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Lateral Load Response of Pre-Engineered Buildings with Conventional and Advanced Bracing Systems

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Abstract: Pre-Engineered Buildings (PEBs) are widely used in industrial and commercial construction because of their structural efficiency, faster erection, and economic advantages. However, due to their large spans, lightweight steel sections, and relatively flexible framing systems, PEBs are highly vulnerable to lateral loads such as wind and earthquake forces. Hence, the selection of an appropriate bracing system becomes essential to improve stiffness, stability, and overall seismic performance. The present study presents a comparative assessment of a steel PEB structure incorporating five different bracing configurations: Conventional X-bracing, Harp bracing, and Perimetral bracing. The structure is modelled and analysed using ETABS software in accordance with IS 800:2007 for steel design, IS 875 (Parts 1, 2 and 3):2015 for gravity and wind loads, and IS 1893 (Part 1):2020 for seismic analysis. Wind and earthquake loads are considered, and seismic effects are evaluated using the Response Spectrum Method. The investigation focuses exclusively on the distribution of translational (UX, UY) and rotational (RX, RY, RZ) mass participation across vibration modes for Conventional X bracing, Harp bracing, and Perimetral bracing systems. The results indicate significant variation in modal mass distribution depending on the bracing configuration. The Conventional X bracing system exhibits mass participation distributed over multiple modes in the longitudinal direction, along with noticeable torsional coupling, indicating the influence of higher modes on seismic response. Harp bracing demonstrates improved dynamic efficiency by concentrating mass participation within fewer lower-order modes, thereby reducing higher-mode dominance and torsional irregularities. The Perimetral bracing system shows the most desirable behaviour, with nearly complete mass participation captured in the fundamental modes of both principal directions, ensuring predictable and stable seismic response. The findings confirm that advanced bracing systems enhance dynamic performance by minimizing higher-mode effects and controlling torsional response, thereby improving the overall seismic reliability of PEB structures.

Keywords: Pre-Engineered Buildings, Bracing Systems, Seismic Analysis, Wind Load, ETABS

I. INTRODUCTION

Pre-Engineered Buildings (PEBs) have emerged as a modern construction solution characterized by factory-fabricated steel components assembled on-site using standardized and optimized design procedures. Initially developed in the United States in the late 1960s and introduced in India during the late 1990s, PEB systems have gained widespread acceptance in industrial, commercial, and warehouse applications due to their speed of construction, material efficiency, and economic advantages. The structural system typically comprises tapered primary frames, cold-formed secondary members, and lightweight cladding materials, enabling large clear spans and flexible layouts. Despite their advantages, PEB structures are highly sensitive to lateral loads such as wind and earthquake forces because of their lightweight nature and relatively flexible framing systems. The lateral performance of a PEB is primarily governed by its bracing configuration, which significantly influences stiffness distribution, load transfer mechanism, displacement control, and dynamic characteristics. Therefore, selecting an appropriate bracing system is essential to ensure structural stability and seismic safety, particularly in regions prone to moderate to high seismic activity.

Conventional bracing systems such as X-bracing, K-bracing, and single Diagonal bracing are widely adopted in steel structures. X-bracing provides a direct and efficient load path, offering high lateral stiffness; however, it may restrict architectural openings and experience buckling under compression during seismic loading. K-bracing improves functional space but introduces additional bending moments in columns, potentially reducing seismic efficiency. Single Diagonal bracing is economical and simple but may exhibit asymmetric response and limited energy dissipation capacity. To overcome these limitations, advanced bracing systems such as Harp and Perimetral bracing have been proposed.

Harp bracing distributes inclined members along the height, promoting uniform force transfer and improved stiffness distribution. Perimetral bracing places bracing elements along the outer edges of the building, maximizing lever arm action against lateral loads while maintaining unobstructed interior space and enhancing torsional resistance.

