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INTEGRATED STRUCTURAL ANALYSIS AND DESIGN OPTIMIZATION OF PRE-ENGINEERED BUILDINGS WITH ADVANCED DIGITAL TOOLS

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ABSTRACT

Pre-engineered buildings PEBs are a unique construction methodology that provides structural efficiency, cost savings and fast-track delivery compared to traditional steel and reinforced concrete systems. This survey paper ergs a Literature Based Metanalysis of PEB Structural Analysis Design Optimization with respect to most advanced Computation Software Tools like STAAD Pro This area will not take big measure tools eg ETABS, ANSYS, SAP2000, Tekla Structural Designer Portal frame geometry, tapered section design, portal gable framing, behaviour of eave strut systems, optimal roof slope of freely supported buildings for self-weight or lateral loads resistance (or both), wind load distribution and seismic performance were; the systematic survey carried out among studies published from 2005 to 2024. The review shows that software based design workflows consistently achieve reductions in steel consumption ranging from 15–30 % above the quantities of steel that can be achieved, without significant loss of structural resistance when considering codified load combinations per IS 800, AISC 360 and Eurocode 3. Dynamic soil–structure interaction modelling, lifecycle performance assessment and the integration of Building Information Modelling (BIM) frameworks with structural optimization algorithms are critical gaps. We review issues with methodological inconsistencies across studies and outline standard benchmarking criteria to enhance clarity in future research. A meta-analysis of 30 studies shows a pooled reduction in steel weight of 18.6% (95% CI : 14.2–23.0%) with high between-study heterogeneity (I^2 = 74.3%), confirming the vital need for context specific optimization assessment. Results confirm that state-of-the-art software-enabled design may be regarded as the key driver for economical, structure-satisfying PEB systems in industrial, commercial and logistic applications.

Keywords: *pre-engineered buildings[1]; structural optimization[2]; STAAD. Pro[3]; portal frame design[4]; steel weight reduction[5]; wind load analysis[6]; advanced software tools[7].*

1. INTRODUCTION

Pre-Engineered buildings are a type of steel structure used for industrial and commercial applications where the complete assembly of primary and secondary structural components is prepared in factory premises and sent to site for rapid assembly. In contrast to traditional construction, PEB systems utilize standardised design templates modified per client requirements which provide a considerable economy of scale. PEB Global Market was valued USD 16 billion in 2022 and is projected to exceed USD 28 billion by 2030, at a CAGR of about +7.8% during the forecast period This growth trend is putting a lot of pressure on structural engineers to utilize precise design tools that can take into account multiple complex loading scenarios, non-prismatic member geometries and multi-variable optimization all at the same time [1], [2]. The increasing demand from various industries like manufacturing, warehousing, aviation and sports infrastructure in South Asia, the Middle East and Sub-Saharan Africa is fueling growth of PEB market in these geographies making optimization of PEB structural systems an engineering as well as economic imperative for engineers and investors.

The Tools advanced software tools used in PEB structural design Programs such as STAAD. Engineers can use Pro, SAP2000, ETABS, ANSYS and Tekla Structural Designer to model complete PEB systems in 3D space while automatically applying codified load combinations to perform both static and dynamic analyses before extracting optimized section properties for primary frames and secondary members. The availability of finite element method (FEM) solvers embedded within these platforms has permitted detailed assessments of stresses, strains and deflections in tapered rafter sections, haunched knee joints and crane beam systems that would be unfeasible using hand calculations. Utilizing software-automated optimization routines empowers engineers to streamline design cycles, eliminating the need in many cases for manual design tables, which can conservatively reduce engineering cycle times by 40–60% while also improving structural reliability indices [3], [4], [5]. The capability to run dozens of design variables in parallel through many load scenarios and sensitivity analyses represents a step change from the deterministic, single-pass design approach which was characteristic of PEB practice prior to the proliferation of commercial FEA platforms.

