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Limit State Design of Alternative Structural Forms for Sugar Factories

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ABSTRACT

Modern sugar factories require the construction of complex industrial buildings that ensure both optimum cost and high operational efficiency. This study explores the application of the Limit State Design (LSD) methodology to various alternative structural forms suitable for sugar factory construction. The research proposes and evaluates multiple structural alternatives aimed at achieving enhanced durability and cost-effectiveness.

The central objectives of the study are to analyze the unique load conditions in sugar factory operations—particularly heavy concentrated loads from gantry systems—along with conventional dead, live, wind, and earthquake loads. It also aims to develop alternative structural forms for critical units and perform comparative LSD analyses between these alternatives and traditional structural designs. The analysis evaluates performance under key limit states, including the Ultimate Limit State (structural failure) and the Serviceability Limit State.

The findings of this research provide a comprehensive framework for designing and constructing next-generation sugar factories that are more resilient, sustainable, and economically viable. By demonstrating the effectiveness of alternative structural forms within a rigorous LSD framework, the study offers valuable guidance for engineers and industry stakeholders seeking to optimize large-scale industrial structures.

Keywords: *Limit State Design (LSD), Alternative Structural Forms, Sugar Factory Structures, Industrial Building Design, Structural Load Analysis, Cost-Effective Construction*

1. INTRODUCTION

The World is entering a new era of industrialization, driven by the concepts of a free economy and the globalization of the world market. The rapid growth of industry has amplified the responsibility of Civil Engineers and Structural Designers, particularly concerning the efficient use of constructional resources like steel and cement. Furthermore, the cost and the ongoing maintenance expenses of the industry. Large industrial sheds, characterized by their extensive spans. Increased heights, and heavy loads (e.g., from gantry cranes), necessitate careful design. Consequently, exploring all possible design options is crucial to ensure the building's safety and economic viability. The efficient utilization of steel, in particular, can lead to significant cost savings in industrial construction. Such efficiency is vital for the nation to manage the high cost and demand for structural steel. In our country, especially in Maharashtra and neighbouring states, the rapidly expanding sugar industry consumes at least 750 tons of structural steel. Therefore, any efforts to optimize the construction costs within this industry could lead to more efficient resource utilization and contribute to the country's overall economic growth.

A typical layout of sugar factory is as shown in the figure 1. Various process zones in the sugar factory are,

1) Mill House
2) Evaporator House
3) Boiler House
4) Boiling House
5) Clarification House
6) Power House
7) Sugar House
8) Work Shop
9) Sugar Godowns

The functions of the various zones are briefly described below.

Sugarcane enters the mill house where it is broken in small pieces. These pieces are crushed and the juice is formed. The juice is transferred to the evaporator for removal of the impurities.

The clear juice is boiled in the boiling house leading to crystallization occurs and the sugar crystals are formed. These crystals are then transferred in sugarhouse.

A workshop is provided for the maintenance purpose and the turbo generators are installed in the powerhouse which provide power to the whole sugar factory. The standard span for sugar factory is 24 m center to center. The height of mill, evaporator, boiler, power and clarification house is normally 16 m. boiling house height varies from 24 m to 27 m depending upon machine suppliers. The height of sugar house is 13 m to 18 m as shown in fig. 2. This dissertation explores alternative structural forms to identify the most optimal structural configuration.

Alternative - 1 Conventional Truss and Column System

The commonly used truss and column system described above referred as alternative-I is shown in Figure 3. [2] Sections provided for various members of the structures and their total weight calculation is presented in Table 1