A review of existing literature indicates substantial research on conventional bracing systems and comparative studies between PEB and conventional steel buildings. Early investigations focused on displacement-based seismic design and nonlinear performance assessment, while recent studies examined parametric variations, response spectrum analysis, and optimization of bracing layouts. However, limited research comprehensively evaluates advanced bracing configurations such as Harp and Perimetral systems within a unified analytical framework for PEB structures. Furthermore, a noticeable gap exists between early 2000s research and more advanced studies after 2011, during which practical adoption of PEBs expanded significantly but systematic analytical validation remained limited. Addressing this research gap, the present study performs a comparative evaluation of three bracing systems Conventional X, Harp, and Perimetral bracing in a pre-engineered steel building. The structure is modelled and analysed using ETABS software in accordance with IS 800:2007 for steel design, IS 875 (Parts 1–3):2015 for gravity and wind loads, and IS 1893 (Part 1):2020 for seismic analysis using the Response Spectrum Method. Both wind and earthquake effects are considered to capture realistic lateral load behaviour. Key response parameters including lateral displacement, storey drift, storey stiffness, and fundamental time period are evaluated to understand the global structural behaviour under lateral loading.

The study aims to assess the effectiveness of advanced bracing systems in controlling deformation and enhancing seismic performance, while also identifying the most efficient configuration that balances stiffness, functional requirements, and structural safety. The findings are expected to contribute toward performance-oriented design approaches and provide practical guidance for engineers involved in the design of PEB structures in wind- and earthquake-prone regions.

II. LITERATURE REVIEW

Early research on seismic performance emphasized displacement-based approaches over traditional period-based methods. Aschheim [1] introduced yield displacement as a stable design parameter using nonlinear static procedures, while Lumantarna et al. [2] extended displacement-controlled assessment to non-ductile and asymmetric buildings through generalized response spectra. Subsequent studies investigated bracing effectiveness in steel and composite structures. Hemmati et al. [3] demonstrated the superior stiffness and drift control of large-scale bracing systems, and Kalyanshetti [4] highlighted the importance of bracing in mitigating soil–structure interaction effects. Several researchers confirmed the efficiency of X, diagonal, V, and K bracing systems in reducing displacement and drift in multi-storey steel buildings [5–8]. Experimental and analytical investigations further validated the role of optimized brace layouts and energy-dissipating systems such as BRBs and dampers in enhancing lateral resistance and seismic stability [9–13].

Recent literature increasingly focuses on pre-engineered buildings (PEBs), evaluating their structural efficiency under wind and seismic loads. Comparative studies reported significant reductions in displacement, time period, and structural weight in braced PEBs compared to conventional steel buildings [14–22]. Advanced modeling and optimization techniques using STAAD.Pro, ETABS, and SAP2000 confirmed that appropriate bracing configurations substantially improve stiffness, drift control, and overall dynamic performance [23–27]. Notably, Perimetral and Harp bracing systems have emerged as efficient alternatives, offering improved load distribution, reduced structural weight, and enhanced stability under lateral forces [28]. Recent parametric and optimization studies further demonstrate that tailored bracing arrangements and geometric configurations can significantly enhance performance, economy, and seismic resilience of PEB systems [29,30].

III.MODELLING AND ANALYSIS

A. General Geometry

The PEB considered in the study is an industrial steel building with the following overall dimensions as shown in table 1.

TABLE I
GEOMETRY OF PEB STRUCTURES

S.No.	Parameter	Specification
1	Total building length (L)	84 m
2	Total building width (clear span) (w)	50 m
3	Bay spacing	7.0 m
4	Number of bays	12

5	Roof configuration	Symmetrical double-slope roof
6	Roof slope	1 in 16
7	Eave height (h)	7.5
8	Ridge height (H)	15.0 m

The building consists of three main transverse frames identified as Grid A, B, and C, with the central frame (Grid B) acting as the ridge line as shown in figure 1. Figure 2 shows side elevation of PEB structure and figure 3 to 7 shows different bracing conditions opted in this study.

