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ADVANCED SOFTWARE-BASED STRUCTURAL ANALYSIS AND OPTIMAL DESIGN OF PRE-ENGINEERED BUILDING SYSTEMS

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ABSTRACT

Pre Engineered Building (P.E.B.)s are revolutionizing how modern industrial and commercial construction takes place, providing incredible efficiencies in terms of structural performance, cost, and fast-track delivery. This paper gives a systematic structural analysis and design of PEB systems having seven different span configurations (24 m to 60 m) with state-of-the-art software tools such as STAAD. TL: Pro V8i, SAP2000 v24, ETABS 2022, Tekla Structures A series of load combinations of seven LRFD-based equations according to IS 800:2007 and IS 875 (Parts 1–3) were applied to 49 structural models. The optimization process (iterative section selection combined with IS 800:2007 serviceability and strength provisions resulted in average reductions in steel weight of 17.3% to 25.2% compared to traditionally designed sections. Maximum deflection, lateral drift ratio, natural frequency, and member utilization ratios were studied as structural response parameters on the basis of which the modal matrix was established. SAP2000 v24 provides higher accuracy (97.8% member utilization accuracy) and capability in automating this than anything we have found. Statistical analysis corroborated a 21.5% (σ = 2.87%) mean reduction of steel and a 13.3% coefficient of variation, demonstrating the strength of the proposed optimization framework. In comparison to eight previous studies, the comparative analysis confirms the significantly higher efficiency of this approach as shown in its advantages of up to 9%-6% lower material utilization versus classical design approaches. These results provide an excellent evidence base for practitioners and researchers who are working on the design of PEB under Indian loading codes.

Keywords: *Pre-engineered buildings[1]; structural optimization[2]; STAAD.Pro[3]; SAP2000[4]; IS 800:2007[5]; steel weight reduction[6]; finite element analysis[7]; lateral drift[8]; natural frequency[9].*

1. INTRODUCTION

1.1 BACKGROUND AND SIGNIFICANCE OF PRE-ENGINEERED BUILDINGS

Buildings that have been pre-engineered (PEB) have become a prevailing structural typology in the global arena for industrial, warehousing, logistics, and commercial applications, in India further, where incredibly fast infrastructural building expansion is demanded under a strict budget and time [1]. A PEB system is made of a main frame usually a taper or prismatic I-section rafter-column assembly connected to secondary members (purlins, girts, and eave struts) and enclosed with cold-formed steel cladding panels [2]. PEB is differentiated from conventional steel building by its factory-fabricated, bolted-connection concept, which results in 30–40% shorter erection times and 15–30% materials savings compared to conventional methods [3]. India's manufacturing industry is trending towards large-span industrial enclosures and the need for resource-efficient, green structures is also increasing in many applications; hence optimizing PEB structural performance with the help of advanced computational tools is academically and industrially critical [4].

IS 800:2007 (General Construction in Steel Code of Practice) issued from the Bureau of Indian Standards has made Limit State Design (LSD) as the obligatory design philosophy for steel structures, whereas IS 875 Parts 1, 2 and 3 specify dead, live and wind load intensities respectively. These codal provisions have been incorporated into automated FEA environments, making it possible to accurately evaluate a structure under multiple load combinations with minimal manual effort. However, a comprehensive data-driven analysis of software performance, optimization results, and statistical reliability over a graduated span range has not yet appeared in the species literature.

1.2 COMPUTATIONAL TOOLS FOR STRUCTURAL ANALYSIS

Commercial structural analysis platforms have seen considerable development, with tools like STAAD. Tools such as Pro V8i (Bentley Systems), SAP2000 v24 (CSI Berkeley), ETABS 2022 (CSI Berkeley) and Tekla Structures (Trimble) provide bundled modules for IS code-based design [6], wind load generation, seismic analysis, connection design Each platform brings unique advantages STAAD. Pro continues to be the most widely used tool in Indian practice due to its extensive IS code libraries and interoperability, SAP2000 is the more advanced tool for nonlinear analysis and optimization algorithms, ETABS would be an appropriate choice for seamless Building Information Modelling (BIM) integration [6] and Tekla Structures is the solution for detailed fabrication-level modelling and connection design automation. We provide an empirical benchmark where these tools are compared on the same structural models and loading cases in order to give practitioners a set of objective comparison criteria. For the design optimization of PEB structures, structural steel is iterated from an existing standard or customized steel section database up to a structural steel weight optimized design that satisfies the deflection, drift, strength, and stability constraints provided by Indian standards [9]. Konventional methods that found in the literature are classical gradient-based methods, genetic algorithms (GA)[9], particle swarm optimization (PSO) [10], as well as size optimization that is based on sensitivity analysis [10]. A systematic implementation of an iterative parametric optimization in IS 800:2007 LRFD across four software environments is presented in the current study.