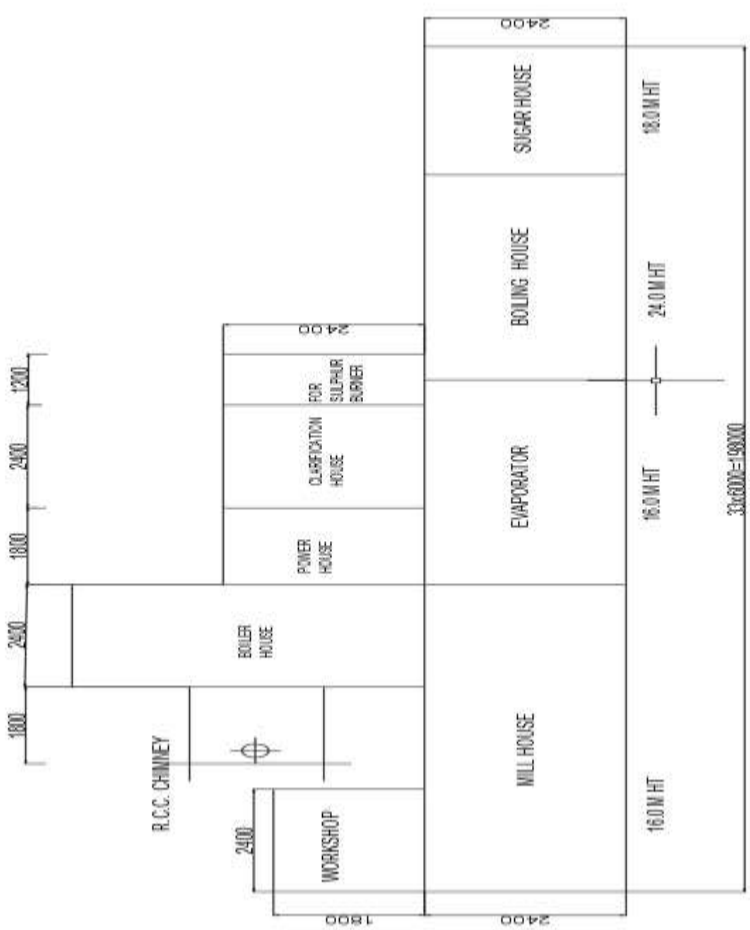

Fig.1. Typical Layout of a Sugar Factory

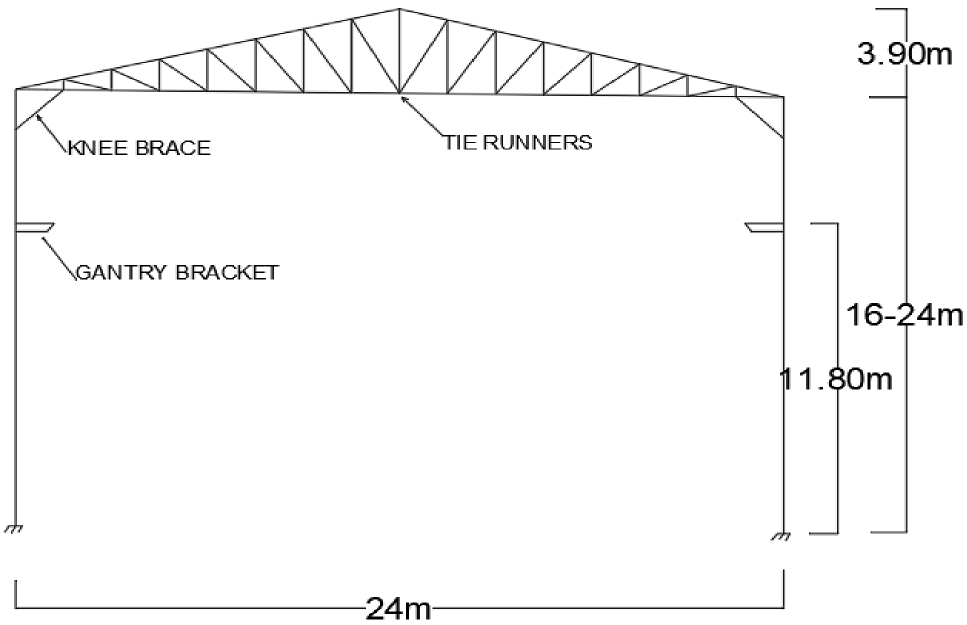

Fig.2. Section – Howe's Truss with Plain Soffit

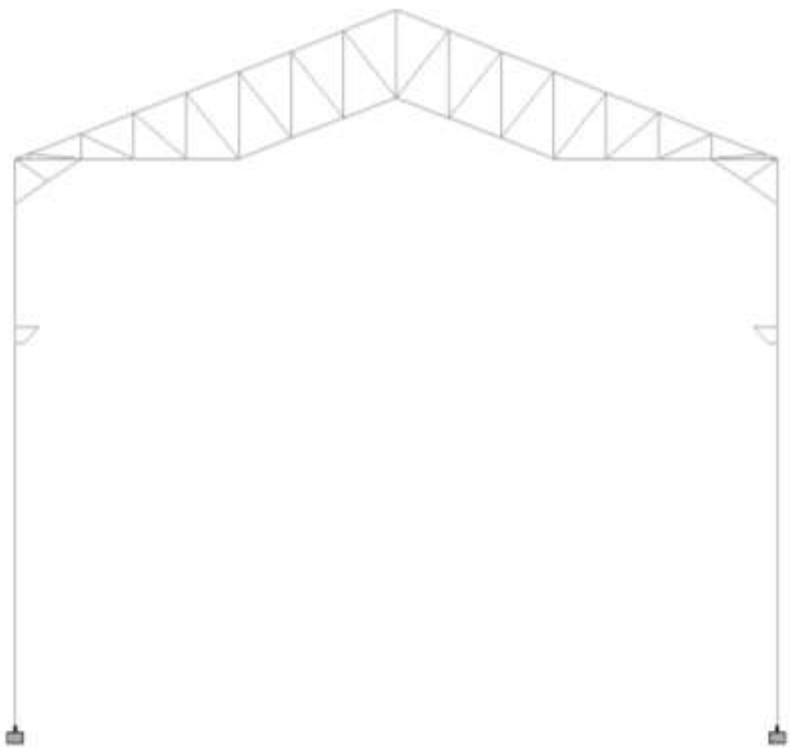

Fig.3. Modified Howe's Truss with Camber in Central Portion

2. LITERATURE REVIEW

Industrial buildings serve the purpose of housing manufacturing processes or storing raw materials. Many large industrial facilities are situated in less populated areas to take advantage of factors like lower land costs, ample space for parking and future expansion, and a more pleasant environment away from urban congestion. Key considerations for selecting an industrial site include topography, subsoil conditions, transportation access, and utility availability.[3]

Makowski's (1973) A practical solution to this issue in braced domes is the incorporation of double-layer bracing. work explored various designs for a two-way car park at Heathrow Airport, likely utilizing space frame principles. [4][5] **Madi (1986)** investigated various designs parameters of double layer space frame grids. A parametric study of various factors affecting the design of double layer space grids was also performed by Madi (1986)[6] **1A.C.R.Djugash and P.R.Natarajan's (1995)** studied offered guidelines for "planning small Industrial Steel Shed Structures." [3] This research aimed to assist engineers in selecting the most suitable structural system and constructing cost-effective small-scale industrial sheds. [7] The study specifically focused on structures with spans ranging from 9m to 18m and heights from 4m to 6m. Space frames, inspired by natural structures, possess remarkable rigidity and lightness due to their three-dimensional component arrangement.[8] Domes are presented as the oldest and a prime example of space structures, efficiently enclosing large volumes with minimal surface area. However, domes can be susceptible to failure under uneven loads due to the inadequate elastic stability of their compression elements. [1]

A.Jayaraman, R.Geethamani, N.Sathyakumar and N.Karthiga shenbagam (2014) a technical paper that compares the Limit State Method (LSM) and Working Stress Method (WSM) for the Structural Design of Roof Trusses and purlins.[9] The main point of the paper is to determine which design method is more economical and efficient. **Kumar, Brahmjeet and Bhupinder (2016)** This Job aims to find the most economical angle section Howe truss by analyzing different spacings, spans and pitches using STAAD.Pro. The study will compare 80 different truss geometries to determine which combination of spacing, span and pitch results in the least steel weight (steel takeoff) calculated manually for loads and then by the software for analysis and design.[10]This addresses the need for an efficient method to select an optimal and cost-effective truss geometry during the design phase.**Varma and Reddy (2016)** Industrial steel chimneys under wind and seismic forces by comparing self-supported and guyed chimneys of varying heights (54m, 72m, 90m) at different wind speeds (33m/s, 44m/s, 50m/s). The study uses STAAD.Pro software to compare maximum lateral displacement and stress, noting that as chimney height increases, wind forces become a predominant factor. [11]**G.S.Mirajkar (2017)** Limit State Method (LSM) this method is a modern approach that offers advantages over both the traditional Working Stress Method (WSM) and the Ultimate Load Method (ULM). [12] **Kumar Jha and M.C.Paliwal (2017)** It describes the scope and methodology of a study on optimizing steel trusses using the fully Stressed Design (FSD) technique in STAAD.Pro V8i software. [13]

H.Sahu and R.Satbhaiya (2019) Nonlinear analysis on three types of steel truss arrangements Fink, Howe and King post for a large, 35mx25m open area using Staad.Pro. The study will also compare how different steel sections (ISHB, channel and angle) affect the results. Trusses are defined as structures where members carry only tension or compression not bending and are assembled to work as a single, strong unit, ideal for creating large open spaces.[14]**P.Bhanarkar and D.Irkullawar (2021)** abstract from an engineering paper comparing various steel sections (Angle Sections, Square Hollow Sections (SHS), Rectangular Hollow Sections (RHS) and Circular Hollow Sections (CHS) for use in trusses, specifically focusing on economy, strength and stability with analysis performed using STAAD.Pro software. The text highlights that tubular sections often offer a more economical and efficient alternative to conventional angle sections, potentially saving 15-20% in material costs due to their better specifications and high flexular strength.[15]**R.S.Mutnal (2021)** Structural steel is an important material used in the construction industry, the main purpose of which is to create a strong skeleton for buildings. This steel, which is 100% recyclable and environment friendly gives shape to the building and holds it together.[16] **Meshram, Sangode and Khedikar (2024)** Structural design and analysis of a multi-story industrial steel truss building, utilizing manual calculations based on Indian Standards (IS) codes. The core components of the building, such as purlins, rafters, roof trusses, wind bracing and columns are described.[17] The analysis specifically incorporates various load combinations, including dead, live and wind loads to evaluate the performance and stability of critical elements like the column base and the steel purlins that support the roof cladding. The findings aim to ensure the buildings safety and performance meet relevant requirements. [17]**Mohammad, Farhana, jaafar, Razman, Surol, Hashim and Azmi (2025) This** research investigate the impact of load combinations and wind pressure on steel structures, aiming to assist engineers in selecting the most suitable construction methods and optimizing section properties for steel structures by anlyzing different load cases and structural sizes using STAAD.Pro software, ultimately highlighting the importance of wind load consideration in bridge design and suggesting further studies on material variations and experimental validations.[18]

3. THEORETICAL FORMULATION

The relevant Code of Practice, IS: 800-1984, applicable to the structural use of hot-rolled steel is largely based on Working Stress Method and results in uneconomic designs. The Limit State Design approach is technically sound and results in significant economy and uniform reliability in completed structures. This method of design also known as load and resistance factor method is not a recent concept. Since 1974 it has been used in Canada and Europe as Limit State Design and as Load and Resistance Factor method in America. IS:800 is in the process of revision and recommends Limit State method for the design of steel elements and structures. Also, it recommends Working Stress method in situations where Limit State method cannot be conveniently adopted.[19]

In the Limit State Design method, the structures is designed to withstand safely all loads likely to act on it throughout its life. It is expected that the structure will satisfy the serviceability requirements, such as limitations of deflection and vibration and will not collapse under accidental loads such as from explosions or impact or due to consequences of human error to an extent not originally expected to occur. The acceptable limit for the safety and serviceability requirements before failure is called a limit state. [20]

The objective of the Limit State design is to achieve a structure that will not become unfit for use with an acceptable target reliability. In other words, the probability of a limit state being reached during its lifetime should be very low. In general, the structure should be designed on the basis of the most critical limit state (on the basis of strength and stability at ultimate load) and then checked for other limit states (deflections, etc. at serviceability loading).[21]

1. Design Procedure of Tension Member

The following design procedure may be adopted

1. Find the required gross area to carry the factored load considering the strength in yielding. i.e.,

$$Ag = \frac{Tu}{(f_y / \gamma m_0)} = \frac{1 \cdot 1Tu}{f_y}$$

$where,$ Tu = factored tensile force.