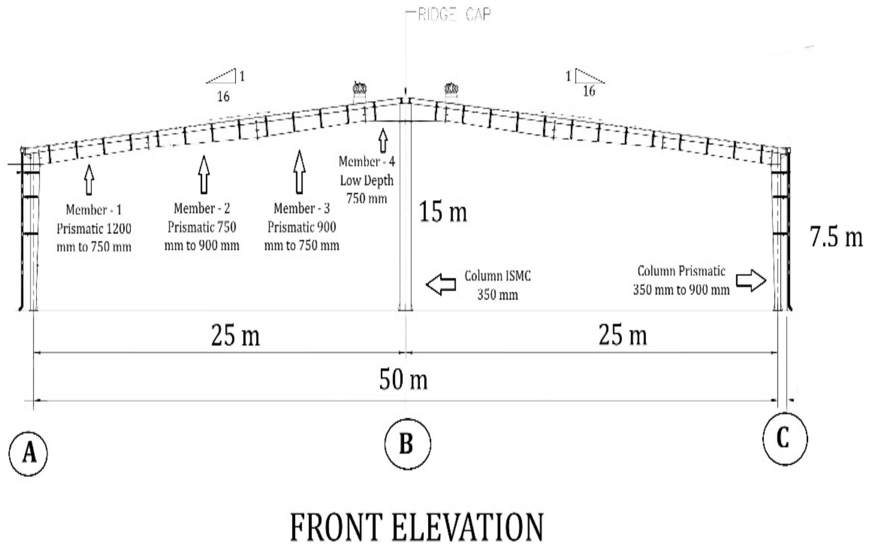

Fig. 1 Front Elevation of PEB Structure

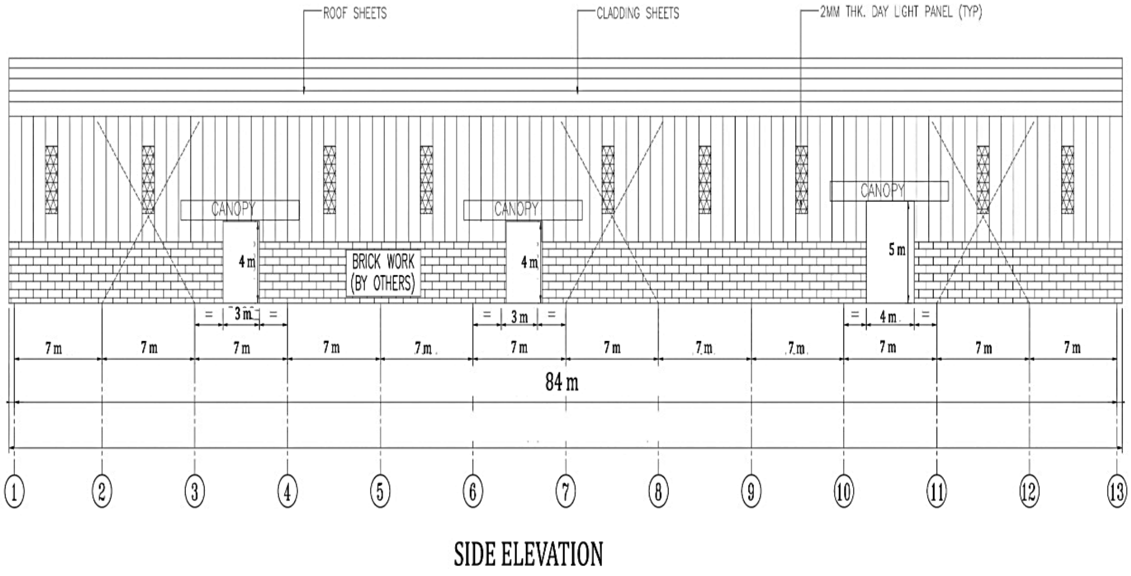

Fig. 2 Side Elevation of PEB Structure

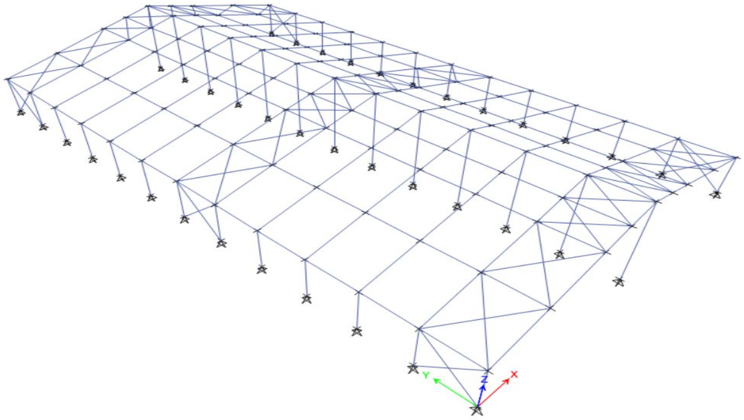

Fig. 3 PEB Structure with Conventional X Bracing

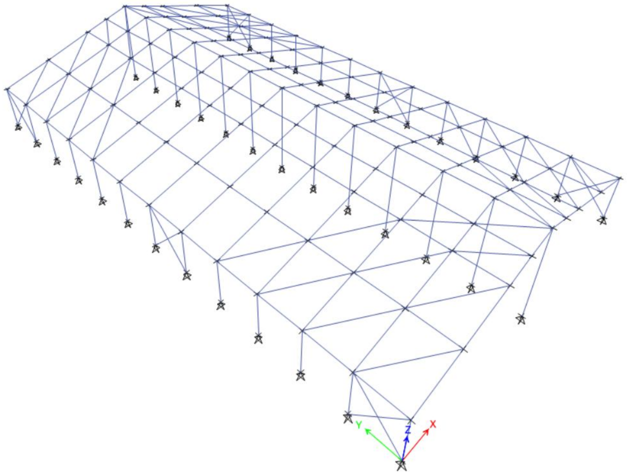

Fig. 4 PEB Structure with Harp Bracing

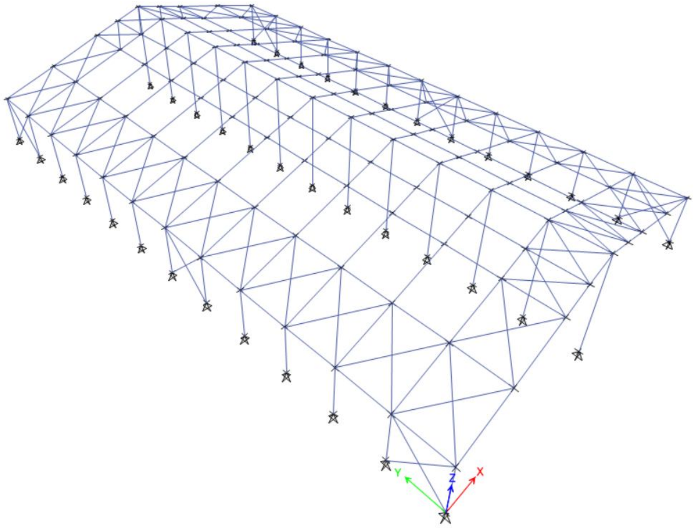

Fig. 5 PEB Structure with Perimetral Bracing

B. Load Calculations

The gravity loading for the PEB structure includes dead load, collateral load, and live load calculated for Grid 2–12 based on a 7 m span. These loads are converted into equivalent line loads (kN/m) for accurate structural modelling and analysis in accordance with relevant IS code provisions. Table 2 shows summary of gravity loads for PEB structure.

TABLE III
SUMMARY OF GRAVITY LOADS CONSIDERED FOR PEB STRUCTURE

Load Type	Description	Intensity (kg/m^2)
Dead Load (DL)	Self-weight of sheeting, purlins, sag rods, and permanent structural components	15
Collateral Load (CL)	Permanent non-structural loads (HVAC, electrical, fire protection, insulation, solar panels)	25
Live Load (LL)	Temporary roof load due to maintenance and occupancy (IS 875 Part 2)	75

