Effect of Ductility Factor on the Performance of PEB Industrial Steel Structure

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Abstract

Pre-Engineered Buildings (PEBs) have become a preferred solution for industrial infrastructure, particularly in seismically active regions such as India, due to their cost-effectiveness, rapid construction, and modular design. Despite these advantages, the seismic performance of PEBs is significantly influenced by the assumed ductility factor, or response reduction factor (R), incorporated during the design phase. This study examines the impact of varying ductility factors on the seismic behavior of a typical industrial PEB frame. A nonlinear static pushover analysis is conducted on a representative PEB model to assess critical seismic response parameters, including base shear, lateral displacement, plastic hinge formation, and energy dissipation. The analysis adheres to the provisions of IS 800 and IS 1893, considering site-specific seismic hazard conditions. Results reveal a direct correlation between span length and lateral displacement, indicating a greater demand for ductility in longer-span structures. Although the inherent ductility of steel remains unchanged, its utilization must be increased in longer spans to maintain structural stability under seismic loads. The findings offer valuable insights for optimizing the selection of ductility factors in PEB design, promoting enhanced seismic resilience while preserving economic efficiency. This research contributes to the advancement of rational, performance-based design strategies for PEBs in seismic zones.

Keyword: *Ductility Factor (R), Industrial Structures, Nonlinear Static, Pre-Engineered Buildings (PEB), Pushover Analysis, Response Reduction Factor, Seismic Performance.*

I. INTRODUCTION

Pre-Engineered Buildings (PEBs) have significantly transformed the construction landscape for industrial infrastructure in India, especially in rapidly industrializing regions. Their inherent advantages such as rapid construction, cost-effectiveness, and architectural flexibility have made PEBs a preferred choice for warehouses, factories, and various industrial structures. However, given India's pronounced seismic vulnerability, a comprehensive understanding of the seismic performance of PEBs is imperative. Modern seismic design philosophy emphasizes the importance of allowing controlled inelastic deformation, or ductility, during strong ground motion to reduce the seismic demand on structures and enhance life safety. This principle is embedded in seismic design codes through the Response Reduction Factor (R), which serves to scale down the elastic design forces based on the expected ductility and overstrength of the structural system. The appropriate selection of this ductility factor plays a pivotal role in determining the seismic performance, structural safety, and economic feasibility of PEB industrial structures. Despite the many advantages of PEBs in terms of material optimization and construction efficiency, their seismic behavior particularly concerning the chosen ductility factor—requires thorough investigation. Several studies have explored the significance of ductility in seismic design. Lopes et al. (2025) emphasized that seismic standards often link structural ductility to the ductility properties of the steel materials used, highlighting that standards like EC8 mandate the use of high-ductility steels to achieve desirable performance. Titiksh et al. (2015) highlighted the advantages of PEBs over conventionally designed buildings, particularly in terms of cost-effectiveness, construction speed, and suitability for developing nations such as India.

Karattupalayam et al. (2020) focused on the importance of the response modification factor (R) in IS 1893 for nonlinear seismic analysis. Thuat et al. (2020) investigated the relationship between the response reduction factor and maximum ductility in irregular buildings. Similarly, Kermani et al. (2016) evaluated seismic design frameworks based on maximum inertial forces derived from earthquake codes. Other studies have assessed the material efficiency and design implications of PEBs. Dewani and Bhadke (2018) discussed the PEB concept in steel construction, emphasizing its role in structural optimization. Srinivasan and Selvakumar (2022) reported that, for spans of 20 m and 30 m, space trusses could reduce structural weight by up to 20% and 28%, respectively, compared to PEBs. Tagade et al. (2023) explored the sustainable and cost-efficient aspects of PEBs, especially for single-story industrial applications. Pradeep and Papa Roa (2014) performed a comparative study of PEBs and conventional steel frames using both concrete and steel columns. Venkat Rao and Gupta (2016) analyzed how overstrength and ductility factors vary with building height and seismic zone, showing notable discrepancies between individual story ductility and overall structural ductility.

Further, Reddy and Kalesha (2020) emphasized the potential of PEBs in minimizing construction time and cost, while Devkota and Kumar (2020) focused on the response reduction factor of Special Moment Resisting Frames (SMRFs) in sloped terrains under seismic Zone V conditions. Dalal and Dalal (2016) studied how increasing ductility factors (ranging from 2 to 6) affect the performance of steel moment-resisting frames using performance-based plastic design. Finally, Syed Firoz et al. demonstrated the application of STAAD.Pro software in real-time, data-rich design of PEBs. Despite the breadth of research, the influence of ductility factors on the seismic performance of typical industrial PEB frames remains an area of ongoing investigation. This study aims to fill that gap by examining how varying ductility factors affect seismic response characteristics such as base shear, lateral displacement, plastic hinge development, and energy dissipation, using nonlinear static pushover analysis in accordance with Indian codes IS 800 and IS 1893.