2. Select suitable shape of the section depending upon the type of structure and the location of the member such that gross area is 25 to 40 per cent more than Ag calculated.
3. Determine the number of bolts or the welding required and arrange.
4. Find the strength considering:
   a) Strength in yielding of gross area
   b) Strength in rupture of critical section and
   c) Strength in block shear

Usually, if minimum edge distance and minimum pitch are maintained, strength in yielding is the least value, hence the design is safe if Ag provided > Ag required.

5. The strength obtained should be more than factored tension, the section may be suitably changed and checked.
6. IS 800-2007 also recommends the check for slenderness ratio of tension members as per the Table 3.1. [20]

Table 1. Maximum values of effective slenderness ratio (From Table 3 of IS 800-2007).[19]

Sr.No.	Member	Max.l/r
1.	A tension member in which a reversal of direct stress occurs due to loads other than wind or seismic forces	180
2.	A member normally acting as a tie in a roof truss or a bracing system not considered effective when subject to possible reversal of stress into compression resulting from the action of wind or earthquake forces	350
3.	Members always under tension other than pretensioned members	400
4.	Tension members, such as bracings, pretensioned to avoid sag, need to satisfy the maximum slenderness ratio limit	No Limit

2. Design Procedure of Compression Member

The following are the usual steps in the design of compression members:

1. Design stress in compression is to be assumed.

For rolled steel beam sections the slenderness ratio varies from 70 to 90. Hence design stress may be assumed as 135 N/mm^2. For angle struts, the slenderness ratio varies from 110 to 130. Hence design stress for such members may be assumed as $90N/mm^2$. For such compression members carrying large loads, the slenderness ratio is comparatively small. For such members design stress may be assumed as 200 N/mm^2.

2. Effective sectional area required is $A = \frac{Pd}{f_{cd}}$
3. Select a section to give effective area required and calculate r_{min}.

4. Knowing the end condition and deciding the type of connection determine effective length.
5. Find the slenderness ratio and hence design stress f_{cd} and load carrying capacity p_d
6. Revise the section if calculated p_d differs considerably from the design load.

Thus, the design of compression member is by a trial-and-error process. [21]

4. PARAMETRIC INVESTIGATION

Various possible structural forms that can be tried for the sugar factory. They are listed here for ready reference.

Alternative 1 – Conventional truss and column system

Alternative 2 - Truss and column system with pipe sections

Alternative 3 – Prismatic gable frame with two channel sections

Alternative 4 – Prismatic gable frame with two pipe sections

Alternative 5 – Prismatic gable frame with four angle sections

Alternative 6 – Prismatic gable frame with four pipe sections

Alternative 7 – Non-prismatic gable frame with two channel sections

Alternative 8 – Non-prismatic gable frame with two pipe sections

Alternative 9 – Non-Prismatic gable frame with four angle sections

Alternative 10 – Non-prismatic gable frame with four pipe sections

Alternative 1 – Conventional truss and column system

A comparative evaluation of these alternatives is performed in this chapter for the mill house of a sugar factory having span 24m, height up to eaves level 16m and total length 66m. The frames are provided at a spacing of 6m c/c. Gantry is also provided in mill house therefore, it is selected for the comparative evaluation of different structural forms. All the alternatives are analyzed as rigid jointed space frames by using STADD-PRO software. Various members are designed by the limit state method (LSM) and total weight is evaluated for each alter

Table 2. Member Details and Weight Calculation for Alternative–1: Conventional Truss and Column System

Sr. No.	**Member**	**Section**	**Wt/m (kN/m)**	**Length of Single Member (m)**	**Nos**	**Total Length (m)**	**Total Weight (kN)**	**Utilization Ratio**
1	Column	2ISMC 300 (0.85 c/c)	0.711	16	24	384	274	0.3-0.8
2	Column lacing	2ISA 35x35x6	0.077	1.6	485	776	60	0.6-0.9
3	Gantry bracket	2ISMC 200	0.438	0.75	72	54	23.7	0.3-0.7
4	Knee brace	2ISA 50x50x6	0.088	1.22	72	58.56	5.15	0.5-0.6
5	Gable end column	2ISMC 400 (0.85 spacing)	0.97	18.5	3	55.5	54	0.5-0.6
6	Gable end column lacing	2ISA35x35x6	0.077	1.6	20	32	2.5	0.5-0.7
	Complete Column	**As above**	**-**	**-**	**-**	**1360**	**419.35**	**-**
7		1) 2ISA 70x70x6	0.124	11.41	20	228	28.3	0.6-0.9

	Principal Rafter	2) 2ISA 110x110x8	0.17	11.41	4	45.6	7.75	0.6-0.9
8	Bottom Member	2ISA 70x70x8	0.124	11.41	24	273.8	34	0.6-0.9
9	Vertical member	1) 2ISA 50x50x6	0.088	2.45	100	245	21.56	0.6-0.9
		2) 2ISA 80x80x8	0.189	2.45	80	196	37	0.6-0.9
10	Inclined member	1) 2ISA 50x50x6	0.088	2.49	120	298.8	26.3	07-0.8
		2) 2ISA 80x80x8	0.189	2.49	48	119.5	22.6	0.6-0.9
	Complete Truss	**As above**	**-**	**-**	**12**	**1406**	**177.51**	**-**
11	Rafter purlin	TATA structure 172x92x4.8	0.183	6	198	1188	217	0.8-0.9
12	Side purlin	ISMC 125	0.125	6	104	625	78	0.5-0.8
13	Tie purlin	ISMC 125	0.125	6	33	198	24.75	0.8-1
14	Tie beam	2ISMC 125	0.25	6	78	468	117	0.5-0.8
15	Sag rod	Tube (40x40x2)	0.023	42.82	12	513.8	11.8	0.6-0.8
16	Bracings	ISA65x65x6 star arrangement	0.114	4.2	144	604.8	69	0.8-0.95
Total						**6364**	**1115**	

Alternative - 2 Conventional Truss and Column System with Pipe Sections

A conventional truss and column system can be effectively implemented using pipe sections, offering a lightweight yet strong structural solution, particularly in applications requiring clear spans and reduced weight. Sections provided for various members of the structures and their total weight calculation is presented in Table 3.

Table 3. Member Details and Weight Calculation for Alternative – 2: Conventional Truss and Column System with Pipe Section

Sr. No.	Member	Section	Wt./m (kN/m)	Length of single member (m)	Nos	Total length (m)	Total Wt. (kN)	Utilization Ratio
1.	Column	2ISMC 400(0.85c/c)	0.97	16	24	384	373	0.1-0.7
2.	Column Lacing	2ISA35x35x6	0.077	1.6	485	776	60	0.6-0.9
3.	Gantry Bracket	2ISMC 200	0.438	0.75	72	54	23.65	0.4-0.7
4.	Knee brace	Tata str. 80x40x4	0.065	1.22	72	87.8	5.7	0.4-0.8
5.	Gable end Column	2ISMC400 (0.85 c/c)	0.97	18.5	3	55.5	54	0.1-0.7
6.	Gable end column lacing	2ISA35x35x6	0.077	1.6	20	32	2.46	0.5-0.7