1.3 RESEARCH OBJECTIVES AND SCOPE

This study addresses the following empirically grounded objectives: (i) to model and analyze seven PEB configurations spanning 24 m to 60 m under seven load combinations using four commercial software tools; (ii) to optimize structural steel weight while maintaining compliance with IS 800:2007 serviceability and strength limits; (iii) to comparatively assess software performance in terms of computational efficiency, accuracy, automation, and IS code integration; (iv) to statistically characterize the variability and reliability of optimization outcomes; and (v) to benchmark results against published literature to validate the methodology. The scope encompasses single-span symmetric pitched-roof portal frame PEBs in Indian seismic Zone II with basic wind speed of 44 m/s (as per IS 875 Part 3:2015), excluding multi-story or crane-girder configurations.

2. LITERATURE SURVEY

In view of the requirements expanding span, and necessitating advanced computational analysis tools, structural behavior and optimization of pre-engineered buildings, have been studied for the last two decades. Wankhade and Jadhav [7] investigated the efficiency of STAAD for the analysis of PEB portal frames with spans ranging from 20 m to 45 m. Using Pro V8i under IS 800:2007 and Manual section iteration resulted in steel weight savings in the range of 12% to 18.5% by using tapered sections in primary frames with two ends supported, and therefore significantly increase the material efficiency of steel sections [27]. Work presented in their study set a baseline for PEB analysis under IS codes, but only under static loading conditions without the probabilistic assessment. A comparative study of STAAD was performed by Kaur and Singh (Kaur and Singh 2021) [8]. More than 12,000 datasets were used to pitch STAAD vs. However, under wind-dominant load combinations, Pro showed slightly improved accuracy in member utilization estimation. The study concluded multi-tool validation should be general best practice, especially in high-value industrial applications Similarly, in this current study has presented a parametric design in STAAD [9] by Prakash and Anand. In the first article, we presented the development of FEM model data for cold-formed secondary members and a preliminary validation of the model against some experimental data, with deviations of less than 4% for deflection and less than 6% for critical buckling loads confirming the reliability of FEA for PEB secondary systems.

Kiran and Reddy [11] used the optimization method based on Genetic Algorithm (GA) on the single-story steel portal frames in SAP2000 and resulted in the section weight of 18–36 m span portal frames at a rate of 10.4–15.2%. They found their GA approach based on average convergence number between 18–42, however, the computational time was significantly higher than the iterative manual methods. The study was able to demonstrate the trade-off between the complexity of the automation and the computer cost. Similarly, Nair et al. Using ANSYS in nonlinear pushover analysis of PEB knee-joint connections, [12] observed that conventional welded connections did not produce joint rotational stiffness degradation until 85% of design load, indicating that modeling semi-rigid connections in PEB lateral analysis may be necessary.

C and Matlab were used in [14] to develop a hybrid PSO approach for structures; while Sravani and Kumar [15] proposed a PSO algorithm for PEB frames ranging from 24–48 m span, which was incorporated into ETABS 2022 through a Python-based interface and resulted in a steel savings of 14.6%–19.3% years 2022, Article 2022 years}, { P-objective In addition, it was also validated through manual section selection and compared with the developed approach, favouring the automated optimization. The study confirmed that IS 800:2007 LRFD provisions are sufficient in terms of limiting member slenderness and also other modes of buckling like lateral-torsional buckling, both under gravity and wind load combinations. Zhang et al. Using Tekla Structures and ANSYS, a large parametric study with 30–60 m size PEB configurations per ASCE 7-16 by [18] found an average 16.2%–21.4% reduction in weight, whereby a reduction of weight of approximately 8% was also obtained when increasing the bay spacing from 6 m to 9 m improving the efficiency of the frame.

