STEEL BUILDINGS IN EUROPE

Single-Storey Steel Buildings
Part 2: Concept Design

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FOREWORD

This publication is a second part of a design guide, *Single-Storey Steel Buildings*.

The 11 parts in the *Single-Storey Steel Buildings* guide are:

Part 1: Architect's guide
Part 2: Concept design
Part 3: Actions
Part 4: Detailed design of portal frames
Part 5: Detailed design of trusses
Part 6: Detailed design of built up columns
Part 7: Fire engineering
Part 8: Building envelope
Part 9: Introduction to computer software
Part 10: Model construction specification
Part 11: Moment connections

Single-Storey Steel Buildings is one of two design guides. The second design guide is *Multi-Storey Steel Buildings.*

The two design guides have been produced in the framework of the European project "Facilitating the market development for sections in industrial halls and low rise buildings (SECHALO) RFS2-CT-2008-0030".

The design guides have been prepared under the direction of Arcelor Mittal, Peiner Träger and Corus. The technical content has been prepared by CTICM and SCI, collaborating as the Steel Alliance.

Contents

SUMMARY

This publication presents information necessary to assist in the choice and use of steel structures at the concept design stage in modern single storey buildings. The primary sector of interest is industrial buildings, but the same information may also be used in other sectors, such as commercial, retail and leisure. The information is presented in terms of the design strategy, anatomy of building design and structural systems that are relevant to the single storey buildings. Other parts in the guide cover loading, the concept design of portal frames, the concept design of trusses and cladding.

1 INTRODUCTION

Single storey buildings use steel framed structures and metallic cladding of all types. Large open spaces can be created, which are efficient, easy to maintain and are adaptable as demand changes. Single storey buildings are a “core” market for steel. However, the use of steel in this type of construction varies in each European country.

Single storey buildings tend to be large enclosures, but may require space for other uses, such as offices, handling and transportation, overhead cranes etc. Therefore, many factors have to be addressed in their design.

Increasingly, architectural issues and visual impact have to be addressed and many leading architects are involved in modern single storey buildings.

This section describes the common forms of single storey buildings that may be designed and their range of application. Regional differences may exist depending on practice, regulations and capabilities of the supply chain.

1.1 Hierarchy of design decisions

The development of a design solution for a single storey building, such as a large enclosure or industrial facility is more dependent on the activity being performed and future requirements for the space than other building types, such as commercial and residential buildings. Although these building types are primarily functional, they are commonly designed with strong architectural involvement dictated by planning requirements and client ‘branding’.

The following overall design requirements should be considered in the concept design stage of industrial buildings and large enclosures, depending on the building form and use:

- Space use, for example, specific requirements for handling of materials or components in a production facility
- Flexibility of space in current and future use
- Speed of construction
- Environmental performance, including services requirements and thermal performance
- Aesthetics and visual impact
- Acoustic isolation, particularly in production facilities
- Access and security
- Sustainability considerations
- Design life and maintenance requirements, including end of life issues.

To enable the concept design to be developed, it is necessary to review these considerations based on the type of single storey building. For example, the requirements for a distribution centre will be different to a manufacturing facility. A review of the importance of various design issues is presented in Table 1.1 for common building types.

Table 1.1 Important design factors for single storey buildings

Type of single storey buildings	Space requirements	Flexibility of use	Speed of construction	Access and Security	Standardization of components	Environmental performance	Aesthetics and visual impact	Acoustic isolation	Design life, maintenance and re-use
High bay warehouses	✓✓	✓✓	✓✓	✓✓	✓✓	✓	✓		
Manufacturing facility	✓✓	✓✓	✓	✓✓	✓		✓	✓✓	✓
Distribution centres	✓✓	✓✓	✓✓	✓✓	✓✓	✓	✓		✓
Retail superstores	✓✓	✓✓	✓	✓✓	✓✓	✓✓	✓✓		✓
Storage/cold storage	✓	✓	✓	✓✓	✓	✓✓	✓		✓✓
Office and light manufacturing	✓	✓	✓	✓	✓	✓✓	✓	✓✓	✓
Processing facility	✓		✓	✓✓	✓	✓		✓✓	✓
Leisure centres	✓	✓✓	✓	✓	✓	✓✓	✓✓	✓	✓
Sports halls	✓✓	✓✓	✓	✓	✓	✓✓	✓✓		✓
Exhibition halls	✓✓	✓✓	✓	✓✓	✓	✓✓	✓✓	✓✓	✓
Aircraft hangars	✓✓	✓	✓	✓✓	✓	✓	✓	✓	✓

Legend: No tick = Not important ✓ = important ✓✓ = very important

1.2 Architectural design

Modern single storey buildings using steel are both functional in use and are designed to be architecturally attractive. Various examples are presented below together with a brief description of the design concept. A variety of structural solutions are possible, which are presented in Sections 2 and 3.

1.2.1 Building form

The basic structural form of a single storey building may be of various generic types, as shown in Figure 1.1. The figure shows a conceptual cross-section through each type of building, with notes on the structural concept, and typical forces and moments due to gravity loads.

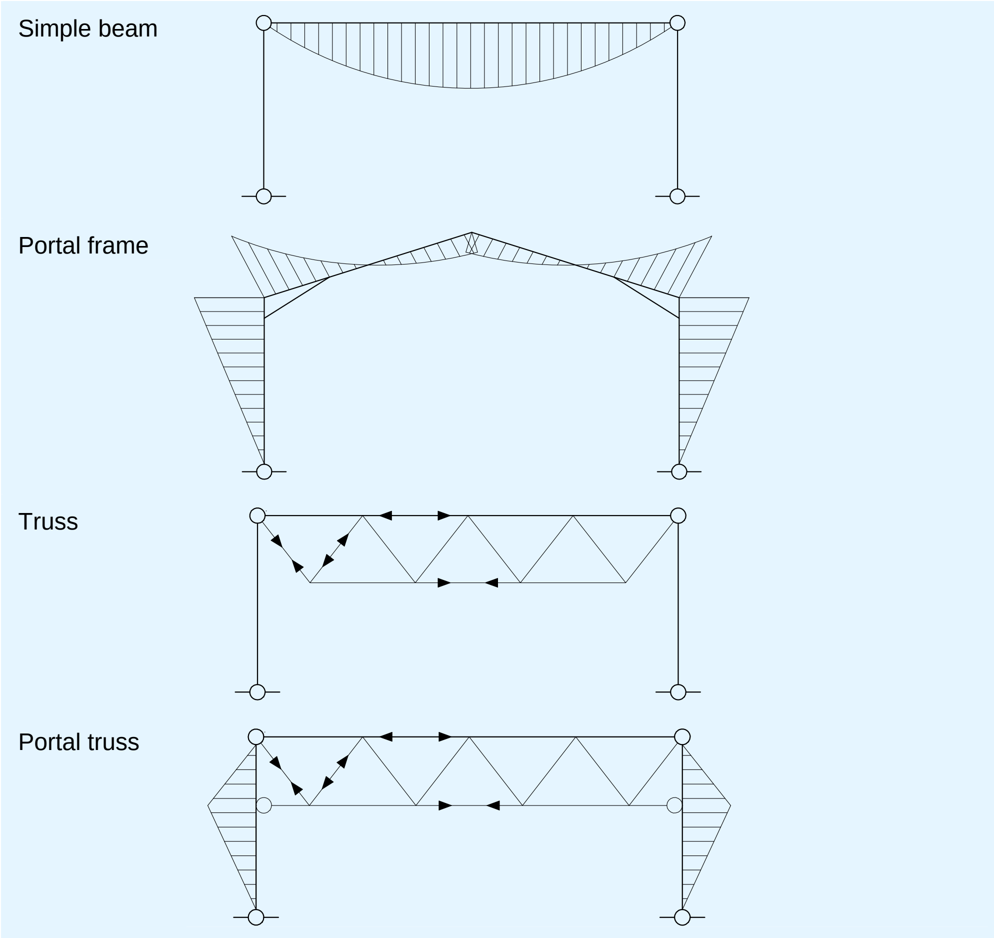


Figure 1.1 Structural concepts

The basic design concepts for each structural type are described below:

Simple roof beam, supported on columns.

The span will generally be modest, up to approximately 20 m. The roof beam may be pre-cambered. Bracing will be required in the roof and all elevations, to provide in-plane and longitudinal stability.

Portal frame

A portal frame is a rigid frame with moment resisting connections to provide stability in-plane. A portal frame may be single bay or multi bay as shown in Figure 1.2. The members are generally plain rolled sections, with the resistance of the rafter enhanced locally with a haunch. In many cases, the frame will have pinned bases.

Stability in the longitudinal direction is provided by a combination of bracing in the roof, across one or both end bays, and vertical bracing in the elevations. If vertical bracing cannot be provided in the elevations (due to industrial doors, for example) stability is often provided by a rigid frame within the elevation.

Trusses

Truss buildings generally have roof bracing and vertical bracing in each elevation to provide stability in both orthogonal directions, as in Figure 1.4. The trusses may take a variety of forms, with shallow or steep external roof slopes.

A truss building may also be designed as rigid in-plane, although it is more common to provide bracing to stabilise the frame.

Other forms of construction

Built–up columns (two plain beams, connected to form a compound column) are often used to support heavy loads, such as cranes. These may be used in portalised structures, but are often used with rigid bases, and with bracing to provide in-plane stability.

External or suspended support structures may be used, as illustrated in Figure 1.6, but are relatively uncommon.

Figure 1.2 Multi bay portal frame structure

Figure 1.3 Use of curved cellular beams in a portal frame

Figure 1.4 Roof trusses and built-up columns

Figure 1.5 Curved cellular beams used in a leisure centre

Figure 1.6 External structure supporting a single storey building

1.3 Choice of building type

Portal frames are considered to be a highly cost-effective way to provide a single storey enclosure. Their efficiency depends on the method of analysis, and the assumptions that are made regarding the restraint to the structural members, as shown in Table 1.2. The assumptions about member stability may vary between countries.

Table 1.2 Efficient portal frame design

Most Efficient	Less Efficient
Analysis using elastic-plastic software	Elastic analysis
Cladding considered to restrain the flange of the purlins and side rails	Purlins and side rails unrestrained
Purlins and side rails used to restrain both flanges of the hot-rolled steelwork	The inside flange of the hot rolled steelwork is unrestrained
Nominal base stiffness utilised	Nominal base stiffness ignored

The reasons for choosing simple beam structures, portal frames or trusses are shown in Table 1.3.

Table 1.3 Comparison of basic structural forms for single storey buildings

Simple beam	Portal frame	Truss
Advantages		
Simple design	Long span	Very long spans possible
	Designed to be stable in-plane	Heavy loads may be carried
	Member sizes and haunches may be optimised for efficiency	Modest deflection
Disadvantages		
Relatively short span	Software required for efficient design	Generally more expensive fabrication
Bracing needed for in-plane stability	Limited to relatively light vertical loading, and modest cranes to avoid excessive deflections	Generally bracing is used for in-plane stability
No economy due to continuity		

1.3.1 Cladding types

The main types of roofing and wall cladding used in single storey buildings are described as follows:

Roofing

- ‘Built-up’ or double layer roofing spanning between secondary members such as purlins.
- Composite panels (also known as sandwich panels) spanning between purlins.
- Deep decking spanning between main frames, supporting insulation, with an external metal sheet or waterproof membrane.

