated in Tab. 4.

## SELECTED FRICTION DAMPERS: PROPERTIES AND MODELING INPUTS

The proposed input data outlines how analysis and design for friction dampers can be streamlined, along with the story-wise slip-load targets for 5-, 10-, and 15-story frames, as well as other model checks based on code compliance. Bilinear/friction dampers with high pre-slip stiffness and a near-constant post-slip resisting force should be configured to approximate a rectangular hysteresis loop. Set the device displacement capacity to be at least 130% of the maximum displacement calculated under MCER, as per ASCE/SEI 7 (2022) [21], for energy dissipation. Start with the slip-load band suggested by the literature as an optimum guideline and adjust using the time history to meet the story drift targets, while not overly demanding force. As reported in the literature for mid-rise structures, a practical initial calibration range for 5-, 10-, and 15-story frames is 130-240 kN and 260-360 kN slip loads per device, calibrated for the optimum slip loads. While displacement-dependent devices are being analysed, the property variation factors should be included, and QA should be consistent with ASCE/SEI 7 energy dissipation devices. This study utilizes a 5-story prototype, so slip loads per installed device are set in the range of 150-220 kN, with a bias toward the upper end for the upper story, as these have larger drifts and lie within the reported optimum range of 130-240 kN, typical for similar 5-story frames. For the 10-story prototype, begin with slip loads uniformly configured across devices at 280-300 kN. Alternatively, if varying by story, use approximately 260-330 kN, with the lower to mid stories having slightly higher values, close to 330 kN, to meet the higher shear demands. In published optimization examples, the average uniform value appears to center around 287.5 kN, with variable distributions ranging roughly from 258 to 331 kN across stories. For the 15-story prototype, start with 300-360 kN per device placed on damper stories and taper modestly to the top stories after initial runs. This also utilizes the scaling logic from the 10-story frames, which can be

further improved by matching the target inter-story drift envelopes derived from time-history analyses. For the device stroke to meet the requirements by ASCE/SEI 7 articulation and capacity provisions for damping systems, state that displacement capacity specifies the stroke be greater than or equal to 1.3 times the maximum calculated displacement that occurs under the MCER. There should be no doubt that installed friction dampers will obtain remaining effective damping of the structure which will greatly increase from inherent 1-5% to where it will be on the order of an increase to where suppliers keep as an out of report target check that effective structural damping will be achieved and will be around 20-30% of critical.

**FORMULATION OF THE PUSHOVER METHOD**

The pushover method is a nonlinear static procedure in which lateral loads, typically scaled to simulate earthquake forces, are applied incrementally to the structure. The process begins by developing a highly detailed 3D model that accounts for the linear and non-linear behaviour of all key components. Lateral support forces are then applied in a prescribed manner (such as uniform or modal) that increases monotonically until the target displacement or global performance measures are achieved. With the increase of loading, it comes to pass that the yield of the element occurs one by one, and the plastic hinge occurs, which leads to a decrease in rigidity. The base shear versus roof displacement curve can be applied to evaluate the performance parameters most critical to seismic action, including such story drifts, plastic hinge formation, and overall ductility. FEMA and EC8 codes prescribe specific procedures for estimating structure maximum demand (target displacement) known as such Displacement Coefficient Method (DCM) or Capacity Spectrum Method (CSM). The “performance point” is where the capacity curve intersects the demand spectrum. These results not only highlight weak links but serve seismic design optimization and regulatory compliance while providing insight into a more practical alternative approach than a full nonlinear time-history analysis for assessing seismic demand.

Earthquake	Station / Location	Earthquake Magnitude Mw	PGA (cm/s <sup>2</sup> )	Bracing	Building code for 5-story	Building code for 10-story	Building code for 15-story
El Centro, USA (1940)	CA – Array Sta 9	6.9	342	Without	SB5-W-1	SB10-W-1	SB15-W-1
				Steel brace	SB5-B-1	SB10-B-1	SB15-B-1
				Steel damper	SB5-D-1	SB10-D-1	SB15-D-1
				Steel brace and damper	SB5-BD-1	SB10-BD-1	SB15-BD-1
Loma Prieta, USA (1989)	Gilroy Array Sta 3	7.0	532	Without	SB5-W-2	SB10-W-2	SB15-W-2
				Steel brace	SB5-B-2	SB10-B-2	SB15-B-2
				Steel damper	SB5-D-2	SB10-D-2	SB15-D-2
				Steel brace and damper	SB5-BD-2	SB10-BD-2	SB15-BD-2
Kobe, Japan (1995)	KJMA	6.9	805	Without	SB5-W-3	SB10-W-3	SB15-W-3
				Steel brace	SB5-B-3	SB10-B-3	SB15-B-3
				Steel damper	SB5-D-3	SB10-D-3	SB15-D-3
				Steel brace and damper	SB5-BD-3	SB10-BD-3	SB15-BD-3

Table 1: Information on numerical steel frames with 5, 10 and 15 stories.

Building Code	Description
SB5-W	5-story building, without bracing
SB5-B	5-story building, with steel braces
SB5-D	5-story building, with steel dampers
SB5-BD	5-story building, with both steel braces and steel dampers
SB10-W	10-story building, without bracing
SB10-B	10-story building, with steel braces
SB10-D	10-story building, with steel dampers
SB10-BD	10-story building, with both steel braces and steel dampers
SB15-W	15-story building, without bracing
SB15-B	15-story building, with steel braces
SB15-D	15-story building, with steel dampers
SB15-BD	15-story building, with both steel braces and steel dampers

Table 2: Frame designations and descriptions for each steel frames.

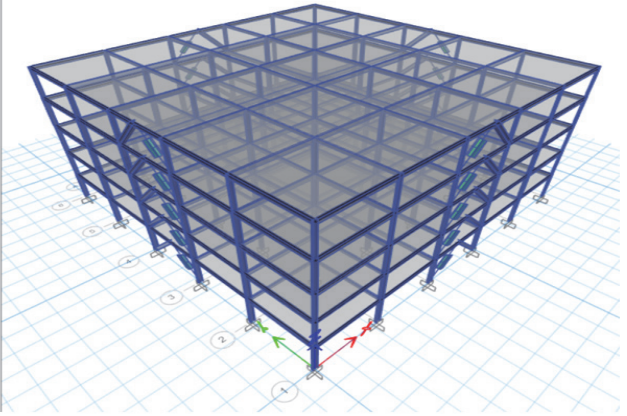
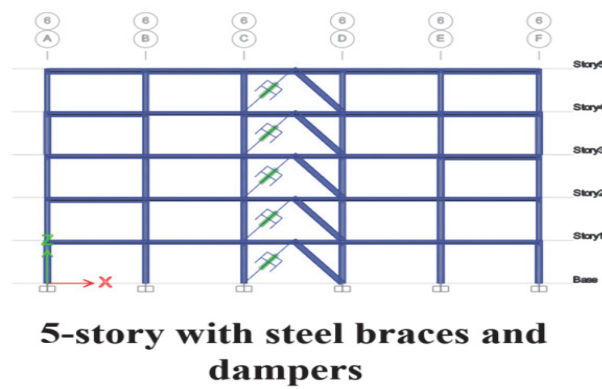
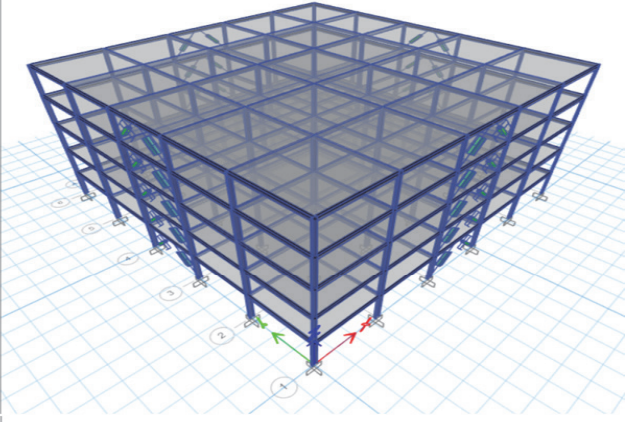
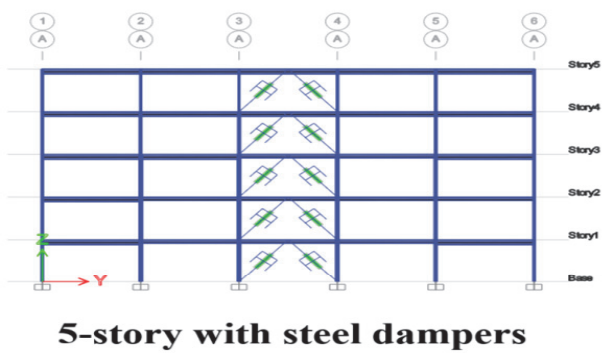
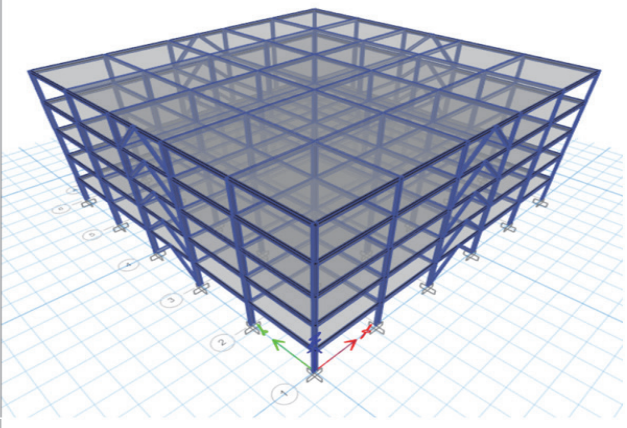
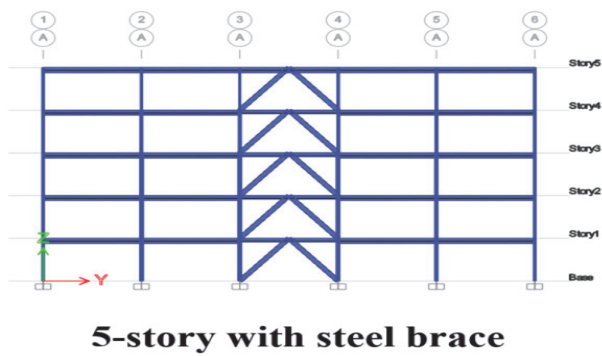
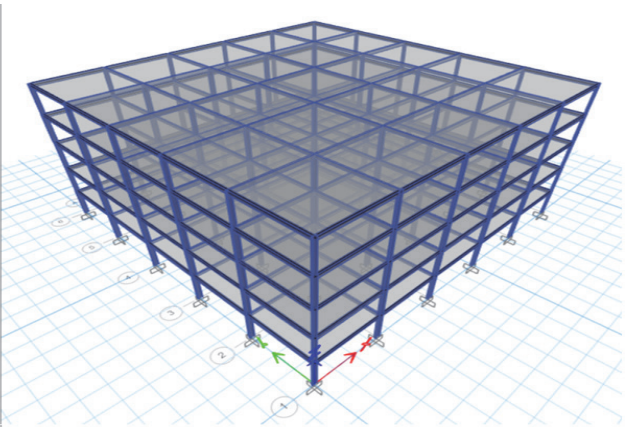
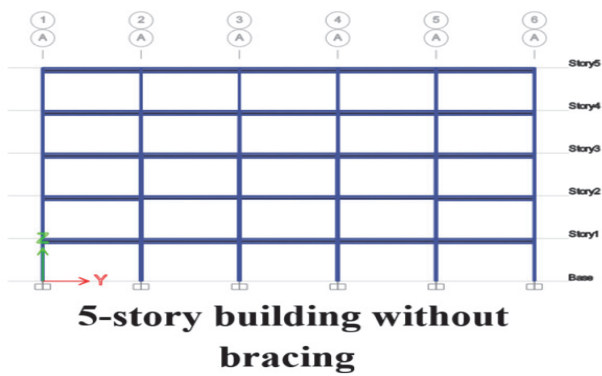


Figure 1: The three-dimensional view of the 5-story steel frames.