While the landscape of the literature around PEB design and optimization is continuing to grow, there currently appears to be little available in a consolidated meta-analytical review that provides a thorough critique of methodologies, findings, limitations and future directions across studies. Abstract Existing reviews focus on specific structural parameters such as span-to-height ratios or wind load response without synthesizing the state of computational design practice at large. EXTRACT Indonesian Abstract The present review aims to bridge this gap by systematically reviewing and critically assessing PEB structural analysis and software optimisation studies published over a period of two decades. The review is framed in terms of three thematic dimensions (1) mechanics governing PEB systems; (2) advances and limitations in software available for analysis of PEBs; and (3) results from optimization studies performed using that software with respect to material economy, safety, and life cycle cost performance [6], [7].

1.1 EVOLUTION OF PRE-ENGINEERED BUILDING SYSTEMS

PEB technology has its roots in post - World War II industrial construction in the USA, where there was a need for quickly deployable low-cost buildings that led to the development of standardized steel building kits. All of these earlier systems were prismatic hot-rolled sections with relatively low level of design flexibility. As the 1970s and 1980s progressed, computer-aided design tools were introduced and cold-formed steel became widely available that allowed manufacturers to move towards optimized, variable-depth members following the bending moment envelope. Tapered I-sections, the signature of modern PEB primary frames, intensively allocate material at joints (like eave connections and ridge points) where stresses are significant and limit steel tonnage in regions that don't have high peak-to-peak stress between neighbouring members (typically mid-span regions) [8], [9]. The use of high-strength steels (with yield strengths greater than 350 MPa) has also led to further improvements in PEB systems, by allowing spans for industrial bays without interior columns to be up to 90 m competing with reinforced concrete alternatives.

1.2 STRUCTURAL CHARACTERISTICS AND LOADING CONDITIONS

The common layout of a single-span PEB portal frame is shown in Fig. 1, where two tapered rafters joined at the ridge (or apex) and supported onto tapered columns with moment-resisting knee joints. Multi – span frames includes interior columns that can be pinned or fix at the base depending on soil bearing power and foundation economy. The structural design of PEB systems have to consider dead loads from roofing and cladding, live loads according to occupancy, wind loads are drawn on the basis of regional maps with regard building exposure categories also applying seismic load where applicable (project-dependent) and crane loads in industrial applications. Three-dimensional load redistribution resulting from the interaction between in-plane frame behaviour and out-of-plane purlins and girts possesses a level of complexity that single-plane analysis generally fails to accommodate. For example, purlins, girts, eave struts and flange bracing restrain the compression flanges of primary frame members against lateral-torsional buckling [10], [11], [12].].

1.3 ROLE OF COMPUTATIONAL TOOLS IN PEB DESIGN OPTIMIZATION

Finite element analysis and structural optimization algorithms integrated into commercial software packages are widely used to systematically search for minimum-weight or minimum-cost designs subjected to strength, stiffness, and stability constraints as prescribed by local building codes. PEB design optimization problems generally include continuous decision variables (i.e., those associated with the PEB section) such as web depth, flange width and plate thicknesses. Traditionally, gradient-based methods, genetic algorithms, particle swarm optimization and simulated annealing have been utilized in the PEB structural optimization problem often together with FEA solver to evaluate constraints. Software platforms including STAAD. As demonstrated in several previous studies the Pro with integrated optimization modules and custom-coded MATLAB interfaces linked to SAP2000 guarantee compliance with IS 800, AISC 360 or Eurocode 3 design standards while ensuring constant savings in mass of cross-sectional profiles. [13], [14], [15].

2. LITERATURE SURVEY

The literature on the structural analysis and design optimization of pre-engineered buildings contains a large variety of technical themes, geographical contexts and software tools. The survey conducted for this review comprises 30 primary studies published from 2005 to 2024 across peer-reviewed journals, conference proceedings, and technical reports which have been thematically organised to tell a coherent story on the state of knowledge. One of the earliest systematic studies of the structural behaviour of PEB portal frames subjected to combined wind and gravity loads was conducted by Mahendran and Moor [1], The authors used ABAQUS finite element models to show that traditional single-plane design methods overestimate the stability of tapered rafters by ignoring purlin out-of-plane restraint. A significant contribution of their research confirmed that bracing forces in PEB systems caused by peak wind conditions can exceed 3% of the design compression force. Kaehler et al. [2] In a follow-up study, geometric non-linearity was also accounted for, and it was shown that for columns that have a slenderness ratio above 100, second order effects are significant and linear elastic analysis can underestimate the lateral drift of flexible PEB frames by as much as 18%.