	Complete Column	**As above**	**-**	**-**	**-**	**1389.3**	**518.81**	**-**
7.	Principal Rafter	Tata str. 122x61x4.5	0.116	11.41	24	274	31.77	0.5-0.9
8.	Bottom Member	Tata str. 122x61x4.5	0.116	11.41	24	274	31.77	0.5-0.9
9.	Vertical member	Tata str. 96x48x4	0.094	2.45	180	441	41.45	0.4-0.9
10.	Inclined member	Tata str. 80x40x4	0.065	2.49	168	418	27.2	0.5-0.9
	Complete Truss	**As above**	**-**	**-**	**12**	**1407**	**132.19**	**-**
11.	Rafter purlin	Tata str. 172x92x4.8	0.183	6	198	1188	217	0.4-0.7
12.	Side purlin	Tata str. 172x92x4.8	0.183	6	104	624	114.2	0.4-0.7
13.	Tie purlin	Tata str. 172x92x4.8	0.183	6	33	198	36.2	0.8-0.9
14.	Tie beam	2ISMC 125	0.250	6	78	468	117	0.4-0.8
15.	Sag rod	Tube 40x40x2	0.023	42.82	12	513.8	11.8	0.4-1
16.	Bracings	ISA65x65x6 star arrangement	0.114	4.2	144	604.8	69	0.8-0.95
Total						**6393**	**1216**	

Alternative – 3 Prismatic Gable Frame with Two Channel Sections

This system consists of a gable frame formed by using two channels connected together with lacing system as shown in Figure 4. The distance between two channels is kept constant which leads to a frame of constant moment of inertia throughout. Sections provided for various members of the structures and their total weight calculation is presented in Table 4.

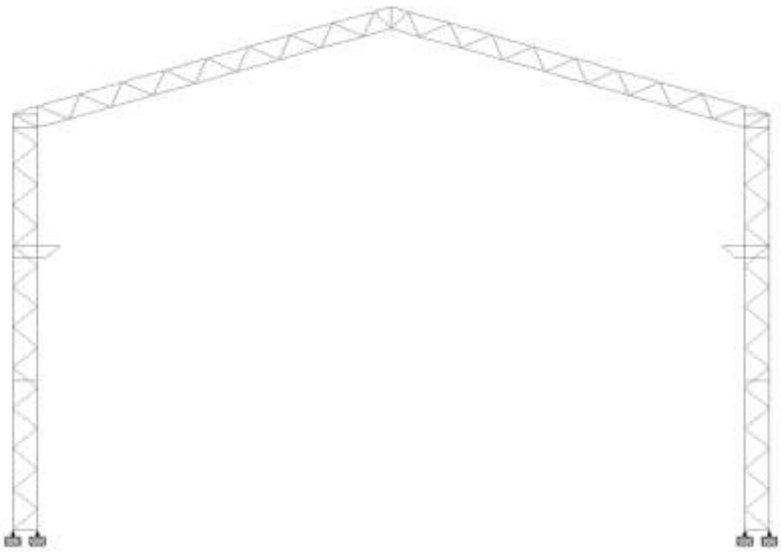

Fig.4. Prismatic Gable Frame with Two Channels

Table 4. Member Details and Weight Calculation for Alternative -3: Prismatic Gable Frame with Two Channel Sections

Sr. No.	Member	Section	Wt./m (kN/m)	Length of single member (m)	No.	Total length (m)	Total weight (kN)	Utilization Ratio
1	Column	ISMC 250	0.298	16	48	768	229	0.3-0.8
2	Column lacing	1)2ISA 35x35x6	0.077	1.6	420	672	51.7	0.6-0.9
		2)2ISA 50x50x6	0.087	1.6	65	104	9	0.4-0.9
3	Gantry Bracket	2ISMC 300	0.711	0.75	96	72	51.2	0.2-0.8
4	Gable end column	2ISMC 400 (0.85 c/c)	0.97	18.5	3	55.5	53.8	0.2-0.6
5	Gable end column lacing	2ISA 35x35x6	0.077	1.6	20	32	2.46	0.5-0.7
	Complete Column	As above	-	-	-	1703.5	397.16	-
6	Rafter Top	ISMC 200	0.216	11.41	24	273.84	59	0.2-0.6
7	Rafter Bottom	ISMC 200	0.216	11.41	24	273.84	59	0.2-0.3
8	Rafter lacing	1)2ISA 35x35x6	0.077	1.6	336	537.6	41.4	0.6-0.9
		2)2ISA 50x50x6	0.087	1.6	204	326.4	28.4	0.6-0.9
	Complete Rafter	As above	-	-	12	1411.68	187.8	-
9	Rafter purlin	Tata str. 172x92x4.8	0.183	6	198	1188	217	0.4-0.7

10	Side purlin	Tata str. 172x92x4.8	0.183	6	104	624	114.2	0.4-0.7
11	Tie purlin	Tata str. 172x92x4.8	0.125	6	33	198	36.2	0.4-0.7
12	Tie beam	2ISMC 125	0.25	6	78	468	117	0.4-0.7
13	Sag rod	Tube 40x40x2	0.023	42.82	12	513.8	11.8	0.4-1
14	Bracings	ISA 65x65x6 star arrangement	0.114	4.2	144	604.8	69	0.8-0.95
Total						6712	1150	

Alternative – 4 Prismatic Gable Frame with Two Pipe Sections

A prismatic gable frame with two pipe sections is a type of structural frame commonly used in buildings, particularly those requiring large clear spans like industrial buildings and warehouses. Sections provided for various members of the structures and their total weight calculation is presented in Table 5.

Table 5. Member Details and Weight Calculation for Alternative – 4: Prismatic Gable Frame with Two Pipe Sections

Sr. No.	**Member**	**Section**	**wt/m (kN/m)**	**Length of single member (m)**	**No.**	**Total length (m)**	**Total weight (kN)**	**Utilization Ratio**
1.	Column	Tube 172x92x4.8	0.183	16	48	768	140.5	0.2-0.7
2.	Column lacing	1)Tube 40x40x4	0.042	1.6	420	672	28.2	0.6-0.9
		2)Tube 48x48x4.5	0.056	1.6	65	104	5.8	0.6-0.8
3.	Gantry Bracket	Tube 172x92x5.4	0.204	0.75	96	72	14.6	0.3-0.9
4.	Gable end Column	2ISMC 400 (0.85 c/c)	0.97	18.5	3	55.5	53.8	0.1-0.5
5.	Gable end column lacing	Tube 40x40x4	0.042	1.6	20	32	1.34	0.5-0.7
	Complete Column	**A above**	**-**	**-**	**-**	**1703.5**	**244.24**	**-**
6.	Rafter Top	Tube 75x75x4.9	0.100	11.41	24	274	27.4	0.4-1
7.	Rafter Bottom	Tube 75x75x4.9	0.100	11.41	24	274	27.4	0.4-1
8.	Rafter lacing	1)Tube 40x40x4	0.042	1.6	336	537	22.5	0.6-0.9
		2)Tube 48x48x4.5	0.056	1.6	204	326	18.2	0.6-0.9
	Complete Rafter	**-**	**-**	**-**	**12**	**1411**	**95.5**	**-**
9.	Rafter purlin	Tata str. 172x92x4.8	0.183	6	198	1188	217	0.4-0.6
10.	Side purlin	Tata str. 172x92x4.8	0.183	6	104	624	114.2	0.4-0.6
11.	Tie purlin	ISMC125	0.125	6	33	198	36.2	0.8-0.9
12.	Tie beam	2ISMC 125	0.250	6	78	468	117	0.4-0.7

13.	Sag rod	Tube 40x40x2	0.023	42.82	12	513.8	11.8	0.4-1
14.	Bracings	ISA 65x65x6 star arrangement	0.114	4.2	144	604.8	69	0.8-0.95
Total						**6711**	**905**	

Alternative – 5 Prismatic Gable Frame with Four Angle Sections

The sway of the gable frames is substantially less as compared to the conventional truss and column system particularly when wind is blowing perpendicular to ridge. However the sway parallel to ridge may be same as that of the first alternative due to restriction of size of column in that direction. This limitation may be overcome by using four angles instead of that two channels so that the distance in z-direction between the angles may be increased in order to increase the stability and reduce the sway in that direction. Sections provided for various members of the structures and their total weight calculation is presented in Table 6