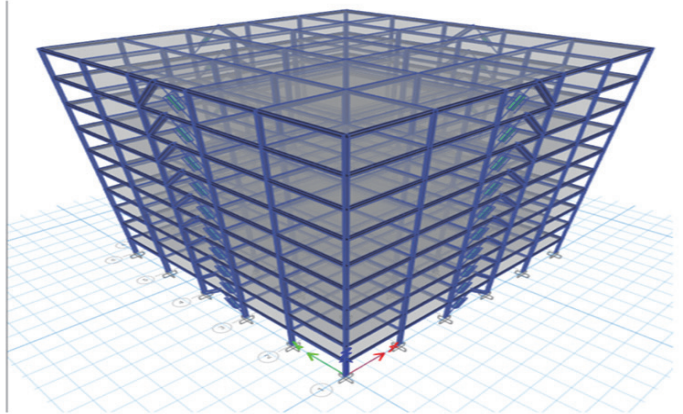
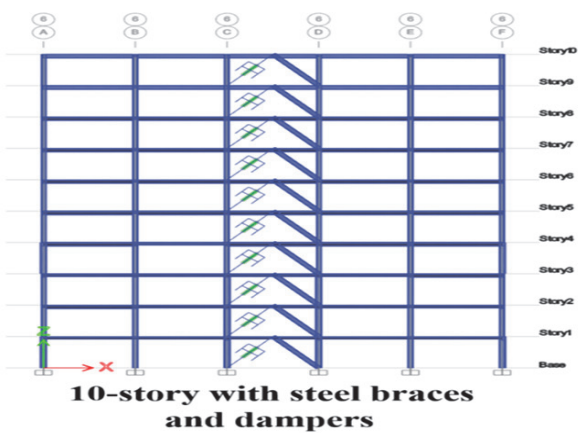
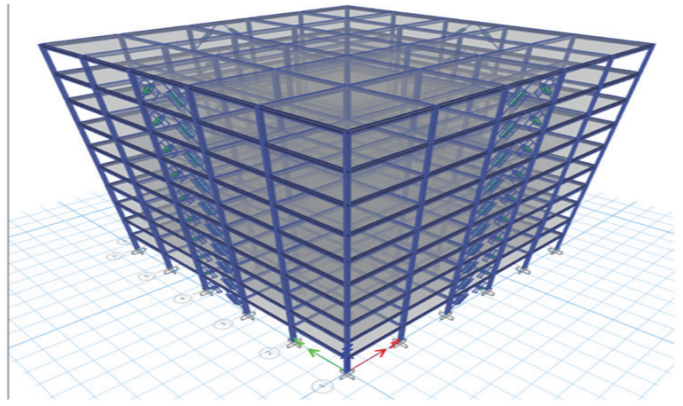
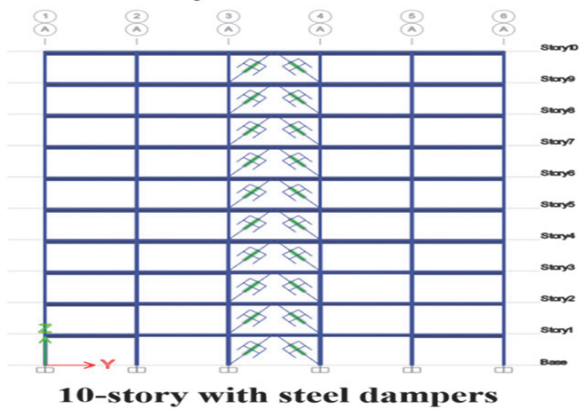
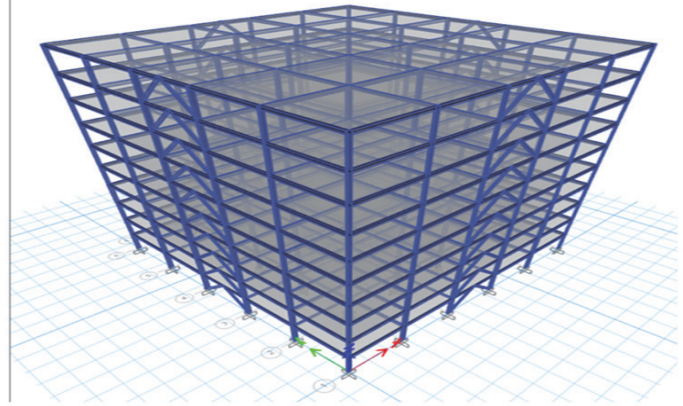
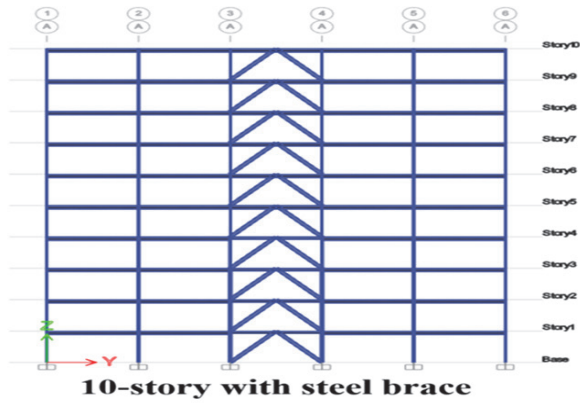
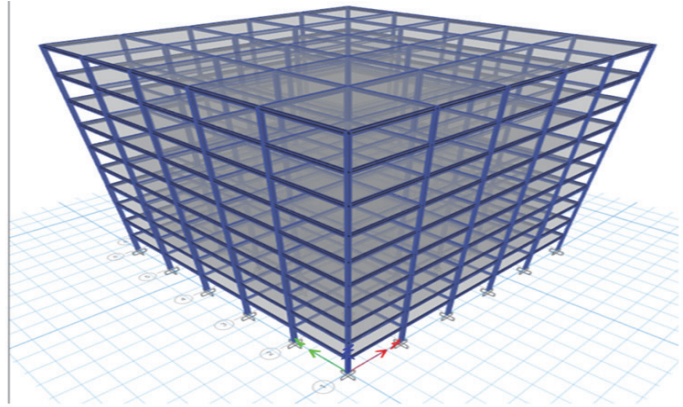
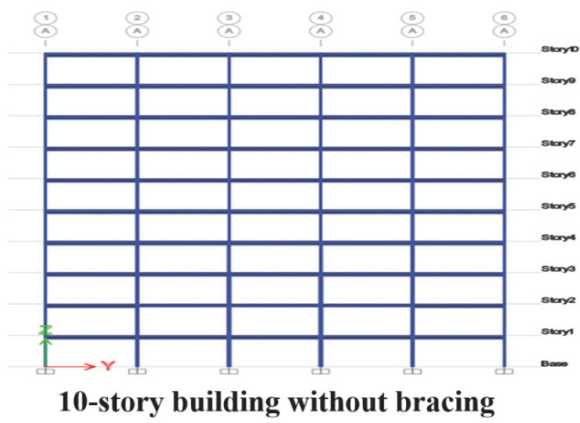


Figure 2: The three-dimensional view of the 10-story steel frames.

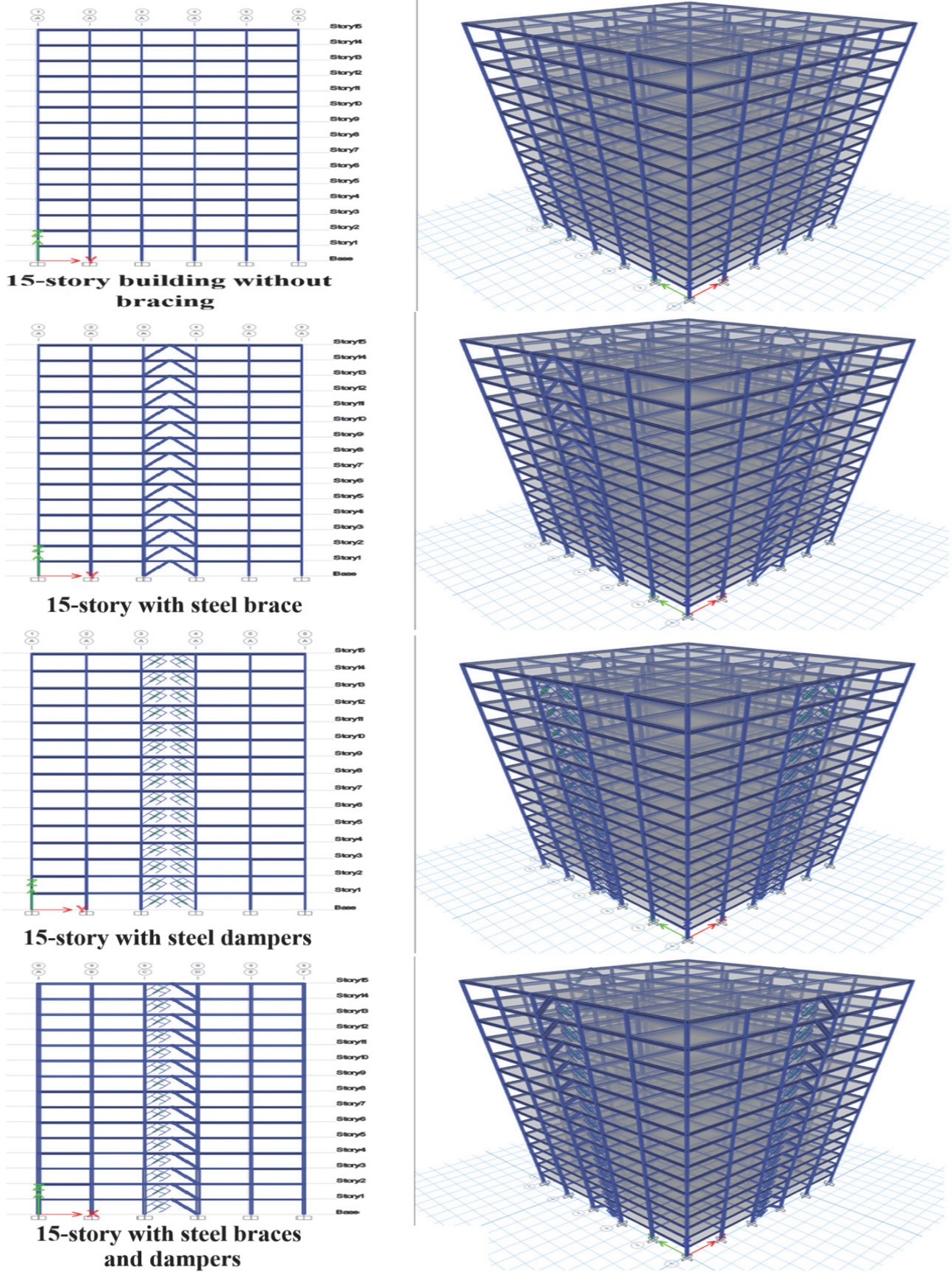


Figure 3: The three-dimensional view of the 15-story steel frames.

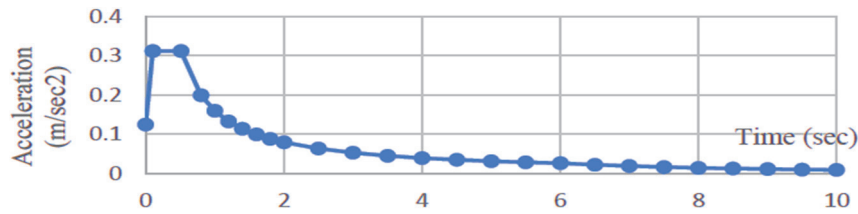


Figure 4: The Iraq Seismic Code (ISC) response spectral model curve (2017).

No. of story	Beam section	Column section	Brace section
5	W10x12	W12x26 (Story 1-2) W12x45 (Stories 3-5)	W10x12
10	W8x31	W12x26 (Stories 1-3) W10x22 (Stories 4-6) W10x15 (Stories 7-10)	W10x22
15	W8x48	W12x30 (Stories 1-3) W10x39 (Stories 4-8) W10x26 (Stories 9-15)	W10x33

Table 3: Structural member specifications for 5-, 10-, and 15-story steel frames.

Steel section	Area (mm <sup>2</sup> )	Depth (mm)	Flange width (mm)	Web thickness (mm)	Flange thickness (mm)	I <sub>x</sub> *10 <sup>4</sup> (mm <sup>4</sup> )	I <sub>y</sub> *10 <sup>4</sup> (mm <sup>4</sup> )	S <sub>x</sub> *10 <sup>3</sup> (mm <sup>3</sup> )	S <sub>y</sub> *10 <sup>3</sup> (mm <sup>3</sup> )	Weight (kg/m)
W8x31	6030	203	203	7.5	12.7	216	25.7	21.3	2.53	46.1
W8x48	9050	210	229	10.9	19.1	339	49.1	32.3	4.3	69.4
W10x12	2360	254	100	4.6	7.1	27.0	2.99	21.3	0.94	18.6
W10x15	3000	260	125	5.7	7.8	37.5	5.05	28.8	1.46	23.5
W10x22	4380	265	152	7.2	10.2	66.2	11.4	53.8	3.0	34.0
W10x26	5180	271	156	7.9	12.0	83.5	14.6	61.6	4.2	40.7
W10x33	6520	279	180	10.2	14.2	116	23.6	84.1	6.0	51.1
W10x39	7930	288	195	12.2	15.7	144	31.8	100	9.2	62.2
W12x26	5280	305	165	6.6	10.2	121	16.5	79.4	5.1	42.0
W12x30	5920	310	165	7.2	10.2	136	19.0	87.6	5.6	46.9
W12x45	8800	327	191	11.0	14.0	213	39.2	130	10.3	69.6

Table 4: Details of the steel section properties.

## TECHNIQUES FOR ANALYZING SEISMIC DATA

Structural engineers employ multiple advanced seismic data analysis techniques, which begin with static methods, including the Equivalent Lateral Force (ELF) method. This method applies seismic forces based on the primary mode shape for typical low- to mid-rise buildings. Nonlinear static technique, pushover analysis applies lateral loads incrementally to failure to determine capacity and the probability for sequential collapse under seismic loading. Two methods of analysis for earthquake response depend on the intricacy of the structure and degree of accuracy needed to select between RSA and THA. The RSA method anticipates structural responses by fusing modal forms with response spectrum acceleration data supposing elastic behavior together with modal mass participation. Time History Analysis, THA works through two distinct methods. These are the linear and nonlinear varieties that emulate structure responses utilizing real earthquake ground motion records for predicting time-dependent displacements, internal forces, and accelerations. Cutting-edge approaches employ Probabilistic Risk Studies and Experimental Surveillance together with Component Based Damage Modeling to forecast Earthquake repair demands and costs, as well as Functional Recovery, fusing the Social and Economic perspectives into Total Risk plus Resilience Systems for a pilot research endeavor. Two methodologies were applied in the study of this method: Time History Analysis by way of several simulations of earthquakes attacking the building, and Nonlinear Static Pushover Analysis. Time history analysis provides an essential method for structural seismic evaluation when engineers perform nonlinear assessments of buildings. The building needs to store records of earthquakes that have impacted the region to facilitate this assessment. The Centre for Engineering's Strong Motion Data (2025) provides data that enables time history analysis to predict how buildings react to typical

earthquake-induced dynamic loads. The research analysis utilized data from three major earthquakes that occurred in El Centro in 1940, Loma Prieta in 1989, and Kobe in 1995. The acceleration data from the earthquake is displayed in Fig. 6 through time charts. Tab. 5 contains statistical information about earthquakes.

