

Structural Optimization of Pre-Engineered Building (PEB) Frames Using Tapered Sections

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Abstract: This study highlights the increasing importance of Pre-Engineered Buildings (PEBs) in modern industrial infrastructure due to their lightweight construction, rapid execution, and cost-effectiveness. Compared to Conventional Steel Buildings (CSBs), PEBs are generally 25–40% lighter and enable 25–50% faster construction, resulting in significant savings in steel consumption, labor, and project duration. However, most existing Indian design codes are primarily developed for conventional steel structures, which often leads to conservative and uneconomical designs when directly applied to PEB systems. PEBs also contribute significantly to sustainable and environmentally friendly industrial construction. A major green feature of PEBs is the use of turbo ventilators, which improve natural ventilation without consuming electricity. These ventilators operate using wind and thermal pressure differences to remove hot air from the building interior, thereby reducing indoor temperatures and minimizing reliance on mechanical ventilation and air-conditioning systems. Another important sustainability aspect is the incorporation of polycarbonate sheets in roof and wall cladding. Typically, around 7% of the cladding area is provided with translucent panels to allow natural daylight into the building, reducing the need for artificial lighting during daytime and lowering energy consumption and operational costs. Improved daylighting also enhances occupant comfort and workplace conditions. In addition, the large unobstructed roof areas of PEBs are well suited for rooftop solar photovoltaic installations. These systems utilize renewable energy efficiently without requiring additional land or support structures, thereby reducing dependence on conventional power sources and lowering carbon emissions. Overall, PEBs provide an effective solution for energy-efficient, sustainable, and green industrial development.

I. INTRODUCTION

1.1 Background of the Study: The construction industry has undergone significant transformation over the past few decades due to increasing demand for structural efficiency, economy, rapid construction, and sustainability. Among the recent advancements in steel construction technology, Pre-Engineered Buildings (PEBs) have become a popular and cost-effective structural solution for industrial, commercial, and infrastructure projects. PEB systems utilize optimized structural configurations, prefabricated components, and advanced analytical techniques to achieve lightweight and cost-effective structures with reduced construction time. Unlike Conventional Steel Buildings (CSBs), which generally use prismatic hot-rolled sections designed for maximum force conditions throughout the member length, Pre-Engineered Buildings employ tapered built-up sections whose depth varies according to bending moment distribution. This concept enables efficient utilization of material by providing larger sections only at locations of higher stress demand and smaller sections where forces are comparatively lower.

The use of tapered built-up members results in several advantages including:

- Reduced steel consumption
- Improved strength-to-weight ratio
- Faster fabrication and erection
- Better structural efficiency
- Reduced foundation loads
- Enhanced economy and sustainability

Modern PEB design also incorporates computer-aided design (CAD) tools and advanced structural analysis software, which facilitate accurate modeling, load analysis, and optimization of structural members. Through iterative analysis and design procedures, engineers can achieve balanced structural performance while satisfying strength and serviceability requirements.

In India, steel structures are mainly designed in accordance with IS 800:2007, which adopts the Limit

State Design methodology. However, many industrial PEB structures are still designed conservatively, resulting in lower utilization ratios and increased steel consumption. Optimization of tapered built-up sections within the framework of Indian Standards can therefore play an important role in improving structural economy and efficiency. With rapid industrialization, infrastructure expansion, warehousing growth, and increasing demand for industrial facilities in India, Pre-Engineered Buildings have become highly relevant due to their speed of construction, adaptability, and sustainability benefits. PEB systems also support modern sustainable construction practices through reduced material usage, recyclability of steel, natural ventilation systems, daylighting arrangements, and provision for rooftop solar installations.

The present study focuses on the structural optimization of Pre-Engineered Building frames using tapered built-up sections under Indian codal provisions. Emphasis is placed on improving utilization ratios, reducing steel consumption, and enhancing overall structural efficiency while maintaining compliance with codal requirements related to strength, stability, and serviceability.

1.2 Need for the Study: Conventional steel structures, though structurally reliable, are generally associated with higher material consumption, increased fabrication effort, and longer construction duration. Their design approach often does not fully utilize the advantages of variable sectional geometry and optimized material distribution.

Pre-Engineered Buildings overcome many of these limitations with tapered built-up sections, prefabrication techniques, and efficient structural systems. However, in many practical applications, PEB frames are still designed conservatively, resulting in underutilized members and unnecessary steel usage.

Optimization of tapered sections offers significant potential for:

- Reduction in structural steel weight
- Improvement in member utilization ratios
- Better alignment between sectional capacity and force demand
- Enhanced fabrication economy
- Reduced project cost and construction time

Although PEB systems are widely used in industrial construction, detailed studies focusing on optimization

of tapered built-up sections under Indian codal provisions are comparatively limited. Therefore, there is a need to investigate the influence of tapered section optimization on structural efficiency, serviceability behavior, and overall economy of industrial PEB structures.

The present study aims to address this requirement by evaluating the performance of optimized tapered sections in an industrial gable-frame Pre-Engineered Building designed in accordance with Indian Standards.

1.3 Objectives of the Study: The primary objectives of the present research are as follows:

- To analyze and design an industrial gable-frame Pre-Engineered Building under Indian codal provisions.
- To optimize tapered built-up sections of primary structural members for improved structural efficiency.
- To evaluate member utilization ratios and sectional performance under various loading conditions.
- To evaluate the impact of dead load, live load, wind load, seismic load, and crane load on the structural behavior of the PEB frame.
- To reduce structural steel consumption through effective optimization of tapered sections while satisfying codal requirements related to strength and serviceability.

To evaluate the economic and sustainability benefits achieved through structural optimization of Pre-Engineered Buildings.

1.4 Scope of the Study: The current study is centred on the structural analysis and optimization of an industrial gable-frame Pre-Engineered Building (PEB):

- Design and analysis carried out in accordance with IS 800:2007 using the Limit State Method
- Optimization of tapered built-up sections for primary framing members such as columns and rafters
- Evaluation of primary and secondary structural components including purlins, girts, and bracing systems
- Analysis conducted under Dead Load, Live Load, Wind Load, Seismic Load, Collateral Load, and Crane Load as per relevant Indian

Standards

- Assessment of steel weight, utilization ratio, deflection behavior, and structural efficiency
- Exclusion of non-structural components such as insulation systems, architectural finishes, and detailed foundation design

The study aims to evaluate the effectiveness of tapered section optimization in achieving economical and structurally efficient industrial PEB systems.

1.5 Methodology: The methodology adopted in the present research consists of the following sequential steps:

- **Literature Review:** Comprehensive review of previous studies related to Pre-Engineered Buildings, tapered section optimization, structural efficiency, and industrial steel structures.
- **Problem Definition:** Selection of an industrial gable-frame Pre-Engineered Building as the case study model.
- **Selection of Structural Parameters:** Finalization of building geometry, bay spacing, roof slope, crane parameters, and loading conditions.
- **Load Calculation:** Determination of Dead Load, Live Load, Wind Load, Seismic Load, Collateral Load, and Crane Load in accordance with relevant Indian Standards.
- **Structural Modeling:** Development of a three-dimensional analytical model using structural analysis software such as STAAD.Pro
- **Structural Analysis:** Analysis of the structural model for various load combinations to obtain member forces, support reactions, and displacements.
- **Design of Structural Members:** Design of primary and secondary structural members as per IS 800:2007.
- **Optimization of Tapered Sections:** Iterative modification of tapered member dimensions to improve utilization ratios and reduce steel consumption.
- **Evaluation of Results:** Assessment of steel weight, member utilization ratio, deflection behavior, and overall structural efficiency.
- **Interpretation and Conclusions:** Interpretation of analytical results and formulation of conclusions and

recommendations based on the findings of the study.