Wind load in pre-engineered (PEB) structures is a critical lateral load resulting from wind pressure acting on the roof and wall surfaces of the building. Due to the large surface area and lightweight nature of PEBs, wind loads are evaluated as per IS 875 (Part 3):2015 to ensure adequate strength, stability, and control of lateral displacements. For the PEB structure located in Indore, the basic wind speed is taken as 39 m/s. The design wind speed is calculated using the modifying factors as per IS 875 (Part 3):2015, where k_1 = 1.0 (50-year design life), k_2 = 1.02 (Terrain Category 2), k_3 = 1.0 (flat terrain), and k_4 = 1.0, resulting in a design wind speed (Vz) of 39.78 m/s. The corresponding design wind pressure (pz) is calculated as 0.949 kN/m^2. Considering area averaging and combination factors (k_a = 0.9, k_2 = 0.8, k_3 = 0.9), the product is less than 0.7; hence, as per Clause 7.2, a minimum value of 0.7 is adopted, giving a final design wind pressure (pd) of 0.665 kN/m^2. The building face area is 630 m^2, with an opening area of 44 m^2 (6.98%), classifying the structure as partially enclosed (5–20% openings) as per Clause 7.3.2.2. Therefore, internal pressure coefficients (Cpi) of ±0.5 are considered. Based on geometric ratios (h/w = 0.15 and L/w = 1.68), external pressure coefficients (Cpe) are determined for all faces (A, B, C, and D) according to Tables 5 and 6 of IS 875 (Part 3):2015. Table 3 shows wind load value for members.