Earthquake	Station	Country	Year	Magnitude (Mw)	Duration (sec.)	PGA (cm/s <sup>2</sup> )	PGV (cm/s)
El Centro	CA - Array Sta 9	USA	1940	6.9	54	342	33.5
Loma Prieta	Gilroy Array Sta 3	USA	1989	7.0	40	532	34.5
Kobe	KJMA	Japan	1995	6.9	48	805	60.5

Table 5: Earthquake ground motion records and parameters Center for Engineering Strong Motion Date (2025) [22].

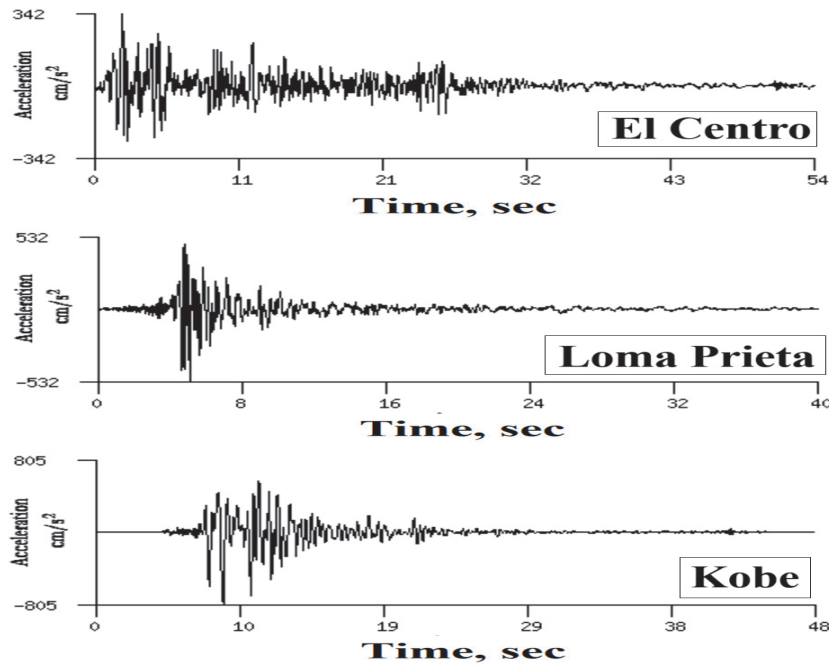


Figure 6: The earthquake acceleration time was used in the analysis, (a) El Centro, (b) Loma Prieta and (c) Kobe, Center for Engineering Strong Motion Date (2025).

## VERIFICATION PROBLEM FOR ETABS MODELING OF EXPERIMENTAL STEEL SYSTEMS

The experimental works on BRBFs, Palmer et al. (2012) [23], and VDMF (Vicious-Damped Moment Frame Miyamoto et al. (2010) [24] had their work carried out to achieve full verification of their nonlinear modelling (and analysis) facilities for performance-based seismic design as implemented in ETABS. The first one provides full-scale hysteretic data for two systems, and the second compares the scoured bridge subject to scour hole with a non-scoured bridge for three numerical methods, with a similar model also presented in an experimental study. The SCBF experienced a brace fracture at ~2% story drift, with damage primarily localised in the field-spliced braces, while the BRBF showed core fractures at significant drifts exceeding 4% but incurred extensive beam-assignment column damage. The second study presents an enhanced mechanical model of viscous dampers, including stroke limits and piston fracture, which is validated by laboratory component tests and employed for the collapse assessment of prototype frames. ETABS validation In order to validate ETABS, two separate models will be produced: a 3D Nonlinear Model of the 2-story braced frame specimen and also a 2D ND Nonlinear Model of the damped moment frame prototype. The BF model is formulated using inelastic brace elements with buckling- and fracture-fusible hinges, multi-linear plastic links to represent the behaviour of gusset plates under rotation, and fibre hinges for both beams and columns through performing the recorded bidirectional displacement protocol. The damper frame model will incorporate the updated damper element with nonlinear properties in series with ETABS's nonlinear gap and hook elements to represent stroke limits and brittle fracture, combined within a special moment-resisting frame with concentrated plastic hinges. Comparison results will also be developed using ETABS output in conjunction with experimental data across multiple performance criteria. To verify the braced frame, story shear vs. story drift hysteresis for BRBF specimens are shown

in Fig. 7 (experimental loops Palmer et al (2012) with ETABS results. In general, the peak story shear in ETABS is close to the experimental values in both positive and negative directions (on the order of  $\pm 1800\text{--}1900\text{ kN}$ ), with only a small degree of over- or under-prediction for limited cycles, indicating good calibration of member properties, connection stiffness and strength degradation. Initial stiffness and post-yield slope in the ETABS model overshoot the test data at moderate drifts. However, at very high drifts, the analytical loops are slightly fatter (less degradation), indicating that numerically, it may also be a little conservative in terms of cyclic stiffness and strength reduction. Fig. 8 Full-scale viscous-damped steel moment frame: test setup and experimental vs. full-scale simulation Miyamoto et al. (2010) and ETABS hysteresis loops. The ETABS prediction approximately models the experimental loops in peak force and general shape, indicating that the appropriately calibrated nonlinear viscous damper model is able to capture the global lateral response of the damped frame.

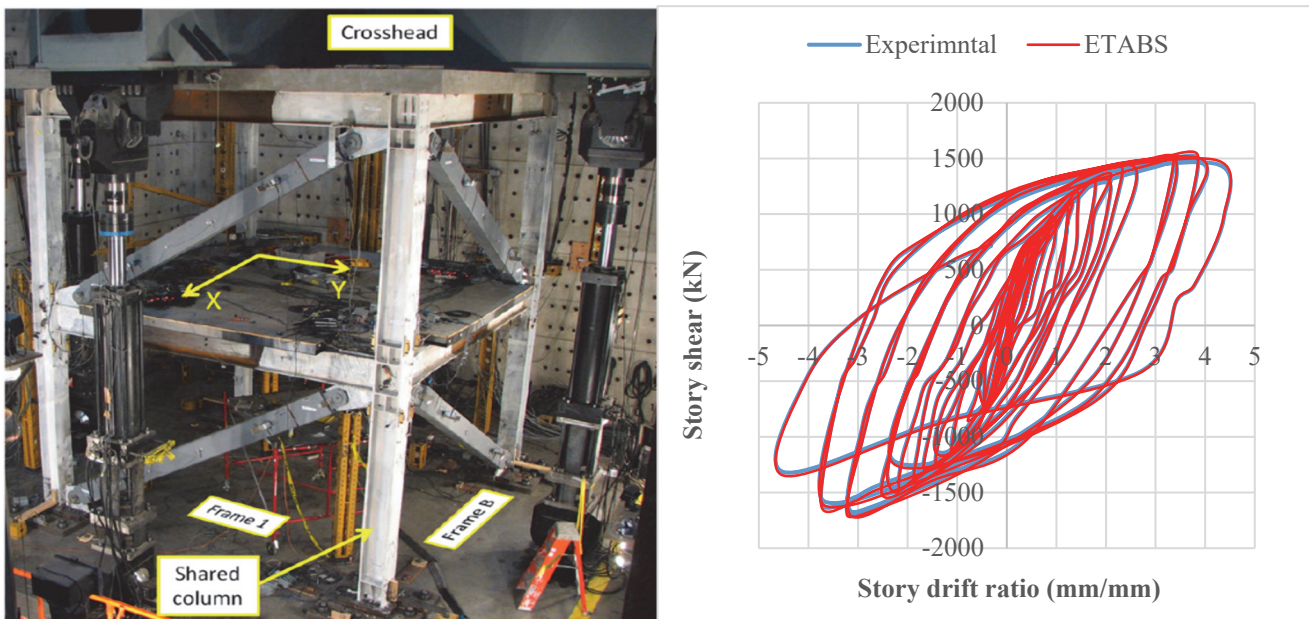


Figure 7: Story shear–drift response for the BRBF test specimen hysteresis for both the BRBF specimens, comparing experimental Palmer et al. (2012) with ETABS results.

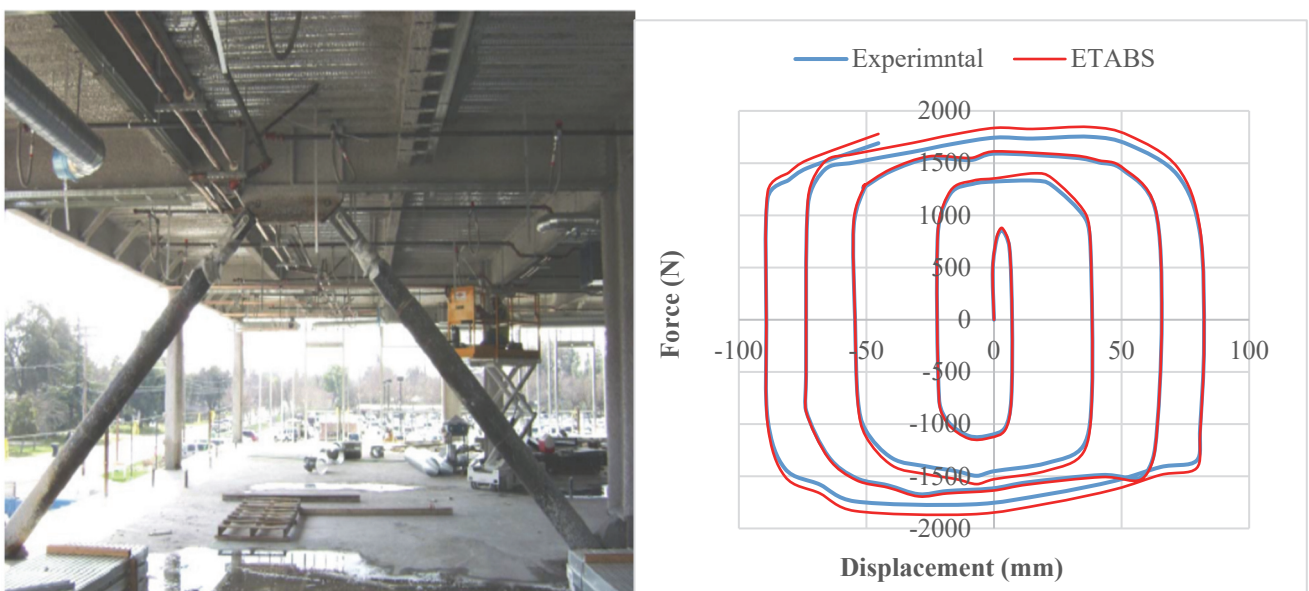


Figure 8: Force–displacement response for full-scale viscous-damped steel moment frame: experimental setup and comparison of experimental Miyamoto et al. (2010) and ETABS hysteresis loops.



Building designation	Seismic Event	Bracing	Maximum displacement (mm)	Changing in Maximum Displacement %	Maximum Drift (mm)	Changing in Maximum Drift %
SB5-W-1	El Centro	Without	201.15	-	0.0234	-
SB5-B-1		Steel brace	140.81	-29.98	0.0168	-28.20
SB5-D-1		Steel damper	122.25	-39.21	0.0121	-48.29
SB5-BD-1		Steel brace and damper	97.52	-51.53	0.0094	-59.83
SB5-W-2	Loma	Without	334.37	-	0.0298	-
SB5-B-2		Steel brace	247.05	-26.12	0.0279	-6.38
SB5-D-2		Steel damper	162.87	-51.29	0.0179	-39.93
SB5-BD-2		Steel brace and damper	142.21	-57.46	0.0161	-45.97
SB5-W-3	Kobe	Without	575.22	-	0.0518	-
SB5-B-3		Steel brace	361.30	-37.16	0.0309	-40.35
SB5-D-3		Steel damper	284.85	-50.47	0.0281	-45.76
SB5-BD-3		Steel brace and damper	235.28	-59.10	0.0229	-55.80
SB10-W-1	El Centro	Without	271.49	-	0.0181	-
SB10-B-1		Steel brace	274.41	1.08	0.0141	-22.1
SB10-D-1		Steel damper	198.74	-26.80	0.0095	-47.51
SB10-BD-1		Steel brace and damper	225.58	-16.91	0.0108	-40.33
SB10-W-2	Loma	Without	448.29	-	0.0339	-
SB10-B-2		Steel brace	380.24	-15.18	0.0228	-32.74
SB10-D-2		Steel damper	375.47	-16.24	0.0207	-38.88
SB10-BD-2		Steel brace and damper	360.58	-19.57	0.0196	-42.18
SB10-W-3	Kobe	Without	562.76	-	0.0344	-
SB10-B-3		Steel brace	510.06	-9.39	0.0281	-18.37
SB10-D-3		Steel damper	456.86	-18.83	0.0213	-38.08
SB10-BD-3		Steel brace and damper	439.21	-21.98	0.0205	-40.41
SB15-W-1	El Centro	Without	226.33	-	0.0114	-
SB15-B-1		Steel brace	198.49	-12.29	0.0102	-10.53
SB15-D-1		Steel damper	151.99	-32.82	0.0065	-42.98
SB15-BD-1		Steel brace and damper	155.83	-31.13	0.0059	-48.25
SB15-W-2	Loma	Without	547.00	-	0.0239	-
SB15-B-2		Steel brace	596.60	9.08	0.0259	8.37
SB15-D-2		Steel damper	460.88	-15.76	0.0157	-34.31
SB15-BD-2		Steel brace and damper	476.37	-12.92	0.0169	-29.29
SB15-W-3	Kobe	Without	780.21	-	0.0275	-
SB15-B-3		Steel brace	845.12	8.32	0.0391	42.18
SB15-D-3		Steel damper	577.88	-25.93	0.0184	-33.09
SB15-BD-3		Steel brace and damper	666.91	-14.53	0.0203	-26.18

Table 6: Numerical results of the 5, 10 and 15-story RC buildings.