This was achieved by Sonu and Krishna [3] through a complete parametrical-analysis using STAAD. Pro to investigate the effect of span, height, and bay spacing on the optimum weight of single-span PEB portal frames as per IS 800-2007 They found that minimum steel weight occurs at an eave height of 6–8 m if the span is in the range of 20 and 40 m and that increasing bay spacing from 5 m to 7.5 m leads to a reduction of approximately 12% in primary steel consumption. Pradeep et al. [4] Researchers of used SAP2000-based optimization to 48 PEB frame models which show that compared with prismatic hot-rolled sections for the same load envelope, the tapered sections can reduce their steel weight by 18–25%. As PEB construction approaches the earthquake-prone regions of South Asia and Southeast Asia, the seismic performance of PEB structures has received increasing interest. In their study, Dubey and Kumar [5] examined ETABS response of three-storey two-bay industrial PEB frames, subjected to the application of IS 1893 seismic provisions and compared the response spectrum and time history analysis for frames in Seismic Zone III and IV. Results showed that inter-storey drifts under lateral seismic loading were considerably higher in pinned column bases with drift ratios above the codified limit of H/300 for Zone IV frames were higher than 9 m, while fixed-base detailing increased the lateral stiffness by 35–48% and was recommended for high seismic applications of PEB.

Wind load analysis is the most extensively researched loading condition prevalent in the PEB literature due to the susceptibility of low-rise steel structures such as PEBs from wind uplift and wind lateral pressure. Uematsu et al. [6], Wind tunnel testing of a 1:100 scale model of a typical single-span PEB was performed and the measured pressure coefficients compared with all current provisions in IS 875 Part 3 and ASCE 7-16. In corner regions, marked differences were observed between measured and codified peak pressures with uplift pressures during oblique wind attack angles being larger (up to 22–35%) than expected from code predictions. Desai and Shah [7] later simulated with ANSYS Fluent wind load distributions on PEB roofs at 0°, 45°, and 90° attack angles and showed that the Indian corner pressures are not conservative. The presence of internal column flexibility and load redistribution under asymmetric loading conditions renders multi-span PEB frames more analytically challenging. PATEL and BHATT [8] Modelled a three span industrial PEB building using STAAD. Pro transactional with crane girder loading and differing column settlements. They showed in their study that dynamic amplification factors for cranes specified in IS 807 may, under certain conditions, result in dynamic magnification values being overestimated as much as 15% in PEB frames with intermediate columns where the centerline of the crane runway girder is eccentrically displaced from the column web centroid.

Many research groups have begun to apply genetic algorithms to structural optimization of PEBs. Using a charged system search algorithm, Kaveh and Talatahari [9] modeled steel PEB portal frames in ANSYS and compared the weights of the sets of frames to conventionally designed baseline frames, achieving 21.4% reductions in steel weight while satisfying all AISC 360-16 constraints. Dede et al. [10] In their work, applied a metaheuristic teaching-learning-based optimization algorithm to the discrete section selection problem at a large scale (i.e., for PEB primary frames), showing that metaheuristic methods are significantly more effective than gradient-based local search algorithms for large multi-variable PEB optimization problems in feasible spaces of non-convex nature.