1.6 Thesis Organization

The present thesis is systematically structured into the following chapters:

- I. **Introduction:** Presents the background of the study, its necessity, objectives, scope, and overall methodology.
- II. **Literature Review:** Presents a comprehensive review of previous research related to Pre-Engineered Building systems, tapered section optimization, structural efficiency, and codal practices.
- III. **Methodology:** Describes the research framework, modeling assumptions, load calculations, optimization procedure, and analytical approach adopted in the study.
- IV. **Model development:** Presents the theoretical basis of PEB behavior, codal provisions, load transfer mechanism, and development of the three-dimensional analytical model.
- V. **Design Results and discussion:** Presents the analytical results obtained from structural analysis and optimization, along with evaluation of steel weight, utilization ratios, deflection behavior, and structural efficiency.
- VI. **Conclusion and Recommendations:** Presents the key outcomes of the study and offers suggestions for future research on the optimization of Pre-Engineered Building (PEB) systems.

II. REVIEW OF LITERATURE

A comprehensive review of past research is essential to establish a solid foundation for analyzing and designing Pre-Engineered Building (PEB) systems. The following section encapsulates notable studies conducted by various researchers, focusing on structural efficiency, economic feasibility, material optimization, and design methodologies comparing Pre-Engineered Buildings (PEB) and Conventional Steel Buildings (CSB).

2.1 Review of Related Research Work:

Hemant Sharma [1]: Conducted a comparative analysis between PEB and CSB using STAAD.Pro. The results indicated a 37% reduction in steel quantity for PEBs,

demonstrating enhanced structural economy and accelerated project delivery.

Abhyuday Titiksh et al. [2]: Explored cost efficiency, rapid construction, and design adaptability of PEB systems, particularly for developing nations. Their study combined analytical and experimental approaches for industrial sheds, concluding PEBs as energy-efficient, economical, and structurally resilient.

Milind Bhojkar and Milind Darade [3]: Optimized steel cross-sections for low-rise industrial structures. Findings revealed PEBs are 30% more economical and 26% lighter than CSBs, underscoring their superiority in cost and weight efficiency.

Sagar Wankhade and Dr. P.S. Pajgade [4]: Investigated the application of PEBs in single-storey buildings and highlighted their advantages in terms of design efficiency, construction speed, and material optimization. The results confirmed that PEBs perform better than conventional steel buildings in both structural behavior and cost efficiency.

Vivek Thakre and Laxmikant Vairagade [5]: Carried out the design and analysis of PEB systems in accordance with IS 800:1984, IS 800:2007, MBMA-96, and AISC-89 standards. Their findings confirmed significant reductions in structural weight and overall cost when designed using IS 800:2007, establishing PEBs as a simple and economical structural solution.

Swati Wakchaure and N. C. Dubey [6]: Showed that designing members based on actual bending moment distribution leads to considerable steel savings. Their study revealed that CSBs are approximately 30% heavier than PEBs, resulting in larger foundation requirements. The authors also emphasized the sustainability and recyclability advantages of PEB systems.

2.2 Comparative Studies Using STAAD.Pro and IS Codes:

Advanced structural analysis tools such as STAAD.Pro, coupled with adherence to Indian Standards (IS 800:2007, IS 875:1987, IS 1893:2002), have been extensively utilized to assess the performance of Pre-Engineered Buildings. Key technical findings are summarized below:

G. Durga Rama Naidu [7]: Used STAAD.Pro to evaluate PEB and CSB frames under varying bay spacings. The results confirmed that tapered PEB

sections offer significant steel weight reduction and superior economic performance.

Jinsha M.S. [8]: Modeled PEB frames with different bay spacings (6 m, 8 m, 10 m, 12 m) under IS 875 (Part 3) wind loading. PEBs maintained stability while achieving optimal cost efficiency for larger bays.

Santosh S. Patil [9]: Performed parametric analysis on industrial PEBs with varying geometries, correlating reduced self-weight and construction duration with geometric optimization.

D. Rakesh [10]: Compared displacement and steel usage between PEBs and CSBs. The results revealed lower deflections and enhanced stiffness in PEBs due to optimized tapered members.

2.3 Summary of Findings:

From the reviewed literature, it is evident that Pre-Engineered Buildings (PEBs) exhibit the following technical advantages over Conventional Steel Buildings (CSBs):

- Significant material savings (25–40%) through optimized tapered members.
- Accelerated construction due to prefabrication and modular assembly.
- Enhanced stiffness and reduced deflection under service loads.
- Economical design with lower fabrication and erection costs.
- Sustainable construction with recyclable materials and smaller foundations.
- High design flexibility accommodating diverse geometries and loading conditions.

Therefore, the consensus among researchers confirms that PEBs represent a technically advanced, economically feasible, and sustainable alternative for modern industrial and infrastructural projects.

III. RESEARCH METHODOLOGY

3.1 Design philosophy

The structure is designed primarily in accordance with Indian codal provisions to satisfy statutory requirements and standard engineering practices adopted in India. The study focuses on achieving structural optimization of Pre-Engineered Building (PEB) frames through the effective use of tapered built-up sections. Emphasis is placed on improving member utilization ratios, reducing

unnecessary steel consumption, and enhancing structural efficiency while maintaining safety, strength, and serviceability requirements prescribed by Indian Standards.

3.2 Research Framework

The research work follows an analytical and optimization-based framework. A typical industrial gable-frame Pre-Engineered Building (PEB) is selected as the study model. The structure is initially analyzed and designed using conventional and tapered member proportions under Indian codal provisions. Subsequently, optimization of primary frame members is carried out by modifying tapered sectional dimensions to achieve improved utilization ratios and efficient material distribution along the member length.

The optimization process involves iterative analysis and design to identify structurally efficient tapered sections capable of satisfying codal requirements with minimum steel usage while maintaining acceptable limits of stress, deflection, and stability. The performance of the optimized frame is evaluated in terms of steel consumption, utilization ratio, displacement behavior, and overall structural efficiency.

3.3 Selection of Building Model

An industrial PEB structure commonly used for warehouse and manufacturing applications is considered for the study. The building geometry, including span, length, bay spacing, eave height, roof slope, and crane parameters, is fixed and maintained constant throughout the analysis. This ensures uniformity in the study and enables accurate assessment of the effectiveness of tapered section optimization without influence from changes in structural configuration.

3.4 Software and Analytical Tool:

STAAD.Pro structural analysis and design software is used for modeling, analysis, and code-based design of the structure. The software can perform three-dimensional space frame analysis and facilitates iterative optimization of structural members. It enables accurate application of loads, generation of load combinations, and extraction of design parameters such as member forces, stresses, displacements, reactions, and utilization ratios.

The software is further utilized to modify tapered member properties and evaluate the effect of sectional optimization on structural performance and steel quantity.

3.5 Structural Modeling Technique:

The Pre-Engineered Building is modeled as a three-dimensional space frame system. Primary structural components such as columns and rafters are modeled using tapered built-up I-sections to simulate actual PEB construction practices. The sectional depth and thickness of members are varied along the member length based on bending moment distribution and structural demand to achieve optimized member utilization.

Secondary members including purlins, girts, and eave struts are modeled as cold-formed Z-sections, while roof and wall bracing systems are incorporated to resist longitudinal and transverse loads. Appropriate support conditions and boundary restraints are assigned to simulate realistic field behavior.

3.6 Material Properties and Assumptions:

Structural steel conforming to relevant Indian Standards is adopted for the study. Material properties including yield strength, modulus of elasticity, density, and Poisson's ratio are adopted as per the relevant codal provisions. Concrete pedestals and foundations are assumed to be rigid and are excluded from the scope of optimization.

All materials are assumed to behave within the linear-elastic range under service loads. The study primarily focuses on optimization of primary steel frame members through tapered section modification while maintaining compliance with strength and serviceability criteria.