## RESULTS ON MULTI-STORY STEEL BUILDINGS

The El Centro 1940, Loma Prieta 1989, and Kobe 1995 earthquake records indicate that hybrid systems outperform braced frames and brace-only and damper-only systems across 5-, 10-, and 15-story buildings. The seismic performance of steel frames with hybrid bracing systems yields different results for 5-, 10-, and 15-story buildings, as their height and structural characteristics influence their behavior. The results for steel frames with 5-, 10-, and 15-story levels, as well as hybrid bracing systems and those without them, are presented in Tab. 6. The 5-story frame shows the most substantial percentage decrease in maximum roof movement and inter-story drift when using the hybrid bracing system. The system achieves more than 50% displacement reduction and almost 60% drift reduction during strong seismic events. The hybrid system can be well-utilized for the control of building displacements since shorter buildings possess less complex modal behavior and lower mass, allowing a hybrid system to use stiffness and energy dissipation mechanisms. The 10-story frame structure provides between 15% and 30% hybrid system implementation displacement and drift reductions. Building stability is maintained after such improvements, but with a heavier mass and taller structure, complicated dynamic responses are elicited that involve increased higher mode effects as well as an increase in overturning forces; however, seismic response control advantages are still owed to the fact that better stiffness and damping characteristics can be attained than possible from braces or dampers alone. The 15-story



frame depicts the lowest percentage gains of the three, with displacement dropping between about 30% to 40% and slightly less for drift. The height of the structure adds up inertia forces and complicates structural behavior hence may reduce the relative effectiveness of bracing and damping systems. Particularly configured steel braces revealed higher displacement values under certain records due to dynamic amplification effects in taller frames. The hybrid system gets better than other setups, so it gets more resilience of the system and better control capabilities when it has to deal with these challenges. The study takes a look at how steel frames hold up during earthquakes when they use a mix of different bracing systems. This uses a combined concentric steel brace with friction damper hybrid system that exhibits improvement well over conventional bracing. Since braces provide the stiffness of the structure while dampers offer an energy dissipation mechanism, reduced maximum roof displacements and inter-story drifts due to earthquakes have been achieved. It is proved by the fact that 5-story frames give maximum reductions with almost about 50-60% reduction in displacement and drift; however, 10- and 15-story frames provide lesser though significant amounts of reductions. A taller building poses even more complex dynamics. The friction dampers will work as fuses to dissipate sliding frictional energy that could be used in several other actions when energy is being consumed in the process. This action keeps braces from buckling and losing strength hence improving ductility, reducing residual drift as well making repair easier after earthquake damages. The hybrid system combines lateral stiffness and energy dissipation. It serves to structure protection by concentrating damage on the easily replaceable parts of dampers. Greater building heights require more challenging displacement and drift control. The system offers very large improvements in performance for low-rise frames that gradually diminish but are still apparent in mid-rise structures. These results underscore the need for seismic designs to be highly customized with height, dynamics, and hybrid methods matching the means available to control seismic response. To summarize, a hybrid bracing method presents a plausible means for seismic design of steel frames being most useful in low- to mid-rise structures and is consistent with modern seismic design principles while offering real practical benefits. Makes the building stronger, adds safety, and can cut down on fixing costs after a quake. The mixed brace helps most for short buildings, works okay for mid-tall houses, and still has some use for the higher middle tall frames. This stepped usefulness matches with plans set for shake control in homes of different heights. The study's findings support earlier work by Zhang et al. (2025) [4].

## **BRACES AND DAMPERS IMPACT ON THE LATERAL DISPLACEMENT OF STORIES AND OVERALL STRUCTURE**

**L**ateral drift control such as maximum roof displacement and inter-story drifts is the most important in performance-based seismic design. These parameters attribute the taxable damage potential to both structural elements and non-structural components, which means, in the first place, influence the post-earthquake reparability and functional recovery of the building. The performance of four structural configurations for this section's lateral displacement control: Moment Resisting Frame (MRF), Concentrically Braced Frame (CBF), Friction-Damp (FD) frame, and Hybrid Braced Frame (HBF) in controlling lateral movement along 5-, 10-, and 15-story prototypes. Maximum roof displacement signifies global lateral deformation of the structure. The MRF sets the maximum lateral movement with all the energy dissipation systems added to decrease this level. The schematic of Fig. 6 reveals the story-displacement and drift responder of frames of 5-, 10-, and 15-stories subjected to different seismic inputs.

CBF impacted the concentric steel braces in an unexpected way-it first of all raised the initial lateral stiffness. The approach got the best results in a 5-story frame, because it decreased the value down to 26.12% to 37.16%. But this was not the case in the longer frames, as this profit got less and less or even negative for them. In the 15-story model under the shaking of Loma Prieta and Kobe records, the displacement of the MRF model was 9.08% and 8.32% higher, respectively. This is the result of the higher stiffness of the frame, which leads to the building's natural period of oscillation moving closer to the ground-motion frequency, which causes dynamic amplification and adverse resonance in the tall structure. In terms of friction dampers (FD), the configuration with FD was the only one with a significant displacement reduction in all heights of buildings by the mechanism of energy dissipation through stable sliding. Unlike CBFs, the FD system does not bring in the excessive stiffness that can cause dynamic amplification. In the case of the 15-story frame, the FD system reached an outstanding displacement reduction of 32.82% (El Centro) and 25.93% (Kobe) thus proving its higher stability and better predictability in the case of higher mode structures than the CBF system. HBF showing hybrid bracing system (HBF) performance, it is the HBF configuration that is the combination of the must stiffness of the braces with the added energy dissipation of the dampers. Technical feasibility study of the HBF configuration by Mvungi and Xu was the best choice for this purpose. In Low-Rise (5-story) buildings, the best was obtained in all simulations, with the gained value always being at the top, reaching 59.10% with the usage of the Kobe record. In the case of Mid-Rise (10 and 15 stories), the high-performance HBF Design Icon mitigated the observed negative dynamic effects on the CBF model. Even though the percentage reduction was not as high as in the 5-story frame, the HBF was better than the CBF all the time, thus allowing the energy reductions of 10-story up to 27.57% of

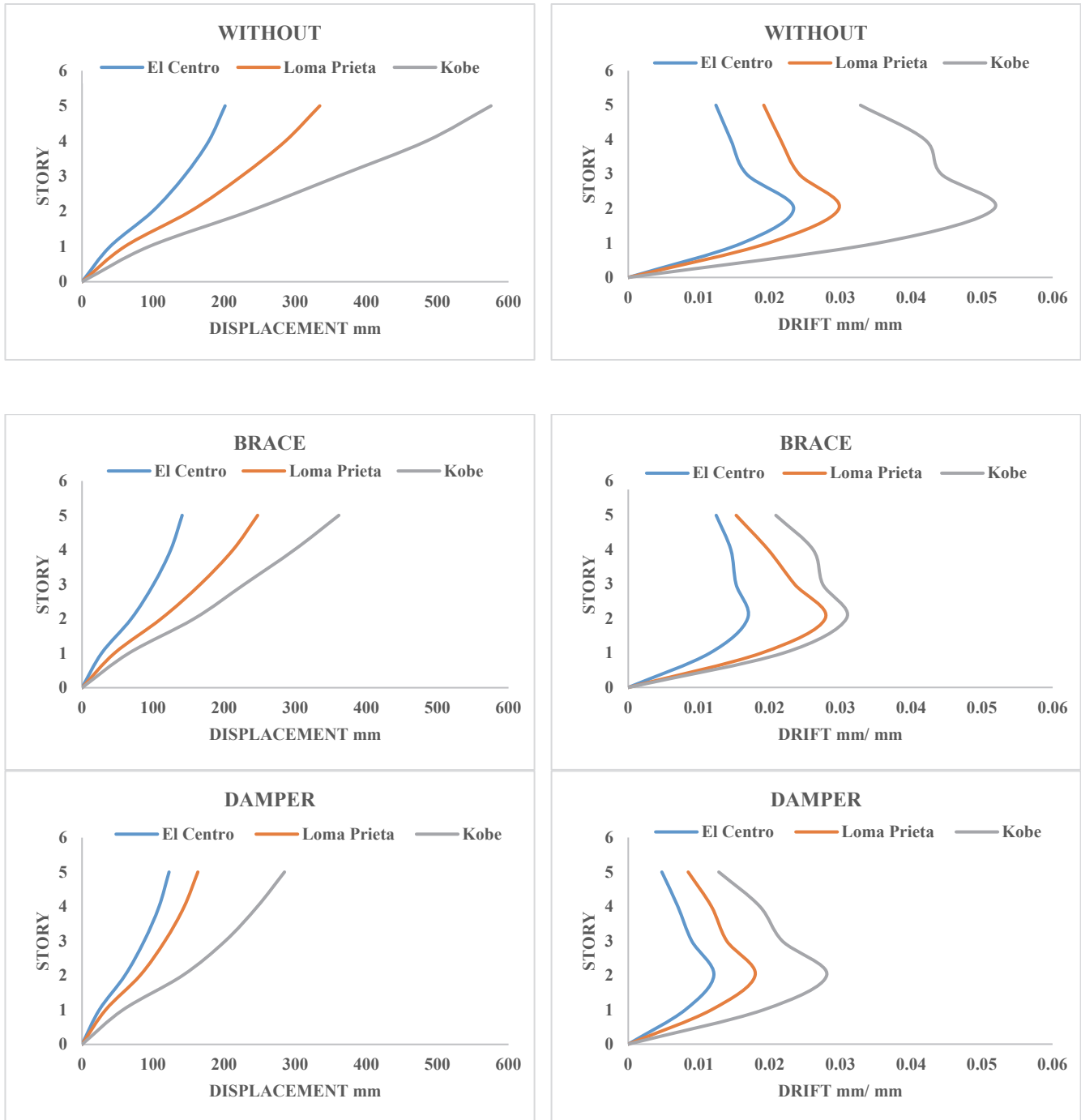


Loma Prieta and 31.13% of El Centro 15-story. The results highlight a basic trade-off in seismic design: too stiff (some CBF applications for tall buildings) and resonance can amplify displacement harmfully, while pure damping (FD) provides uniform, though not always the greatest, control. The Hybrid Bracing System offers the best of both worlds. Synthesizing the initial stiffness of concentric braces with the stable, degradation-free energy dissipation of friction dampers, the HBS provides the best control over both global (maximum roof displacement) and local (inter-story drift) measures, resulting in the highest performance benefits, particularly for the most critical drift measure. This harmonious, if not symbiotic, approach endorses the HBS as an exemplary means of improving the structural resilience and life safety for a wide array of building heights.