Walls

- Sheeting, orientated vertically and supported on side rails.
- Sheeting or structural liner trays spanning horizontally between columns.
- Composite or sandwich panels spanning horizontally between columns, eliminating side rails.
- Metallic cassette panels supported by side rails.

Different forms of cladding may be used together for visual effect in the same façade. Examples are illustrated in Figure 1.7, Figure 1.8 and Figure 1.9. Brickwork is often used as a “dado” wall below the level of the windows for impact resistance, as shown in Figure 1.8.

Figure 1.7 Horizontal spanning sheeting

Figure 1.8 Large windows and use of composite panels with “dado” brick wall

Figure 1.9 Horizontal composite panels and 'ribbon' windows

1.4 Design requirements

Design requirements for single-span buildings are presented as follows:

1.4.1 Actions

Permanent actions

Permanent actions are the self weight of the structure, secondary steelwork and cladding. These may be calculated from EN 1991-1-1.

Typical weights of materials used in roofing are given in Table 1.4.

If a roof only carries normal imposed roof loads (i.e. no suspended machinery or similar) the self weight of a steel frame is typically 0,2 to 0,4 kN/m^2 when expressed over the plan area of the roof.

Table 1.4 Typical weights of roofing materials

Material	Weight (kN/m^2)
Steel roof sheeting (single skin)	0,07 – 0,12
Aluminium roof sheeting (single skin)	0,04
Insulation (boards, per 25 mm thickness)	0,07
Insulation (glass fibre, per 100 mm thickness)	0,01
Liner trays (0,4 mm – 0,7 mm thickness)	0,04 – 0,07
Composite panels (40 mm – 100 mm thickness)	0,1 – 0,15
Steel purlins (distributed over the roof area)	0,03
Steel decking	0,2
Three layers of felt with chippings	0,29
Slates	0,4 – 0,5
Tiling (clay or plain concrete tiles)	0,6 – 0,8
Tiling (concrete interlocking)	0,5 – 0,8
Timber battens	0,1

Variable actions

Variable actions should be determined from the following Eurocode parts:

EN 1991-1-1 for imposed roof loads
EN 1991-1-3 for snow loads
EN 1991-1-4 for wind actions

EN 1991-1-1 recommends a uniform load of 0,4 kN/m^2 for roofs not accessible except for normal maintenance and repair (category H). A point load of 1,0 kN is also recommended, but this will only affect the design of the sheeting and not the main structural elements.

EN 1991-1-3 includes several possible load cases due to snow, including uniform snow and drifted snow, which typically occurs in valleys, behind parapets etc. There is also the possibility of exceptional snow loads.

The value of the snow load depends on the building's location and height above sea level.

EN 1991-1-4 is used to determine wind actions, which depend on altitude, distance from the sea and the surrounding terrain.

The determination of loads is covered in detail in a separate chapter of this guidance.

Loading due to services will vary greatly, depending on the use of the building. A typical service loading may be between 0,1 and 0,25 kN/m^2 as measured on plan, depending on the use of the building. If air handling units or other significant equipment loading is to be supported, the service load should be calculated accurately.

1.4.2 Temperature effects

In theory, steel frames expand and contract with changes in temperature. Often, the temperature change of the steelwork itself is much lower than any change in the external temperature, because it is protected. It is generally accepted that the movement available when using bolts in clearance holes is sufficient to absorb any movement due to temperature.

It is recommended that expansion joints are avoided if possible, since these are expensive and can be difficult to detail correctly to maintain a weather-tight external envelope. In preference to providing expansion joints, the frame may be analysed including the design effects of a temperature change. The temperature actions may be determined from EN 1991-1-5, and combinations of actions verified in accordance with EN 1990. In most cases, the members will be found to be adequate.

Common practice for industrial buildings in Northern Europe, in the absence of calculations, is that expansion joints do not need to be provided unless the length of the building exceeds 150m. In warmer climates, common practice is to limit the length to around 80m. Although it is good practice to position the vertical bracing mid-way along the length of the structure, to allow free expansion at both ends of the structure, this is not always possible or desirable. Many orthodox industrial structures have bracing at each end, or at intervals along the length of the structure, with no expansion joints, and perform perfectly well.

1.4.3 Thermal performance and air-tightness

The thermal performance of single storey buildings and enclosures is increasingly important because of their large surface area. Thermal performance also includes prevention of excessive heat loss due to air infiltration, known as ‘air-tightness’.

There is a strong inter-relationship between the types of cladding and thermal performance. Modern steel cladding systems, such as composite panels, can achieve U-values of less than 0,2 W/(m^2K).

Air-tightness is assessed based on full-scale tests after completion of the structure in which the internal volume is pressurised - generally to 50 Pa (this may vary in different countries). The volume of air that is lost is measured and must be less than a given figure – typically 10m^3/m^2 /hour.

1.4.4 Fire resistance

Fire resistance requirements are dependent on a wide range of issues, such as the combustible contents of the building, effective means of escape and occupation density (e.g. for public spaces). Generally, in single storey buildings, the means of escape is good and most enclosures are designed for fire resistance periods of 30 minutes or less. An exception may be office space attached to these buildings.

National regulations are often more concerned to limit fire spread to adjacent structures, rather than the performance of the particular structure, especially if the structure is an industrial building. The determining factor is often the distance to the adjacent boundary. If such regulations apply, the usual solution is to ensure the integrity of the elevation that is adjacent to the boundary. This is commonly ensured by providing cladding with fire resistance, and ensuring that the primary supporting structure remains stable – by protecting the steelwork on that elevation, and designing the elevation steelwork to resist the forces applied by any other parts of the structure that have collapsed.

For many building types, such as exhibition halls, fire engineering analysis may be carried to out demonstrate that active protection measures are effective in reducing fire temperatures to a level where the structure is able to resist the applied loads in the fire scenario without additional fire protection.

1.5 Sustainability

Sustainable construction must address three goals:

- Environmental criteria
- Economic criteria
- Social criteria

These three criteria are met by construction in steel:

Environmental criteria

Steel is one of the most recovered and recycled materials. Some 84% is recycled with no loss of strength or quality, and 10% reused. Before demolishing a structure, extending a building's life is generally more beneficial. This is facilitated by steel construction, since large column-free spaces give flexibility for change in use. Advances in the manufacturing of raw materials means that less water and energy is used in production, and allows for significant reductions in noise, particle and CO_2 emissions.

Economic criteria

Steel construction brings together the various elements of a structure in an integrated design. The materials are manufactured, fabricated and constructed using efficient production processes. The use of material is highly optimised and waste virtually eliminated. The structures themselves are used for all aspects of modern life, including logistics, retail, commercial, and manufacturing, providing the infrastructure on which society depends. Steel construction provides low investment costs, optimum operational costs and outstanding flexibility of building use, with high quality, functionality, aesthetics and fast construction times.

Social criteria

The high proportion of offsite fabrication in steel buildings means that working conditions are safer, controlled and protected from the weather. A fixed location for employees helps to develop communities, family life and the skills. Steel releases no harmful substances into the environment, and steel buildings provide a robust, safe solution.

Single storey structures

The design of low-rise buildings is increasingly dependent on aspects of sustainability defined by criteria such as:

- Efficient use of materials and responsible sourcing of materials
- Elimination of waste in manufacturing and in construction processes

- Energy efficiency in building operation, including improved air-tightness
- Measures to reduce water consumption
- Improvement in indoor comfort
- Overall management and planning criteria, such as public transport connections, aesthetics or preservation of ecological value.

Steel framed buildings can be designed to satisfy all these criteria. Some of the recognised sustainability benefits of steel are:

- Steel structures are robust, with a long life. Properly detailed and maintained, steel structures can be used indefinitely
- 10% of structural steel sections are re-used[1]
- Approximately 95% of structural steel sections are recycled
- Steel products can potentially be dismantled and reused, particularly modular components or steel frames
- Steel structures are lightweight, requiring smaller foundations than other materials
- Steel is manufactured efficiently in factory controlled processes
- All waste is recycled in manufacture and no steel waste is produced on site
- Construction in steel maximises the opportunity and ease of extending buildings and change of use
- High levels of thermal insulation can be provided in the building envelope
- Prefabricated construction systems are rapidly installed and are much safer in terms of the construction processes.

Different sustainability assessment measures exist in various European countries[2].

2 CASE STUDIES ON SINGLE STOREY BUILDINGS

The following case studies illustrate the use of steel in single storey buildings, such as show rooms, production facilities, supermarkets and similar buildings.

2.1 Manufacturing hall, Express Park, UK

Figure 2.1 Portal frame during construction

The portal frame shows in Figure 2.1 forms part of a new production facility for Homeseeker Homes, who manufacture portable homes for residential parks. The project comprises a 150 m long production hall, an adjacent office building and a separate materials storage building.

The production hall is a duo-pitch portal frame with a 35 m clear span and a height of 9 m to the underside of the haunch. The production hall has to accommodate four overhead gantry cranes, each with a safe working load of 5 t. Two cranes may be used in tandem, and the forces arising from this loading case had to be carefully considered. The longitudinal surge from the cranes is accommodated by bracing in the elevations, which also provides longitudinal stability. There are no expansion joints in the production hall – the bracing was designed to resist any loads from thermal expansion.

To control the lateral deflection at the level of the crane rail, the frames, at 6 m centres, are rather stiffer than an equivalent structure without cranes. The columns are 762 mm deep and the rafters 533 mm deep.

The gable frames are portal frames instead of a braced gable frame constructed from columns and simply-supported rafters, to reduce the differential deflection between the end frame and the penultimate frame.

The facility is relatively close to the site boundary, which meant that the boundary elevations had to have special consideration. A fire load case was analysed and the column bases designed to resist the overturning moment from grossly deformed rafters. The cladding on the “boundary” elevations was also specified to prevent fire spread.

The 380 t of steelwork in the project was erected in six weeks.

2.2 Supermarket, Esch, Luxembourg

Figure 2.2 Supermarket in Esch , Luxembourg using curved cellular beams

Curved 20 m span cellular beams were used to provide an exposed steel structure in a supermarket in Esch, Luxembourg, as shown in Figure 2.2. The beams used HEB 450 sections that were cut and re-welded to form beams with 400 mm diameter openings. The curved cellular frames were placed 7,5 m apart and the columns were also 7,5 m high and are illustrated in Figure 2.3. The structure was designed using fire engineering principles to achieve an equivalent 90 minutes fire resistance without additional fire protection.

Figure 2.3 Portal frame structure using curved cellular beams

2.3 Motorway Service station, Winchester, UK

Cellular beams provide an attractive solution for long span public spaces, as in this motorway service restaurant in Winchester, UK, shown in Figure 2.4. The 600 mm deep doubly curved cellular beams spanned 18 m onto 1,2 m deep cellular primary beams that spanned 20 m between H section columns. The cellular beams also provided for service distribution above the kitchen area.

Figure 2.4 Double curved cellular beams and primary beams

2.4 Airbus Industrie hanger, Toulouse, France

The Airbus production hall in Toulouse covers 200000 m^2 of floor space and is 45 m high with a span of 117 m. It consists of 8 m deep lattice trusses composed of H sections. Compound column sections provide stability to the roof structure. The building is shown in Figure 2.5 during construction. Sliding doors create a 117 m × 32 m opening in the end of the building. Two parallel rolling cranes are installed each of 50 m span and 20 tonnes lifting capacity.