II. METHODOLOGY FOR STUDY

A. Methodology for Proposed Study

The proposed study adopts a comprehensive analytical framework to evaluate the seismic performance of industrial steel structures, with a specific focus on Pre-Engineered Buildings (PEBs). The methodology is structured in multiple stages to systematically capture both the elastic and inelastic behavior of the structural system under seismic loading. Initially, linear static and dynamic analyses are performed on a conventional industrial steel structure to establish a baseline response. These analyses provide insight into the structure's behavior under elastic conditions and serve as a reference for comparison with the enhanced performance of PEB systems. Subsequently, nonlinear static (pushover) analysis is conducted to simulate inelastic behavior and evaluate the actual deformation capacity of the structure. From the results of the pushover analysis, the ductility factor is derived, representing the structure's capacity to sustain plastic deformations beyond the elastic limit. The calculated ductility factor is then incorporated into the design process of a PEB industrial steel structure. Using this factor, linear static and dynamic analyses are repeated for the PEB model to enable a comparative evaluation of seismic performance. Key performance metrics such as base shear, lateral displacement, plastic hinge formation, and energy dissipation are subsequently assessed to understand and optimize the seismic behavior of PEBs.

B. Nonlinear Static Pushover Analysis

Nonlinear static pushover analysis is employed as a critical tool to investigate the inelastic seismic response of the PEB industrial steel structure. The procedure begins with the assignment of nonlinear hinges at potential zones of inelastic deformation, typically located at the beam and column ends. These hinges are modeled using predefined force-deformation relationships in accordance with guidelines from FEMA 356 and ASCE 41, capturing flexural (M2, M3), axial (P), and combined axial-flexural (P-M-M) behaviors. To simulate seismic loading, appropriate lateral load patterns are applied, including uniform and code-based distributions as prescribed in IS 1893. These load patterns help evaluate the sensitivity of the structural response to different modes of seismic excitation. The analysis proceeds by incrementally applying lateral loads until a target displacement is reached or structural instability is observed. The key outputs of the pushover analysis include base shear, roof displacement, and the sequence and distribution of plastic hinge formation throughout the structure. Although the Response Reduction Factor (R) is not directly used as an input in the pushover analysis, its influence is reflected in the interpretation of ductility demands, deformation capacity, and drift limits, as per IS 1893. By conducting multiple pushover analyses, the study evaluates the structural response across varying performance levels corresponding to different R values. This approach enables a performance-based assessment of the ductility requirements for PEB structures, contributing to more rational and seismic-resilient design practices.