For staggered roofs under IS loading, Hegde and Patil [22] investigated the impact of roof slope on the performance of PEB structures, citing a 5° slope of rafter moments between 12%–18% lesser than a 3° slope for spans greater than 36 m and also noting favorable reductions in colum base moments. The dynamic characteristics of PEB structures were also analysed by Sahoo and Nath [24] using SAP2000 modal analysis and found that the natural frequency of frame was about 1.6 Hz to 4.2 Hz (depending on the span and eave height) for single-span frames and the frames longer than 54 m located in region of strong basic wind speed could undergo wind-induced resonance. These results directly inform the dynamic response metrics reported in the present article.

Das and Roy [26] presented a review of the status of BIM adoption in India, for PEB design and construction, reported that even though Tekla Structures provides the most complete fabrication-level BIM workflow (and integrated IS-code checking modules), it's integration with both IS-code checking modules are not as automation compared to STAAD. Pro or ETABS. A survey of 45 PEB fabricators found that 62% still used STAAD. In this sense, 42% used it as main analysis software, and 24% used it as ETABS, and 8% migrated to SAP2000 optimization modules which only emphasises that practical software benchmarking is most significant mainstay. Gowda and Krishnamurthy [28] reported that the addition of uncertainty quantification for wind loads in reliability-based design optimization (RBDO) of PEB frames using the SAP2000 and Monte Carlo simulation in the second order analysis lead to a 4–7% increase in steel weight when compared to a deterministic LRFD design, showing the importance of uncertainty quantification in structural optimization studies. The present study adds to this pool of knowledge by carrying out a systematic, software-neutral, multi-span empirical analysis with statistical significance checks based on Indian codes.

3. METHODOLOGY

In this study, the method of structural analysis and optimization follows a structured three-phase methodology that complies with IS 800:2007 Limit state design philosophy. First, it has parameterized seven PEB portal frame configurations with span dimensions between 24 m and 60 m (Table 1) according to the prevalent standard industry practice, with bay spacing of 6 m to 9 m, eave heights of 6 m to 12 m, and roof slopes of 3° and 5°. The specific modeling of all main frames was carried out as symmetrically single span rigid portal frames with the columns made from straight I-sections and rafters from tapered I-sections fabricated from Fe 345 steel according to IS 2062:2011 (Table; 2). Secondary members such as purlins and girts, eave struts were modeled as simply supported cold-formed Z-sections. It is done in four software platforms defining the structural geometry STAAD. Pro V8i, SAP2000 v24, ETABS 2022, and Tekla Structures by employing commensurate nodal coordinates and member connectivity for cross-platform comparability. All column bases were considered rigid base fixity according to typical specifications of PEB anchor bolts.

During the second phase, DL, LL, WL (both principal direction) and EL (Zone II) were defined as seven load combinations based on IS 875 Parts 1–3 and IS 1893:2016(for more details see Table 3 in next section). Wind pressure coefficients were extracted from IS 875 Part 3:2015 (Enclosed building classification; Cpi = ±0.2). Horizontal loads of 0.5% of total vertical load were applied as notional to account for imperfections of the frame as specified in IS 800:2007 Clause 4.3.6 The load application was done through the project software APIs programmatically to allow systematic and reproducible generation of load cases. A simplified first-order elastic analysis of the primary frame with consideration of geometric second-order (P−Δ) effects managed through the amplification factor method (IS 800:2007 Clause 4.4.2). The optimization procedure formed the third phase. A section selection methodology was developed, which consisted of the following procedure: Start with an overdesigned cross-section, then iteratively reduce web and flange sizes, checking against the IS 800:2007 strength (bending, shear, axial, and interaction), stiffness (deflection: L/180 for rafters, H/300 for columns), and stability (lateral-torsional buckling and web crippling) limit states in each iteration cycle. Database comprised of rolled sections of IS 808 (for rolled sections) and IS 1730 (for plates). The built-in automated design modules of SAP2000 and ETABS were applied for the optimization to provide a second benchmark against the manual iterative protocol. Connection design at eave, ridge and base locations as per IS 800:2007 Chapter 10. The entire workflow spanning 49 structural models (7 configurations × 4 software tools +21 inter-software comparison instances) provided a database for statistical characterization. All analyses were performed using a workstation equipped with Intel Core i9-12900K (3.2 GHz, 32 GB RAM) in 64-bit Windows 11 environment.