Figure 2.5 View of Airbus Industrie hanger during construction

2.5 Industrial hall, Krimpen aan den Ijssel, Netherlands

This production hall is 85 m in length, 40 m wide and 24 m high with full height doors at the end of the building, as shown in Figure 2.6. The roof structure consists of an inclined truss. Because of the lack of bracing in the end walls, the structure was designed to be stabilised through the columns assisted by in-plane bracing in the roof and side walls.

Figure 2.6 View of doors being lifted into place in Hollandia's building in Krimpen aan den Ijssel

2.6 Distribution Centre and office, Barendrecht, Netherlands

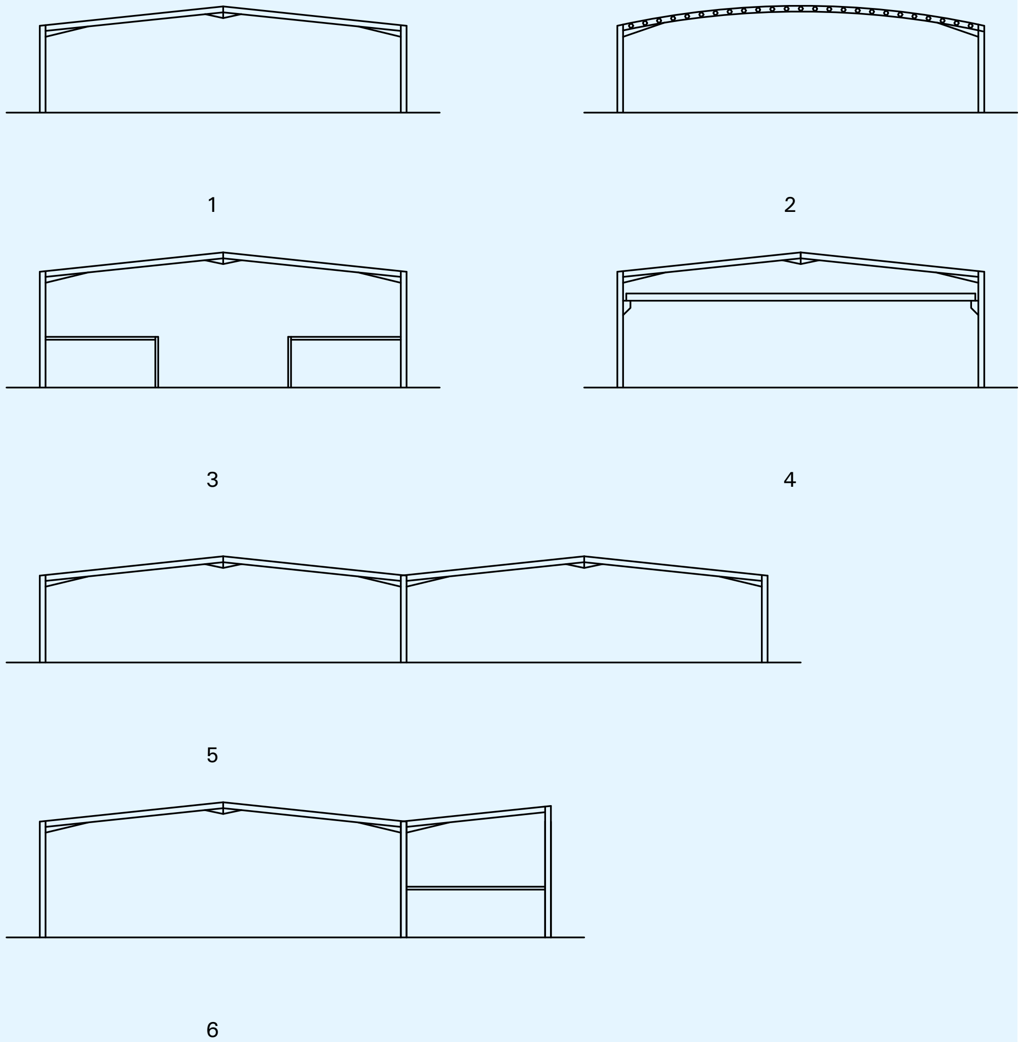
This 26000 m^2 distribution centre for a major supermarket in the Netherlands comprises a conventional steel structure for the distribution area and a two storey high office area that is suspended above an access road, as shown in Figure 2.7. This 42 m long office building comprises a 12 m cantilever supported by a two storey high internal steel structure with diagonal bracing. The structure uses H section beams and columns with tubular bracing.

Both the warehouse and office buildings are provided with sprinklers to reduce the risk of fire, and the steelwork has intumescent coating so that it can be exposed internally. The warehouse internal temperature is 2°C and the steelwork of the office is thermally isolated from the warehouse part.

Figure 2.7 Distribution centre, Barendrecht, NL showing the braced cantilever office structure

3 CONCEPT DESIGN OF PORTAL FRAMES

Steel portal frames are widely used because they combine structural efficiency with functional form. Various configurations of portal frame can be designed using the same structural concept as shown in Figure 3.1.



1 Duo-pitch portal frame
2 Curved portal frame (cellular beam)
3 Portal with internal offices
4 Portal with crane
5 Two-span portal frame
6 Portal with external offices

Figure 3.1 Various types of portal frame

3.1 Pitched roof portal frame

A single-span symmetrical portal frame (as illustrated in Figure 3.2) is typically of the following proportions:

- A span between 15 m and 50 m (25 m to 35 m is the most efficient)
- An eaves height (base to rafter centreline) of between 5 and 10 m (7,5 m is commonly adopted). The eaves height is determined by the specified clear height between the top of the floor and the underside of the haunch.
- A roof pitch between 5° and 10° (6° is commonly adopted)
- A frame spacing between 5 m and 8 m (the greater frame spacings being used in longer span portal frames)
- Members are I sections rather than H sections, because they must carry significant bending moments and provide in-plane stiffness.
- Sections are generally S235 or S275. Because deflections may be critical, the use of higher strength steel is rarely justified.
- Haunches are provided in the rafters at the eaves to enhance the bending resistance of the rafter and to facilitate a bolted connection to the column.
- Small haunches are provided at the apex, to facilitate the bolted connection

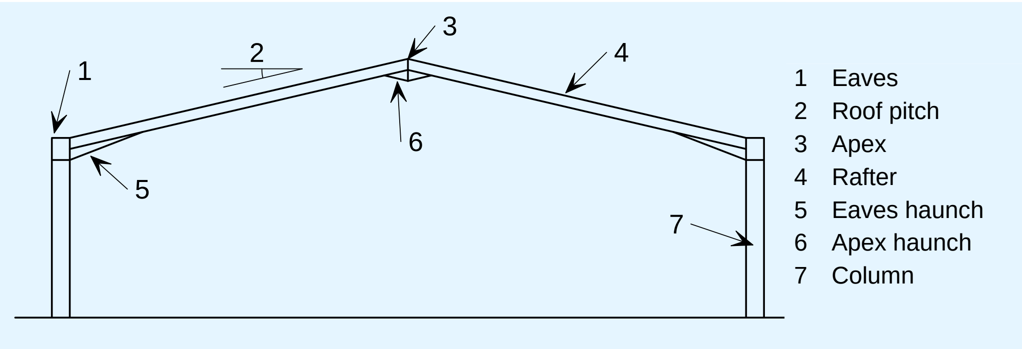
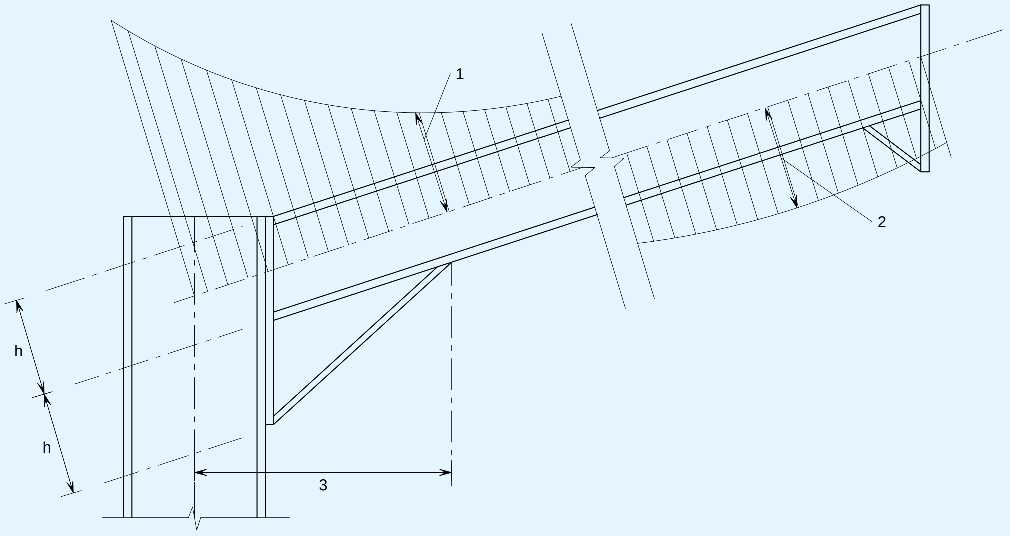


Figure 3.2 Single-span symmetric portal frame

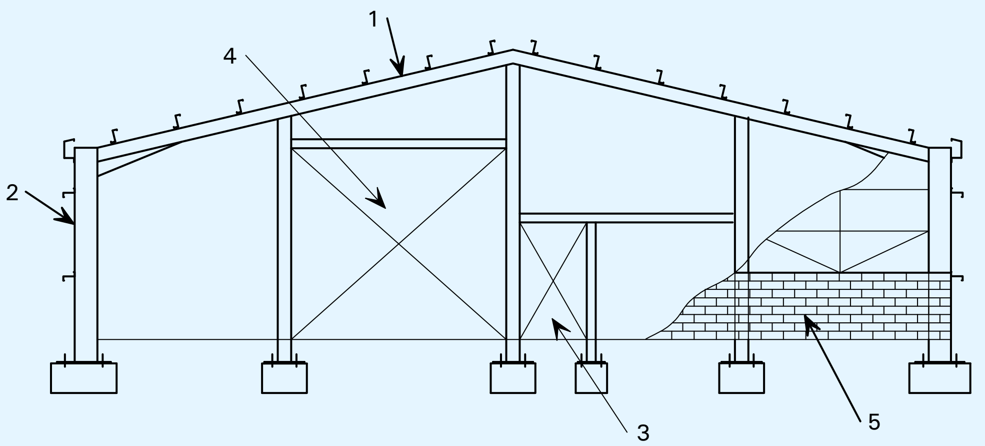
The eaves haunch is typically cut from the same size rolled section as the rafter, or one slightly larger, and is welded to the underside of the rafter. The length of the eaves haunch is generally 10% of the span. The length of the haunch means that the hogging bending moment at the “sharp” end of the haunch is approximately the same as the maximum sagging bending moment towards the apex, as shown in Figure 3.3.



1 Moment at the "sharp" end of the haunch
2 Maximum sagging moment
3 Haunch length

Figure 3.3 Rafter bending moment and haunch length

The final frames of a portal frame are generally called gable frames. Gable frames may be identical to the internal frames, even though they experience lighter loads. If future extension to the building is envisaged, portal frames are commonly used as the gable frames, to reduce the impact of the structural works. A typical gable frame is shown in Figure 3.4.