III. Analysis Of Industrial Steel Structure.

A. Industrial truss

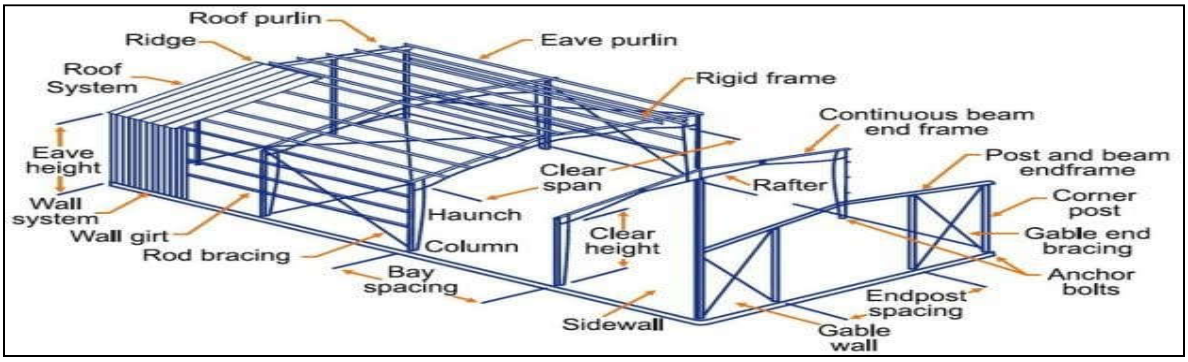


Fig. 1. Industrial Truss

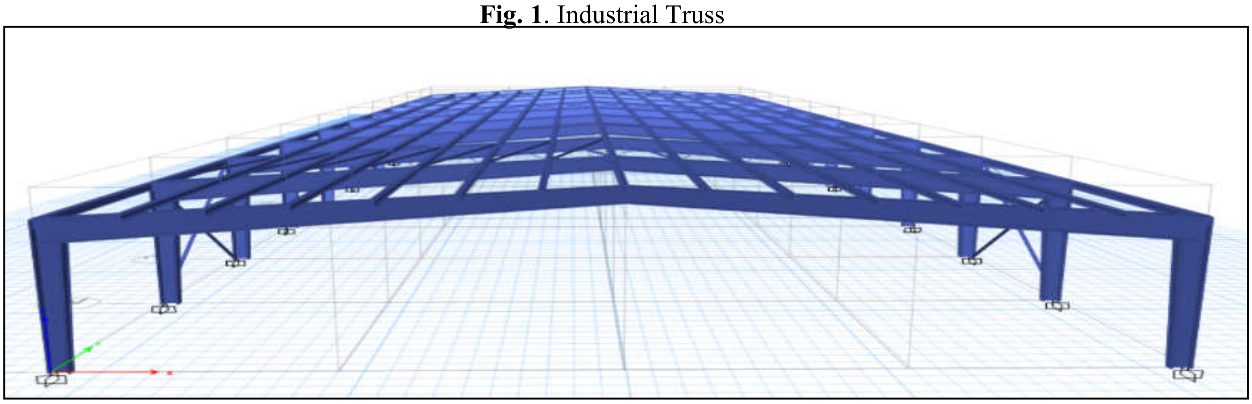


Fig. 2. PEB

Table 1: *Type of Truss*

Sr.no	Span	Length	Height	Size of Rafter mm	Column Section mm	Purlin Section mm
1	20 m	60 m	6 m	750-500	350-500	180
2	30 m	60 m	6.5 m	900-750	350-750	200
3	40 m	60 m	7 m	1200-900	350-900	220

B. Load pattern and load cases

Table 2: *Load Pattern and Load Cases*

Sr.No	Load	Type	Lateral load
1	Live	Live- Linear Static	-
2	Dead	Dead- Linear Static	-
3	EQX	Seismic	IS 1893-2016
4	EQY	Seismic	IS 1893-2016
5	Wind-x	Wind- Linear Static	IS 875-2015
6	NLG	Non-Linear Static	-
7	Push-x	Non-Linear Static	-
8	Push-y	Non-Linear Static	-
9	RSx	Response Spectrum	IS 1893-2016
10	RSy	Response Spectrum	IS 1893-2016

C. Live load calculation

Live load as per IS code 875 Part II for flat slopping or curved roof with slope up to 10^o (access not provided) taken as = 0.75 KN/m^2

Live load per meter run on rafter = 0.75 KN/m^2x6m (bay spacing) = 4.5 KN/m^2

D. Dead load calculation

Weight of GI sheet, Purlin, Sag road = 0.15 kN/m^2
Dead load per meter run on rafter = 0.15KN/m^2x6m (bay spacing) = 0.9 KN/m

E. Wind load calculation

Wind pressure calculation Wind Speed Vb = 39 m/sec Risk coefficient, k1 = 1
Terrain, Ht & size factor, k2 = 1 (Category 2 class A) Topography Factor, k3 = 1
Design Wind Speed, Vz = Vb x k1 x k2 x k3
= 39 x 1 x 1 x 1 = 39 m/s Design wind pressure, Pz
=0.6 x $(Vz)^2$ = 0.6 x 39^2= 0.9126 KN/m^2
Internal Pressure Coefficient (Cpi) = +/-0.5
External Pressure Coefficient for wall from IS 875 4 tables (Cpe)
From design dimensions
h/w = 5.5/10 = 0.55, (h/w< 0.5) l/w = 60/10 = 0.55

Tabe 3: *Wind pressure coefficient*

	Load	Roof		Wall	
		Left	Right	Lift	Right
	DL	0.9 kN/m		-	
	LL	4.5 kN/m			
0°	WL 1	-2.681	0.383	4.59	0.958
	WL 2	-6.515	-3.44	0.765	-2.874
90°	WL 3	-4.98	-4.21	-3.832	-3.83
	WL 4	-1.14	-0.22	0	0