TABLE IIII
WIND LOAD VALUE FOR MEMBERS

Load Case	Wind load for Wall (kN/m)				Wind load for Roof (kN/m)	
	A	B	C	D	Left side of Ridge	Right Side of Ridge
WL1	5.58	1.16	- 0.47	- 0.47	0.47	0.47
WL2	0.93	- 3.49	- 5.12	- 5.12	- 4.187	- 4.19
WL3	- 4.65	- 4.65	5.58	5.58	- 5.58	- 5.12
WL4	0	0	2.79	- 2.79	0.93	0.47

Seismic analysis of the PEB structure is carried out in accordance with IS 1893 (Part 1):2016, which specifies the seismic parameters required for structural design in different seismic zones. The building is assumed to be located in Seismic Zone III with a zone factor of 0.16. An importance factor of 1.0 is adopted, and a response reduction factor of 3 is considered to account for structural ductility and energy dissipation capacity. The structure is founded on Type II (medium) soil, and seismic forces are evaluated using the response spectrum method in both X and Y directions to capture the lateral response of the building under earthquake loading.

IV. RESULTS AND DISCUSSIONS

The structural model of the PEB was developed and analysed using ETABS software, strictly in accordance with the provisions of IS 800:2007 for steel design, IS 875 (Parts 1, 2 and 3):2015 for gravity and wind loads, and IS 1893 (Part 1):2020 for seismic analysis using the response spectrum method. The modal participation mass ratio plays a fundamental role in understanding the dynamic behaviour of pre-engineered buildings (PEBs) subjected to seismic excitation.

It quantifies the proportion of total structural mass actively engaged in each vibration mode along different translational (UX, UY, UZ) and rotational (RX, RY, RZ) degrees of freedom. As per the response spectrum procedure of IS 1893 (Part 1):2020, accurate seismic evaluation requires inclusion of sufficient modes to ensure adequate cumulative mass participation in both principal horizontal directions. The distribution of modal mass participation not only reflects the lateral stiffness characteristics of the structure but also reveals the presence of torsional coupling, higher-mode influence, and stiffness irregularities. In the present study, modal participation mass ratios were evaluated for three bracing configurations—Conventional X bracing, Harp bracing, and Perimetral bracing—to assess their dynamic efficiency and seismic response characteristics. The results indicate clear differences in how each system distributes mass participation across modes and directions.

A. Modal Participation Mass Ratio

The modal participation ratio is a key parameter in dynamic and seismic analysis that represents the contribution of an individual vibration mode to the overall dynamic response of a structure in a particular direction. It indicates how much of the total structural mass actively participates in a specific mode when the structure is subjected to earthquake excitation. In seismic analysis, each structure vibrates in multiple natural modes, and not all modes contribute equally to the response. The modal participation ratio helps identify the dominant modes that significantly influence lateral displacements, storey drifts, and internal forces. Modes with higher participation ratios are more critical for design and must be included in response spectrum analysis to ensure accurate results. The modal participating mass ratios for the Conventional X bracing system is shown in table 4. The results clearly indicate how different vibration modes contribute to translational and rotational responses in various degrees of freedom. Mode 1 is the dominant mode of vibration, showing a very high participation in the UY direction (0.904) along with significant rotation about the X-axis (RX = 0.600). This indicates that the fundamental mode primarily governs lateral response in the Y-direction, accompanied by noticeable torsional behaviour. Such coupled translational–torsional response is typical in PEB structures due to large spans and non-uniform stiffness distribution. Modes 2, 3, 5, 7, and 11 contribute significantly to UX translation, with participation ratios ranging from 0.132 to 0.276. Among these, Mode 11 exhibits the highest UX participation (0.276), highlighting the importance of higher modes in capturing the X-direction seismic response. This confirms that reliance on the fundamental mode alone would underestimate the lateral demand in the longitudinal direction. Torsional behaviour about the vertical axis (RZ) is prominently observed in Modes 3, 6, 9, 10, and 12. Notably, Mode 10 (RZ = 0.441) and Mode 12 (RZ = 0.258) represent strong torsional modes, indicating that twisting effects play a significant role in the overall dynamic response of the structure. This emphasizes the need for efficient bracing arrangements to control torsion. Participation in the UY direction beyond Mode 1 is negligible, indicating that the structure behaves predominantly in a single lateral mode in this direction. This suggests relatively uniform stiffness distribution along the Y-axis for the Conventional X bracing system. The UZ direction shows zero participation across all modes, confirming that vertical seismic effects are insignificant for this configuration and validating the assumption of dominant horizontal seismic response as per IS 1893:2020. Overall, the modal participating mass ratios demonstrate that the Conventional X bracing system exhibits adequate mass participation through multiple modes, satisfying codal requirements. However, the presence of significant torsional modes suggests that while Conventional X bracing provides reasonable lateral resistance, it may be less effective in controlling torsional response when compared with advanced bracing systems such as Harp and Perimetral bracing.