1 Rafter
2 Column
3 Personnel door
4 Roller shutter door
5 Dado wall (brickwork)

Figure 3.4 Typical details of an end gable of a portal frame building

Alternatively, gable frames can be constructed from columns and short rafters, simply supported between the columns as shown in Figure 3.5. In this case, gable bracing is required, as shown in the figure.

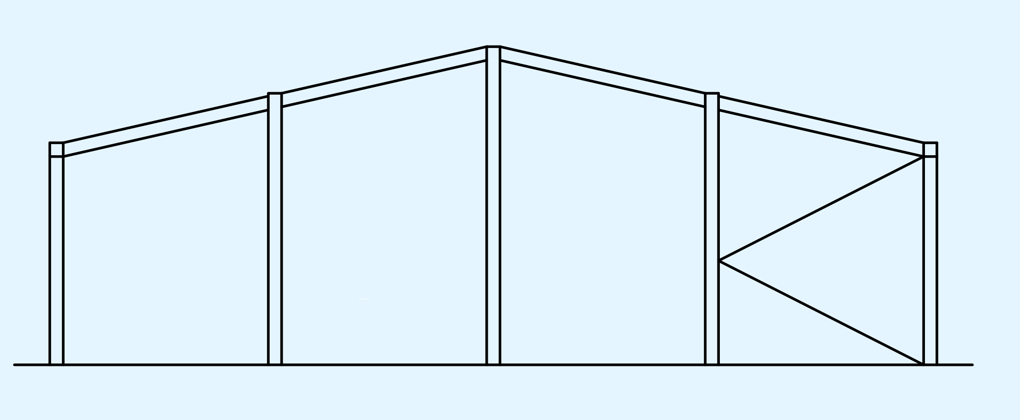
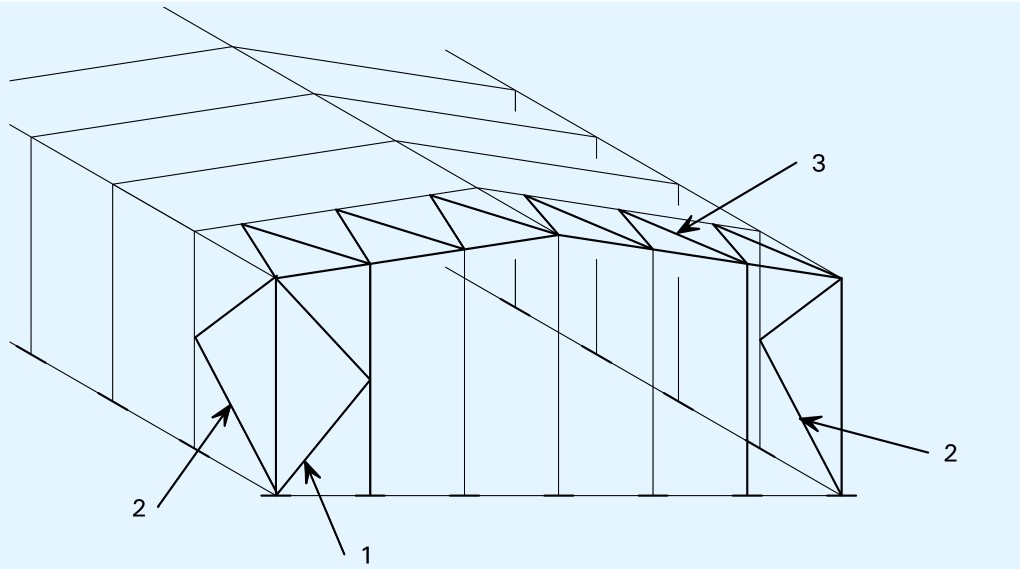


Figure 3.5 Gable frame (not a portal frame)

3.2 Frame stability

In-plane stability is provided by frame continuity. In the longitudinal direction, stability is provided by vertical bracing in the elevations. The vertical bracing may be at both ends of the building, or in one bay only. Each frame is connected to the vertical bracing by a hot-rolled member at eaves level. A typical bracing arrangement is shown in Figure 3.6.

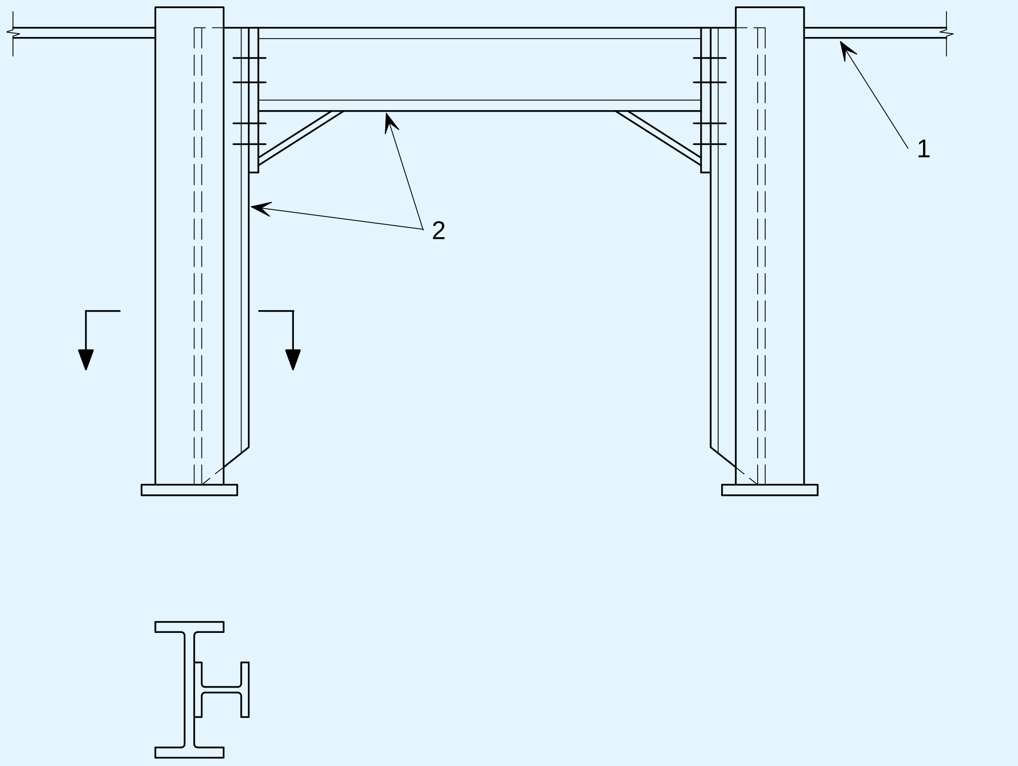


1 Vertical bracing in the gable
2 Vertical bracing in the walls
3 Roof bracing

Figure 3.6 Typical bracing in a portal frame

The gable columns span between the base and the rafter, where the reaction is carried by bracing in the plane of the roof, back to the eaves level, and to the foundations by the vertical bracing.

If diagonal bracing in the elevations cannot be accommodated, longitudinal stability can be provided by a rigid frame on the elevation, as shown in Figure 3.7.



1 Eaves strut
2 Rigid frame

Figure 3.7 Rigid frame alternative to vertical bracing

3.3 Member stability

Member stability should be checked using expressions 6.61 and 6.62 of EN 1993-1-1. For economic design, restraints to the rafter and column must be considered. The purlins and side rails are considered adequate to restrain the flange that they are attached to, but unless special measures are taken, the purlins and side rails do not restrain the inside flange. Restraint to the inside flange is commonly provided by bracing from the purlins and side rails, as shown in Figure 3.8. The bracing is usually formed of thin metal straps, designed to act in tension, or from angles designed in compression if bracing is only possible from one side.

If the bracing shown in Figure 3.8 is not permitted by national regulations, restraint may be provided by a system of hot-rolled members.

This form of bracing will be required whenever the inside flange is in compression. This situation arises:

- On the inside of the column and the inside of the rafter in the haunch region, in the gravity load combination
- Towards the apex of the rafter, in the uplift combination.

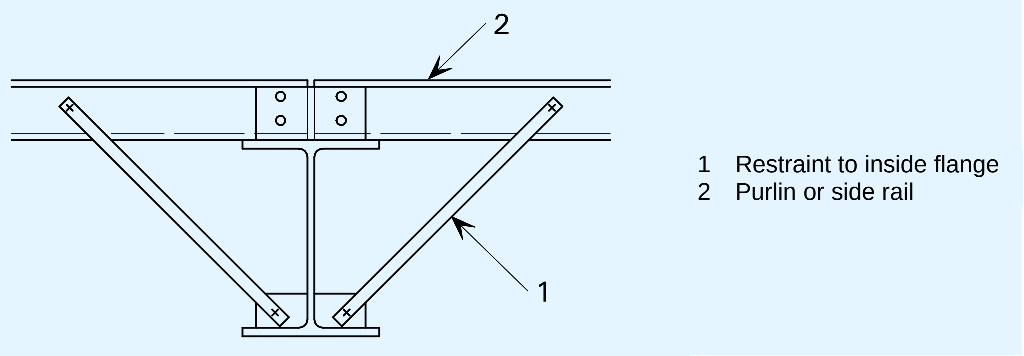


Figure 3.8 Typical bracing to the inside flange

The arrangement of restraints to the inside flange is generally similar to that shown in Figure 3.9. In some instances, it may not be possible to restrain the inside of the column flange. In these circumstances, a larger column section may have to be chosen, which is stable between the underside of the haunch and the base.

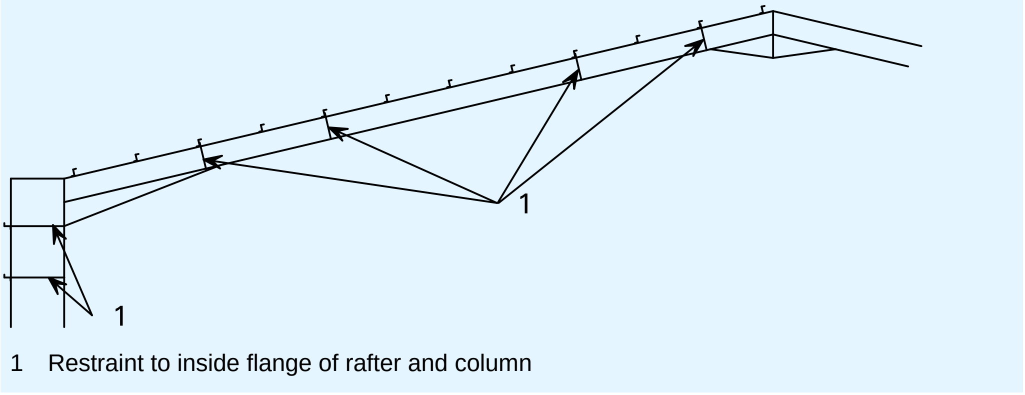


Figure 3.9 General arrangement of restraints to the inside flange

In all cases, the junction of the inside face of the column and the underside of the haunch, as shown in Figure 3.10, must be restrained. The restraint may be of the form shown in Figure 3.8, or may be by a hot-rolled member provided for that purpose.