Table 6. Member Details and Weight Calculation for Alternative – 5: Prismatic Gable Frame with Four Angle Section

Sr. No.	Member	Section	Wt/m (kN/m)	Length of single member (m)	No.	Total length (m)	Total weight (kN)	Utilization Ratio
1.	Column	ISA100x100x8	0.118	16	96	1536	182	0.3-0.9
2.	Column lacing	2ISA35x35x6	0.077	1.6	970	1552	119.2	0.6-0.9
3.	Gantry Bracket	ISMC200	0.216	0.75	96	72	15.5	0.7-0.9
4.	Gable end Column	2ISMC 400 (0.85 c/c)	0.97	18.5	3	55.5	53.8	0.2-0.9
5.	Gable end column lacing	Tube 40x40x4	0.042	1.6	20	32	1.34	0.5-0.7
	Complete Column	**-**	**-**	**-**	**-**	**3247.5**	**371.84**	**-**
6.	Rafter Top	ISA100x100x8	0.118	11.41	24	274	32.3	0.6-0.9
7.	Rafter Bottom	ISA80x80x6	0.094	11.41	24	274	25.7	0.6-0.9
8.	Rafter lacing	2ISA35x35x6	0.077	1.6	1080	1728	133	0.6-0.9
	Complete Rafter	**-**	**-**	**-**	**12**	**2276**	**191**	**-**
9.	Rafter purlin	Tata structure 172x92x4.8	0.183	6	198	1188	217	0.5-0.8
10.	Side purlin	Tata structure 172x92x4.8	0.183	6	104	624	114.2	0.5-0.8
11.	Tie beam	Tata structure 172x92x4.8	0.183	6	78	468	85.65	0.5-0.8
12.	Sag rod	Tube 40x40x2	0.023	1.75	315	552	12.7	0.2-0.9
13.	Bracings	ISA 65x65x6 star arrangement	0.114	4.2	144	604.8	69	0.8-0.95
Total						**8960**	**1061**	

Alternative – 6 Prismatic Gable Frame with Four Pipe Sections

A prismatic gable frame with four pipe sections would refer to a type of gable frame structure where each structural element (columns and inclined rafters) has a uniform cross-section along its length (prismatic) and these members are fabricated from circular or rectangular hollow structural steel sections (pipe sections). Gable frames are characterized by their inclined sides and high peak. Sections provided for various members of the structures and their total weight calculation is presented in Table 7

Table 7. Member Details and Weight Calculation for Alternative – 6: Prismatic Gable Frame with Four Pipe Sections

Sr. No.	Member	Section	Wt/m (kN/m)	Length of single member (m)	No.	Total length (m)	Total weight (kN)	Utilization Ratio
1.	Column	Outside-Tata structure 72x72x4	0.080	16	48	768	61.4	0.2-0.8
		Inside- Tata structure 91.5x91.5x4.5	0.138	16	48	768	106	0.3-0.7
2.	Column lacing	Tube 40x40x4	0.042	1.6	970	1552	65	0.2-0.5
3.	Gantry Bracket	Tube 172x92x5.4	0.204	0.75	96	72	14.7	0.2-0.8
4.	Gable end Column	2ISMC 400 (0.85 c/c)	0.97	18.5	3	55.5	53.8	0.2-0.5
5.	Gable end column lacing	Tube 40x40x4	0.042	1.6	20	32	1.34	0.5-0.7
	Complete Column	**As above**	**-**	**-**	**-**	**3247.5**	**302.24**	**-**
6.	Rafter Top	Tata structure 60x60x4.8	0.077	11.41	24	274	21	0.3-0.6
7.	Rafter Bottom	Tata structure 60x60x4.8	0.077	11.41	24	274	21	0.3-0.6
8.	Rafter lacing	1)Tube 40x40x4	0.042	1.6	1080	1728	73	0.2-0.5
	Complete Rafter	**As above**	**-**	**-**	**12**	**2276**	**115**	**-**
9.	Rafter purlin	Tata structure 172x92x4.8	0.183	6	198	1188	217	0.2-0.5
10.	Side purlin	Tata structure 172x92x4.8	0.183	6	104	624	114.2	0.2-0.5
11.	Tie beam	Tata structure 172x92x4.8	0.183	6	78	468	85.65	0.2-0.5
12.	Sag rod	Tube 40x40x2	0.023	1.75	315	552	12.7	0.6-0.7
13.	Bracings	ISA 65x65x6 star arrangement	0.114	4.2	144	604.8	69	0.8-0.95
Total							**916**	

Alternative – 7 Non-Prismatic Gable Frame with Four Pipe Sections

A non-prismatic gable frame with four pipe sections refers to a gable shaped steel structure where the members (the rafters and columns) are not uniform in cross-section (non-prismatic) and are constructed from four separate pipe sections. This design is commonly used in industrial buildings, offering a balance between structural efficiency and material usage. Sections provided for various members of the structures and their total weight calculation is presented in Table 8

Table 8. Member Details and Weight Calculation for Alternative – 7: Non-Prismatic Gable Frame with Four Pipe Sections

Sr. No.	Member	Section	Wt/m (kN/m)	Length of single member (m)	No.	Total length (m)	Total weight (kN)	Utilization Ratio
1.	Column	Outside Leg – Tata structure 72x72x4	0.080	16	48	768	61.4	0.3-0.8
		Inside Leg – Tata structure 91.5x91.5x4.5	0.138	16	48	768	106	0.3-0.8
2.	Column lacing	Tube 40x40x4	0.042	1.6	970	1552	65	0.2-0.8
3.	Column haunches	Tata structure 72x72x4	0.080	1	396	396	31.6	0.2-0.5
4.	Gantry Bracket	Tube 172x92x5.4	0.204	0.75	96	72	14.7	0.2-0.8
5.	Gable end Column	2ISMC 400 (0.85 c/c)	0.97	18.5	3	55.5	53.8	0.2-0.4
6.	Gable end column lacing	Tube 40x40x4	0.042	1.6	20	32	1.34	0.5-0.8
	Complete Column	**As above**	**-**	**-**	**-**	**3603**	**333.84**	**-**
7.	Rafter Top	Tata structure 60x60x4.8	0.077	11.41	24	274	21.08	0.3-0.6
8.	Rafter Bottom	Tata structure 60x60x4.8	0.077	11.41	24	274	21.08	0.3-0.6
9.	Rafter lacing	Tube 40x40x4	0.042	1.6	1080	1728	72.6	0.2-0.8
10.	Rafter haunches	Tata structure 60x60x4.8	0.077	1	198	198	15.2	0.2-0.5
	Complete Rafter	**As above**	**-**	**-**	**12**	**2474**	**129.96**	**-**
11.	Rafter purlin	Tata structure 172x92x4.8	0.183	6	198	1188	217	0.2-0.8
12.	Side purlin	Tata structure 172x92x4.8	0.183	6	104	624	114.2	0.2-0.8
13.	Tie beam	Tata structure 172x92x4.8	0.183	6	78	468	117	0.2-0.8
14.	Bracings	ISA 65x65x6 star arrangement	0.114	4.2	144	604.8	69	0.8-0.95
Total						**8962**	**981**	

Alternative - 8 Non-Prismatic Gable Frame with Four Angle Sections

This frame is similar to the frame described in alternative-V. The only difference is that the depth of section is increased at few locations in order to reduce stresses as mentioned in alternative-X such a frame is shown in Figure 5. Sections provided for various members of the structures and their total weight calculation is presented in Table 9

Table 9. Member Details and Weight Calculation for Alternative – 8: Non-Prismatic Gable Frame with Four Angle Sections