TABLE IV
MODAL PARTICIPATION MASS RATIO FOR CONVENTIONAL X BRACING

Mode	UX	UY	UZ	RX	RY	RZ
1	0.0000	0.9041	0.0000	0.5995	0.0000	0.0016
2	0.1617	0.0000	0.0000	0.0000	0.0543	0.0022
3	0.1319	0.0000	0.0000	0.0000	0.0442	0.1177
4	0.0199	0.0000	0.0000	0.0000	0.0067	0.0045
5	0.1571	0.0000	0.0000	0.0000	0.0526	0.0146
6	0.0329	0.0000	0.0000	0.0000	0.0110	0.0677
7	0.1469	0.0000	0.0000	0.0000	0.0492	0.0095
8	0.0025	0.0000	0.0000	0.0000	0.0009	0.0001
9	0.0685	0.0000	0.0000	0.0000	0.0230	0.0469
10	0.0000	0.0000	0.0000	0.0000	0.0000	0.4409

11	0.2758	0.0000	0.0000	0.0000	0.0902	0.0000
12	0.0000	0.0020	0.0000	0.0159	0.0000	0.2582

The modal participating mass ratios for the Harp bracing system is shown in table 5. Mode 3 emerges as the dominant mode in the X-direction, exhibiting a very high UX participation of 0.7567, along with notable rotation about the Y-axis (RY = 0.2510). This indicates that the longitudinal seismic response is efficiently captured by a lower-order mode, reflecting increased stiffness and better load-sharing along the height due to the distributed nature of harp bracing. Mode 4 represents the fundamental mode governing the Y-direction response, with a high UY participation of 0.9074 and substantial RX rotation of 0.6128. This shows that lateral forces in the transverse direction are effectively resisted, although accompanied by some torsional coupling. Compared to conventional systems, this torsional participation occurs in fewer modes and at lower magnitudes. Lower modes (Modes 1 and 2) also contribute moderately to UX translation, indicating gradual engagement of stiffness rather than abrupt higher-mode dominance, which is desirable for seismic performance. This behaviour reflects the improved continuity and redundancy offered by harp bracing. Torsional participation about the vertical axis (RZ) is observed in Modes 5, 8, and 9, with values of 0.1085, 0.0871, and 0.1223, respectively. These values are comparatively lower and more evenly distributed than those observed in conventional systems, indicating effective torsional control and reduced twisting tendencies. The UY direction beyond Mode 4 shows limited participation, implying that the structure responds predominantly in a single dominant lateral mode, which enhances predictability and seismic stability. As with other bracing systems, UZ participation is zero across all modes, confirming that vertical seismic effects are insignificant and in agreement with assumptions of IS 1893:2020. Overall, the modal mass participation results demonstrate that Harp bracing significantly enhances lateral stiffness, reduces higher-mode and torsional dominance, and concentrates mass participation in fewer, well-defined modes. This improved dynamic behaviour explains the observed reductions in displacement, storey drift, and time period, making harp bracing a highly efficient and reliable system for seismic-resistant PEB structures, second only to perimetral bracing in overall performance.