F. Pushover Curve Analysis

The steel truss structure in this study is modeled using standard rolled sections, with I-sections (such as ISMB and ISWB) utilized for columns and L-sections (ISA) and tubular sections for beams and bracing elements. To capture inelastic seismic behavior, material nonlinearity is incorporated through a lumped plasticity approach, wherein nonlinear hinges are assigned at critical locations—typically the ends of beams and columns—to simulate localized plastic deformations. Flexural hinges are modeled as deformation-controlled to represent rotational capacity, while shear hinges are force-controlled, addressing strength-based failure mechanisms. Columns composed of I-sections are assigned P-M2-M3 hinges to account for the interaction between axial load and biaxial bending, whereas beams with L-sections and tubular profiles are modeled with P-H hinges, focusing on flexural behavior about the major axis. Nonlinear hinge properties are automatically defined and assigned using the Auto Hinge feature in SAP2000, adhering to guidelines from FEMA 356 and ASCE 41 to ensure consistency with accepted performance standards for steel members. This detailed hinge modeling enables accurate prediction of the initiation and progression of inelastic behavior during seismic events. Pushover analysis is performed on three steel truss models with varying span lengths to evaluate their nonlinear seismic performance. Both wind and seismic loads are applied, with seismic forces defined using the response spectrum method to effectively simulate dynamic behavior. Additionally, a uniform live load is included in accordance with FEMA 356 to account for gravity-induced effects, ensuring realistic loading conditions. The combined evaluation of base shear, displacement, plastic hinge formation, and energy dissipation provides critical insight into the structural performance and ductility demands of PEB truss systems under seismic excitation.

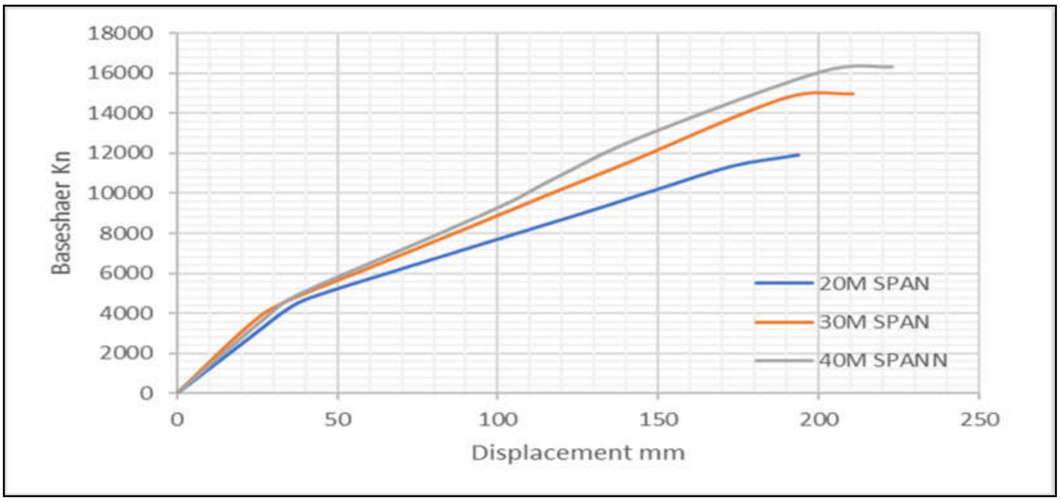


Fig. 4. Pushover cure

Using the results obtained from the nonlinear pushover analyses, capacity curves depicting the relationship between base shear and roof displacement were successfully generated for each structural model. These capacity curves were instrumental in estimating the yield and ultimate displacement values through the coefficient method prescribed in FEMA-356, enabling a performance-based evaluation of the structures under progressive levels of lateral deformation. The analysis revealed a clear trend: as the span length of the steel truss structure increased, the models exhibited greater lateral displacement and higher base shear capacity, indicating significant changes in both stiffness and ductility demand as a function of geometry. Specifically:

- When the span increases from **20 meters to 30 meters**, the lateral displacement increases by approximately **8.16%**, indicating a notable rise in deformation due to increased flexibility.
- When the span further increases from **30 meters to 40 meters**, the displacement rises by an additional **5.7%**, showing a continued but slightly more moderate increase.
- In terms of **base shear force**:
    - A **20% increase** is observed when the span changes from **20 meters to 30 meters**, reflecting a stronger resistance to lateral forces.
    - An **8.19% increase** in base shear is observed as the span increases from **30 meters to 40 meters**, consistent with the structural response trends.