Sr. No.	Member	Section	Wt/m (kN/m)	Length of single member (m)	No.	Total length (m)	Total weight (kN)	Utilization Ratio
1.	Column	ISA100x100x8	0.118	16	48	768	90.6	0.4-0.8
		ISA110x110x8	0.170	16	48	768	130.6	0.4-0.9
2.	Column lacing	2ISA35x35x6	0.077	1.6	970	1552	119.5	0.6-0.9
3.	Column haunches	ISA65x65x6	0.074	1	396	396	29.3	0.5-0.7
4.	Gantry Bracket	ISMC200	0.216	0.75	96	72	15.5	0.4-0.9
5.	Gable end Column	2ISMC 400 (0.85 c/c)	0.97	18.5	3	55.5	53.8	0.7-0.9
6.	Gable end column lacing	Tube 40x40x4	0.042	1.6	20	32	1.34	0.5-0.7
	Complete Column	**As above**	**-**	**-**	**-**	**3643.5**	**440.64**	**-**
7.	Rafter Top	ISA 90x90x8	0.137	11.41	24	274	37.5	0.6-0.9
8.	Rafter Bottom	ISA75x75x6	0.086	11.41	24	274	23.6	0.5-0.7
9.	Rafter lacing	1)2ISA 35x35x6	0.077	1.6	1000	1600	112	0.5-0.7
		2)2ISA 50x50x6	0.087	1.6	80	128	11.14	0.5-0.7
10.	Rafter haunches	ISA65x65x6	0.074	1	198	198	14.6	0.5-0.7
	Complete Rafter	**As above**	**-**	**-**	**12**	**2474**	**198.84**	**-**
11.	Rafter purlin	Tata structure 172x92x4.8	0.183	6	198	1188	217	0.4-0.6
12.	Side purlin	Tata structure 172x92x4.8	0.183	6	104	624	114.2	0.4-0.6
13.	Tie beam	Tata structure 172x92x4.8	0.183	6	78	468	117	0.4-0.7
14.	Bracings	ISA 65x65x6 star arrangement	0.114	4.2	144	604.8	69	0.8-0.95
Total						**9002**	**1157**	

Alternative -9 Non-Prismatic Gable Frame with Two Pipe Sections

The design approach offers a unique blend of structural efficiency and aesthetic possibilities. Sections provided for various members of the structures and their total weight calculation is presented in Table 10.

Table 10. Member Details and Weight Calculation for Alternative – 9: Non-Prismatic Gable Frame with Two Pipe Section

Sr. No.	Member	Section	Wt/m (kN/m)	Length of single member (m)	No.	Total length (m)	Total weight (kN)	Utilization Ratio
1.	Column	Tube 172x92x4.8	0.180	16	48	768	138.2	0.2-0.8
2.	Column lacing	1)Tube 40x40x4	0.042	1.6	440	704	30	0.4-0.9
		2)Tube 48x48x4.5	0.056	1.6	25	40	2.24	0.7-0.8
3.	Column haunches	Tube 172x92x4.8	0.180	1	216	216	39	0.2-0.5
4.	Gantry Bracket	Tube 172x92x5.4	0.204	0.75	96	72	14.68	0.3-0.9
4.	Gable end Column	2ISMC 400 (0.85 c/c)	0.97	18.5	3	55.5	53.8	0.2-0.9
5.	Gable end column lacing	Tube 40x40x4	0.042	1.6	20	32	1.34	0.5-0.7
	Complete Column	**As above**	**-**	**-**	**-**	**1887.5**	**279.26**	**-**
6.	Rafter Top	Tube 75x75x4.9	0.100	11.41	12	137	13.70	0.5-0.8
7.	Rafter Bottom	Tube 38x38x4	0.039	11.41	12	137	5.33	0.3-0.6
8.	Rafter lacing	1)Tube 40x40x4	0.042	1.6	440	704	30	0.4-0.9
		2)Tube 48x48x4.5	0.056	1.6	100	160	9	0.7-0.8
9.	Rafter haunches	Tube 38x38x4	0.039	1	108	108	4.2	0.2-0.5
	Complete Rafter	**As above**	**-**	**-**	**12**	**1246**	**62.23**	**-**
10.	Rafter purlin	Tata str. 172x92x4.8	0.183	6	198	1188	217	0.8-0.9
11.	Side purlin	Tata structure 172x92x4.8	0.183	6	104	624	114.2	0.8-0.9
12.	Tie beam	Tata structure 172x92x4.8	0.183	6	78	468	85.65	0.8-0.9
13.	Bracings	ISA 65x65x6 star arrangement	0.114	4.2	144	604.8	69	0.8-0.95
Total						**6018**	**747**	

Alternative -10 Non-Prismatic Gable Frame with Two Channel Sections

The bending moments in a gable frame of alternative-III are normally large at eaves level and at the crown. An increase in moment of inertia at these locations may help in reducing the stresses. It is achieved by providing haunches at these locations as shown in Figure 6. Sections provided for various members of the structures and their total weight calculation is presented in Table 11.

Table 11. Member Details and Weight Calculation for Alternative -10: Non-Prismatic Gable Frame with Two Channel Sections

Sr. No.	Member	Section	Wt/m (kN/m)	Length of single member (m)	No.	Total length (m)	Total weight (kN)	Utilization Ratio
1.	Column	ISMC 250	0.298	16	48	768	289	0.2-0.8
2.	Column lacing	1)2ISA35x35x6	0.077	1.6	440	704	54.20	0.5-0.8
		2)2ISA50x50x6	0.088	1.6	25	40	3.52	0.4-0.6
3.	Column haunches	ISMC 250	0.298	1	216	216	64.36	0.2-0.4
3.	Gantry Bracket	ISMC200	0.216	0.75	96	72	15.55	0.3-0.9
4.	Gable end Column	2ISMC 400 (0.85 c/c)	0.97	18.5	3	55.5	53.8	0.1-0.5
5.	Gable end column lacing	Tube 40x40x4	0.042	1.6	20	32	1.34	0.5-0.8
	Complete Column	**As above**	**-**	**-**	**-**	**1887.5**	**481.77**	**-**
6.	Rafter Top	ISMC 200	0.216	11.41	24	274	60	0.3-0.7
7.	Rafter Bottom	ISMC 200	0.216	11.41	24	274	60	0.3-0.7
8.	Rafter lacing	1)2ISA35x35x6	0.077	1.6	440	704	55.20	0.5-0.8
		2)2ISA50x50x6	0.088	1.6	100	160	14	0.4-0.6
9.	Rafter haunches	ISMC 200	0.216	1	108	108	24	0.2-0.5
	Complete Rafter	**As above**	**-**	**-**	**12**	**1520**	**213.2**	**-**
10.	Rafter purlin	Tata structure 172x92x4.8	0.183	6	198	1188	217	0.4-0.6
11.	Side purlin	Tata structure 172x92x4.8	0.183	6	104	624	114.2	0.4-0.6
12.	Tie beam	Tata structure 172x92x4.8	0.183	6	78	468	85.65	0.4-0.7
13.	Bracings	ISA 65x65x6 star arrangement	0.114	4.2	144	604.8	69	0.8-0.95
	Total					**6292**	**1181**	