3.7 Load Identification and Classification:

The structure is analyzed for all relevant loads as prescribed in Indian Standards. The following load cases are considered:

- Dead Load: Self-weight of structural members, roof and wall sheeting
- Live Load: Roof live load
- Collateral Load: Loads due to lighting fixtures, services, and accessories
- Wind Load: Acting in transverse, longitudinal, and uplift directions

- Seismic Load: Horizontal forces due to earthquake effects
- Crane Load: Vertical wheel loads, lateral surge forces, and longitudinal braking forces

Each load is applied independently and in suitable load combinations to determine critical structural responses. The optimization process is carried out considering the most critical load combinations governing member strength, stability, and serviceability requirements.

3.8 Load Calculation as per Indian Standards:

Load calculations for the Pre-Engineered Building are carried out in accordance with relevant Indian Standard codal provisions. Dead loads, live loads, and wind loads are evaluated as per IS 875 (Part 1), IS 875 (Part 2), and IS 875 (Part 3) respectively. Seismic loads are determined in accordance with IS 1893 (Part 1), while the design of steel structural members is performed as per IS 800:2007 using the Limit State Method.

Wind load calculations are carried out considering parameters such as basic wind speed, terrain category, topography factor, importance factor, internal and external pressure coefficients, and height variation effects. Seismic loads are evaluated using the design horizontal seismic coefficient method considering seismic zone, importance factor, response reduction factor, and soil condition.

Crane loads including vertical wheel loads, impact loads, lateral surge forces, and longitudinal braking forces are applied in accordance with relevant Indian Standards and prevailing industrial design practices.

3.9 Load Combinations:

Load combinations are generated in accordance with IS 800:2007 and relevant loading standards to evaluate the structure under critical strength and serviceability conditions. The combinations include the effects of dead load, live load, wind load, seismic load, collateral load, and crane load acting individually and in combination.

Wind and seismic loads are considered in both positive and negative directions to capture the most unfavorable structural response. The governing load combinations are identified based on critical values of bending moment, axial force, shear force, deflection, and utilization ratio.

3.10 Structural Analysis:

The modeled structure is analyzed using three-dimensional linear static analysis for all defined load combinations. The analysis results include axial forces, bending moments, shear forces, support reactions, and nodal displacements of the structural system.

Attention is given to vertical deflection, lateral sway, frame stability, and crane-induced effects, as these parameters significantly influence the behavior and performance of Pre-Engineered Buildings. The analytical results obtained from the software are used as the basis for sectional optimization and evaluation of structural efficiency.

3.11 Design and Optimization Procedure:

The design of primary and secondary structural members is carried out in accordance with IS 800:2007. Primary frame elements such as columns and rafters are designed using tapered built-up sections. The optimization process involves gradual modification of sectional dimensions, flange thickness, web thickness, and taper proportions to improve member utilization ratios and reduce excess steel consumption.

The optimization is performed iteratively using structural analysis software until satisfactory utilization ratios are achieved while ensuring compliance with codal requirements related to strength, stability, and serviceability. The study primarily focuses on obtaining structurally efficient tapered sections with balanced stress distribution and economical steel usage.

The optimized structural configuration is evaluated based on:

- Reduction in total structural steel weight
- Improvement in utilization ratio
- Compliance with allowable deflection limits
- Structural stability under critical loading conditions
- Practical feasibility of tapered member fabrication

3.12 Comparative Evaluation Parameters:

The performance of the optimized Pre-Engineered Building frame is evaluated based on the following parameters:

- Total structural steel weight
- Utilization ratio of primary frame members
- Tapered member sectional properties
- Maximum vertical deflection
- Maximum lateral displacement
- Governing load combinations
- Structural stability and serviceability performance
- Fabrication efficiency and practical suitability of tapered sections

These parameters are used to assess the effectiveness of tapered section optimization in improving the structural efficiency of the PEB system.

3.13 Summary of Methodology:

The methodology adopted in this study provides a systematic approach for the analysis and structural optimization of Pre-Engineered Building frames using tapered built-up sections under Indian codal provisions. The procedure ensures uniformity in structural configuration, loading conditions, analytical assumptions, and design criteria throughout the study.

By incorporating iterative optimization techniques, the study aims to achieve improved utilization ratios and reduced steel consumption while maintaining compliance with strength and serviceability requirements prescribed by Indian Standards.

3.14 Methodology Flowchart (Conceptual)

The overall research methodology adopted in the present study is summarized through the sequential steps presented below. The flowchart represents the systematic progression of the work from identification of the research problem to optimization and evaluation of the Pre-Engineered Building frame.

Step 1: Identification of research problem and objectives

Step 2: Selection of industrial Pre-Engineered Building (PEB) model

Step 3: Fixing of building geometry and structural parameters

Step 4: Selection of relevant Indian Standards for loading and steel design

Step 5: Three-dimensional modeling of the PEB frame in STAAD.Pro/ETABS

Step 6: Assignment of material properties, support conditions, and boundary restraints

Step 7: Calculation and application of dead, live, wind, seismic, collateral, and crane loads as per Indian Standards

Step 8: Generation of codal load combinations as per IS 800:2007

Step 9: Structural analysis for determination of member forces, reactions, and deflections

Step 10: Design of primary and secondary structural members using tapered built-up sections

Step 11: Iterative optimization of tapered sections to improve utilization ratio and reduce steel consumption

Step 12: Verification of strength, stability, and serviceability requirements under critical load combinations

Step 13: Extraction and evaluation of results including steel weight, utilization ratios, and deflection behavior

Step 14: Assessment of structural efficiency and optimization effectiveness

Step 15: Interpretation of findings and formulation of conclusions and recommendations

IV. THEORETICAL CONSIDERATION AND MODEL DEVELOPMENT

4.1 Introduction:

This chapter presents the theoretical framework and model development adopted for the structural analysis and optimization of the Pre-Engineered Building (PEB). It outlines the fundamental design principles, codal provisions, structural behavior, and modeling assumptions used to develop an accurate analytical model of the industrial gable frame structure.

The primary objective of this chapter is to establish the theoretical basis for optimization of tapered built-up sections in PEB frames designed under Indian codal provisions. Emphasis is placed on improving structural efficiency through enhanced utilization ratios, reduction in steel consumption, and effective distribution of material according to structural demand while maintaining compliance with strength and serviceability requirements.

4.2 Theoretical Considerations in PEB Design

4.2.1 Structural Concept of PEB: Pre-Engineered Buildings are designed based on the concept of structural optimization, in which member geometry is varied according to the distribution of internal forces along the member length. Unlike conventional hot-rolled prismatic sections, PEB members are generally

fabricated as tapered built-up sections, resulting in improved structural efficiency and economical steel usage.

The use of tapered sections provides the following advantages:

- Reduced steel consumption
- Efficient load transfer mechanism
- Improved strength-to-weight ratio
- Better utilization of material along member length
- Economical fabrication and erection

The primary framing system generally consists of rigid portal frames designed to resist both gravity and lateral loads effectively.

4.2.2 Load Transfer Mechanism: The load transfer mechanism in a PEB structure follows a systematic structural path:

- Roof loads → Purlins → Rafters → Columns → Foundations

Lateral loads such as wind and seismic forces are resisted through:

- Portal frame action in the transverse direction
- Bracing systems in the longitudinal direction

The effectiveness of this load transfer system governs the stability and overall performance of the structure.

4.2.3 Design Philosophy: The structural design adopted in the present study is performed as per IS 800:2007 following the Limit State Design approach. The design philosophy is based on achieving adequate strength, stability, durability, and serviceability with optimum utilization of structural steel.