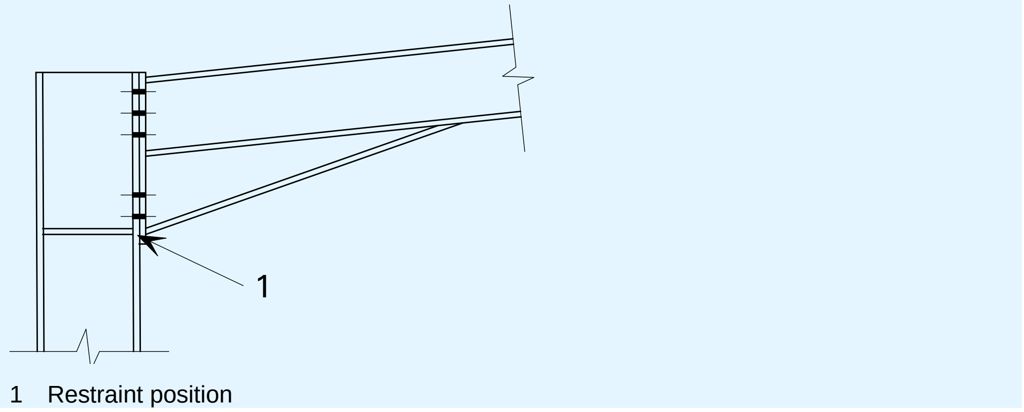


Figure 3.10 Restraint at the haunch / column junction

3.4 Preliminary Design

3.4.1 Main frames

Although efficient portal frame analysis and design will use bespoke software, preliminary design is simple. In most circumstances, a reasonable estimate of the maximum bending moments will be obtained by considering only the vertical loads. Combinations of actions including wind actions must be validated in the final design, and may be important for preliminary design if the wind actions are onerous (e.g. near the sea, or if the portal frame is tall).

Based on the vertical load alone, charts that provide initial sizes are given in Section 8.

As an alternative to the sizes given in Section 8, the bending moment at the eaves and apex can be calculated based on an elastic analysis.

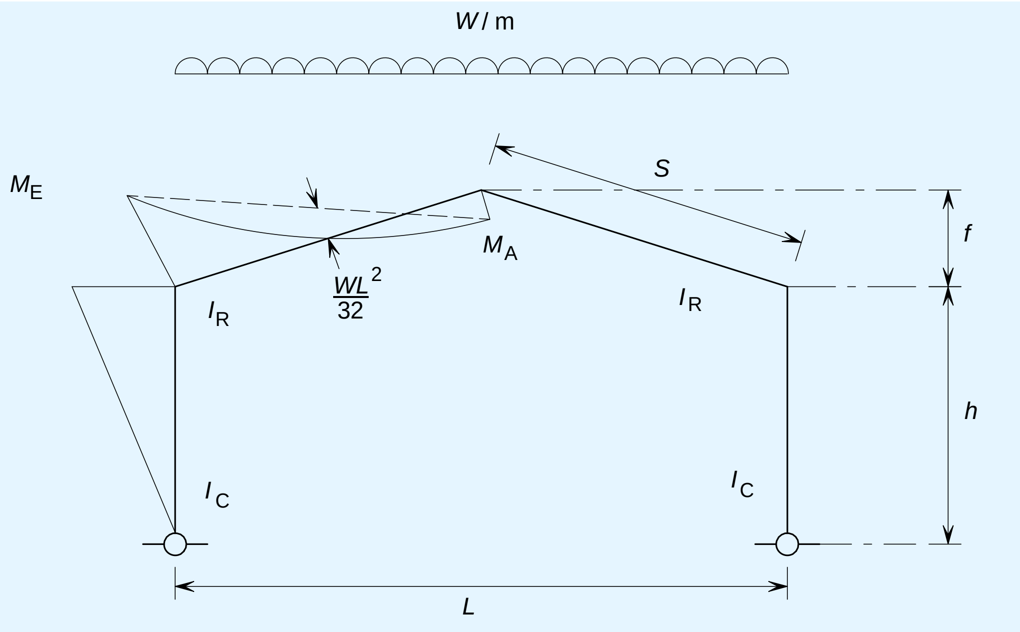


Figure 3.11 Details of a pinned base portal frame

For the pinned base frame shown in Figure 3.11, the bending moment at the eaves, M_E and at the apex M_A can be calculated as follows:

$$M_E = \frac{wL^2(3+5m)}{16N} \quad \text{and} \quad M_A = \frac{wL^2}{8} + m \times M_E$$

where:

$N = B + mC$

$C = 1 + 2m$

$B = 2(k + 1) + m$

$m = 1 + \phi$

$\phi = f/h$

$$k = \frac{I_R}{I_C}\frac{h}{s}$$

It may be assumed for preliminary design that $I_C = 1{,}5 \times I_\mathrm{R}$

Given the bending moments around the frame, the rafter should be chosen so that the moment resistance exceeds both the moment at the “sharp” end of the haunch and the maximum sagging moment (a little larger than the moment at the apex).

3.4.2 Gable columns

Gable columns are generally designed as simply supported from base to rafter. The primary loads are the wind actions. The internal pressure or suction will contribute to the loading on the gable column. Often, the critical design case will be pressure inside the building and suction on the outside, when the inside flange of the gable post is unrestrained. If national regulations allow, a restraint to the inside flange may be provided from a sheeting rail to increase the buckling resistance.

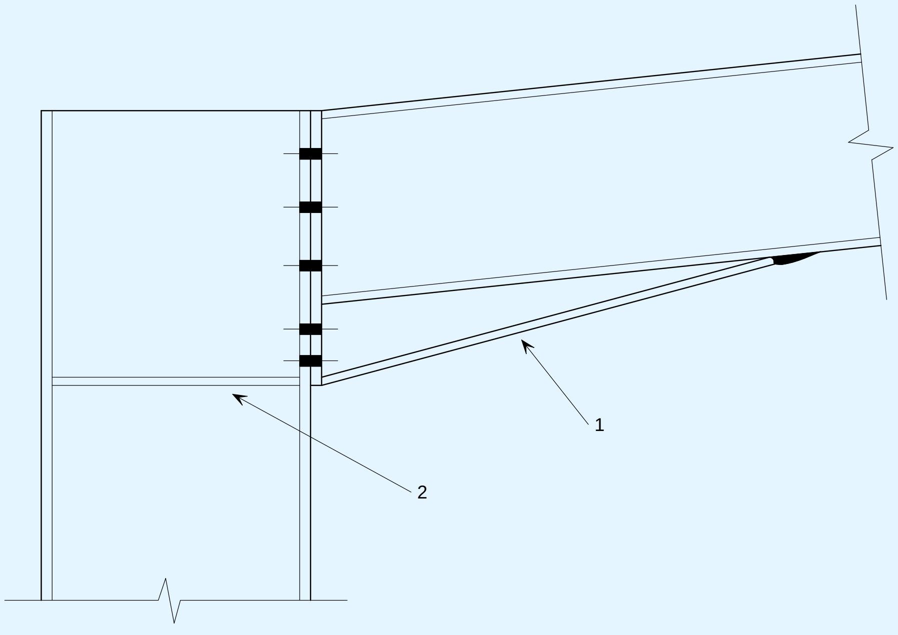
3.4.3 Bracing

At the preliminary design stage, it is convenient to calculate the overall longitudinal load on the structure. This shear must be the horizontal component of the load carried by the vertical bracing. The most heavily loaded roof bracing will be the member nearest the eaves. The longitudinal eaves member carries the load from the roof bracing to the vertical bracing. Bracing members may be hollow sections, angle sections or flat steel. Flat steel is assumed to resist tension forces only.

3.5 Connections

3.5.1 Eaves connection

A typical eaves connection is shown in Figure 3.12. In almost all cases a compression stiffener in the column (as shown, at the bottom of the haunch) will be required. Other stiffeners may be required to increase the bending resistance of the column flange, adjacent to the tension bolts, and to increase the shear resistance of the column web panel. The haunch is generally fabricated from a similar size beam to the rafter (or larger), or fabricated from equivalent plate. Typically, the bolts may be M24 8.8 and the end plate 25 mm thick S275.



1 Haunch
2 Compression stiffener

Figure 3.12 Typical eaves connection

3.5.2 Apex connection

A typical apex connection is shown in Figure 3.13. The apex connection primarily serves to increase the depth of the member to make a satisfactory bolted connection. The apex haunch is usually fabricated from the same member as the rafter, or from equivalent plate. Typically, the bolts may be M24 8.8 and the end plate 25 mm thick S275.

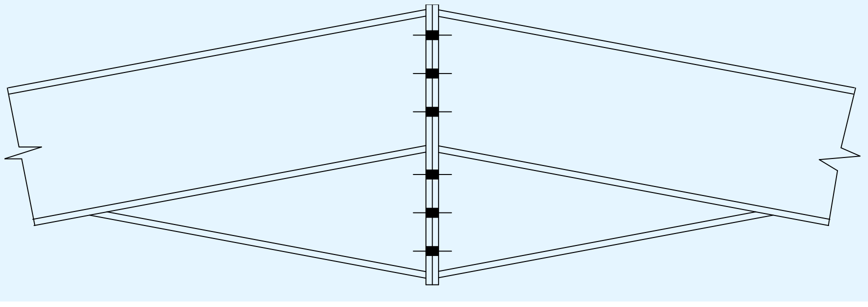


Figure 3.13 Typical apex connection

3.5.3 Bases

A typical pinned base is shown in Figure 3.14. The base plate is generally at least as thick as the flange of the column. Most authorities accept that even with four holding down bolts as shown in Figure 3.14, the base is still pinned. Alternatively, the base may have only two holding down bolts, on the axis of the column, but this may make the erection of the steelwork more difficult.

Columns are normally located on a number of steel packs, to ensure the steelwork is at the correct level, and the gap between the foundation and the steelwork filled with cementicious grout. Large bases should be provided with an air hole to facilitate complete grouting.

Holding down bolts are generally embedded in the foundation, with some freedom of lateral movement (tubes or cones) so that the steelwork can be aligned precisely. The holes in the base plate are usually 6 mm larger than the bolt diameter, to facilitate some lateral alignment.