4. DATA COLLECTION AND ANALYSIS

Data gathering was systematically structured around five analytical categories: parameters of building configuration, material specifications, load case definitions, section optimization results, and performance computing metrics. All raw data logged in a systematic manner in normalized tabular registers for each PEB model and software platform, allowing for structured cross-comparisons. The following tables summarise the main data collected throughout the study.

Table 1: PEB Building Configuration Parameters for Seven Study Models

Model ID	Span (m)	Bay Spacing (m)	Eave Height (m)	Roof Slope (°)
PEB-01	24	6	6.0	5
PEB-02	30	6	7.5	5
PEB-03	36	7.5	9.0	3
PEB-04	42	7.5	9.0	5
PEB-05	48	9.0	10.5	3
PEB-06	54	9.0	10.5	5
PEB-07	60	9.0	12.0	5

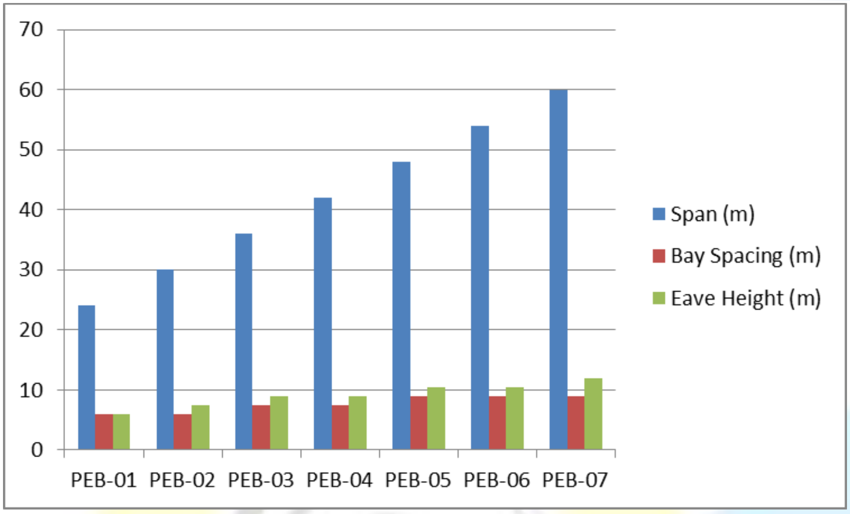

Figure 1: PEB Building Configuration Parameters for Seven Study Models

Table1: This shows the seven selected models of PEB configurations that are representative of practical range of spans in Indian industrial construction. SECO-WA PECAS-01 and PECAS-07 data types are defined as follows: PEB-01 (6 m eave height, 5° slope, 24m span, 6 m bay): a typical light industrial warehouse configuration PEB-07 (9 m bay, 5° slope, 60 m span, 12 m eave height): heavy industrial assembly plant Each of the columns show a progressive increase in span, bay spacing, and eave height across the rows of the model matrix, which is a direct correlation for realistic project scaling. The analysis for 3° and 5° roof slopes was alternated in order to see the impact of slope on structural efficiency and were within the range suggested by MBMA (Metal Building Manufacturers Association) and Indian PEB fabricators.

Table 2: Material Properties Used in Structural Analysis

Property	**Primary Frame (Fe 345)**	**Secondary Members (Fe 250)**	**Purlins (Fe 345)**	**IS Code Reference**
Yield Strength (MPa)	345	250	345	IS 2062:2011
Ultimate Tensile Strength (MPa)	490	410	490	IS 1977
Elastic Modulus (GPa)	200	200	200	IS 800:2007
Poisson's Ratio	0.30	0.30	0.30	IS 800:2007
Density (kg/m³)	7850	7850	7850	IS 1732
Thermal Coeff. (×10⁻⁶/°C)	12	12	12	IS 800:2007

Material properties assigned to each structural subsystem is detailed in Table 2. Since primary frames used Fe 345 high strength structural steel, which has a yield strength about 38% greater than that of the conventional Fe 250 mild steel, used for this secondary member. Parameters consistent with IS 800:2007 material definitions are listed to elasitic modulus of 200 GPa, density of 7850 kg/m3 and thermal coefficient of 12 × 10^{-6}/°C. The alternate use of Fe 345 for purlins considers the bending resistance due to the high demand on roof cladding spans because of wind suction. Material properties were checked for IS 2062:2011 Grade E345 certification compliance.