- The optimization process focuses on:
- Increasing utilization ratio of tapered members
- Reducing excess steel usage
- Achieving balanced stress distribution
- Maintaining allowable deflection limits
- Ensuring structural safety under critical loading conditions

The design adopts partial safety factors for loads and material strengths as prescribed in Indian Standards.

4.2.4 Types of Loads Considered: The following loads are considered in the theoretical formulation:

- Dead Load (DL) : Self-weight of structural components and cladding

- Live Load (LL) : Roof live loads as per codal provisions
- Wind Load (WL) : External pressure, Internal pressure, Uplift forces
- Seismic Load (EQ) : Horizontal inertia forces, Based on zone factor and importance factor
- Crane Load (CL) : Vertical wheel loads, Impact loads, Lateral surge forces, Longitudinal braking forces,

4.3 Codal Provisions Adopted

The analysis and design of the structure are carried out in accordance with the following Indian Standard codes:

- IS 800:2007 – General Construction in Steel – Code of Practice
- IS 875 (Part 1) – Dead Loads
- IS 875 (Part 2) – Imposed Loads
- IS 875 (Part 3) – Wind Loads
- IS 1893 (Part 1) – Criteria for Earthquake Resistant Design of Structures

4.4 Theoretical Analysis of Structural Elements

4.4.1 Bending Behavior of Tapered Members: In Pre-Engineered Building systems, the depth of rafters and columns varies along the member length in accordance with bending moment distribution. Maximum depth occurs at supports (maximum moment)

- Maximum depth is provided near supports where bending moments are high
- Minimum depth is provided near regions of lower bending moments

This variation in sectional depth enables efficient utilization of steel and reduces unnecessary material concentration in low-stress regions.

4.4.2 Axial and Flexural Interaction:

- Adequate strength
- Stability against buckling

PEB columns and rafters are subjected to combined axial compression and bending moments due to gravity and lateral loads. Therefore, the members are designed considering interaction effects between axial force and flexure.

The design must satisfy codal interaction requirements to ensure:

- Adequate load-carrying capacity
- Stability against buckling
- Safe performance under combined loading conditions

4.4.3 Deflection Criteria: Serviceability requirements play an important role in determining the size and stiffness of structural members. Excessive vertical or lateral deflection may adversely affect structural performance and functional requirements.

- Typical deflection limits considered are:
- Roof deflection limits
- Lateral sway limits
- Crane girder deflection limits

Deflection control significantly influences optimization of tapered sections and member proportions.

4.4.4 Stability and Buckling: The structure is checked for various modes of instability including:

- Local buckling
- Global buckling
- Lateral torsional buckling

Bracing systems are incorporated to improve overall structural stability and reduce effective member lengths under compression.

4.5 Model Development

4.5.1 Description of Building Model: An industrial gable-frame Pre-Engineered Building structure is selected for the present study with the following general characteristics:

- Single-span industrial building
- Symmetrical gable roof configuration
- Uniform bay spacing
- Provision for crane system
- Steel portal frame structural arrangement

The selected configuration represents typical industrial warehouse and manufacturing structures commonly adopted in practice.

4.5.2 Geometric Parameters: The following geometric parameters are defined for development of the analytical model:

- Span length - 25.50 m
- Building length - 205.50 m
- Bay spacing - 10.00 m
- Eave height - 8.50 m
- Roof slope - 1 in 10

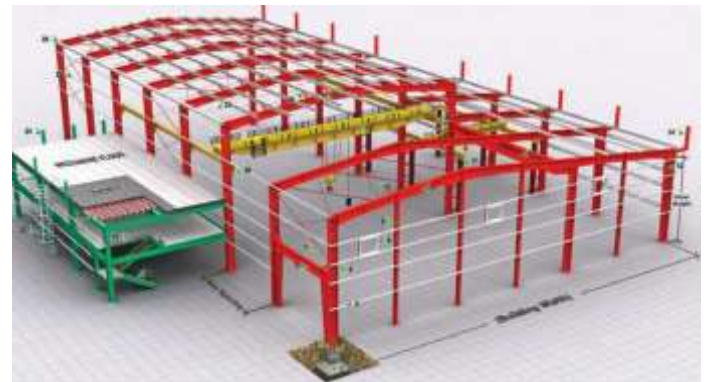
- Crane capacity and hook height: 10T and 6m

These parameters are maintained constant throughout the study to ensure consistency in optimization analysis.

4.5.3 Structural Components: The analytical model consists of the following structural components:

- Primary Members: Columns and Rafters
- Secondary Members: Purlins (Z-sections), Girts (Z-sections), Eave struts
- Bracing System: Roof bracing, Wall bracing, Tie rods

The arrangement of these components ensures adequate strength, stiffness, and stability of the overall structural system.



1. Concrete Footing	8. Splayed Clipping (Window/Lower)	15. Lean To Frame	22. Eave Strut
2. Anchor Bolts	9. End Wall Wood Column	16. Crane Beam	23. Side wall Girt
3. Base Plate	10. Roof Bracing (Angle/Rod/Cable)	17. Crane Column	24. Flush Fascia Frame
4. End Wall Girt	11. Main Frame Rafters	18. EOT Crane	25. Cage Ladder
5. Portal Bracing	12. Jack Beam	19. Roof Purlin	26. Deck Panel with Steel Mesh
6. Main Frame Straight Column	13. Main Frame Tapered Column	20. Floor Bracing	27. Hand Rail (Steel)
7. Wall Bracing (Angle/Rod/Cable)	14. Cantilevered Fascia Frame	21. Sag Rod	28. Staircase (Channel/Rails/C Channel
			29. Crane Bracket

Figure 1: PEB Skeleton Structure and Components

4.5.4 Modeling Approach: The structure is modeled as a three-dimensional space frame using structural analysis and design software. The analytical model is developed to accurately simulate the actual behavior of the Pre-Engineered Building under various loading conditions. The following modeling assumptions are adopted:

- Primary frame members are connected using rigid joints to simulate moment-resisting portal frame action
- Column supports are modeled as pinned or fixed depending on practical design requirements
- Tapered built-up sections are defined using variable sectional properties along the member length
- Secondary members such as purlins, girts, and eave struts are modeled as line elements
- Bracing members are incorporated to

provide longitudinal stability and lateral restraint

- The analytical model is developed considering realistic geometry, loading conditions, and support behavior

The modeling approach enables accurate evaluation of member forces, displacements, stability characteristics, and utilization ratios necessary for structural optimization.

4.5.5 Material Properties: The following material properties are assumed:

- Structural steel with uniform grade
- Modulus of elasticity (E) = 2×10^5 MPa
- Poisson's ratio = 0.3
- Yield strength = constant for both designs. Yield strength of steel is assumed as per relevant Indian Standard specifications
- Material behavior is considered linear-elastic within the service load range

Uniform material properties are maintained throughout the study to ensure consistency in optimization results.

4.5.6 Boundary Conditions: Appropriate boundary conditions are assigned to represent realistic structural behavior. The following assumptions are considered:

- Column bases are modeled as pinned or fixed depending on design requirements
- Lateral restraints are provided through roof and wall bracing systems
- Support conditions are assigned to restrain translations and/or rotations as required
- Bracing members are assumed effective in transferring longitudinal forces

The adopted boundary conditions ensure structural stability and realistic load transfer within the analytical model.

4.5.7 Load Application: Loads are applied to the analytical model in accordance with Indian codal provisions and practical industrial loading conditions. The loading arrangement includes:

- Dead loads applied as self-weight of members and uniformly distributed permanent loads
- Live loads applied on roof members as specified in IS 875
- Wind loads applied as pressure and suction loads on roof and wall surfaces
- Seismic loads applied as equivalent static lateral forces
- Crane loads applied at crane bracket levels including vertical wheel loads, impact

loads, lateral surge forces, and longitudinal braking forces

The load application procedure ensures accurate simulation of critical loading scenarios governing the design of PEB frames.