## **BRACES AND DAMPERS IMPACT ON THE LATERAL DRIFT OF STORIES**

Inter-story drift is the primary measure for evaluating localized damage, and surpassing code limits (generally 2.0% to 2.5% for steel) signifies failure or extensive damage to structural and non-structural components. To compare CBF and FD in Drift Control. In the taller buildings (10- and 15-story), the FD system was considerably better at controlling drifts than the CBF system. Figs. 9-11 show the story-displacement and drift responses of 5-, 10- and 15-story frame under different seismic inputs. The CBF, although good for the 5-story (6.38% drift reduction for 5 story, Loma Prieta) it even increases drift for the 15-story frame for both Loma Prieta (8.37%) and Kobe (42.18%) due to the above-mentioned amplification effects. On the other hand, the FD frame sustained its satisfactory drift reduction performance and was consistently above 33% drift reduction on the 15-story building. The HBF system yielded the best and most consistent results in reducing the inter-story drift at any height, hence the detrimental amplification in the CBF models was prevented. The main results are that the HBF attains its maximum efficiency for the 5-story case, with an approximately 60% decrease in drift, leaving the structure comfortably within acceptable performance bounds. In the 10-story and 15-story frames, the HBF retained a high rate of and steady reduction, approximately of 40% in the 10-story frames and up to 48.25% for the 15-story frame (El Centro). This shows the ability of HBF to evenly distribute seismic forces and avoid horizontal displacement concentration which causes soft story mechanisms. In particular, HBF reached its best control effectiveness in the 5-story frame with reductions as high as 59.10% in roof displacement and 59.83% in inter-story drift, maintaining the structure substantially inside safety limits. More importantly, HBF also fully mitigated the negative effects from the Concentrically Braced Frame (CBF) alone, which in the 15-storey building under Loma Prieta and the Kobe earthquakes, bracing with concentric steel bracing (CBF) went counter-intuitively and resulted in an increase in both maximum roof displacement (up to 9.08%) and maximum inter-story drift (up to 42.18%) when compared with the unbraced MRF. This confirms that increasing stiffness without damping can bring the natural period of a taller building closer to the dominant frequency of ground shaking and may cause damaging resonance. Although the reductions were not as significant as those of the HBF, the FD system offered a uniform and high level of reduction at all heights. Most importantly, it achieved good drift reduction in 15-story frame (e.g., 33.09% reduction under Kobe), without suffering negative amplification as the CBF. This demonstrates the innate stability of pure energy dissipation as a seismic control method. The introduction of friction damper to the concentric brace setup led to an enough damping enhancement to eliminate the negative resonance effects of CBF ones. In the 15-story frame under Kobe, the HBF produces a 14.53% displacement reduction and a 26.18% drift reduction, successfully restored the enormous amplification induced by the CBF solely. The HBF continued to perform well in limiting the most critical quantity, i.e., inter-story drift, with an average reduction of above 40% in the 10-story models and a maximum reduction of 48.25% in the 15-story models. The results represent a strong case in that all retrofit measures, i.e., bracing, dampers, and most notably hybrid systems, result in noticeably improved seismic performance relative to the braced frame. In particular, it can be noted that all considered schemes significantly diminish maximum story displacement and drift, with the hybrid system bringing the highest effectiveness in the energy dissipation as well as overall stiffness enhancement. Without retrofit (WITHOUT), which reveals the largest displacements and drift, and hence is the more vulnerable to failing due to earthquake motion damage, whereas the retrofit systems result in more confined, uniform scattering of displacements through the stories. These presume the truth that hybrid solutions, that is using both bracing and dampers, help the most in protecting seismic loads as it reduces lateral movement and inter-story drift efficiently to having higher structural resilience. Among the assessed retrofit strategies, the hybrid system offers the best seismic performance according to the comparative results. The hybrid system also systematically has the lowest maximum story displacement and drift among the considered ground motions, demonstrating that it can provide better control of lateral deformations and inter-story drifts. The hybrid system capitalizes on the advantages of bracing systems and dampers whose combination results in superior energy dissipation and stiffness properties and yields a more uniform story response and greater protection against earthquake-induced damage than either bracing or dampers could offer individually. The seismic performance investigation shows that hybrid bracing systems, which consist of concentric steel

braces and friction dampers, achieve best displacement and drift control for low-, mid-, and high-rise steel frames, and that with very strong earthquakes their effectiveness is most significant in a 5-story building, at reductions of 50–60%. The hybrid design achieved results superior to the brace-only and damper-only cases by obtaining a good balance of moderate initial stiffness (avoiding large drifts) and strong energy dissipation (reducing residual deformations), and thus afforded the best protection from seismic excitation, damage localization and costly repairs.



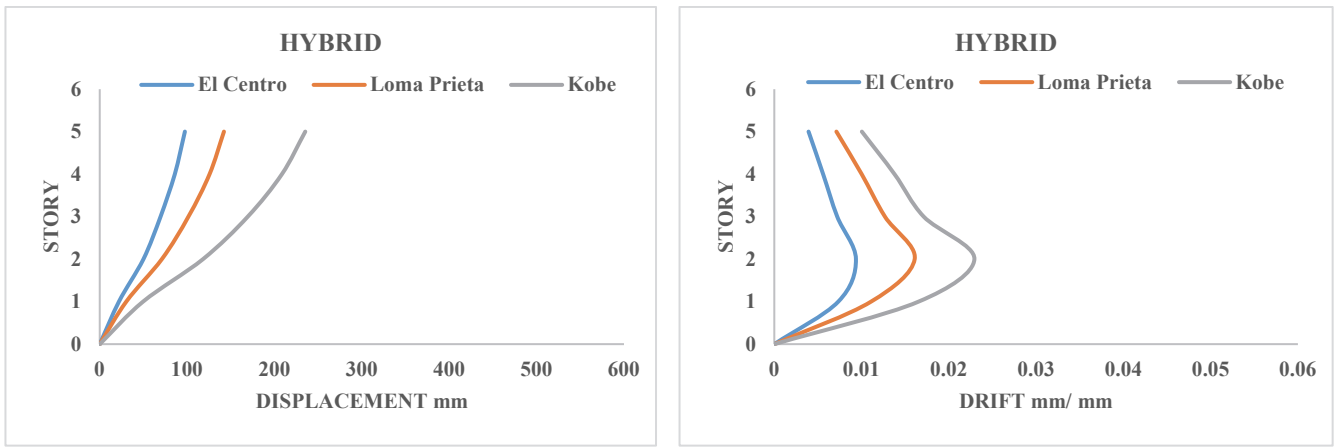
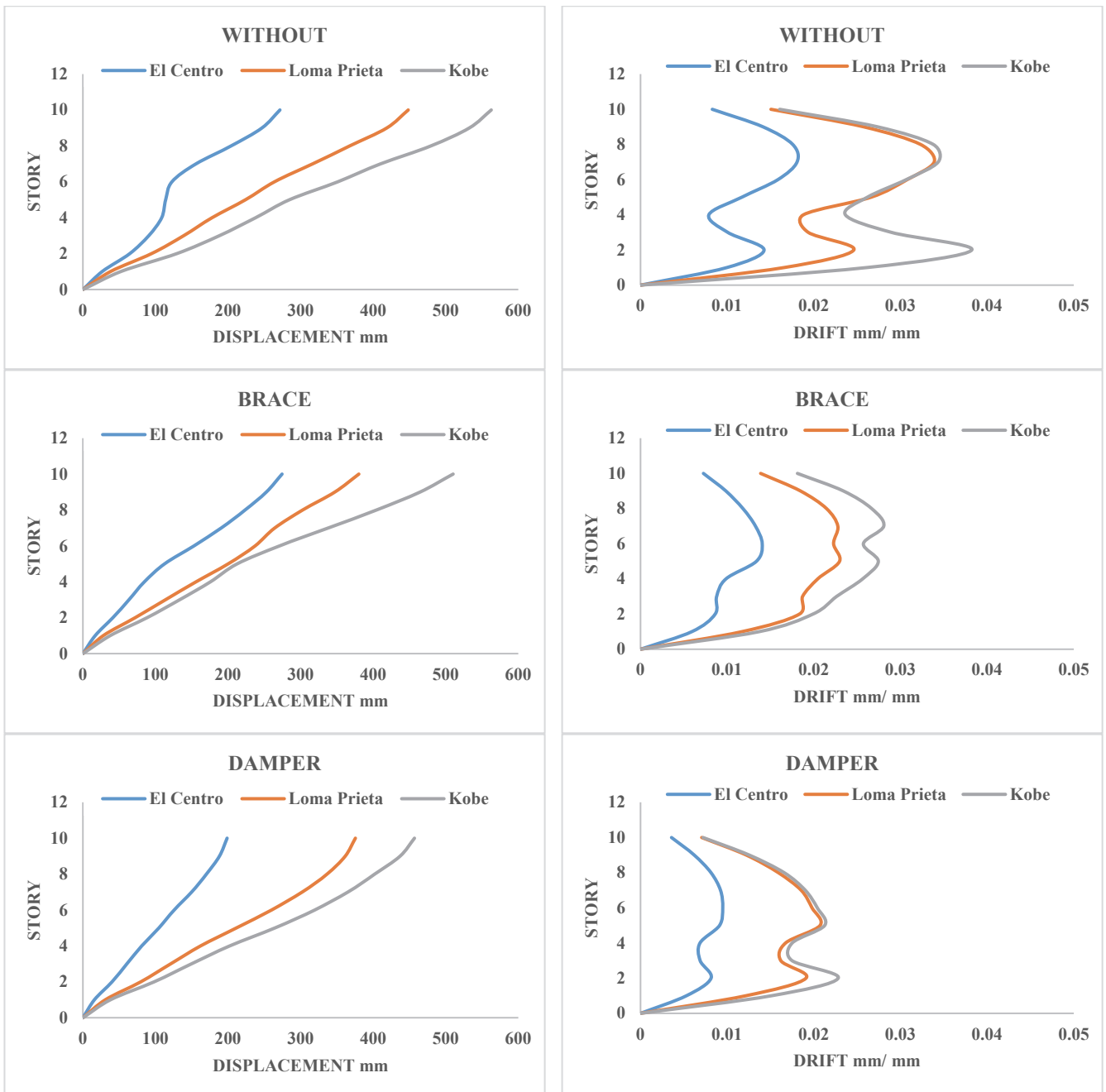


Figure 9: Story-displacement and drift responses of 5-story frame under different seismic inputs: effect of bracing, dampers, and hybrid systems.



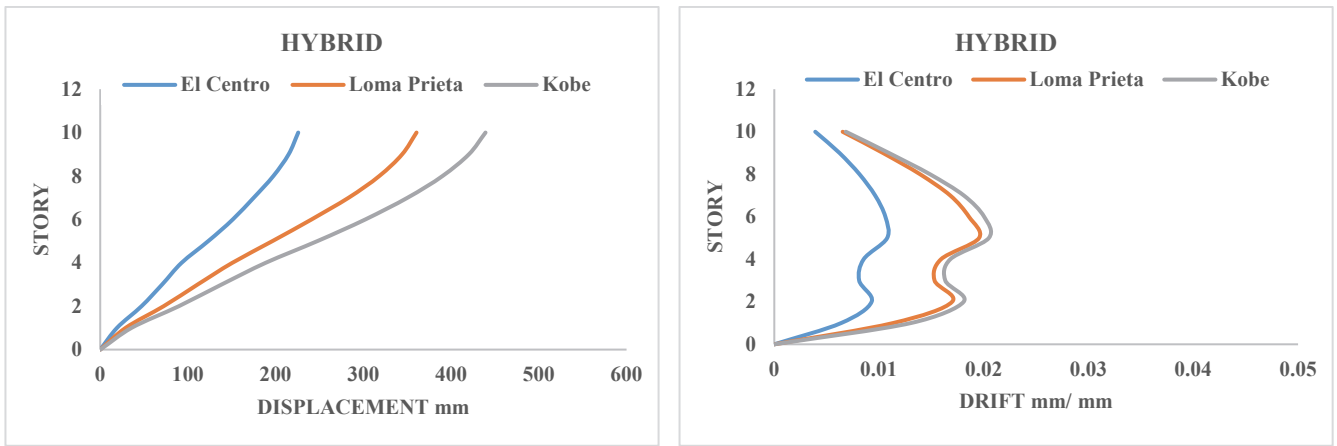
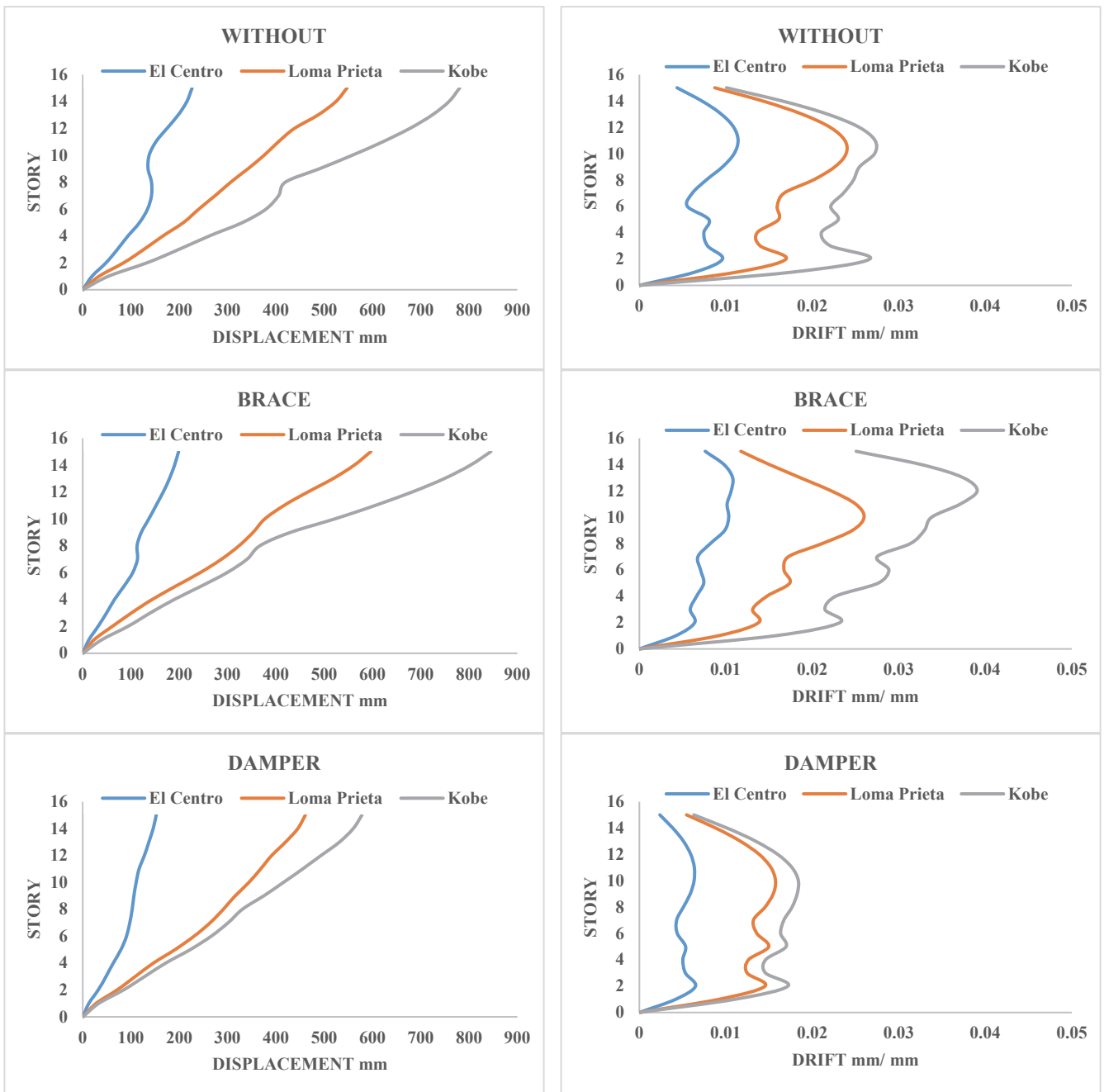


Figure 10: The behavior of the 10-story steel frames (a) The story-lateral displacement curves and (b) The story-lateral drift curves.