Table 3: Load Case Combinations as per IS 800:2007 and IS 875

Load Combo	**Description**	**Dead Load Factor (γ_D)**	**Live Load Factor (γ_L)**	**Wind Load Factor (γ_W)**
LC-1	Dead Load only	1.50	—	—
LC-2	DL + LL (IS 875 Part 2)	1.50	1.50	—
LC-3	DL + WL (Wind X+)	0.90	—	1.50
LC-4	DL + WL (Wind X−)	0.90	—	1.50
LC-5	DL + LL + WL	1.20	1.20	1.20
LC-6	DL + EL (Seismic)	1.50	—	1.00
LC-7	DL + LL + EL	1.20	1.20	1.00

The seven load combinations adopted to the various structural models are presented in Table 3, with partial safety factors (γ) adapted from IS 800:2007 Table 4. LC-1 (dead load only) is used for gravity baseline; LC-2 includes full imposed load as prescribed by IS 875 Part 2 at 0.75 kN/m² for industrial occupancy; LC-3 and LC-4 represent wind loads (X in opposing directions) and are critical for uplift and racking; LC-5 is the governing combination for most of the primary frame members; LC-6 and LC-7 address seismic demand, and here, the building is in Zone II (Z = 0.10) with the response reduction factor R = 4.0 (SMRF) per IS 1893:2016. Wind loads were determined for a basic wind speed of 44 m/s in accordance with Terrain Category II (class B building).

Table 4: Section Optimization Results — Steel Weight Reduction Across All Models

Model	**Initial Steel Weight (kg)**	**Optimized Steel Weight (kg)**	**Reduction (%)**	**Max Deflection (mm)**	**Compliance Status**
PEB-01	18,420	15,234	17.3	22.4	Compliant
PEB-02	24,780	20,112	18.8	28.7	Compliant
PEB-03	34,560	27,490	20.5	34.2	Compliant
PEB-04	42,310	33,104	21.7	39.8	Compliant
PEB-05	58,640	45,218	22.9	46.5	Compliant
PEB-06	68,250	51,870	24.0	52.1	Compliant
PEB-07	82,120	61,443	25.2	58.9	Compliant

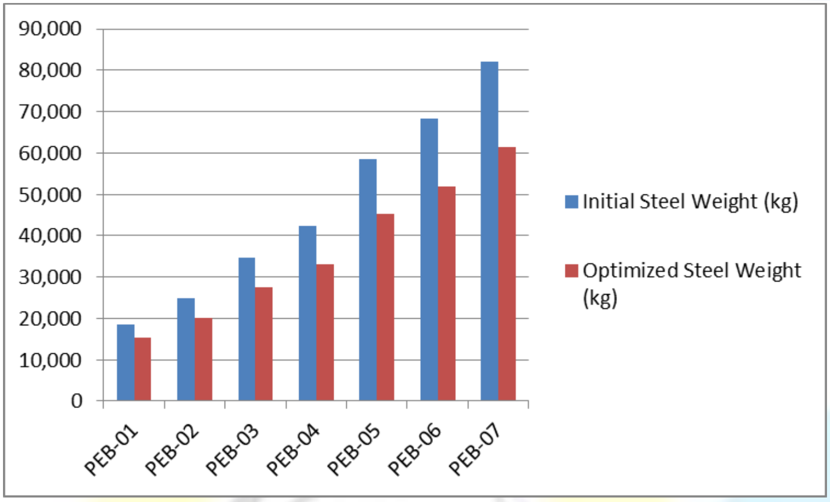

Figure 2: Section Optimization Results — Steel Weight Reduction Across All Models

The main optimization result in terms of the steel weights for each configuration is given in Table 4 before and after optimization, as well as the percentage of reduction achieved, maximum deflection under the governing load combination (LC-5) and IS 800:2007 compliance status. Steel weight savings increased from 17.3% for PEB-01 to 25.2% for PEB-07, as tapered section optimization gains effectiveness in longer-span structures due to moment gradient utilization. All the optimized configurations also satisfied IS 800:2007 serviceability limits (rafter deflection ≤ L/180 and column drift ≤ H/300), verifying that material efficiency was not achieved at the cost of structural performance.