4.5.8 Load Combinations: Load combinations are generated in accordance with IS 800:2007 Limit State design provisions. The combinations consider the simultaneous effect of gravity, wind, seismic, collateral, and crane loads under critical conditions.

The governing load combinations are identified based on:

- Maximum bending moment
- Maximum axial force
- Maximum shear force
- Maximum vertical deflection
- Maximum lateral displacement
- Critical utilization ratio

These load combinations form the basis for design verification and optimization of tapered structural members.

4.6 Model Validation

To ensure accuracy, the developed model is verified by:

- Checking geometry and connectivity
- Validating support conditions
- Comparing reactions with applied loads
- Ensuring stability under all load cases

4.7 Summary

This chapter established the theoretical basis and analytical modeling approach adopted for the structural optimization of the Pre-Engineered Building frame. The structural behavior, load transfer mechanism, design philosophy, and codal provisions relevant to Indian Standards were discussed in detail.

A comprehensive three-dimensional analytical model was developed using tapered built-up sections, realistic loading conditions, and appropriate boundary restraints. The modeling approach was formulated to evaluate member forces, deflections, stability characteristics, and utilization ratios accurately.

V. RESULTS AND DISCUSSION

5.1 Introduction

This chapter presents the results obtained from the structural analysis and optimization of the Pre-

Engineered Building (PEB) frame designed under Indian codal provisions. The study focuses on evaluating the effectiveness of tapered section optimization in improving structural efficiency, increasing utilization ratios, reducing steel consumption, and maintaining satisfactory serviceability performance.

The analytical results obtained from the conventional and optimized PEB models are systematically compared and interpreted to assess the influence of tapered section modification on member behavior, deflection characteristics, and overall economy of the structure.

5.2 Overview of Analysis Results

The structural model was analyzed under identical geometric, material, and loading conditions using Indian Standard codal provisions. Optimization of tapered built-up sections was carried out iteratively to achieve improved utilization ratios and efficient material distribution along the member length.

The outputs extracted from the analysis include:

- Member forces (axial force, shear force, and bending moment)
- Nodal displacements
- Total structural steel weight
- Member utilization ratios
- Deflection behavior of primary structural members

The results obtained from the initial design and optimized design configurations are used for evaluating structural performance and optimization effectiveness.

Table 1: Design Analysis results – Conventional design

Conventional Design - Member forces



Conventional Design - Node displacements

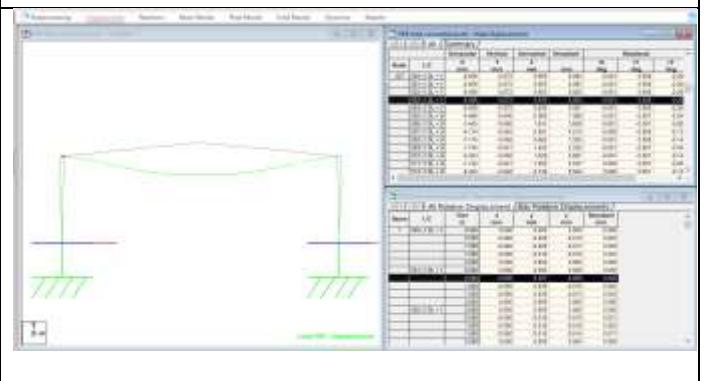


Table 2: Design Analysis results – Tapered design

Tapered Initial Design - Member forces



Tapered Initial Design - Node displacements

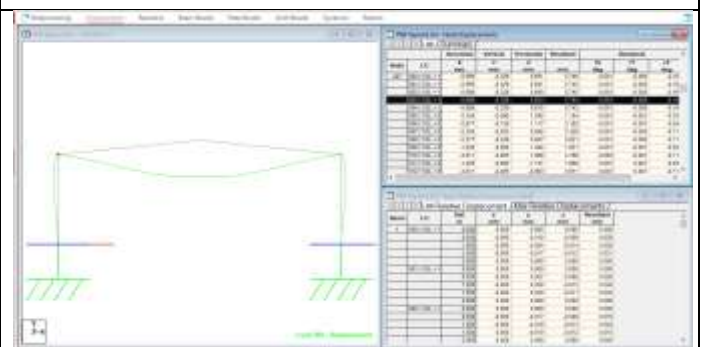
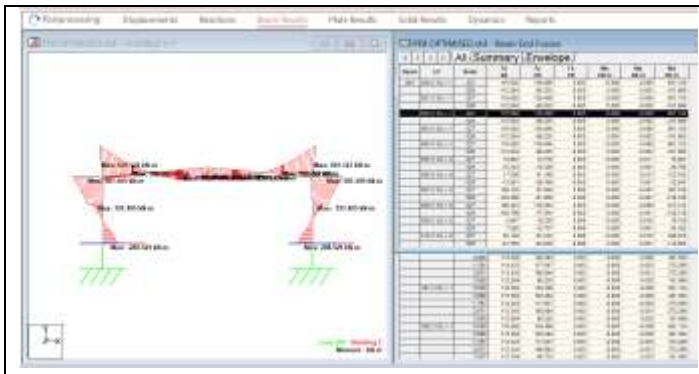
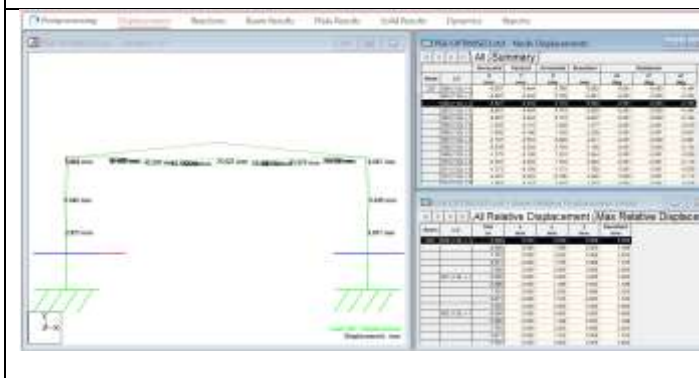


Table 3: Design Analysis results – Tapered optimized design

Tapered Optimized design - Member forces



Tapered Optimized design - Node displacements

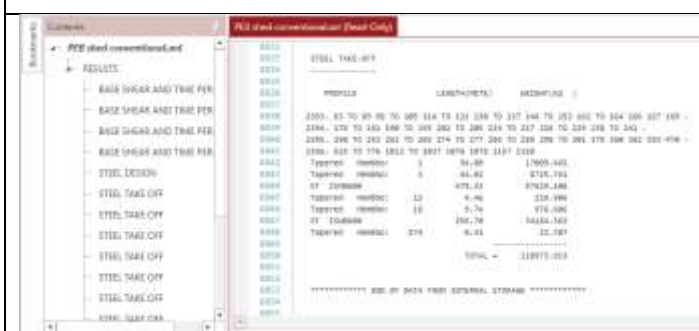


5.3 Comparison of Structural Steel Weight

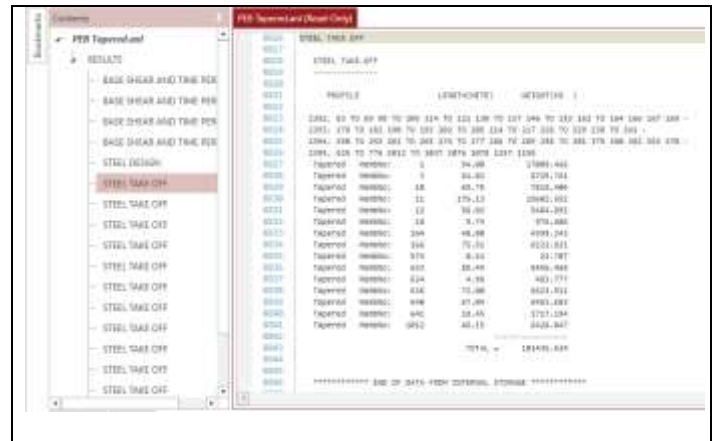
One of the most important parameters considered in the optimization study is the total structural steel consumption of the PEB frame.