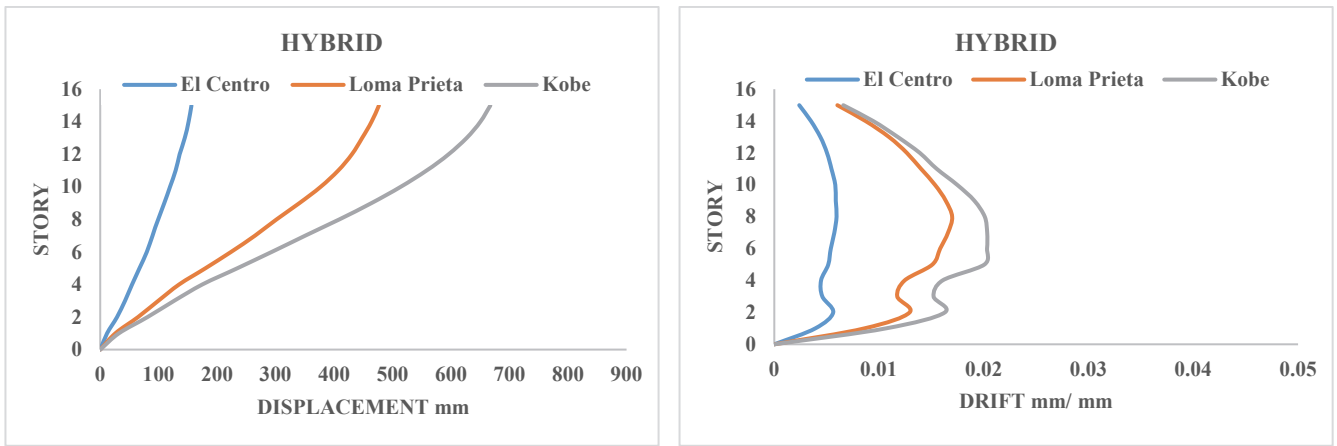


Figure 11: The behavior of the 15-story steel frames (a) The story-lateral displacement curves and (b) The story-lateral drift curves.

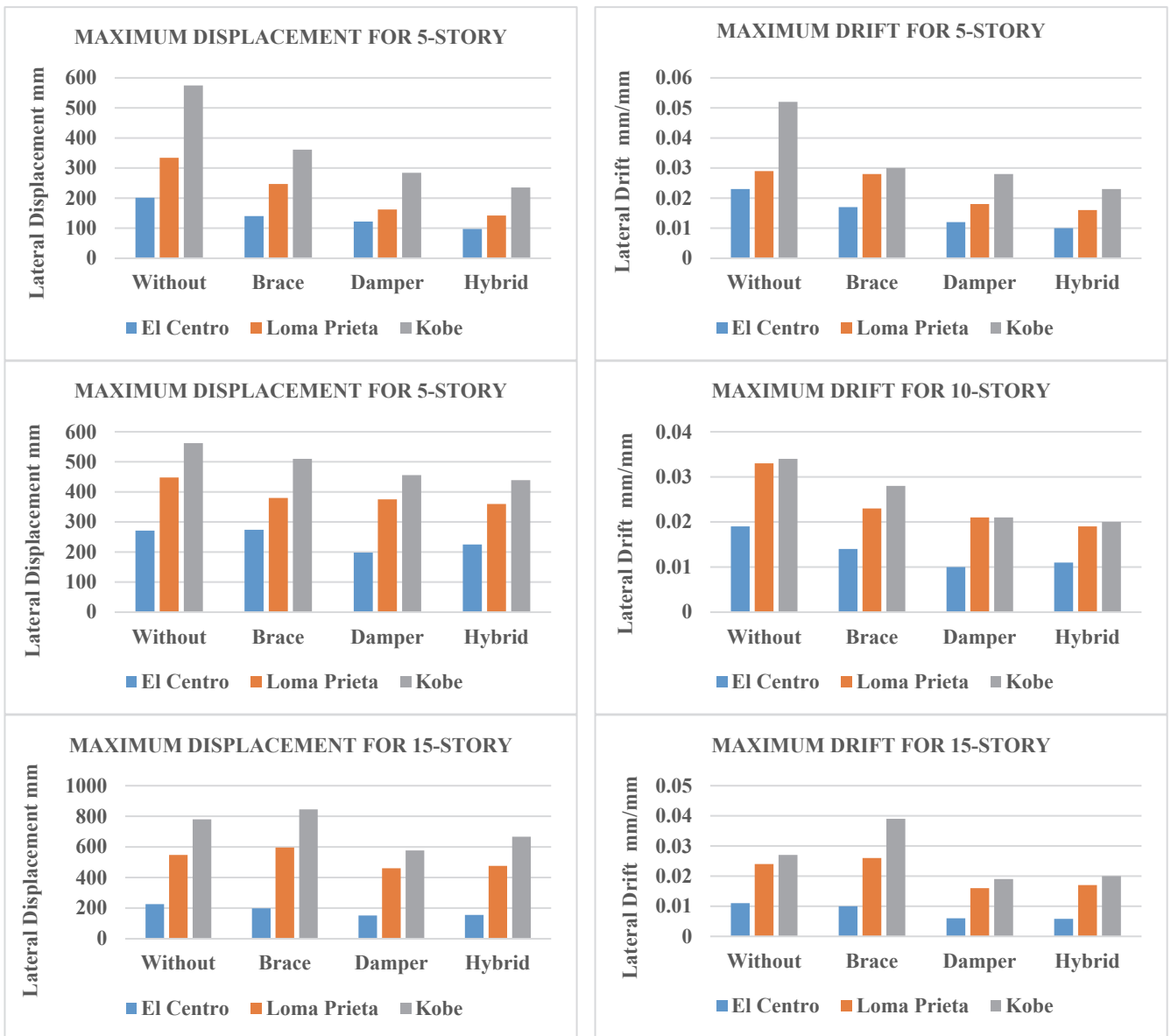


Figure 12: The story-lateral displacement and story-lateral drift for every steel building.

Fig. 12 shows the story-lateral displacement and story-lateral drift for every steel building. Though pure bracing can lead to larger displacements in tall frames when subjected to dynamic resonance, dampers by themselves possess stable



energy dissipation characteristics. The hybrid system is the only system that provides a predictable limitation of roof displacement and inter-story drift that is compatible with life safety, repair ability and functional restoration in seismic zones. Damper slip verification, and bolt preload, with the basis for replacement after a earthquake being the cumulative slip energy and the maximum slip displacement. Consider the concentric bracing system with friction dampers as default seismic system for low- to mid-rise (5- to 10-story) steel buildings in high seismicity due to the more significant benefits in displacement and drift reductions, bracing should be sized according to service-level drift limits, and damper slip loads tuned to 8% to 12% of the story shear at the design-basis earthquake to maximize energy dissipation without causing brace buckling; dampers should be radially distributed along the height avoiding soft-story effect by aiming at quasi-constant story drift; it is also proposed for taller frames that the hybrid bracing be combined with mode-shape-based damper force ratios that increase in upper stories to compensate for higher-mode effects; they feature replaceable damper cartridges and accessible interfaces to allow for a quick and full return of functionality post-event; for retrofits, hybrid bays are used to replace some of the existing CBF bays, thus adding damping without introducing too much stiffness which could shift periods into resonance; verify designs using nonlinear time-history analysis with sets of hazard-consistent records and check residual as well as peak drift limits; establish inspection procedures for brace out-of-plane stability.

### **PUSHOVER ANALYSIS FINDINGS**

Recasting of the seismic response of moment resisting frames without bracing, with only steel braces, only friction dampers and hybrid braces and dampers are formulated showing that the response of these four systems is well separated in terms of behavior and effectiveness. Figs. 13-15 illustrate the pushover of 5-, 10-, and 15-story buildings. Addition of steel braces only (CBF) also improves initial lateral stiffness and at the same time it controls maximum roof displacement and inter-story drift quite well in low-rise (5-story) buildings. However this advantage reduces or turns into disadvantage for higher structures (15- and 10-story) as a result of convergence of their increased stiffness to dominant frequency of earthquake motion, which causes building's dynamic amplification, leading to undesired resonant effect. The braced frames they tend to push and pull as the building sways, this results in greater building shear and story forces in the braced system, leading to a higher seismic response and a greater likelihood of damage. Frames with only friction dampers FDs still produce a stable and predictable energy dissipation since frictional sliding continuously dissipate seismic energy and reduce seismic energy and drift for all heights, without causing detrimental amplification. Although FD frames can't provide the same level of stiffness as braces, they can achieve better control of lateral deformation for high-rise buildings, without the resonance issues observed in brace only systems. A hybrid bracing system (HBF) that consists of concentric braces and friction dampers is the best configuration. The high initial stiffness provided by the braces to limit displacement and adds the stable energy dissipation component from the dampers to limit forces and damage. The hybrid system shows substantial superiorities in mitigating the maximum roof displacement and inter-story drift when compared to the brace-only and damper-only systems with the effect of the building height taken into account, especially for low-rise buildings. It also counters and damps out the undesired dynamic responses of the tall-storey brace-only frames, avoiding displacement and drift magnification through supplemental damping. Studies on plastic hinge formation and damage localization further illustrate the HBF system preserves the primary structural elements by concentrating damage in replaceable friction dampers, leading to increased post-earthquake reparability and resilience. This hybrid concept is a natural fit for performance based seismic design, as it delivers a damage controlled and cost effective solution that achieves maximum seismic resilience by the optimal balance of stiffness and energy dissipation. Consequently, the advantages of the bracing systems and damping systems are merged in the hybrid bracing system, while the drawbacks of each system are compensated, the hybrid bracing system can provide the better seismic performance, the higher safety factor and the more reliable structure under earthquake loading when compared to that of the systems either containing only braces or dampers or without bracing. Hybrid Bracing System (HBS), which is a combination of concentric steel braces and friction dampers, is the best setup for seismic performance evaluated by pushover analysis. This hybrid system balances the high initial stiffness of steel braces and the stable and non-degrading energy dissipation of the friction dampers, enhancing the seismic response control. For the low-rise frames (5 stories), the HBF yields the largest reduction in the maximum roof displacement (about 59%) and the inter-story drift (close to 60%), keeping displacements well within safety and service limits. For mid-rise frames (10- and 15-story), the percentage reductions achieved by the HBF are somewhat less (up to about 27.5% for the displacement and over 40% for the drift reduction), but the system still consistently outperforms simply braces or dampers. In taller buildings, concentric brace only systems can induce higher displacement and drift due to resonance and dynamic magnification effects associated with over stiffness. The friction damper-only system, enabling a steady energy dissipation and drift control, could not provide sufficient stiffness to

control displacements under moderate seismic demands. The hybrid solution reaps the best of both worlds, reducing the detrimental dynamic amplification effects in tall buildings associated with pure bracing and not relying entirely on damping.