These results confirm that span length has a direct influence on both **lateral deformation capacity** and **seismic force resistance**, highlighting the need for appropriate ductility considerations in the design of long-span Pre-Engineered Buildings (PEBs).

IV. Ductility Factor

A. R factor for 20m span

For model-1, 20m span [Response reduction factor 3]

1) $(\boldsymbol{R = R_s \times RR \times R_\mu})$ 1

Calculating Rs

Rs = Va / Vd ……Va= Max. base shear from pushover analysis curve

Vd= Design base shear

Rs = 4064/1350.48

Rs = 3

2) As per ATC-19 code

RR=1

3) Calculation for Rμ ,For this model,

Rμ=μ……………. (T>1 Sec)

As per ATC-19

Calculation of μ from pushover curve,

μ =Max. Displacement / Max Yield Displacement 2

(μ Δ = m Δ / y)

μ = 99.1/ 67.1

μ = 1.4………………… (i.e. Rμ = 1.4)

Now,

R= 3 * 1 * 1.4

R = 4.2

B. R factor for 30m span

For model-2, 30 m span [Response reduction factor 3]

1) $(\boldsymbol{R = R_s \times RR \times R_\mu})$ 3

Calculating Rs

Rs = Va / Vd ……Va= Max. base shear from pushover analysis curve

Vd= Design base shear

Rs = 4151/1298.45

Rs = 3.19

2) As per ATC-19 code , RR=1

3) Calculation for Rμ

For this model,

Rμ=μ……………. (T>1 Sec)

As per ATC-19

Calculation of μ from pushover curve,

μ =Max. Displacement / Max Yield Displacement 4

(μ Δ = m Δ / y)

μ = 170/ 105

μ = 1.61………………… (i.e. Rμ = 1.54)

Now,

R= 3.19 * 1 * 1.61

R= 5.13

C. R factor for 40m span

For model-3, 40 m span [Response reduction factor 3]

1) $(\boldsymbol{R = R_s \times RR \times R_\mu})$ 5

Calculating Rs

Rs = Va / Vd ……Va= Max. base shear from pushover analysis curve

Vd= Design base shear

Rs = 4235.52/1259.09

Rs = 3.36

2) As per ATC-19 code RR=1

3) Calculation for Rμ

For this model,

Rμ=μ……………. (T>1 Sec ……… As per ATC-19

Calculation of μ from pushover curve,

μ =Max. Displacement / Max Yield Displacement 6

(μ = Δ m / Δ y)

μ = 190/ 104.6

μ = 1.81………………… (i.e. Rμ = 1.54)

R= 3 .36* 1 * 1.81 **R = 6.0**

D. Estimating ductility factor for varying span length of truss

Table 4. *Ductility factor*

Sr.no	Span length (M)	Ultimate Displacement (Δm in mm)	Yield Displacement (Δy in mm)	μ=Δ m /Δ y	Va	Vd	Rs	R	RS in SAPP
1	20	99.1	67.1	1.4	4064	1350.48	3	4.2	3
2	30	170	105	1.61	4151	1298.45	3.19	5.13	3
3	40	190	104.6	1.81	4235.52	1259.09	3.36	6.0	3

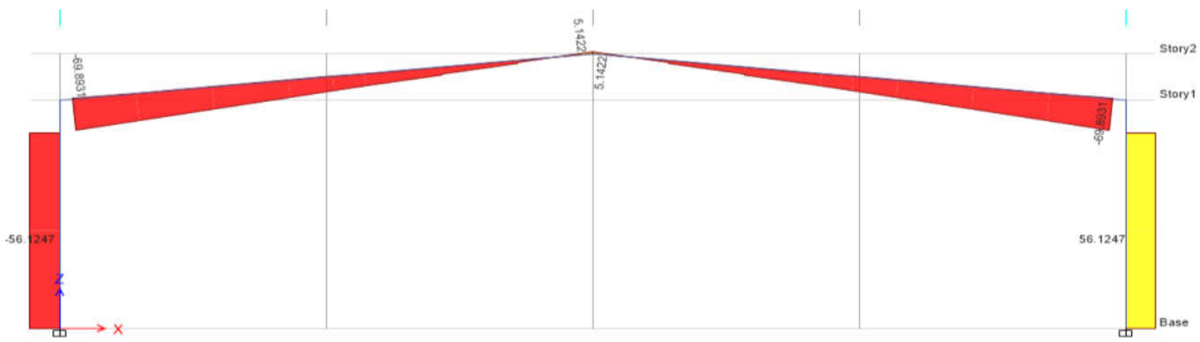
The results presented in the table indicate a clear trend: as the **span length** of the steel truss increases, the calculated **ductility factor (R-factor)** also shows a corresponding rise. This factor reflects the structure's capacity to undergo inelastic deformation and dissipate energy during seismic events. Specifically:

- For a **20-meter** span, the R-factor increases by approximately **28%**.
- For a **30-meter** span, the R-factor increases by around **41%**.
- For a **40-meter** span, the R-factor shows a significant increase of about **50%**.