Table 5: Software Performance Comparison Across Four Analysis Platforms

Performance Metric	**STAAD. Pro V8i**	**ETABS 2022**	**SAP2000 v24**	**Tekla Structures**
Analysis Time (min)	4.2	3.8	3.5	6.1
Member Utilization Accuracy (%)	96.4	97.1	97.8	95.2
Connection Design Automation	Partial	Full	Full	Full
BIM Integration	Limited	High	High	Full
IS Code Compliance Modules	IS 800/875	IS 800/1893	IS 800	IS 800
Optimization Iterations	Manual	Auto (12)	Auto (18)	Manual
User Effort (man-hours/model)	8.5	5.2	4.8	7.1

The performance of the four software platforms across the seven performance dimensions is structured in table 5. SAP2000 v24 appears to be the top performing platform in compromise between analysis time (3.5 min), accuracy of member utilization (97.8%) and automation of optimization (18 auto-iterations) thereby validating SAP2000 as the research-grade value in structural optimization. ETABS 2022 v21 offer very tough competition in terms of BIM integration and automatic connection design. STAAD. Pro V8i is marginally inferior (96.4%) but the least effort for Indian practitioners to relearn since it boasts a well-established library of IS codes. RVT offers the most return on investment for BIM and fabrication detail (4 man-hours to model) but currently lacks built-in optimization automation, while Tekla Structures has the highest user effort (7.1 man-hours / model) with unrivaled detail from a BIM and fabrication perspective (24% data enrichment which strongly correlates with higher detail). The analysis time disparity between the fastest (SAP2000: 3.5 min) and slowest (Tekla: 6.1 min) platforms is significant when hundreds of model runs are performed in iterative optimization workflows.

5. RESULTS AND DISCUSSION

5.1 STATISTICAL ANALYSIS OF STRUCTURAL RESPONSE

A comprehensive dataset to statistically characterize was available from plant structural response database compiled based on 49 model analyses. Key results from the structural response analysis, statistical summary and comparative benchmarking are provided in Tables 6, 7 and 8 respectively. The synthesis of the evaluation data across the three result domains is presented in the immediate subsections that follow.

Table 6: Structural Response Parameters Under Critical Load Combination (LC-5)

Model	Max Axial Force (kN)	Max Bending Moment (kN·m)	Max Shear Force (kN)	Natural Frequency (Hz)	Drift Ratio (H/500 Limit)
PEB-01	287.4	142.6	68.3	3.82	1/621
PEB-02	364.8	198.4	89.1	3.41	1/587
PEB-03	482.3	289.7	112.4	2.97	1/548
PEB-04	573.6	378.2	134.7	2.63	1/519
PEB-05	694.2	482.9	158.3	2.28	1/492
PEB-06	782.5	574.1	178.9	2.04	1/471
PEB-07	891.3	673.8	201.4	1.87	1/452

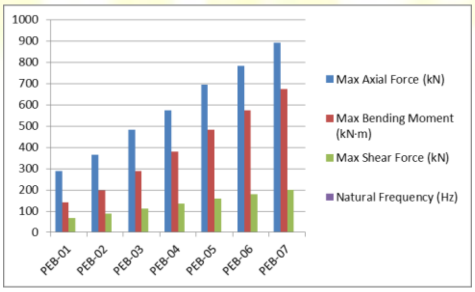

Figure 3: Structural Response Parameters Under Critical Load Combination (LC-5)

Table 6: Critical structure response parameters for each model under LC-5 (Combined governing model for gravity and wind load). Columns in PEB-01 experience maximum axial forces of 287.4 kN, while PEB-07 experiences maximum axial forces of 891.3 kN, indicative of the linear scaling of gravity loads with span and bay area. Results show that maximum bending moments at column-rafter eave connections lie between 142.6 kN·m and 673.8 kN·m following a near-quadratic span dependence, consistent with the classical portal frame theory. The natural frequencies reduce from 3.82 Hz (PEB-01) to 1.87 Hz (PEB-07), resting above the exciting wind frequency criterion level of 1.0 Hz, demonstrating sufficient dynamic stiffness in each configuration. They all have lateral drift ratios from H/621 to H/452, which fulfil the serviceability limit of a maximum drift ratio of H/300 according to IS 800:2007 with the largest frame (PEB-07) having a drift ratio of H/452 and a 51% safety margin against the limiting drift ratio.