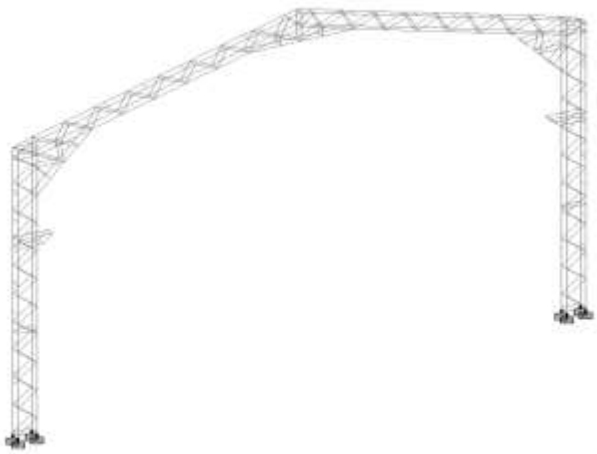

Fig.5 Non-Prismatic Gable Frame with Four angles

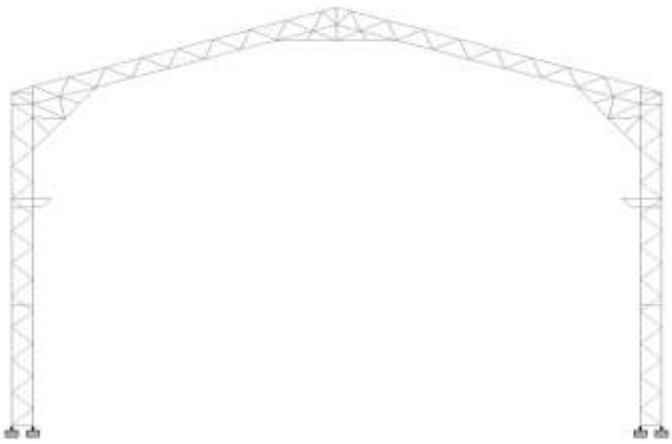

Fig.6. Non-Prismatic Gable Frame with Two Channels

Table 12. Weight of Various Members of All Alternatives in % of Total Weight

Sr. No.	Alternative	Primary System		Secondary System			Tertiary System			Total Weight (kN)	Maximum Deflection (mm)
		Columns (%)	Truss/ Rafter (%)	Rafter Purlin (%)	Side Purlin (%)	Tie Beam (%)	Sag Rod (%)	Tie Purlin (%)	Bracings (%)		
1.	Conventional Truss and Column System	37.6	15.9	19.4	7.0	10.4	1	2.2	6.1	1115	δx = 81.45
2.	Conventional Truss and Column System with Pipe Sections for truss and channels for columns	37.5	11.8	19.4	9.4	10.4	1	3.2	6.1	1216	δy = 27.14
3.	Prismatic Gable Frame with Two Channel Sections	34.5	16.3	18.8	9.9	10.1	1	3.1	6	1150	δx = 24.2
4.	Prismatic Gable Frame with Two Pipe Sections	26.9	10.5	23.9	12.6	12.9	1.3	4	7.6	905	δx = 57
5.	Prismatic Gable Frame with Four Angel Sections	35.0	18	20.4	10.7	8	1.1	3.4	6.5	1061	δx = 51
6.	Prismatic Gable Frame with Four Pipe Sections	32.9	12.5	23.6	12.4	9.3	1.3	3.9	7.5	916	δx = 73.8
7.	Non-Prismatic Gable Frame with Four Pipe Sections	34.0	13.2	22.1	11.6	11.9	1.2	3.6	7	981	δx = 38.7
8.	Non-Prismatic Gable Frame with Four Angle Sections	38.0	17.1	18.7	9.8	10.1	1.0	3.1	5.9	1157	δx = 32
9.	Non-Prismatic Gable Frame with Two Pipe Sections	37.3	8.3	29.0	15.2	11.4	1.6	4.8	9.2	747	δx = 42
10.	Non-Prismatic Gable Frame with Two Channel Sections	40.8	18	18.3	9.7	7.2	1.0	3.0	5.8	1181	δx =15.6

5. RESULTS AND DISCUSSIONS

Comparative evaluation of various members of different alternatives is presented in Table 12. Following points can be observed from the table and the figures.

- The load carrying systems in steel structures can be divided into primary system consisting of columns and trusses or rafters, secondary systems consisting of purlins and beams connecting columns and tertiary system consisting of various types of bracings and ties. It can be observed that the primary and secondary systems each consume 37%-54% of the total weight of steel and the tertiary system consumes 9%-16% of the total weight.
- Structural alternatives can be classified in various ways. Depending upon sections used for various members such as pipe sections or open sections like angle or channel sections, based on systems used to support the roof such as trusses or built-up rafter

like systems and based on the form such as prismatic and non-prismatic forms of the structures. Table 12. reveals that the optimum weight depends broadly on above three factors.

- All the alternatives using pipe sections for the members consume less weight than those with open sections like angle and channel sections. Pipe sections due to their shape and comparatively lesser thickness for the same weight have more radius of gyration leading to lesser slenderness ratios. Even in second alternative wherein pipe section is used for truss and channel sections for columns, the weight of truss with pipe sections is less as compared to the first alternative.
- Last column of Table 12. shows the maximum deflections in the structure. As the height of structure is 16m, the maximum permissible deflection in lateral direction $\delta x = 16000/325 = 49$ mm. Maximum lateral deflection is observed in case of alternative-1, where trusses are used. Trusses are very flexible in lateral direction and cannot provide effective lateral support to the frames leading to large deformations. This requires either trusses to be made box type or size of columns need to be increased as done in the second alternative. Though deflection in second alternative is reduced however, weight of the structure is substantially increased and it is highest amongst all the alternatives tried.
- Lateral deflection in prismatic frame structures with two channels (alternative-3) is substantially reduced. However, use of channel sections for the primary system substantially increases weight of structure.
- Weight of structure in prismatic frames with pipes or angle sections (alternatives 4 to 6) substantially reduces as compared to the first three alternatives. However, lateral deflections are more in the prismatic frames as compared to the non-prismatic frames.
- Non-prismatic gable frames with two pipe sections (alternatives 9) gives minimum weight and lateral deflections are also within permissible limits. However, its stability in perpendicular direction is a problem due to very small lateral dimension and stiffness.
- Non-prismatic gable frames with four pipe sections (alternatives 7) seems to be a better choice from optimum weight, lateral deflections and stability in the perpendicular direction point of view.

Thus, the study shows importance of choice of structural system, its form and type of sections to be used in optimising weight and stability of large size steel structures.