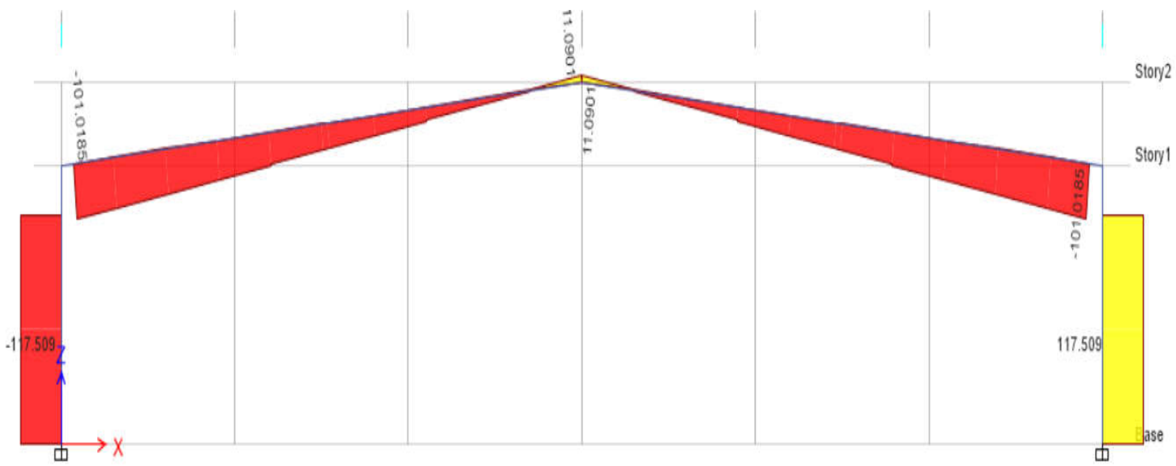
This increasing trend indicates that longer-span steel trusses inherently exhibit greater ductility and improved energy dissipation capacity, primarily due to their enhanced flexibility and deformation potential under seismic loading. A higher response reduction factor (R-factor) signifies the structure’s ability to accommodate larger nonlinear deformations without experiencing collapse, thereby allowing for a reduction in seismic design forces as permitted by code provisions such as IS 1893. These findings highlight the critical importance of accurately determining and applying appropriate R-factors in the seismic design of Pre-Engineered Building (PEB) structures to achieve an optimal balance between structural safety and economic efficiency.