Table 4: Comparison of Structural Steel Weight

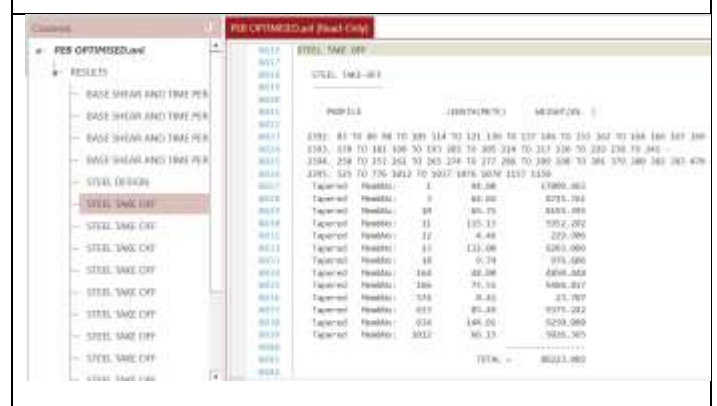
Conventional Design



Tapered initial design



Tapered Optimized design



Observations:

- Optimization of tapered sections resulted in noticeable reduction in overall steel weight
- Improved distribution of sectional depth along rafters and columns reduced unnecessary material concentration
- Higher utilization ratios enabled more efficient use of structural steel without compromising safety and serviceability requirements
- Optimization reduced overdesign in low-stress regions of the structural members

Typical Trend Observed:

- Optimized tapered sections resulted in measurable reduction in steel tonnage compared to the initial design
- Steel savings were primarily observed in rafters and columns due to improved sectional efficiency

Discussion: The reduction in steel weight demonstrates the effectiveness of tapered section optimization in achieving economical PEB design. By varying sectional dimensions according to bending moment distribution, structural material is utilized more efficiently along the member length.

The optimized design achieves balanced structural performance with lower steel consumption while satisfying codal requirements related to strength, stability, and serviceability.

5.4 Member Size and Sectional Efficiency

5.4.1 Columns

- Optimization improved utilization ratio of column sections
- Excessive flange and web dimensions in low-stress regions were reduced
- Improved axial-flexural interaction behavior resulted in more efficient column sections

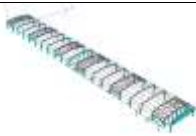
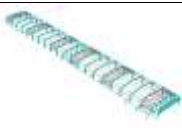
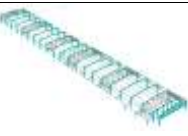
Discussion: The optimized column sections exhibited better stress distribution and reduced steel usage while maintaining adequate load-carrying capacity and stability against buckling.

5.4.2 Rafters

- Rafter sections were optimized by varying taper proportions according to bending moment distribution
- Greater sectional depth was maintained near supports where bending moments were high
- Reduced depth was provided near regions of lower moment demand

Discussion: Optimization of rafter geometry significantly improved structural efficiency by aligning sectional properties with actual force requirements. The tapered configuration enabled effective utilization of steel and reduction in unnecessary member weight.

Fig 2: 3-D Views of Model and Main Frame

Conventional Design	Tapered initial design	Tapered Optimized design
Model		
		
Main Frame		
		

Section: ISMB, ISWB	Tapered	Taper optimised
		

5.4.3 Secondary Members

- Minimal variation was observed in purlins and girts during optimization
- Secondary members were governed mainly by practical spacing and serviceability requirements

Discussion: Since secondary structural members are generally standardized cold-formed sections, the scope for optimization was comparatively limited. However, proper coordination with the optimized primary framing system contributed to overall structural efficiency.

5.5 Deflection Behavior

Deflection is one of the most critical serviceability parameters influencing the design of Pre-Engineered Buildings.

Observations:

- Optimized sections exhibited slightly higher deflections compared to the initial design
- Deflections remained within permissible limits specified by Indian Standards
- Reduction in steel weight increased structural flexibility to a controlled extent
- Critical deflections were observed near rafter mid-span regions

Discussion: The optimization process aimed to achieve an effective balance between structural economy and serviceability performance. Although optimization reduced member stiffness in certain regions, all deflection values remained within allowable codal limits.

Proper control of vertical and lateral deflections is especially important in industrial buildings supporting crane systems and large-span roof structures.

5.6 Load Combination Effects

Load combinations significantly influence the design forces and optimization of structural members.

Observations:

- Wind load combinations governed the design of rafters and bracing members
- Crane load combinations had significant influence on column design and lateral stability
- Combined gravity and lateral load cases produced critical utilization ratios in primary frame members
- Seismic load effects were comparatively less significant depending on the seismic zone considered

Discussion: The governing load combinations played an important role in determining the final optimized member configuration. Optimization was performed considering the most critical combinations producing maximum bending moments, axial forces, and deflections.

Efficient tapered section design enabled the structure to resist critical loading conditions with improved material utilization.

5.7 Structural Response under Different Loads

5.7.1 Dead and Live Loads

- Dead and live loads primarily governed gravity load behavior of rafters and columns
- Member forces under these loads remained within permissible design capacities

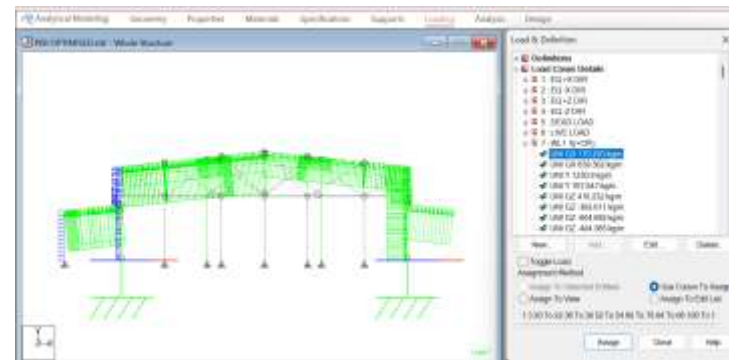
Discussion: The structural response under gravity loading demonstrated stable load transfer through the primary framing system and secondary structural members.

5.7.2 Wind Loads

- Wind loads produced significant lateral forces and uplift effects on the structure
- Wind load combinations governed the design of roof bracing and certain rafter sections

Optimized tapered members effectively resisted lateral load effects while maintaining structural stability.

Fig 3: Wind Load Diagram as per IS 875



Discussion: Wind loading was one of the critical parameters influencing member optimization in long-span industrial PEB structures. Proper taper variation improved structural resistance against bending and uplift effects.

5.7.3 Seismic Loads

- Seismic loads produced comparatively lower structural response depending on the seismic zone considered
- Lateral bracing systems contributed significantly to seismic stability.

Although seismic forces were relatively smaller compared to wind loads in the present study, they were incorporated in the analysis to ensure complete compliance with Indian codal provisions.

5.7.4 Crane Loads

- Crane loads had substantial influence on column design and support reactions
- Vertical wheel loads and surge forces governed certain critical load combinations
- Crane-induced deflections influenced serviceability performance of the structure

Discussion: Crane loading is one of the most important design considerations in industrial PEB structures. The optimized structural system successfully resisted crane-induced forces while maintaining acceptable deflection and stability characteristics.

5.8 Utilization Ratio of Members

Utilization ratio is an important parameter used to evaluate the efficiency of structural member design. It represents the ratio of the actual stress or force demand in a member to its permissible design capacity under governing load combinations.