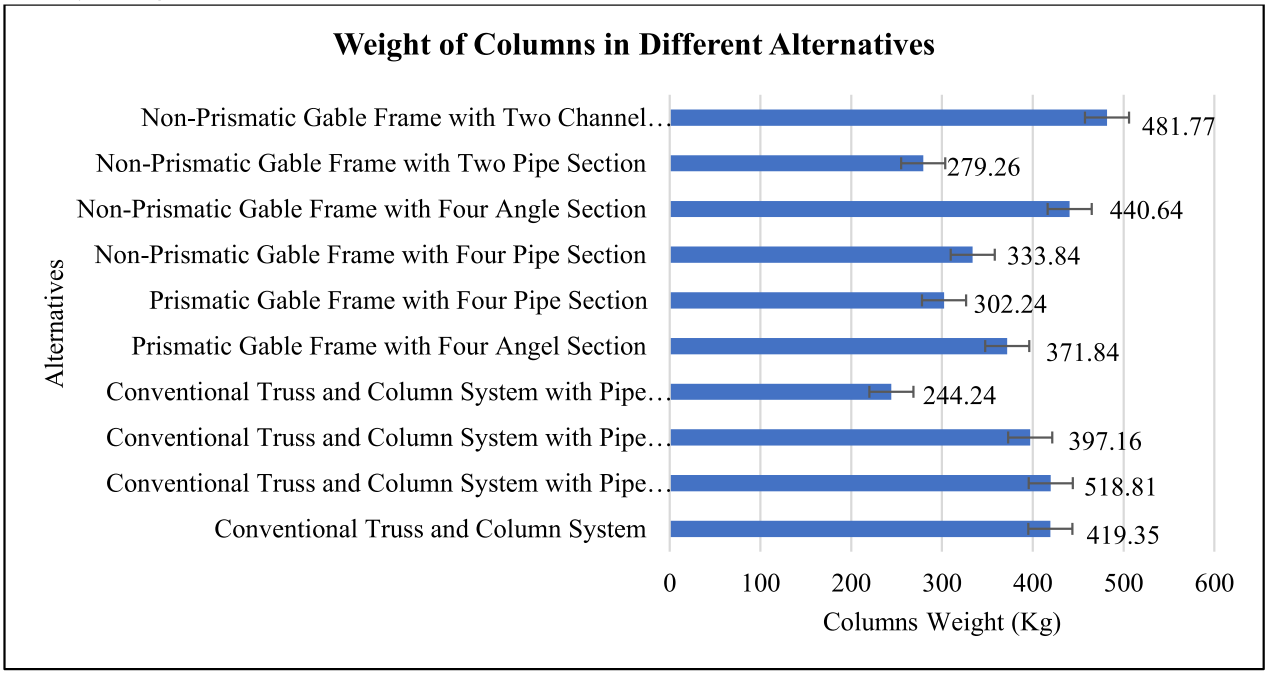

Fig.7. Weight of Columns in Different Alternatives

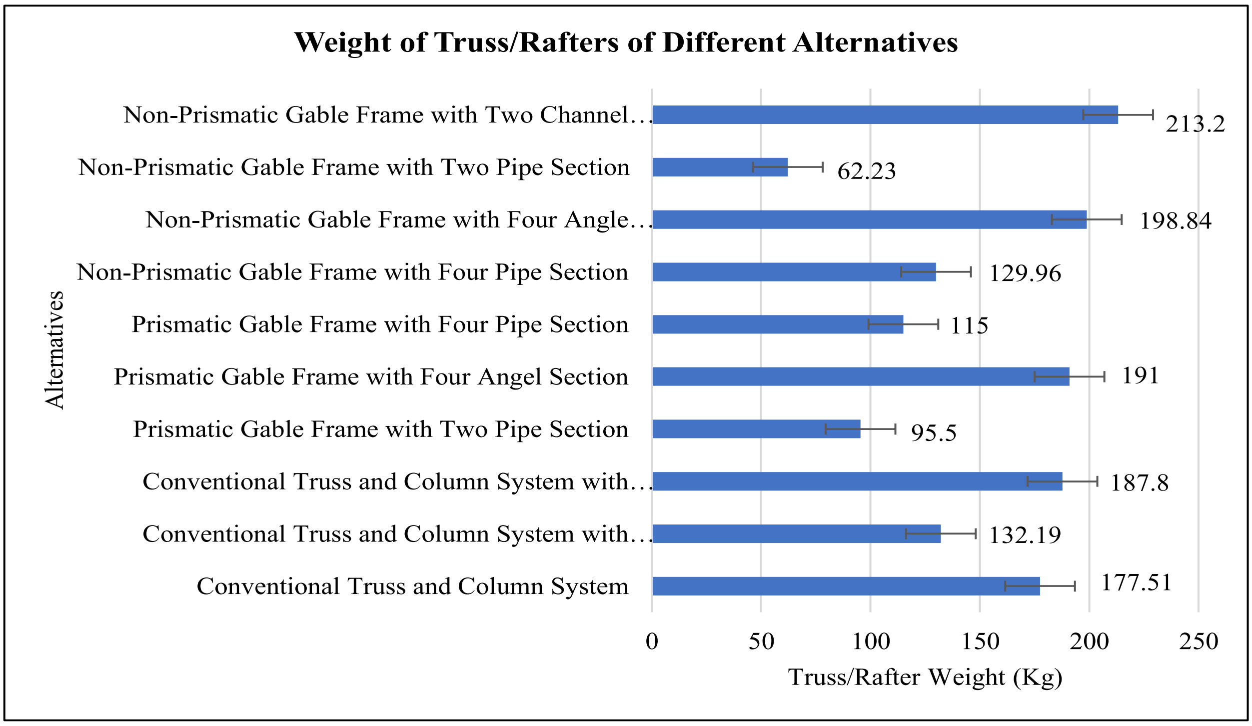

Fig.8. Weight of Truss/Rafters of Different Alternatives

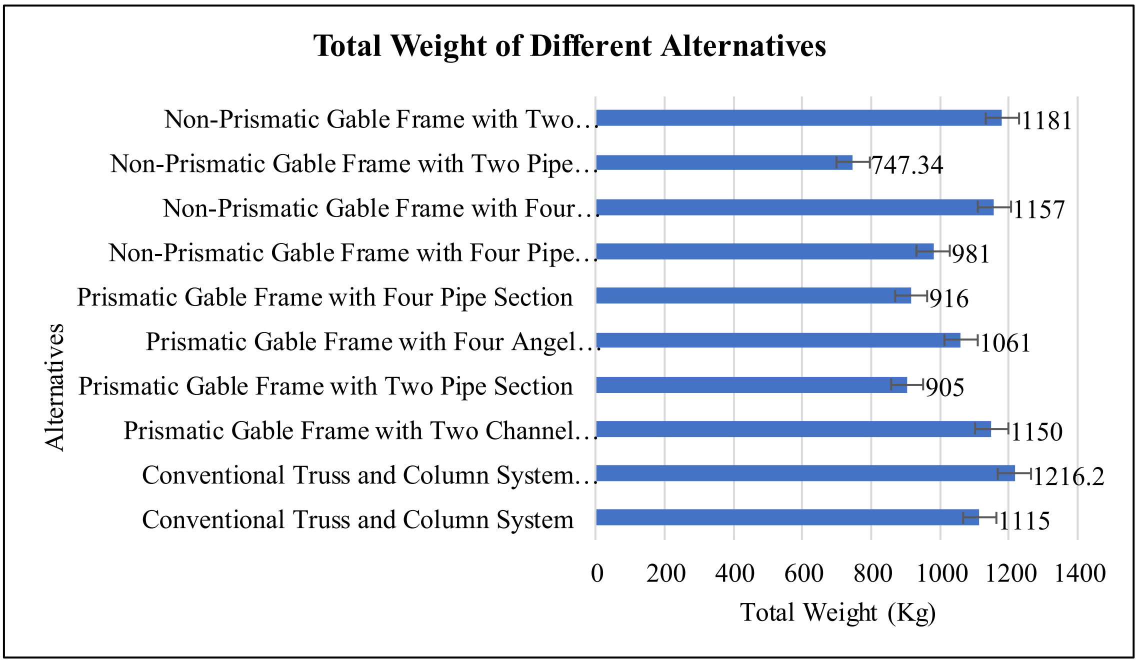

Fig.9. Total Weight of Different Alternatives

6. CONCLUSIONS

Parametric investigation is performed for different alternative structural forms for sugar factories in this dissertation. The study highlights significance of selecting appropriate structural system, its form and the type of sections to be used for optimizing weight of large sized steel structures. This is based on analysis of various alternatives and their impact on lateral deflection and structural weight. Optimal weight of steel structures depends on factors like the type of sections used (pipe or open sections) the roof support system (trusses or built-up rafters), and the form of the structure (prismatic or non-prismatic). The detail discussion and conclusions are presented earlier that are summarized here. Few prominent conclusions are as follows:

- The load carrying systems in steel structures can be divided into primary system consisting of columns and trusses or rafters, secondary systems consisting of purlins and beams connecting columns and tertiary system consisting of various types of bracings and ties. It can be observed that the primary and secondary systems each consume 37%-54% of the total weight of steel and the tertiary system consumes 9%-16% of the total weight.
- Notably, pipe sections are found to be more efficient than open sections due to their shape and higher radius of gyration, leading to reduced slenderness ratios and overall reduction in weights of different members.
- Trusses are very flexible in lateral direction and cannot provide effective lateral support to the frames leading to large deformations. This requires either trusses to be made box type or size of columns need to be increased as done in the second alternative.
- Lateral deflections in prismatic frames are more as compared to the non-prismatic frames.
- Non-prismatic gable frames with two pipe sections (alternatives 9) gives minimum weight and lateral deflections are also within permissible limits. However, its stability in perpendicular direction is a problem due to very small lateral dimension and stiffness.
- Non-prismatic gable frames with four pipe sections (alternatives 7) seems to be a better choice from optimum weight, lateral deflections and stability in the perpendicular direction point of view.

Thus, the study shows importance of choice of structural system, its form and type of sections to be used in optimising weight and stability of large size steel structures.

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Part 2-Imposed loads

Part 3-Wind loads

3. IS: 1893-2002(Part 1) Criteria for Earthquake Resistant Design of Structures

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