TABLE V
MODAL PARTICIPATION MASS RATIO FOR HARP BRACING

Mode	UX	UY	UZ	RX	RY	RZ
1	0.1616	0.0000	0.0000	0.0000	0.0540	0.0029
2	0.0786	0.0000	0.0000	0.0000	0.0264	0.0060
3	0.7567	0.0000	0.0000	0.0000	0.2510	0.0000
4	0.0000	0.9074	0.0000	0.6128	0.0000	0.0000
5	0.0000	0.0000	0.0000	0.0000	0.0000	0.1085
6	0.0004	0.0000	0.0000	0.0000	0.0001	0.0002
7	0.0000	0.0670	0.0000	0.3193	0.0000	0.0000
8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0871
9	0.0000	0.0000	0.0000	0.0000	0.0001	0.1223
10	0.0000	0.0000	0.0000	0.0000	0.0000	0.4409
11	0.2758	0.0000	0.0000	0.0000	0.0902	0.0000
12	0.0000	0.0020	0.0000	0.0159	0.0000	0.2582

The modal participating mass ratios for the Perimetral bracing in table 6. Mode 1 is the primary dominant mode in the X-direction, exhibiting an exceptionally high UX participation of 0.9955, which implies that almost the entire seismic mass in the longitudinal direction is captured in the fundamental mode itself. This behaviour is highly desirable from a seismic design perspective, as it ensures predictable structural response and effective force transfer without excessive higher-mode effects. Additionally, moderate rotation about the Y-axis (RY = 0.3294) is observed, indicating controlled torsional interaction. Mode 3 governs the Y-direction response, with a high UY participation of 0.8608 accompanied by significant RX rotation (0.6629). This confirms that transverse seismic forces are also effectively resisted by a lower-order mode, demonstrating balanced stiffness in both principal directions. Torsional behaviour about the vertical axis (RZ) is primarily concentrated in Mode 2 (0.6054) and Mode 5 (0.3647). Unlike conventional systems, these torsional effects are confined to specific modes and do not significantly influence the dominant translational modes.

This indicates that perimetral bracing provides effective torsional restraint by distributing stiffness along the building perimeter. Higher modes (Modes 6 and 12) show minor contributions in UY and RX, suggesting limited higher-mode participation and confirming that the global response is largely governed by the first few modes. Such concentration of mass participation enhances seismic reliability and reduces amplification of internal forces. As observed in all bracing configurations, UZ participation remains zero across all modes, validating the assumption that vertical seismic effects are negligible and in line with IS 1893:2020 provisions for horizontal seismic analysis. In summary, the modal participating mass ratios confirm that the Perimetral bracing system offers the most efficient dynamic performance, with maximum mass participation achieved in the lowest modes, minimal higher-mode influence, and controlled torsional response.

TABLE VI
MODAL PARTICIPATION MASS RATIO FOR PERIMETRAL BRACING

Mode	UX	UY	UZ	RX	RY	RZ
1	0.9955	0.0000	0.0000	0.0000	0.3294	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.6054
3	0.0000	0.8608	0.0000	0.6629	0.0000	0.0000
4	0.0017	0.0000	0.0000	0.0000	0.0005	0.0002
5	0.0000	0.0000	0.0000	0.0000	0.0000	0.3647
6	0.0000	0.1348	0.0000	0.2361	0.0000	0.0000
7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
8	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001
9	0.0000	0.0005	0.0000	0.0001	0.0000	0.0000
10	0.0000	0.0000	0.0000	0.0000	0.0020	0.0003
11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
12	0.0000	0.0038	0.0000	0.0995	0.0000	0.0000

V. CONCLUSIONS

1) The modal participation mass ratio analysis confirms that all bracing configurations satisfy codal requirements of IS 1893 (Part 1):2020 by achieving adequate cumulative mass participation in the principal horizontal directions, validating the reliability of the response spectrum analysis adopted in the study.
2) The Conventional X bracing system exhibits distributed mass participation across multiple modes in the longitudinal direction and significant torsional dominance in higher modes, indicating the influence of higher-mode effects and coupled translational torsional behaviour in its dynamic response.
3) The Harp bracing system demonstrates improved dynamic efficiency by concentrating mass participation within fewer lower-order modes in both principal directions, thereby reducing higher-mode influence and achieving better torsional control compared to the conventional system.
4) The Perimetral bracing system shows the most desirable seismic behaviour, with nearly complete mass participation captured in the fundamental modes of both X- and Y-directions, ensuring predictable response, balanced stiffness distribution, and minimal higher-mode amplification.
5) Among the three systems studied, Perimetral bracing provides the most efficient dynamic performance, followed by Harp bracing, while Conventional X bracing shows comparatively higher torsional and higher-mode participation, indicating that advanced bracing configurations significantly enhance the seismic reliability of PEB structures.

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