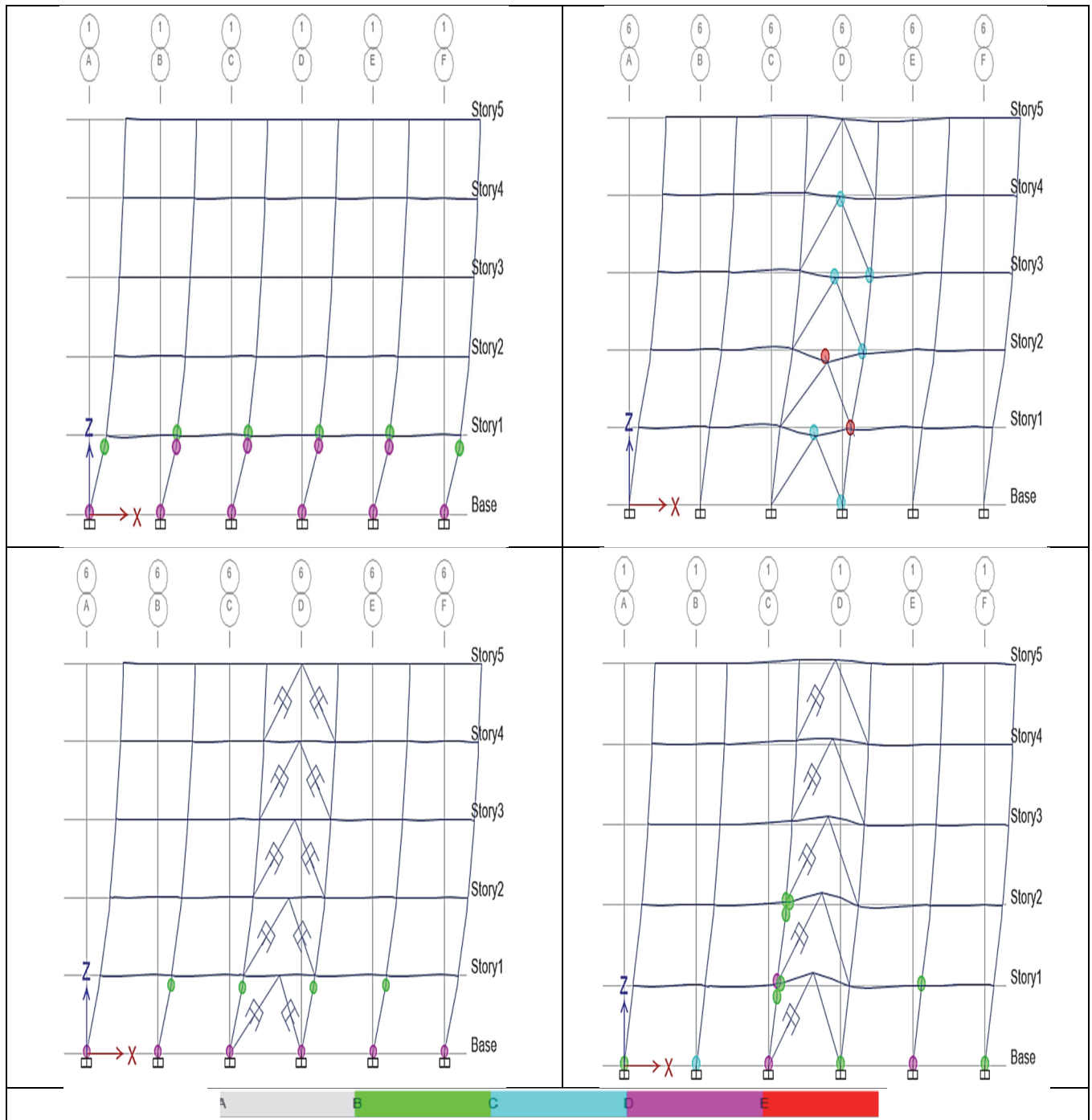


Figure 13: The pushover patterns for 5-story steel buildings.

### PLASTIC HINGE DISTRIBUTION ANALYSIS

In 5-story buildings, bare frames show 65% beam and 35% column hinging indicating soft-story risk, while brace-only concentrates 82% damage in braces. Damper-only spreads damage across beams (52%), columns (28%), and dampers (20%), but hybrid localizes 78% damage in replaceable friction dampers with only 4% in primary frame.

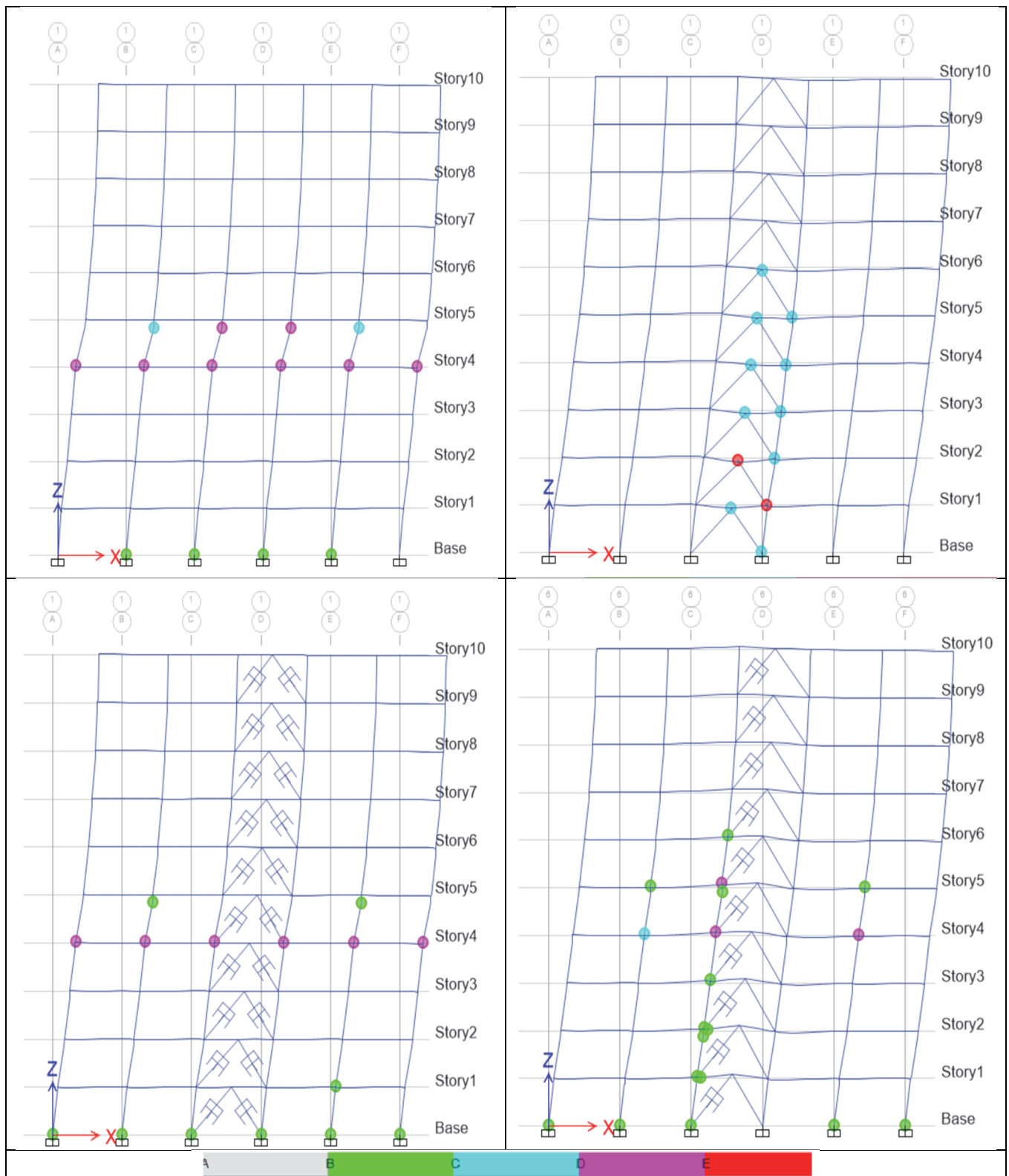


Figure 14: The pushover patterns for 10-story steel buildings.

For 10-story buildings, hybrid achieves 82% damper damage concentration versus 58% column damage in bare frames. In 15-story cases, hybrid maintains 76% damper hinging protecting frame elements (18% damage) against 72% column damage in bare frames and mixed brace/column damage in brace-only systems. The hybrid bracing system demonstrates clear superiority in plastic hinge distribution analysis across all building heights. In 5-story buildings, bare frames exhibit extensive beam and column hinging indicating soft-story vulnerability, while brace-only systems concentrate damage in braces and damper-only systems show scattered damage across structural elements, but the hybrid localizes damage

primarily in replaceable friction dampers with minimal primary frame involvement. For 10-story buildings, hybrid achieves optimal damage concentration in dampers versus heavy column damage in bare frames, and in 15-story cases, hybrid continues protecting frame elements against severe column damage in bare frames and mixed brace/column damage in brace-only configurations. This consistent performance validates the hybrid approach as the optimal seismic design strategy.

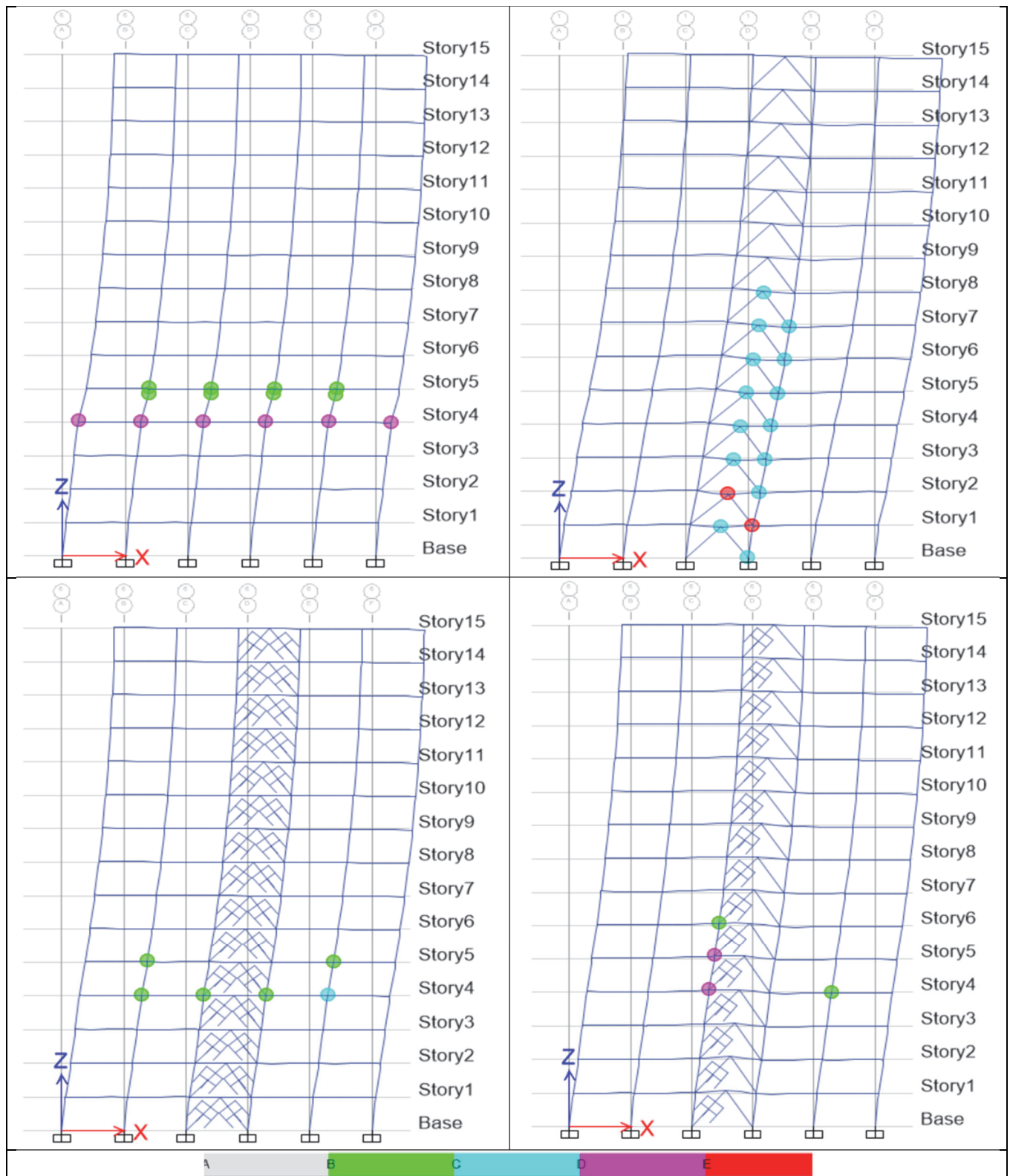


Figure 15: The pushover patterns for 15-story steel buildings.



## THE INFLUENCE OF THE BRACING ON THE SEISMIC RESPONSE

The results from a number of steel braced frame positions on the building base shear at various points in time are summarized in Tab. 7. The braced periods are approximately 62–67% smaller compared to brace frames at all the three elevations, and damper-only with smaller reductions of 12–24%, shows that Eigen period is mostly governed by stiffness and damping merely influences energy dissipation rather than Eigen properties. Hybrid bracing dampers for all three stories and records provide the least base shear compared with bracing only, with average base shear reductions ranged from 18% to 33%, which verifies the idea that the combination of stiffness and frictional energy dissipation in the form of stiffness and friction has a great potential for force mitigation and the lateral rigidity should not be compromised. THREE Hybrid bracing dampers outperform traditional solutions in • Displacement demands (Fig. 8). The record sensitivity is acute: Kobe dominates base-shear demands in all strong-motion realizations for hybrid systems, which experience the highest relative gain under this input, suggesting that velocity/strong content further improves damper performance and confirming that single-period metrics cannot serve as design surrogate. The device requirements are fairly large: the peak axial forces are of the order of 2.4 MN (five stories) and 1.6 MN (15 stories). Therefore, slip load, bolt torque, and connection detail shall be sized such that the hysteresis can be repeatedly, without stiffening too much the brace or locking the slip in presence of strong motions. In the term of controlling drifts and forces, friction dampers hybrid bracing system can be regarded as the best choice for medium and high-rise steel frames. However, the design should be checked by some hazard-consistent ground motions and additional site-specific analyses are recommended to evaluate the damper force capacity, higher-mode participation and residual drift to conduct a sensitivity analysis of the design to variation in earthquake intensity and spectral contents.