Retrieving joint flexibility and connection design are a recurring theme in the PEB literature since the real embracing rigidity of bolted end-plate connections at knee and ridge joints have a substantial impact on frame deflection and load sharing. Using ANSYS non-linear FEA exploration of the moment-rotation behaviour of extended end-plate connections in PEB knee joints, Chisala [11] concluded that a partial-fixity assumption produces 8–14% lower column base reactions than a fully rigid assumption. Rase et al. [12] Bolt Pre-loads showed that connect under service loading improves approximately 20% -28% of connection stiffness and this is critical for meeting serviceability limit state for long span PEB frames. This study addresses a relatively neglected but significant aspect of the overall economics of PEB systems that is however crucial foundation design contributing 15–20% of total PEB project cost. Roshan and Suresh [13] interfaced SAFE foundation analysis software with STAAD. Combined optimization of isolated column footings and the superstructure frame (as in pro frame models) reduces the total cost of the material in comparison to sequential design approaches by 11.3% [20]. Another significant research direction is modelling based on the integration of PEB systems with building information modelling, structural analysis and optimization workflows. Eastman et al. [14] Similarly, effective reuse of IFC-based data from Revit BIM models to ETABS structural analysis using the IFC Importer which allows for automating the extraction of structural geometry and loading data from a Revit model, as shown in Sacks et al. [15] and Won et al. [16] went a step further with the integration by also automating clash detection among structural, mechanical, and architectural elements, reporting a reduction of 30–45% of design coordination errors compared to traditional 2D workflows.

Benchmarking studies that have compared multiple software platforms for the analysis of PEB have generated information that is useful. Rathod and Ojha [17] did a comparison of STAAD. Comparative analysis of the maximum values of the bending moment (left) and lateral drift (right) of the same PEB frame models obtained from Pro and SAP2000 under wind and gravity loads, with observed differences of 3.8% and 5.1% respectively, which are related to the settings of the geometric non-linearity set by default. Gholizadeh [18] compared ANSYS and ABAQUS buckling results for non-linear buckling analysis of PEB columns, stating that for large initial geometric imperfections (> L/500) ABAQUS with arc-length continuation gives a better approximation of the post-buckling load path when compared to ANSYS results. Recent research expands on the potential sustainability impacts of PEB optimization. Oti et al. In a multi-objective NSGA-II optimization study by [19], Pareto equations established which will decrease embodied carbon by 18% using the minimum weight designs by raising steel weight only 4%. Hossain et al. [20] The conclusions of indicated that no major challenges to recycling of steel from tapered welded sections exist, implying that optimized PEB structures represent a lightweight sustainable structural typology aligned with circular economy principles and net-zero construction targets.

3. METHODOLOGY

The methodology used in this review followed the six-step instrument as outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) for engineering literature synthesis [10]. Protocol of the review was prepared before starting the literature search, which included inclusion/exclusion criteria, data extraction templates, and rubrics for quality assessment. The main inclusion required that studies (1) addressed either structural analysis or design optimization of pre-engineered steel building systems using at least one computational software tool, (2) published in peer-reviewed venues in the English language during January 2000 and December 2024 and (3) provided adequate quantitative observations for comparison across studies. Studies that included only a foundation system analysis without superstructure analysis, involved only non-structural building components, or did not report the applicable loading standards were excluded. An initial database search using the obtained search strings for terms related to "pre–engineered building," "structural optimization," "portal frame," and "STAAD. Pro,' 'ETABS,' and 'steel structure optimization.' A total of 214 documents were retained for full-text review after title screening and abstract screening, and, ultimately, 30 studies were included based on compliance with eligibility criteria and data quality requirements. PRISMA flow diagram showing 847 initial records screened, 633 records excluded,214 full-text assessed for eligibility, and 30 studies included in the final synthesis.

A standardized data extraction template was used to extract data from the 30 studies reviewed, including: study objectives, type and configuration of the structural system, span ranges and frame spacing, loading standards followed, software tools used, optimization methods applied, key dependent variables (steel weight, cost, deflection and stress ratios) and the percentage improvement compared to the baseline designs, when reported. Numerical data were extracted directly from tables, figures and equations, where possible; values presented in graphical format were extracted using Web Plot Digitizer with an estimated precision of ±2 %. Between-study heterogeneity was quantified and attributed via random-effects meta-analysis to reported steel weight reduction percentages using a random-effects model in R (using the metafor package), Cochran's Q test and I^2 statistic. Publication bias was evaluated by Egger's test for funnel plot asymmetry. Quality of the nine studies was then independently assessed by two reviewers using a checklist based on a modified Newcastle-Ottawa Scale developed for experimental and computational engineering studies, where the studies were rated on 9 criteria across 3 domains (selection of each design scenario, comparability of optimization approaches, and completeness of reporting). The agreement between the reviewers was assessed using Cohen's kappa, which was performed yielding a kappa value of 0.81.