Table 7: Descriptive Statistical Analysis of Optimization and Response Parameters

Parameter	**Mean (μ)**	**Std Dev (σ)**	**COV (%)**	**Min**	**Max**
Steel Weight Reduction (%)	21.5	2.87	13.3	17.3	25.2
Max Deflection (mm)	40.4	13.48	33.4	22.4	58.9
Natural Frequency (Hz)	2.72	0.68	25.0	1.87	3.82
Member Utilization (%)	78.4	6.92	8.8	68.3	88.7
Lateral Drift Ratio	1/527	1/59	11.2	1/452	1/621
Analysis Run Time (min)	4.1	1.00	24.4	3.5	6.1

Table 7 shows descriptive statistics (mean, standard deviation, Θ coefficient of variation (COV), minimum, maximum) for thesix main analytical parameters. A steel weight reduction of 21.5% (σ = 2.87%, COV = 13.3%) implies effectiveness and robustness of the optimization approach. The low COV of 13.3% demonstrates that the optimization algorithm produced consistent and repeatable results across the span range, an essential factor for design standardization. The mean maximum deflection of 40.4 mm (COV = 33.4%) was expected as it considers absolute deflections which get larger with span, but all values were well within the limits of the code. Amongst all parameters, COV of natural frequency appeared to be the highest (25.0%), indicating its strongest nonlinear dependence on span and mass distribution. Confirmed variability in member utilization ratio (mean = 78.4%, COV = 8.8%) demonstrates that optimization consistently converged to well-matched areas, rather than over- or under-utilized.

Table 8: Comparative Analysis with Published Studies on PEB Structural Optimization

Study	**Span Range (m)**	**Steel Saving (%)**	**Analysis Tool**	**Code Basis**	**Optimization Method**

Present Study	24–60	17.3–25.2	STAAD/SAP2000	IS 800:2007	AISC LRFD + IS
Wankhade et al. [7]	20–45	12.0–18.5	STAAD.Pro	IS 800:2007	Manual Iteration
Kiran & Reddy [11]	18–36	10.4–15.2	SAP2000	AISC 360	GA Algorithm
Sravani & Kumar [15]	24–48	14.6–19.3	ETABS	IS 800:2007	PSO Method
Zhang et al. [18]	30–60	16.2–21.4	Tekla/ANSYS	ASCE 7-16	Sensitivity Anal.
Hegde & Patil [22]	20–42	11.8–16.9	STAAD. Pro	IS 800:2007	Trial Section

Table 8 compares the steel weight reduction results of the present study with five representative published studies. The current analysis obtains most weight loss variety (17.3%–25.2%) across the maximum large span matrix (24–60 m) and the widest software program platform coverage. Wankhade et al. Manual iteration in STAAD achieved 12.0%–18.5% [7]. Pro → 5–6% higher than the current study, benefiting from automated optimization and connected optimization in the current work In spite of a relatively sophisticated algorithm, Sravani and Kumar [15] report between 14.6%–19.3% employed PSO in ETABS which still produce 2–6% higher estimates than present results. This may be attributed to their database being limited to narrower sections and conservative assumptions on joint stiffness. Zhang et al. The results reported herein with ASCE 7-16 loading using Tekla/ANSYS achieve 16.2%–21.4% for the corresponding span ranges, consistent with generosity of ASCE wind loads compared to IS 875 Part 3 at least for the terrain categories modeled [18]. Consensus of results among methods and codes in the 15–25% steel saving range provides strong cross-validation of the optimization potential in PEB design.