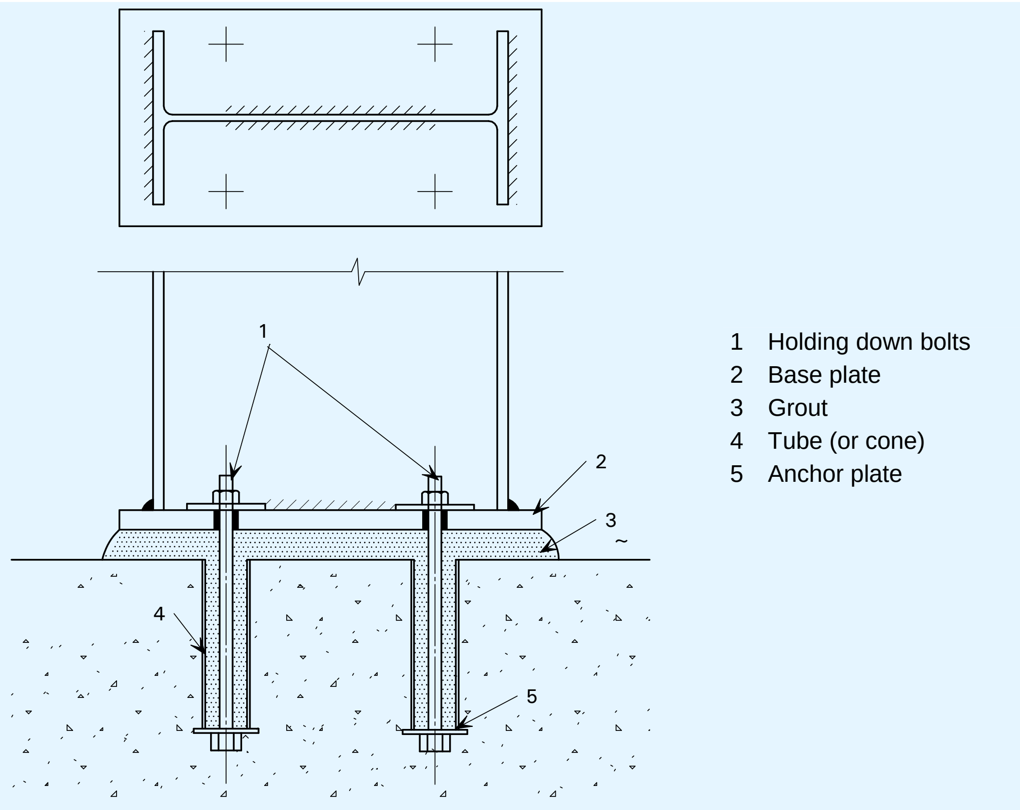


Figure 3.14 Typical portal base detail

3.5.4 Bracing Connections

Forces in portal frame bracing are generally modest. Typical connections are shown in Figure 3.15. Gusset plates should be supported on two edges, if possible.

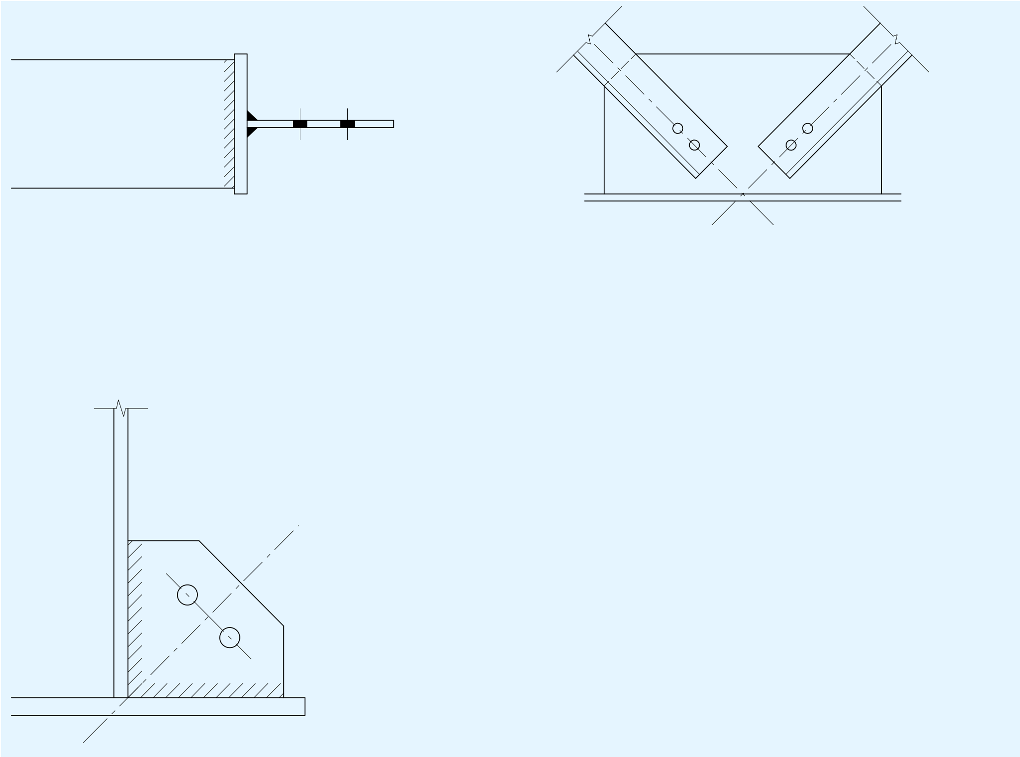


Figure 3.15 Typical bracing connections

3.6 Other types of portal frame

The features of an orthodox portal frame were described in Sections 3.1 to 3.5. The basic structural concept can be modified in a number of ways to produce a cost effective solution, as illustrated below.

3.6.1 Portal frame with a mezzanine floor

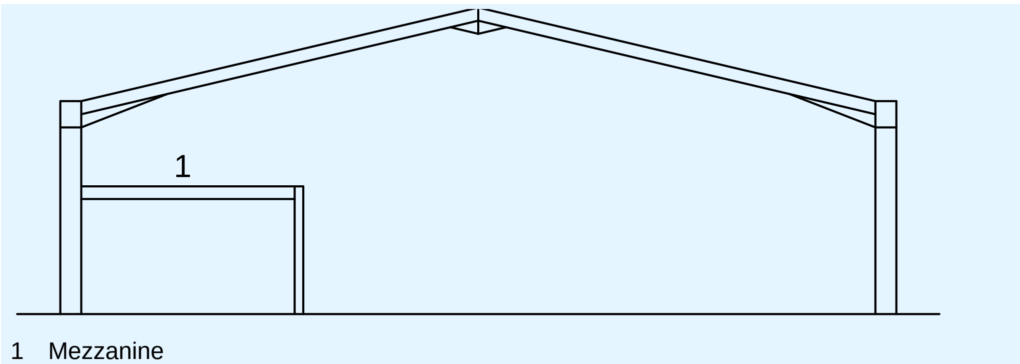
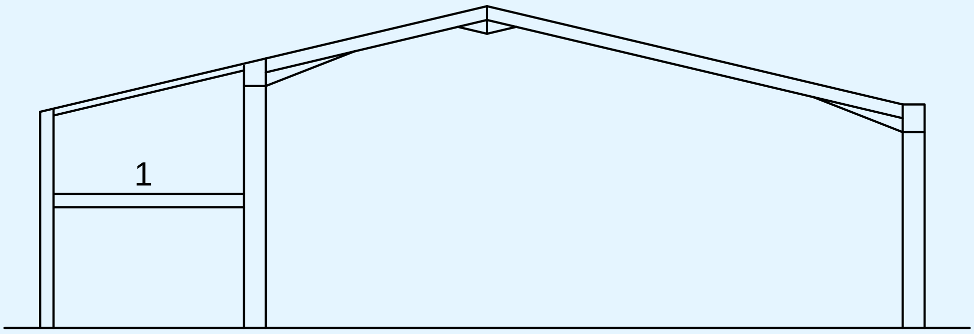


Figure 3.16 Portal frame with internal mezzanine floor

Office accommodation is often provided within a portal frame structure using a mezzanine floor (as illustrated in Figure 3.17). The mezzanine floor may be partial or full width. It can be designed to stabilise the frame. Often, the internal floor of the office space requires fire protection.

Figure 3.17 Portal frame with intermediate floor

3.6.2 Portal frame with external mezzanine



1 Mezzanine

Figure 3.18 Portal frame with external mezzanine

Offices may be located externally to the portal frame which creates an asymmetric portal structure (as illustrated in Figure 3.18). The main advantage of this framework is that large columns and haunches do not obstruct the office space. Generally, this additional structure depends on the portal frame for its stability (the members often have nominally pinned connections to the main frame) and the members can be relatively lightweight.

3.6.3 Portal frame with overhead crane

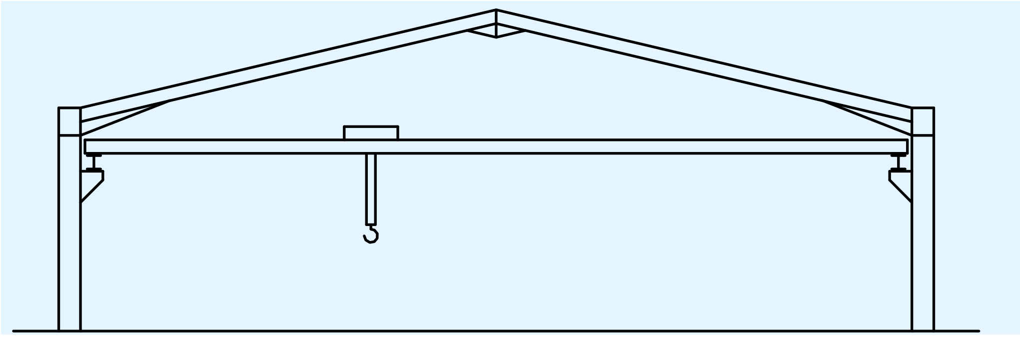
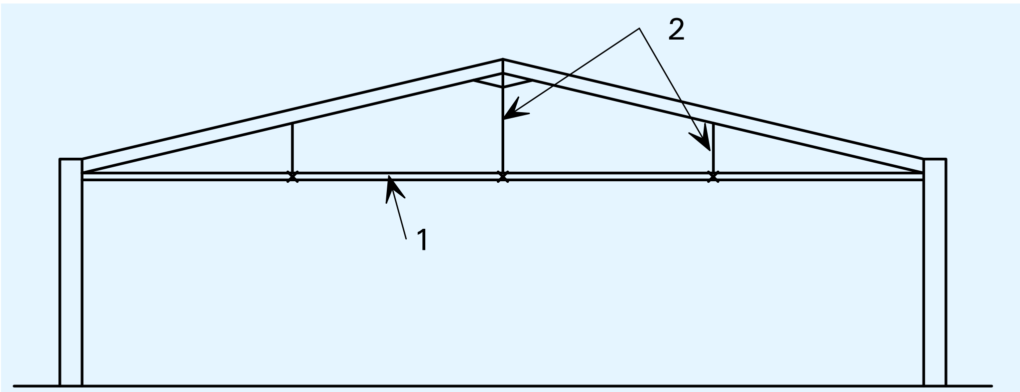


Figure 3.19 Crane portal frame with column brackets

For cranes of relatively low capacity (up to say 20 tonnes), portal frames can be used to support the crane beam and rail, as illustrated in Figure 3.19. The outward movement (spread) of the frame at the level of the crane rail is likely to be of critical importance. Use of a horizontal tie member or fixed column bases may be necessary to reduce this spread.

For larger cranes, a structure with a roof truss will be appropriate (see Section 4) as the column spread is minimised. For very heavy loads, built-up columns are appropriate, as introduced in Section 6. Detail design guides cover both the design of trusses[3] and the design of built-up columns[4].

3.6.4 Tied portal frame



1 Tie
2 Hangers (required for longer spans)

Figure 3.20 Tied portal frame

In a tied portal frame, as illustrated in Figure 3.20, the spread of the eaves and the bending moments in the frame are greatly reduced. Large compression forces will develop in the rafters, which reduce the stability of the members. Second-order software must be used for the design of tied portals.