Table 5: Steel Utilization Ratio - Conventional Design

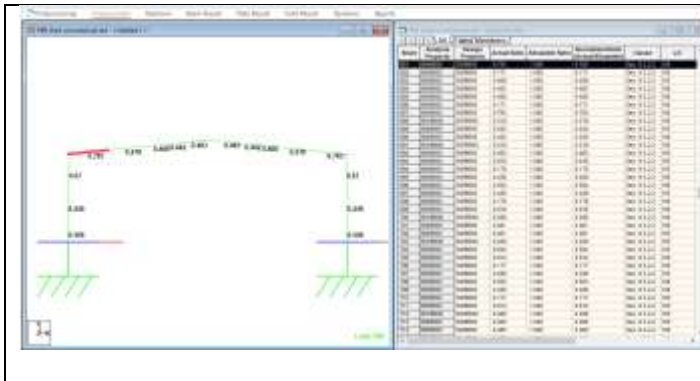


Table 6: Steel Utilization Ratio - Tapered Initial Design

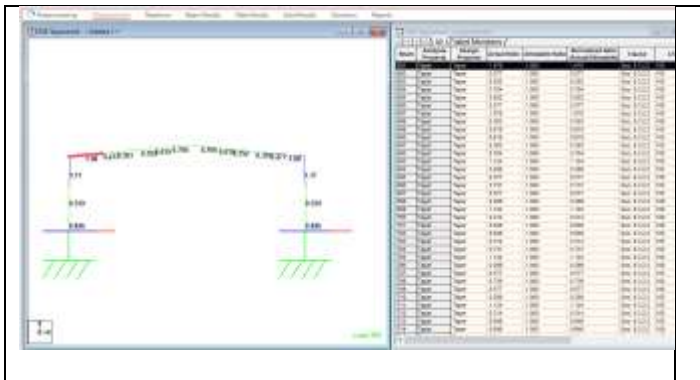
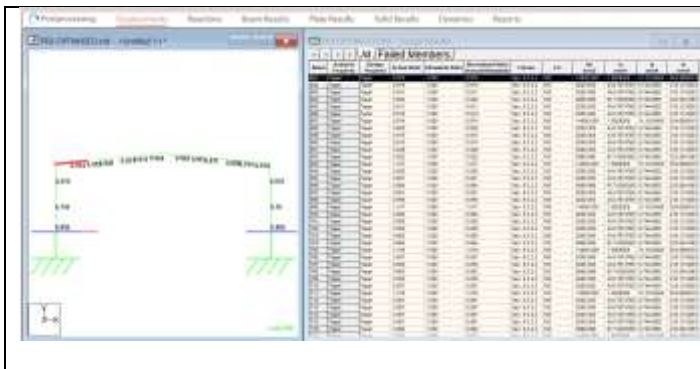


Table 7: Steel Utilization Ratio - Tapered optimized Design



Observations:

- Optimized tapered sections showed higher utilization ratios compared to the initial design configuration
- Member utilization ratios approached the desirable design range without exceeding permissible limits
- Rafters and columns exhibited improved utilization after optimization of flange thickness, web thickness, and taper proportions
- Optimization reduced underutilized regions in primary structural members
- Most optimized members demonstrated balanced stress distribution along the member

length

Discussion: Higher utilization ratios indicate more efficient use of structural steel and better alignment between sectional capacity and actual force demand. The optimization process enabled the tapered members to achieve improved structural efficiency by minimizing excess material in low-stress regions while maintaining adequate strength in critical zones.

The increase in utilization ratio demonstrates that the optimized design achieves a more economical structural configuration without compromising safety, stability, or serviceability requirements prescribed by Indian Standards.

However, utilization ratios were maintained within acceptable codal limits to ensure sufficient safety margins and reliable structural performance under critical loading conditions.

5.9 Comparative Summary of Key Parameters

The following table presents the comparative evaluation between the initial PEB design and the optimized tapered section design developed under Indian codal provisions.

Fig 4: Comparison of Key Parameters

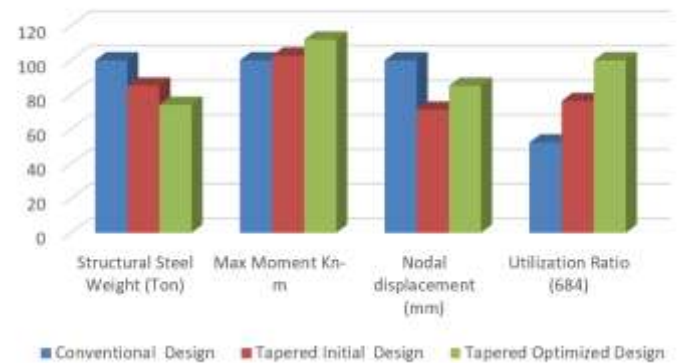


Table 8: Comparison of Key Parameters

Parameter	Tapered Initial Design	Tapered Optimized Design	Observation
Structural Steel Weight	Higher	Lower	Optimization reduced overall steel consumption
Member Sizes	Larger sections	Optimized tapered	Improved sectional

Parameter	Tapered Initial Design	Tapered Optimized Design	Observation
		sections	efficiency achieved
Deflection	Lower	Slightly higher (within permissible limits)	Serviceability maintained within codal limits
Utilization Ratio	Lower	Higher	Better material utilization obtained
Structural Efficiency	Moderate	Improved	Balanced stress distribution achieved
Tapered Section Performance	Conventional taper proportions	Refined taper optimization	Enhanced efficiency of primary members
Load Response	Conservative member sizing	Efficient force-based sizing	Optimized design matched actual force demand
Fabrication Economy	Comparatively higher steel requirement	Reduced material requirement	Improved overall economy

Discussion: The comparative evaluation clearly indicates that optimization of tapered built-up sections significantly improves the structural efficiency of the Pre-Engineered Building frame. The optimized model achieved higher utilization ratios and reduced steel weight while maintaining compliance with strength, stability, and serviceability requirements prescribed by Indian Standards.

5.10 Economic Evaluation

Optimization of tapered built-up sections resulted in noticeable improvement in the overall economy of the Pre-Engineered Building structure. Reduction in

unnecessary steel usage directly contributed to lower material consumption and improved fabrication efficiency.

Observations:

- Reduction in structural steel weight decreased the overall material cost of the structure
- Optimized tapered sections improved fabrication efficiency by achieving balanced material distribution
- Efficient member sizing reduced excess steel concentration in low-stress regions
- Improved utilization ratios contributed to economical structural performance
- Reduced member weight may also contribute to lower transportation and erection costs

Overall Insight:

Structural optimization of tapered sections resulted in a more economical PEB system

- Efficient material utilization reduced the overall steel requirement while maintaining codal compliance
- The optimized design achieved a balance between structural safety, serviceability, and economy
- The study demonstrates that effective optimization of tapered sections can significantly improve the cost efficiency of industrial Pre-Engineered Buildings.

5.11 Discussion on Sustainability

Reduction in steel consumption through structural optimization contributes positively toward sustainable construction practices. Efficient utilization of structural steel reduces the overall environmental impact associated with material production, fabrication, and transportation.

Sustainability Benefits of Optimized PEB Structures

- Lower embodied carbon due to reduced steel consumption
- Reduced use of construction materials
- Improved resource efficiency
- Reduced fabrication waste
- Faster construction process with lower environmental disturbance

In addition to structural optimization, Pre-Engineered Building systems inherently support several sustainable construction features such as:

- Provision for solar panel installation on roof surfaces
- Natural lighting through polycarbonate roof sheets
- Natural ventilation using turbo ventilators and ridge ventilators
- Reduced construction waste due to prefabrication techniques
- Reusability and recyclability of steel structural components

Thus, optimization of PEB structures not only improves structural and economic performance but also enhances environmental sustainability and resource efficiency.