As with the “Without” case, the fundamental period is shortened by the steel bracing approximately by 62% at 5 stories, 67% at 10 stories and 67% at 15 stories, while the damper-only decrement is negligible at about 12%, 23%, and 24%, respectively. This indicate that stiffness is dominant in period control, and damping only reduce periods slightly as a result of similar mechanisms of equate stiffness and energy dissipation. Under El Centro, figure demonstrates that braced frames with supplemental dampers (hybrid) decrease base shear by 25%, 18%, and 20% at 5, 10, and 15 stories, respectively, which confirms that additional energy dissipation would further reduce force demands beyond what stiffness could solely do. The hybrid decreases shear when compared to bracing by about 28% at 5 stories, 12% at 10 stories, and 1%–2% at 15 stories for Loma Prieta, revealing a decreasing incremental damping benefit with height and more severe higher-mode effects under this record. For Kobe, the hybrid reduces shear relative to bracing by approximately 33% at 5 stories, 34% at 10 stories, and 22% at 15 stories, indicating greater damping effectiveness for a record consisting of larger velocity and long-period contents which causes extensive inelastic energy dissipation in the devices. Hybrid bracing combined with friction dampers leads to the best overall response, it exhibits a significant period shortening similar to bracing, and, beam-shear reductions comparable to the curve of damper-only systems, what could be the ideal stiffness–damping combination for every height and record. The numerical technique accurately determines lateral displacement, maximum drift, and base shear. It corresponds to Zhang et al. (2025) [4].

Number of stories	Building code	Steel brace Position	Period sec	Frequency cycle/sec	Maximum axial load of damper P (kN)	Base shear Vmax (kN)		
						El Centro	Loma Prieta	Kobe
5	SB5-W	Without	3.423	0.292	-	5559.2	8188.9	13248.1
	SB5-B	Steel brace	1.299	0.77	-	10500.8	13770.2	19914.0
	SB5-D	Steel damper	3.02	0.331	1508.7	3487.0	5077.3	8314.9
	SB5-BD	Steel brace and damper	1.972	0.507	2423.1	3996.7	5911.7	8884.1
10	SB10-W	Without	10.0	0.1	-	4177.7	6892.4	10877.0
	SB10-B	Steel brace	3.245	0.308	-	5371.5	10532.5	12490.8
	SB10-D	Steel damper	7.739	0.129	846.5	2280.1	5200.6	6519.8
	SB10-BD	Steel brace and damper	4.406	0.227	1272.5	3418.8	6025.4	7106.4
15	SB15-W	Without	16.827	0.059	-	2648.7	4654.8	7283.2
	SB15-B	Steel brace	5.616	0.178	-	3797.8	8264.8	14243.9
	SB15-D	Steel damper	12.722	0.079	827.9	1800.9	3926.9	4738.3
	SB15-BD	Steel brace and damper	7.191	0.139	1614.1	2106.9	4607.6	5643.6

Table 7: Seismic performance of 5-, 10-, and 15-story steel frames with and without hybrid bracing and friction dampers.



## CONCLUSIONS

The study's findings are as follows:

1. The hybrid system achieves the largest reductions in roof displacement and inter-story drift across all building heights and records, with peak reductions near 59% in 5-story frames.
2. In 10 and 15-story frames, reductions remain substantial, about 15-31% in displacement and 40-48% in drift, surpassing single system alternatives despite higher mode effects.
3. Concentric bracing alone can amplify responses in taller buildings by shortening the period toward dominant ground motion frequencies, increasing displacement and drift in certain earthquakes.
4. Friction dampers alone provide stable, non-degrading energy dissipation and consistently reduce drift without inducing harmful resonance, though they offer less stiffness control than bracing.
5. The hybrid approach balances initial stiffness with frictional energy dissipation, avoiding brace-only amplification while exceeding damper-only control of global and local deformations.
6. The hybrid retains advantageous period shortening while leveraging damping to limit forces and displacements, yielding a balanced dynamic response.

## LIMITATIONS OF THE STUDY

The authors recognize several limitations that may limit the generalizability of the results from their research. Firstly, the study relies on a limited number of structural forms and seismic records (El Centro 1940, Loma Prieta 1989, Kobe 1995), which may not completely capture the wide spectrum of earthquake behaviors or building geometries experienced in real design practice. Second, although the numerical models are validated against existing experimental results, they are based on simplified formulations concerning material interaction, connection details, and damper hysteretic properties, which may have neglected detailing complexities that exist in practice, such as local buckling or cumulative fatigue. Third, attention has been paid to medium-rise steel frames (5-, 10-, and 15-floor buildings) of office use; whereas the applicability of the proposed hybrid system for tall buildings or such structures with irregularity level and different functional types (i.e., industry/residential building, etc.) could be a subject of further investigation. Moreover, economic considerations and practical aspects related to construction and maintenance (e.g., damper replacement after earthquakes, the cost of new energy dissipaters, and on-site replace ability) are not accounted for herein but would be central to a real implementation. The hybrid system technology analysis demonstrated better performance across all types of analysed scenarios; however, its excess for site-specific hazards and variations in regional codes remains a subject of further customized investigation.

## PRACTICAL IMPLICATION FOR DESIGNERS

Designers are recommended to adopt the hybrid bracing system for steel moment-resisting frames in seismic regions, as it provides an optimal combination of both stiffness and damping that can control drifts and avoid resonance. For high-rise structures, it is also important to avoid brace-only schemes, as they may increase the response. Friction dampers need to be designed to account for 8–12% of the story shear and evenly distributed throughout the structure to prevent soft stories. All designs require nonlinear time-history analysis for verification. Importantly, the system must be designed to have dampers as easily replaceable sacrificial items to safeguard the main structure and promote rapid post-earthquake recovery.

## FUTURE RESEARCH RECOMMENDATIONS

Future work could extend the scope by considering how the hybrid system performs in taller (20+ story) irregular and non-office buildings under a larger suite of near-fault and long-period ground motions. Research is also required to formulate and validate simplified, yet robust design strategies; optimization procedures for damper distribution, in addition to explicit performance-based criteria related to risk recovery. In addition, systematic research and development, such as detailed cost-benefit analyses, full-scale experimental tests of connections and damper reliability, and the integration of smart or adaptive damper technologies, need to be performed to improve the practicality, robustness, and economy necessary for widespread use.



## REFERENCES

- [1] Thongchom, C., Mirzai, N. M., Chang, B. and Ghamari, A. (2022). Improving The CBF Brace's Behavior Using I-Shaped Dampers, Numerical and Experimental Study, *Journal of Constructional Steel Research*, 197, p.107482. DOI: <https://doi.org/10.1016/j.jcsr.2022.107482>.
- [2] Park, M. J., Ghamari, A. and Jaya, R. P. (2025). An Experimental and Numerical Study of an Innovative Flexural Damper to Improve the Behavior of CBF Braces, *Structures*, 76, p. 108935. DOI: <https://doi.org/10.1016/j.istruc.2025.108935>.
- [3] Maseer, M. S. and Abdulridha, A. J. (2025). Enhancing Performance of Beam-Column Joints in Reinforced Concrete Structures Using Carbon Fiber-Reinforced Polymers (CFRP): A Novel Review, *Hybrid Advances*, 10, p. 100444. DOI: <https://doi.org/10.1016/j.hybadv.2025.100444>.
- [4] Zhang, Y., Wang, Y., Zhou, Z. and Wang, C. (2025). Seismic Performance Analysis of Hybrid Braced Steel Frames With Self-Centering Braces and Fluid Viscous Damping Braces, *Structures*, 78, p. 109342. DOI: <https://doi.org/10.1016/j.istruc.2025.109342>.
- [5] Paronesso, M. and Lignos, D. G. (2022). Seismic Design and Performance of Steel Concentrically Braced Frame Buildings with Dissipative Floor Connectors, *Earthquake Engineering and Structural Dynamics*, 51(15), pp. 3505-3525. DOI: <https://doi.org/10.1002/eqe.3733>.
- [6] Ashrafi, A. and Imanpour, A. (2021). Seismic Response of Steel Multi-Tiered Eccentrically Braced Frames. *Journal of Constructional Steel Research*, 181, p. 106600. DOI: <https://doi.org/10.1016/j.jcsr.2021.106600>.
- [7] Qiu, C. and Du, X. (2021). Performance-Based Seismic Design of Multi-Story CBFS Equipped With SMA-Friction Damping Braces, *Bulletin of Earthquake Engineering*, 19(6), pp. 2711–2737. DOI: <https://doi.org/10.1007/s10518-021-01060-w>.
- [8] Harba, I. S., Abdulridha, A. J. and Al-Shaar, A. (2022). Numerical Analysis of High-Strength Reinforcing Steel with Conventional Strength in Reinforced Concrete Beams under Monotonic Loading, *Open Engineering*, 12(1), pp. 817-833. DOI: <https://doi.org/10.1515/eng-2022-0365>
- [9] Harba, I. S. and Abdulridha, A. (2017). Finite Element Analysis of RC Tapered Beams under Cyclic Loading. *Al-Nahrain Journal for Engineering Sciences*, 20(2), pp. 378-396. <https://nahje.com/index.php/main/article/view/117>.
- [10] Pnevmatikos, N. G. (2012). New strategy for controlling structures collapse against earthquakes. *Natural Science*, 04(08), 667-676. DOI: <https://doi.org/10.4236/ns.2012.428088>
- [11] Pnevmatikos, N., Konstandakopoulou, F., Papagiannopoulos, G., Hatzigeorgiou, G., & Papavasileiou, G. (2020). Influence of earthquake rotational components on the seismic safety of steel structures. *Vibration*, 3(1), pp. 42-50. DOI: <https://doi.org/10.3390/vibration3010005>.
- [12] Seker, O. and Shen, J. (2017). Developing an All-Steel Buckling Controlled Brace, *Journal of Constructional Steel Research*, 131, pp. 94-109. DOI: <https://doi.org/10.1016/j.jcsr.2017.01.006>.
- [13] Abdulridha, A. J., Risan, H. K. and Harba, I. S. (2018). Numerical Analysis of Two-Way RC Slab with a Sawn Up Opening Strengthened by CFRP, *International Journal of Civil Engineering and Technology*, 9(8), pp. 1159-1167. [https://iaeme.com/Home/article\\_id/IJCIET\\_09\\_08\\_117](https://iaeme.com/Home/article_id/IJCIET_09_08_117).
- [14] Abdulridha, A. J., Taki, Z. N. and Harba, I. S. (2018). Numerical Analysis of Reinforced Concrete Beam Strengthened by CFRP Subjected to Monotonic Loading, *International Journal of Civil Engineering and Technology*, 9(10), pp. 894-904. [https://iaeme.com/Home/article\\_id/IJCIET\\_09\\_10\\_091](https://iaeme.com/Home/article_id/IJCIET_09_10_091).
- [15] Rakhsa, F., Hatami, S., Azandariani, M. G., Mansourkhani, A. A. and Davani, M. (2024). Resistance of Eccentric Braced Steel Frames Against Progressive Collapse and Overload Factor, *Structures*, 70, p. 107933. DOI: <https://doi.org/10.1016/j.istruc.2024.107933>.
- [16] Cheng, Q., Guo, Y., Yin, Y. and Lian, M. (2025). Seismic performance assessment of steel braced frames with segmentally controlled steel braces. *Structures*, 81, 110212. DOI: <https://doi.org/10.1016/j.istruc.2025.110212>.
- [17] FEMA 356. (2000). Pre-standard and Commentary for the Seismic Rehabilitation of Buildings. Federal Emergency Management Agency, Washington DC. <https://www.nehrp.gov/pdf/fema356.pdf>
- [18] CSI. (2022). ETABS software version 2022. Computers and structures, Inc
- [19] Seismic Provisions for Structural Steel Buildings, ANSI/AISC 341. (2016). In CRC Press eBooks (pp. 410-465). DOI: <https://doi.org/10.1201/b11248-16>
- [20] Building Research Centre, Ministry of Construction and Housing. (2017). Iraqi Seismic Code: Requirements for buildings (ISC 2017). Baghdad, Iraq; Building Research Centre.
- [21] ASCE/SEI-7. Minimum Design Loads and Associated Criteria for Buildings and Other Structures. (2022). American Society of Civil Engineers eBooks. DOI: 10.1061/9780784415788.
- [22] Center for Engineering Strong Motion Date. (2025). CESMD Strong-Motion Data Set. <https://strongmotioncenter.org/cgi-bin/CESMD/archive.pl>



- [23] Palmer, K. D., Roeder, C. W., Lehman, D. E., Okazaki, T. and Shield, C. (2012). Experimental performance of steel braced frames subjected to bidirectional loading. *Journal of Structural Engineering*, 139(8), pp. 1274–1284. DOI: [https://doi.org/10.1061/\(asce\)st.1943-541x.0000624](https://doi.org/10.1061/(asce)st.1943-541x.0000624).
- [24] Miyamoto, H. K., Gilani, A. S. J. and Wada, A. (2010). Viscous damper limit states and collapse analysis of steel frame buildings with dampers. *Tokyo Tech Research Repository (Tokyo Institute of Technology)*, 5, pp. 3793–3802. [http://t2r2.star.titech.ac.jp/cgi-in/publicationinfo.cgi?q\\_publication\\_content\\_number=CTT100617259](http://t2r2.star.titech.ac.jp/cgi-in/publicationinfo.cgi?q_publication_content_number=CTT100617259)