3.6.5 Mansard or curved portal frames

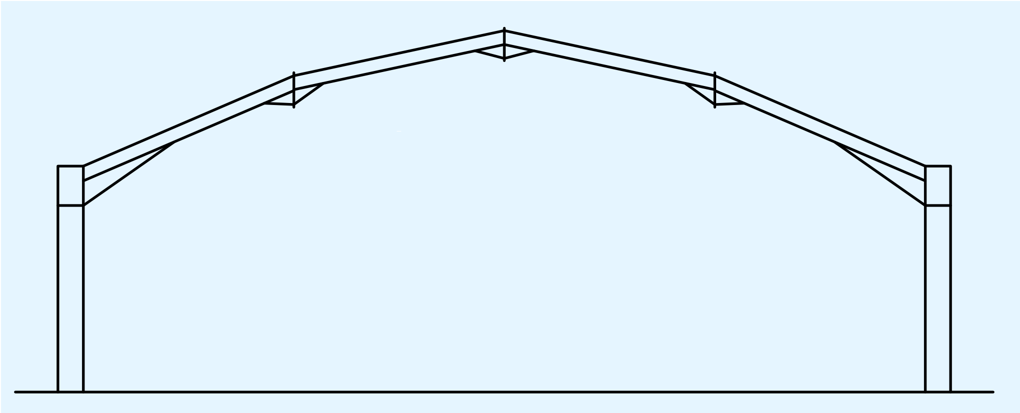


Figure 3.21 Mansard portal frame

A mansard portal frame consists of a series of rafters and haunches, as illustrated in Figure 3.21, which creates a pseudo-curved frame. The connections between the members may also have small haunches to facilitate the bolted connections.

Curved rafter portals as illustrated in Figure 3.22 are often used for architectural applications. The rafter can be curved to a radius by cold bending. For spans greater than approximately 18 m, splices may be required in the rafter because of limitations of transport.

Alternatively, a curved external roof must be produced by varying the lengths of purlin brackets supported on a rafter fabricated as a series of straight elements, as shown in Figure 3.23.

Figure 3.22 Curved beams used in a portal frame

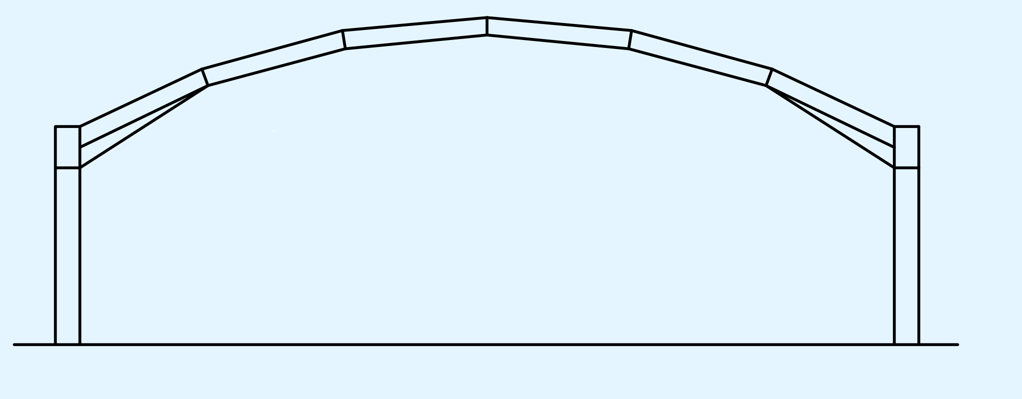
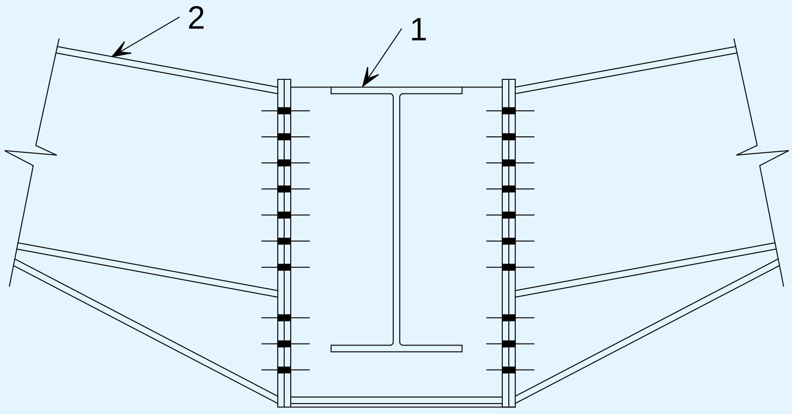


Figure 3.23 Quasi- curved portal frame

3.6.6 Multi bay portal frame

Multi-bay portal frames may be designed by using intermediate columns, as shown in Figure 3.24. If the number of internal columns must be minimised it is possible to remove every second internal column, or to only leave one internal column every third frame. Where the internal column is removed, a deep beam (often known as a "valley" beam) is designed to span between the remaining columns. Continuity of the rafters is achieved by using a haunch connection to the valley beam, as shown in Figure 3.25.

Figure 3.24 Multi-bay portal frame



1 Valley beam
2 Rafter

Figure 3.25 Connection to valley beam

4 CONCEPT DESIGN OF TRUSS BUILDINGS

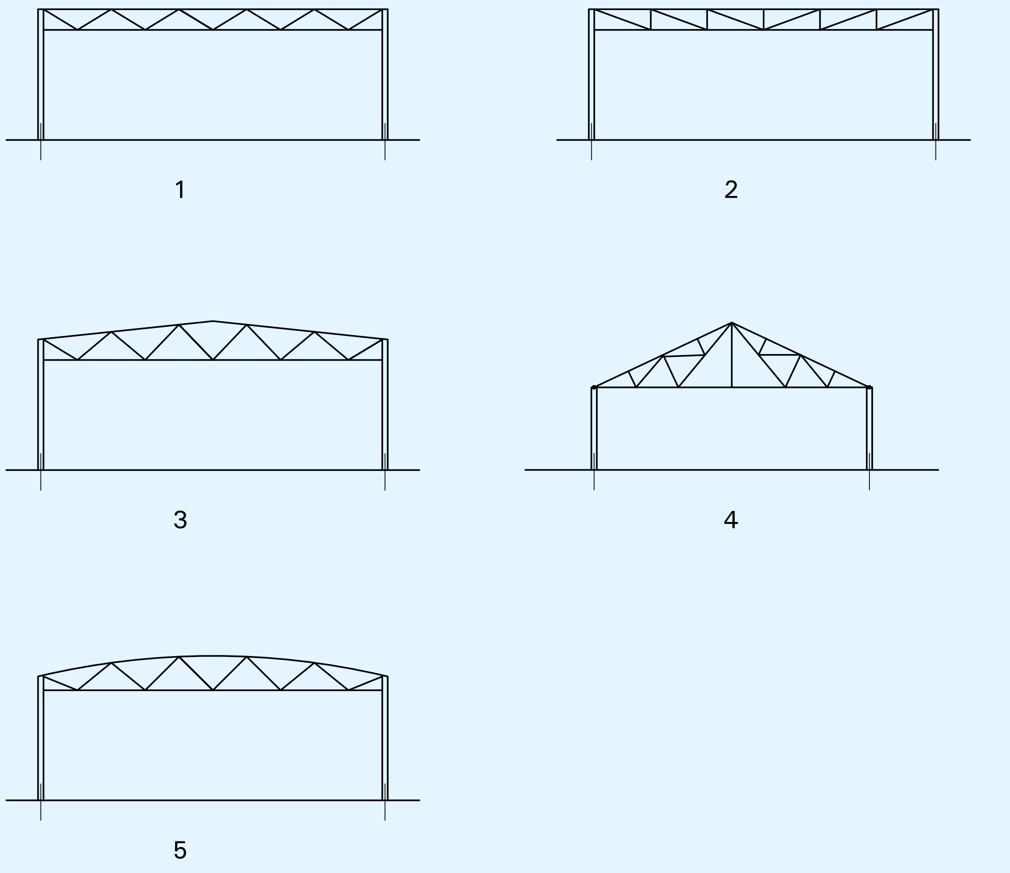
4.1 Introduction

Many forms of truss are possible. Some of the common types of truss for single storey buildings are shown in Figure 4.1.

Trusses are used for long spans, and particularly when significant loads must be carried by the roof structure, as the vertical deflection can be controlled by varying the member sizes.

For industrial buildings, the W-truss N-truss and duo-pitch truss are common. The Fink truss is generally used for smaller spans. Comparing the W-truss and N-truss:

- The W-truss has more open space between the internal members
- The internal members of the W-truss may be larger, because a long diagonal member must carry compression – the compression members in the N-truss are short.



1 W-truss
2 N-truss
3 Duo-pitch truss
4 Fink truss
5 Curved truss

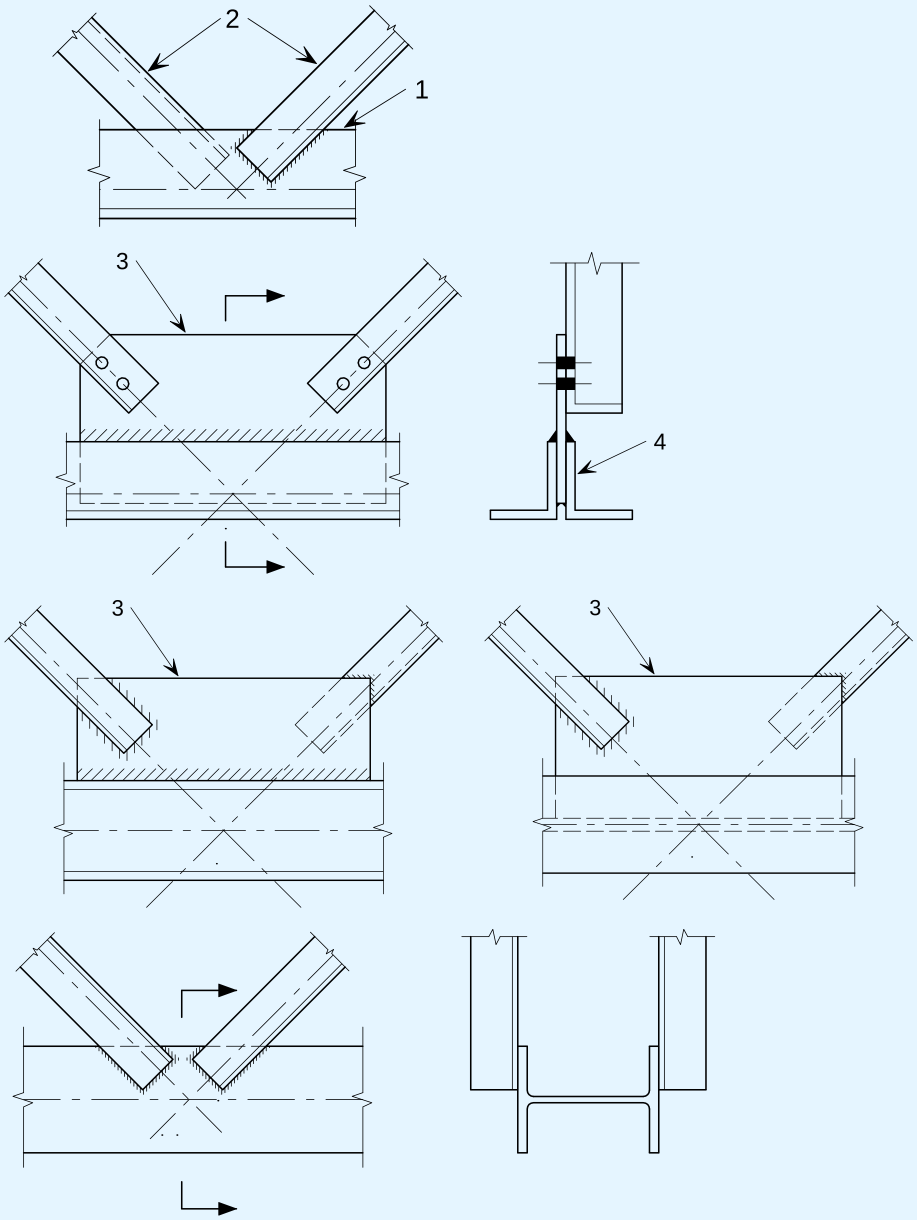
Figure 4.1 Various forms of lattice truss used in industrial buildings

4.2 Truss members

Unless there are special architectural requirements, truss members are chosen to produce a simple connection between the chords and the internal members. Common combinations as shown in Figure 4.2 are:

- Tees used as chords, with angles used as web members. The angles may be welded or bolted to the stem of the Tee.
- Double angle members as chords, and single (or double) angles as internal members. The connections are made with a gusset plate welded between the angles forming the chords.
- Rolled sections as chords, with the web in the plane of the truss. The internal members are usually angle members, connected via a gusset plate welded to the chord.
- Rolled sections as chords, but with the web perpendicular to the plane of the truss. The connections to the chord members may be via gusset plates welded to the web, although the connections will need careful detailing. A simple, effective alternative is to choose chords that have the same overall depth, and connect the internal members to the outside of both flanges, generally by welding.
- For heavily loaded trusses, rolled I or H sections, or channel sections may be used as the internal members. In such a large truss, developing economic connections will be important and both the members and internal members should be chosen with this in mind.