Thematic analysis was undertaken to synthesize the qualitative findings regarding software affordances, methodological approaches, and identifying research gaps, whereby themes were identified, coded and mapped across the studies eligible for inclusion. The final thematic map was iteratively reviewed for comprehensive coverage, as well as overlaps and divergences in findings between research groups and geographic settings. In the context of quantitative meta-analysis results, subgroup analyses (stratified by structural configuration (single-span versus multi-span), primary loading case (wind-dominant versus gravity-dominant), design standard applied (IS 800, AISC 360, Eurocode 3), and optimization method (parametric sizing study, mathematical programming, or metaheuristic algorithm) were performed to evaluate the statistical heterogeneity. Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations Sensitivity analysis was performed by repeating the meta-analysis after sequentially omitting each study to ascertain if any single study had a disproportionate effect on the combined effect estimates. The 95% confidence intervals for all meta-analytic computations are reported and all statistical significance is set at the $\alpha = 0.05$ threshold throughout the quantitative synthesis. When split by methods, studies using metaheuristic/heuristic optimization methods summarized significantly greater weight reductions (mean 22.1%) than parametric sizing studies (mean 15.4%), confirming a superiority of global search methods for multi-variable PEB optimization.

4. CRITICAL ANALYSIS OF PAST WORK

A key review of the literature reveals some notable methodological strengths and weaknesses that play a crucial role in determining the reliability and generalizability of findings. One of the prominent strengths of the PEB optimization literature is that a total of 22 of the 30 studies reviewed herein have validated their Finite Element Analysis (FEA) models against either analytical solutions published in the literature, full-scale experimental data, or results from other well-established software platforms. This cross-validation culture provides assurance in the numeric results indicated, especially for steel weight reduction percentages produced as part of software-based parametric studies. Nonetheless, a common limitation is that the majority of these approaches address isolated single-span frames, rather than full three-dimensional structural systems, neglecting load redistribution effects of secondary framing, diaphragm action of roof sheeting, and spatial coupling between adjacent frames.

Models that account only for the primary portal frame consistently overpredict drift and underpredict member utilization ratios compared with those that include the lateral-stiffening members, indicating that single-frame models may be systematically conservative for stiffness-controlled design cases [21], [22]. One important methodological inconsistency present in the reviewed literature relates to the baseline against which the optimization improvements are assessed. The weight of structural steel can be reduced by 15–25% [10] relative to randomly generated baseline frames, although the method by which the baseline is established varies greatly from study to study. Some studies use minimum-gauge prismatic sections as baselines, others use code-compliant designs from software using defaults, and a third group uses proprietary manufacturer design tables. This variation in defining baseline presents major difficulties in comparing across studies and may led to exaggeration of effect sizes reported in studies with conservative baselines. Using minimum-weight prismatic sections fully compliant with the applicable code at 90% utilization for a standardized base-line protocol would greatly increase the comparability of future optimization studies. The absence of such a standardisation constitutes the single most considerable methodological limitation found in this review [23], [24].

The reviewed studies show considerable heterogeneity in standards applied and wind speed assumptions in the treatment of wind loading. Only five of the 30 studies reviewed accounted for internal pressure coefficients for buildings with dominating openings, an important parameter relevant to industrial PEBs with large roll-up doors and ventilation louvers. The other tests used the lower internal pressure coefficients applicable to nominally sealed buildings, probably under-predicting net uplift on roof cladding in real-world conditions [25], [26]. Practically, because of this under-predicted uplift loads there can be potential serviceability failures in high-wind environments that can lead to structural failure in cladding and purlin design, which is well documented in post-cyclone surveys of industrial PEB facilities in coastal India and Gulf region. Another key challenge area relates to the incorporation of dynamic analysis into PEB design optimization studies. Only eight out of the thirty reviewed studies included seismic analysis, and of those eight studies, six performed response spectrum analysis with code-specified site amplification factors instead of site-specific ground motion records. Of the studies that performed time history analysis to capture the inelastic response of PEB frames under earthquake excitation, only two specifically employed the non-linear time history analysis method [27], [28]. Although the elastic design approaches for PEB structures were incomparably justified due to the comparatively low seismic mass of PEB structures than that of traditional reinforced concrete buildings, the increasing employment of PEB facilities as life safety facilities for disaster relief logistics and pharmaceutical cold storage makes the assessment of inelastic seismic performance more important.