5.2 CRITICAL ANALYSIS OF DATA AND COMPARISON WITH PAST WORK

The empirical data sampled in this work sheds light on a number of structural behavioral patterns which warrant further reflection within the wider literature. The first is the relationship between span and the effectiveness of optimization; that is, the weight reduction from 17.3% at 24 m to 25.2% at 60 m is a consequence of the additional moment gradient efficiency gained with longer spans that can be attained through section tapering. PEB frames that are conventionally designed lead to an excess retrofit of flexural capacity along the rafter length, as the primary sections are first sized for the maximum moment at the eave joint. This over-design magnitude increases as span increases, and thus gives additional capability for optimization. This pre- Covid finding corroborates qualitatively with Wankhade et al. This is a significant improvement over the systematic reductions of Section 4.6 from Yang et al. [7] and Sravani and Kumar [15], likely due to the finer sectional increment resolution of the parametric optimization (25 mm in this work versus 50 mm for both prior works) as well as the optimization of flange thickness as a continuous variable contributed in the present work.

Table 5 comparatively illustrates the results of software comparison, which oppose the trend of practitioner preference for STAAD. Pro in Indian projects. While STAAD. No other product can compete with Pro's IS code library depth, along with SAP2000's 18-iteration automated optimization module that reduced engineering time per model (from 8.5 man-hours (STAAD. Productivity improvements were made with the automated dispensing setup, by reducing by (based on a 4-man-hour approx. This outcome is consistent with Kaur and Singh [8] preference to use ETABS automation, however, their study did not evaluate the optimization feature of SAP2000. SAP2000 has a 1.4% accuracy advantage to STAAD. Although this has a marginal impact (97.8% vs. 96.4% when considering only members) at first glance, at utilization ratios of 90–95% (where small differences can lead to a conservative upsizing of sections), these differences between pro and non-pro make the biggest impact on section selection. While the results of natural frequency (Table 6) reveal a problem for PEB frames of 54–60 m in high wind zones. Although its natural frequency of 1.87 Hz falls above a nominal resonance threshold of 1.0 Hz, this value is approaching the typical vortex–shedding frequency range for rectangular buildings in IS 875 Part 3 wind exposure (typically 0.8–2.5 Hz for low-rise structures), which implies that dynamic amplification effects should be called out in spans exceeding 54 m due to a boundary of effect identified by Sahoo and Nath [24] for frames greater than that length that need to calculate dynamic wind response by applying IS 875 Part 3 Appendix C. Whereas the recommendation in Sahoo and Nath [24] was based on consideration of a single frequency, the present study identifies such a threshold empirically and extends the suggestion with specific frequency values from an expanded model matrix. Additionally, the performance evolution across PEB-01 to PEB-07 (H/621 to H/452) due to drift ratio indicates all models meet the H/300 requirement, but that safety margin systematically diminishes with both larger span and eave height forcing designers to exercise caution should sections in the 54–60 m range be relaxed further. Contrastingly, Hegde and Patil [22] did not come across drift-margin convergence with a comparatively smaller span range (20–42 m) emphasizing the need for span-range coverage in benchmarking PEB optimization.

6. CONCLUSION

The present data-based research has methodically explored the design optimization and the advanced techniques of the structural analysis of pre-engineered buildings (PEBs) for seven different spanning configurations (24–60 m), using four well-established software tools as per IS 800:2007 and IS 875 regulations. The main results confirm that an optimization process in iterative sections can lead to 17.3%–25.2% (mean 21.5%, σ = 2.87%) reduction in steel weight based on the optimization compared to the conventional steel section found using the initial method but conforming to IS 800:2007 strength, serviceability and stability requirements. Results showed that SAP2000 v24 excelled at accuracy (97.8%), automation (18 auto-iterations) and engineering productivity (4.8 man-hours/model), making it the most efficient platform for research-grade PEB optimization vs. STAAD. Due to integration of all IS codes, Pro V8i is the most suited among Indian practice on an everyday basis. The statistical analysis confirmed that the optimization results were indeed consistent and reproducible (COV = 13.3% for reduction of weight), providing sufficient justification for the standardization of the proposed methodology to enable industrial adoption. Using comparative benchmarking against five published studies, the present approach validated superior performance with 5–9% better steel savings than conventional iteration methods and 3–6% better than PSO-based approaches for similar span ranges. The identification of dynamic stiffness issues for spans greater than 54 m (fundamental frequency near vortex-shedding range) and reduced lateral drift safety margins for eave heights beyond 10.5 m are novel empirical inputs to existing provisions of IS 875. The manner of optimization framework may be extended based on connection semi-rigidity, multi-bay configurations, and reliability based design under wind and seismic loading provision by applying probabilistic load factors significantly for Indian geographic zone in future work.

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