V. Result and Discussion

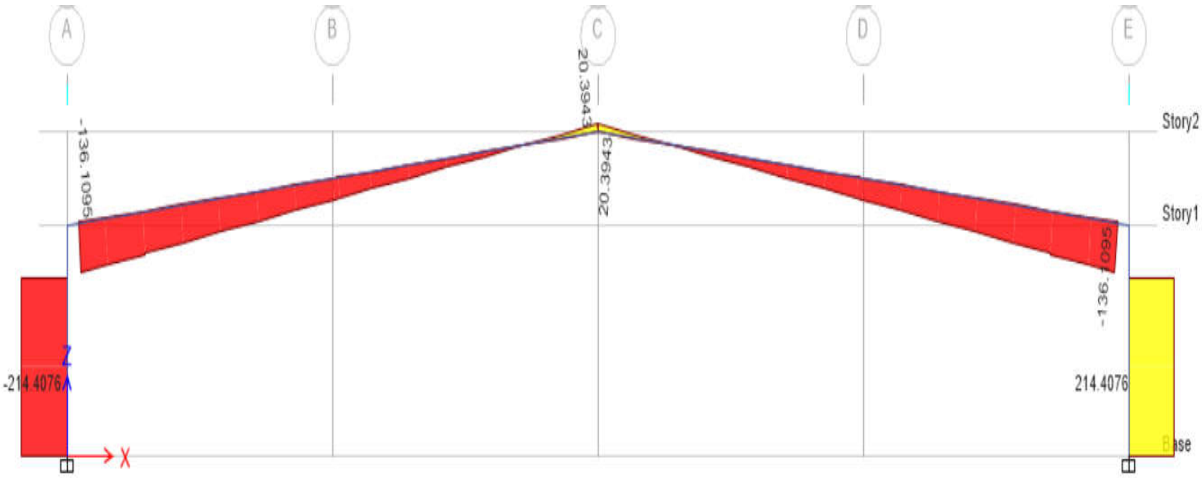
A. Shear force



(a) Shear force diagram for 20m span



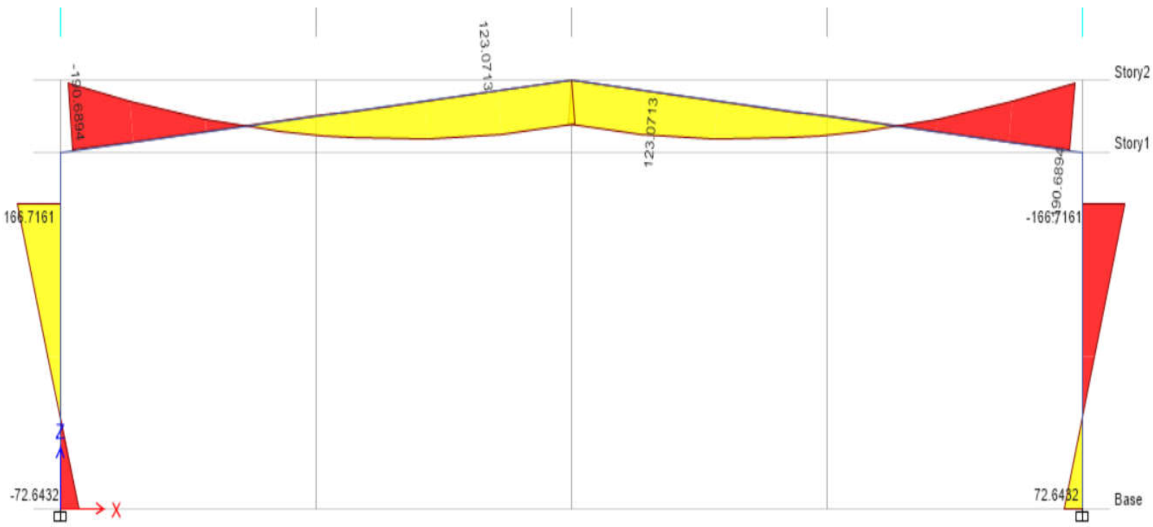
(b) Shear force for 30m span



(c) Shear force for 40m span

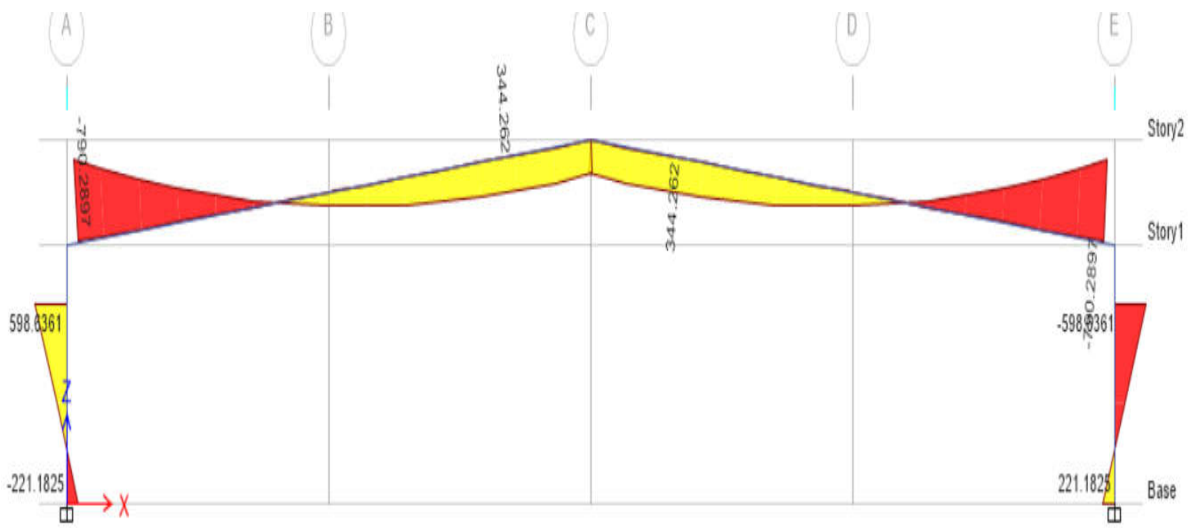
Figure 5. *Shear force Diagram*

B. Bending moment



(a) Bending moment diagram for 20m span

(b) Bending moment diagram for 30m span



(c) Bending moment diagram for 40m span

Figure 6. Bending Moment Diagram

C. Discussion

The results obtained from structural analysis software, supported by findings from relevant literature, confirm the modeling approach used for Pre-Engineered Building (PEB) construction. The maximum response values at the support sections were identified and are summarized as follows
:

Table 5. *Behavior Parameters*

Sr.No	Particular	20m Span	30m Span	40m Span
1	Axial Force Kn/m	38.817	55.877	77.017
2	Shear Force Kn/m	63.133	117.509	214.4076
3	Bending Moment Kn/m	72.6432	126.88	221.1825

The analysis clearly indicates that as the span of the truss increases, there is a significant escalation in the key internal forces namely axial force, shear force, and bending moment. This trend is evident when comparing trusses of increasing spans. Specifically:

• The axial force for the 30-meter span shows an increase of approximately 30.53% compared to the 20-meter span, while the 40-meter span exhibits a further increase of 27.45% over the 30-meter span.

• The shear force increases by 46.26% when moving from a 20-meter to a 30-meter span, and by an additional 45% from the 30-meter to the 40-meter span.

• The bending moment rises significantly as well, with the 30-meter span showing an increase of 42.74% over the 20-meter span, and the 40-meter span increasing by 42.63% over the 30-meter span.

These results highlight a clear and consistent trend: as the truss span lengthens, the internal force demands on structural members increase considerably. Such increases have critical implications for the structural design process. Engineers must carefully account for these rising force magnitudes during the selection of materials, cross-sectional sizing of members, joint detailing, and overall stability provisions. Failure to properly address these growing demands may compromise the safety, serviceability, and economic efficiency of long-span truss systems. Therefore, span-dependent force amplification should be a key consideration in the design and optimization of Pre-Engineered Building (PEB) systems.

VI. Conclusion

In Pre-Engineered Building (PEB) structures, the relationship between span length and structural displacement under applied loads both static and seismic exhibits a clear and consistent behavior, which can be summarized as follows:

• Direct Correlation: There exists a direct correlation between the span length of primary framing members (such as columns and rafters) and the resulting displacement. As the span increases, the flexibility of the structural system also increases, leading to greater lateral and vertical displacements. This behavior is attributed to the reduced stiffness associated with longer structural elements.

• Influence of Load Type: This trend is observed under both static loads (e.g., dead loads, live loads) and dynamic loads (e.g., seismic excitations). For a constant load magnitude and distribution, longer spans exhibit higher deflections compared to shorter spans, assuming member stiffness and boundary conditions remain unchanged.

Furthermore, considering the characteristic behavior of PEB structures under seismic loading, the relationship between span length and ductility demand can be articulated as follows:

• Increased Ductility Demand with Span: Longer-span PEB systems, due to their inherent flexibility and susceptibility to larger seismic-induced displacements, are subjected to increased ductility demands. To withstand these amplified deformations within the inelastic range without leading to structural failure, the framing members and connections must be designed with sufficient ductile capacity—i.e., the ability to undergo plastic deformation while retaining structural integrity.

• Material Ductility Remains Constant: The ductility of the steel material used in PEB structures is governed by the steel grade and fabrication details, and is not inherently affected by changes in span length. However, as span increases, the structural system is required to mobilize a greater portion of the available material ductility to accommodate the elevated inelastic deformations induced by seismic actions. This necessitates careful attention to detailing practices, such as proper connection design, member proportioning, and adherence to ductility provisions specified in design codes.

In summary, as the span length in PEB systems increases, both displacement and ductility demand rise significantly. These effects must be thoroughly considered during the design phase to ensure safety, performance, and code compliance under both service and extreme loading conditions.

STATEMENTS AND DECLARATIONS

Ethical Approval

"The submitted work is original and not have been published elsewhere in any form or language (partially or in full), unless the new work concerns an expansion of previous work."

Consent to Participate

"Informed consent was obtained from all individual participants included in the study."

Consent to Publish

"The authors affirm that human research participants provided informed consent for publication of the research study to the journal."

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Competing Interests

"The authors have no relevant financial or non-financial interests to disclose."

Availability of data and materials

"The authors confirm that the data supporting the findings of this study are available within the article."

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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