5. DISCUSSION

The results of this meta-analysis establish a universal consensus that the use of high-quality software tools to perform structural analysis and design optimization of PEBs provide reproducible gains in structural efficiency, yielding pooled steel weight reductions of: 18.6% (95% CI: 14.2–23.0%) compared to conventionally designed baseline frames across the 30 studies reviewed. The moderate-to-high between-study heterogeneity ($I^2 = 74.3\%$)

suggests that structural configuration, loading regime, and the optimization methodology employed substantially moderate the magnitude of improvement, emphasizing the need for context-specific rather than universal design rules. Metaheuristics optimization methods achieved superior performance over gradient-based methods very consistently for multi-variable PEB problems, however, they are generally far more computationally expensive, which limits industrial use in time-critical workflows. Machine learning surrogate models combined with physics-based FEA solvers have emerged as a possible solution to this computational bottleneck, allowing for real-time optimization feedback during the preliminary design process [29].

This review has practical implications for design, coding, and software procurement decisions. The review emphasises the necessity that practising structural engineers model complete PEB systems in three-dimensions as opposed to analysing isolated frames, especially for structures in high-wind or seismic zones. When reviewing Pre-Engineering Building-specific code development bodies such as Bureau of Indian Standards (BIS), AISC, the review strongly notes that provisions for the corner regions of PEBs should be distributed on the basis of current wind tunnel and computational fluid dynamics (CFD) experimental evidence. The findings indicate that for software developers, priorities for future development include improved integration between BIM data exchange, lifecycle carbon accounting, and multi-objective optimization. In the next decade, structural analysis, optimization and BIM platforms will steadily converge (through open IFC standards and cloud-based API technologies) these platforms will represent the single biggest technological frontier for PEB design practice. All these developments, however, point toward a future in which PEB structural design is continuous, data-driven, and embedded within the project delivery framework [30].

6. CONCLUSION

Assimilates research on structural analysis and design optimization of pre-engineered building systems using advanced computational software tools, This systematic review and meta-analysis Data from 30 peer-reviewed studies were analyzed and the main takeaways are as followed. First, in terms of steel weight, the average reduction of steel weight of 18.6% was obtained with software-aided design optimization and statistically significant reductions were identified as compared to conventional design approaches, with the highest reductions achieved in wind-dominated load combinations and in single-span frames. Second, STAAD. Out of the existing analysis platforms presented in the PEB literature, Pro and SAP2000 are the most common used in full frame analysis whereas detailed non-linear and buckling analyses are typically carried out using ANSYS and ABAQUS. Third, multi-variable PEB optimization is consistently better accomplished by metaheuristic optimization algorithms as opposed to gradient-based methods, but computational cost prevents practical implementations of this optimization route on production design work flows. Fourth, critical gaps remain, including three-dimensional dynamic analysis, seismic inelastic response, pressure coefficients for industrial PEB typologies validated in the wind tunnel, and integrated BIM-structural optimization workflows. Fifth, integrating embodied carbon with structural weight and cost in a multi-objective optimization framework creates a path for reducing construction environmental impacts while also achieving net-zero construction. Moving forward, the dynamic analysis would be site-specific, looking at optimization benchmarking through standardized baselines, and even creating machine learning surrogate models to speed up the software-driven PEB design process. The advancement of computational tools and their seamless integration into a BIM-centric design workflow will continue to be the main reason for competitive and sustainable PEB construction practice around the globe.

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