5.12 Key Findings

The major findings obtained from the present study are summarized as follows:

- Optimization of tapered built-up sections significantly reduced the overall structural steel weight of the Pre-Engineered Building.
- Improved utilization ratios were achieved through efficient distribution of sectional properties along the member length.
- Tapered section optimization enhanced structural efficiency without violating strength and serviceability requirements prescribed by Indian Standards.
- Deflection control was one of the governing parameters influencing optimization of rafters and primary frame members.
- Wind load combinations and crane load effects governed the design of several critical structural members.
- Optimized sections provided balanced stress distribution and reduced unnecessary material concentration in low-force regions.
- Secondary structural members showed comparatively smaller scope for optimization compared to primary frame members.
- The optimized structural configuration achieved improved economy, fabrication efficiency, and sustainability performance.
- All optimized structural members satisfied codal requirements related to strength, stability, and serviceability under critical loading conditions.

5.13 Summary

This chapter presented the results obtained from the structural analysis and optimization of the Pre-Engineered Building frame using tapered built-up sections under Indian codal provisions. The analytical results were evaluated in terms of steel consumption, member utilization ratio, deflection behavior, load response, and structural efficiency.

The study demonstrated that optimization of tapered sections significantly improves material utilization and reduces structural steel weight while maintaining adequate strength, stability, and serviceability performance. The optimized PEB configuration achieved a balanced and economical structural solution suitable for industrial applications.

VI. CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 Introduction

This chapter presents the overall conclusions drawn from the structural analysis and optimization of the Pre-Engineered Building (PEB) frame using tapered built-up sections under Indian codal provisions. The study focused on improving structural efficiency, increasing member utilization ratios, reducing steel consumption, and maintaining satisfactory serviceability performance under prescribed loading conditions.

Based on the analytical findings and discussions presented in the preceding chapters, the key conclusions and recommendations for future research are summarized in the following sections.

6.2 Conclusions

6.2.1 Structural Efficiency

- Pre-Engineered Buildings (PEBs) demonstrate high structural efficiency due to the use of tapered built-up sections in primary framing systems.
- Variation of sectional depth according to bending moment distribution enables effective utilization of structural steel.
- Optimization of tapered sections significantly reduces unnecessary material concentration in low-stress regions while maintaining adequate structural strength and

stability.

industrial structures.

6.2.2 Effectiveness of Tapered Section Optimization

- Optimization of tapered built-up sections improved the utilization ratio of primary structural members.
- Iterative modification of flange thickness, web thickness, and taper proportions resulted in more balanced stress distribution along member length.
- The optimized configuration achieved improved structural efficiency without violating codal requirements related to strength and serviceability.
- Tapered section optimization proved effective in reducing overdesign in rafters and columns.

6.2.3 Steel Consumption and Economy

- Optimization of structural members resulted in reduction of total structural steel weight compared to the initial design configuration.
- Reduced steel consumption contributes directly to improved economic performance of the structure.
- Efficient material utilization may also reduce fabrication, transportation, and erection costs.
- The study demonstrates that economical PEB design can be achieved through proper optimization of tapered sections under Indian codal provisions.

6.2.4 Deflection and Serviceability

- Deflection control was one of the governing criteria influencing optimization of primary frame members.
- Optimized sections exhibited slightly higher deflections compared to the initial design; however, all values remained within permissible codal limits.
- Proper optimization achieved a balance between structural economy and serviceability requirements.
- Serviceability considerations were particularly important for crane-supported

6.2.5 Member Utilization

- Optimized structural members exhibited higher utilization ratios compared to the conventional design configuration. Improved utilization ratios indicate better alignment between sectional capacity and actual force demand.
- Efficient utilization of material contributed significantly to reduction in steel weight and enhancement of structural economy.
- All utilization ratios were maintained within permissible limits to ensure adequate safety margins.

6.2.6 Load Effects and Structural Behavior

- Wind load combinations and crane load effects significantly influenced the design of primary structural members.
- Crane-induced forces governed several critical load combinations affecting columns and rafters.
- The optimized structural system successfully resisted gravity, wind, seismic, and crane loads while maintaining stability and serviceability performance.
- Bracing systems played an important role in controlling lateral displacement and improving overall structural stability.

6.2.7 Sustainability Aspects

- Reduction in steel consumption through structural optimization contributes positively toward sustainable construction practices.
- Optimized PEB structures contribute to the reduction of embodied energy and carbon emissions associated with steel manufacturing and fabrication processes.
- Pre-Engineered Buildings inherently support sustainable features such as:
 - Natural ventilation using turbo ventilators
 - Daylighting through polycarbonate roof sheets
 - Provision for rooftop solar installations

- Reduced construction waste through prefabrication
- The study confirms that optimized PEB systems provide both economic and environmental benefits for industrial construction.

6.3 Overall Conclusion

From the present study, it can be concluded that:

- Pre-Engineered Buildings provide an efficient, economical, and sustainable structural solution for industrial applications.
- Optimization of tapered built-up sections considerably improves structural efficiency and effective utilization of materials.
- Proper variation of sectional geometry according to bending moment distribution leads to reduction in steel consumption without compromising safety and serviceability requirements.
- Indian codal provisions provide a reliable framework for achieving structurally safe and optimized PEB systems.
- Adoption of optimization techniques in the design of tapered members can substantially improve the economy and practical performance of industrial steel structures.

6.4 Scope for Further Work

Although the present study provides valuable insights into optimization of Pre-Engineered Building frames, several areas remain available for future research and development.

6.4.1 Advanced Analysis Techniques

- Incorporation of non-linear analysis to evaluate actual structural behavior under extreme loading conditions
- Dynamic analysis for detailed assessment of seismic response and vibration characteristics
- Study of geometric and material nonlinearity effects on tapered members

6.4.2 Optimization Studies

- Development of automated optimization

algorithms for tapered section design

- Integration of optimization techniques with structural analysis software
- Application of artificial intelligence and machine learning methods for weight and cost optimization

6.4.3 Parametric Studies

Further research may be carried out to study the influence of Span variation, Bay spacing, Roof slope, Eave height, Crane capacity, Wind speed and seismic zone on the structural efficiency and economy of Pre-Engineered Buildings.

6.4.4 Experimental Validation

- Experimental testing of tapered built-up members and structural connections
- Full-scale testing of PEB frames under actual loading conditions
- Validation of analytical results through laboratory investigations

6.4.5 Sustainability and Life-Cycle Assessment

- Detailed life-cycle cost analysis (LCCA) of optimized PEB systems
- Evaluation of environmental impact using life-cycle assessment (LCA) techniques
- Assessment of recyclable and reusable steel components in sustainable construction

6.4.6 Connection Design and Detailing

- Detailed investigation of bolted and welded connections in tapered built-up sections
- Optimization of connection detailing for improved constructability and fabrication efficiency
- Study of connection behavior under cyclic and dynamic loading conditions

6.4.7 Integration with Modern Construction Technologies

- Integration of Building Information Modeling (BIM) with PEB design and detailing
- Application of prefabrication and modular construction techniques
- Use of digital fabrication and automated manufacturing systems for PEB construction

6.5 Final Remarks

The present study highlights the significant potential of Pre-Engineered Buildings as an economical, efficient, and sustainable solution for modern industrial construction. Optimization of tapered built-up sections under Indian codal provisions proved effective in improving structural performance and reducing steel consumption while maintaining adequate safety and serviceability.

With continued advancements in structural optimization techniques, computational analysis tools, and modern fabrication technologies, Pre-Engineered Building systems are expected to play an increasingly important role in future infrastructure development and sustainable industrial construction practices.

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