The detailed design of trusses is covered in *Single-storey steel buildings. Part5: Detailed design of trusses*[3].



1 Tee section
2 Angle members
3 Gusset plate
4 Double angle chord

Figure 4.2 Typical truss members

A truss fabricated from rolled sections is illustrated in Figure 4.3.

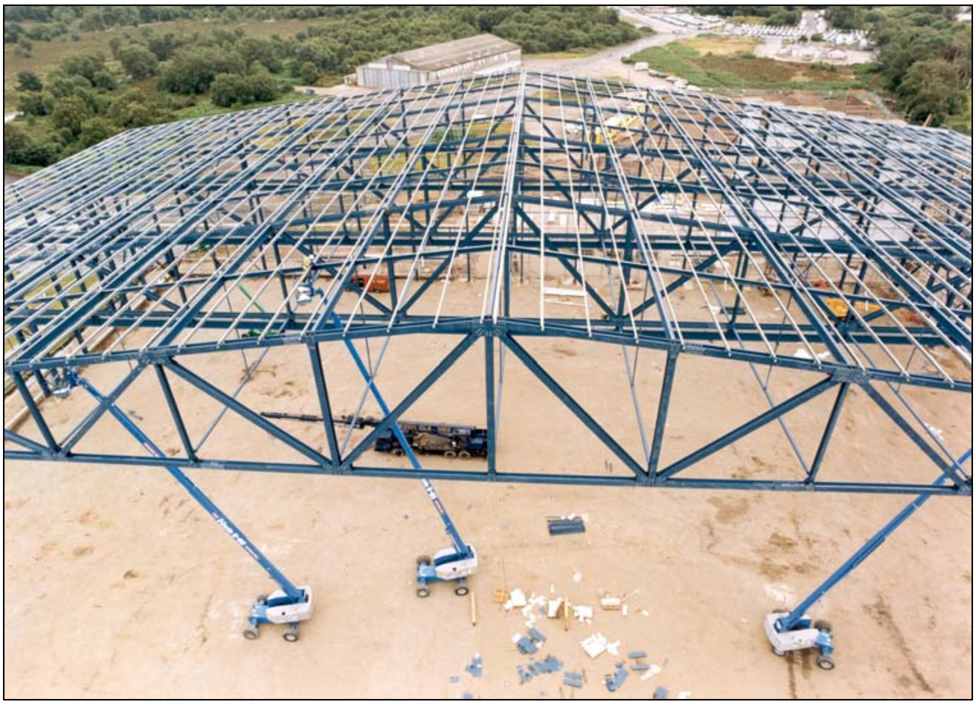
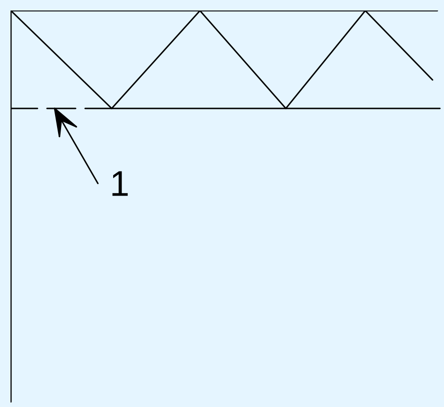


Figure 4.3 Truss fabricated from rolled sections

4.3 Frame stability

In most cases, frame stability is provided by bracing in both orthogonal directions, and the truss is simply pinned to the supporting columns. To realise a pinned connection, one of the chord members is redundant, as shown in Figure 4.4, and the connection of that redundant member to the column is usually allowed to slip in the direction of the axis of the chord.



1 Redundant member

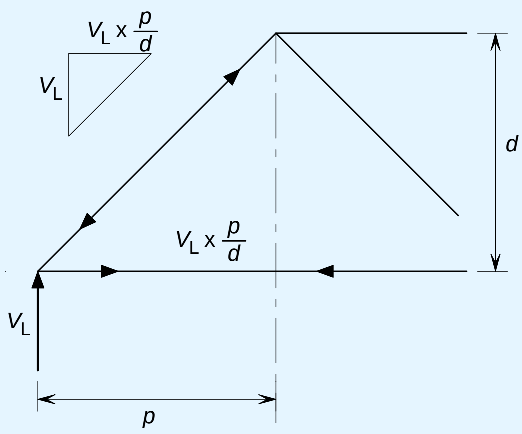
Figure 4.4 Redundant member in a simply supported truss

In the longitudinal direction, stability is usually provided by vertical bracing.

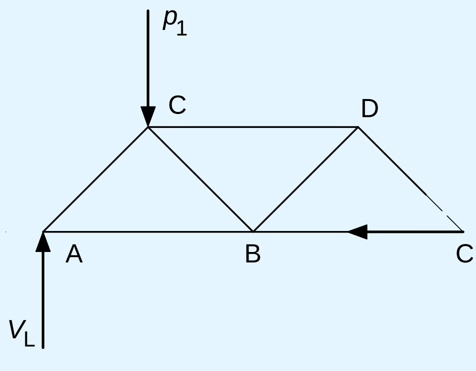
4.4 Preliminary design

At the preliminary design stage, the following process is recommended:

1. Determine the loading on the truss. See Section 1.4.1. At the preliminary design stage it is sufficient to convert all loads, including self weight, to point loads applied at the nodes and assume that the entire truss is pin-jointed. This assumption is also generally adequate for final design. As an alternative, the roof loads may be applied at the purlin positions and the chords assumed to be continuous over pinned internal members, but the precision is rarely justified.
2. Determine a truss depth and layout of internal members. A typical span : depth ratio is approximately 20 for both W- and N-trusses. Internal members are most efficient between 40° and 50°.
3. Determine the forces in the chords and internal members, assuming the truss is pin-jointed throughout. This can be done using software, or by simple manual methods of resolving forces at joints or by taking moments about a pin, as shown in Figure 4.5.



Resolving forces at joints



Taking moments around node D determines the force CB

Figure 4.5 Calculation of forces in a pin-jointed truss

A very simple approach is to calculate the maximum bending moment in the truss assuming that it behaves as a beam, and divide this moment by the distance between chords to determine the axial force in the chord.

4. Select the compression chord member. The buckling resistance is based on the length between node points for in-plane buckling. The out-of-plane

buckling is based on the length between out-of-plane restraints – usually the roof purlins or other members.

5. Select the tension chord member. The critical design case is likely to be an uplift case, when the lower chord is in compression. The out-of-plane buckling is likely to be critical. It is common to provide a dedicated system of bracing at the level of the bottom chord, to provide restraint in the reversal load combination. This additional bracing is not provided at every node of the truss, but as required to balance the tension resistance with the compression resistance.
6. Choose internal members, whilst ensuring the connections are not complicated.
7. Check truss deflections.

4.5 Rigid frame trusses

The structures described in Sections 4.1 and 4.4 are stabilised by bracing in each orthogonal direction. It is possible to stabilise the frames in-plane, by making the truss continuous with the columns. Both chords are fixed to the columns (i.e. no slip connection). The connections within the truss and to the columns may be pinned. The frame becomes similar to a portal frame. For this form of frame, the analysis is generally completed using software. Particular attention must be paid to column design, because the in-plane buckling length is usually much larger than the physical length of the member.

4.6 Connections

Truss connections are either bolted or welded to the chord members, either directly to the chord, or via gusset plates, as shown in Figure 4.6.

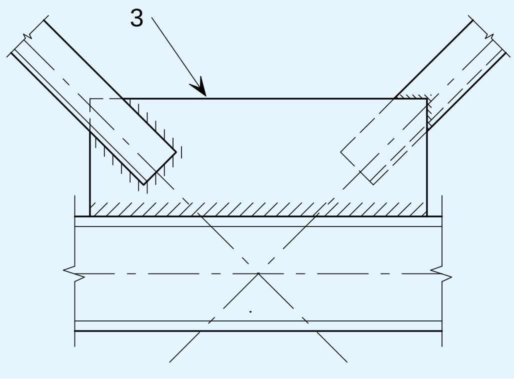


Figure 4.6 Truss connections

Trusses will generally be prefabricated in the workshop, and splices maybe required on site. In addition to splices in the chords, the internal member at the splice position will also require a site connection. Splices may be detailed with cover plates, or as “end plate” type connections, as shown in Figure 4.7.

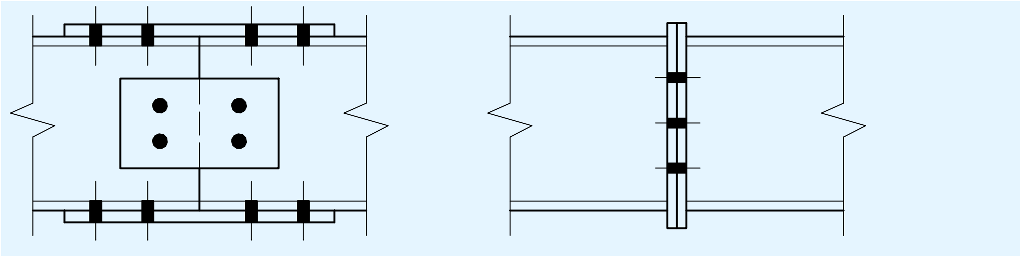


Figure 4.7 Splice details

Ordinary bolts (non-preloaded) in clearance holes may give rise to some slip in the connection. If this slip is accumulated over a large number of connections, the defection of the truss may be larger than calculated. If deflection is a critical consideration, then friction grip assemblies or welded details should be used.

5 SIMPLE BEAM STRUCTURES

For modest spans, (up to approximately 20 m) a simple beam and column structure can be provided, as illustrated in Figure 5.1. The roof beam is a single rolled section, with nominally pinned connections to the columns. The roof beam may be straight, precambered, perforated or curved. The roof may be horizontal, or more commonly with a modest slope to assist drainage. Ponding of water on the roof should be avoided with a slope, or precambered beam.

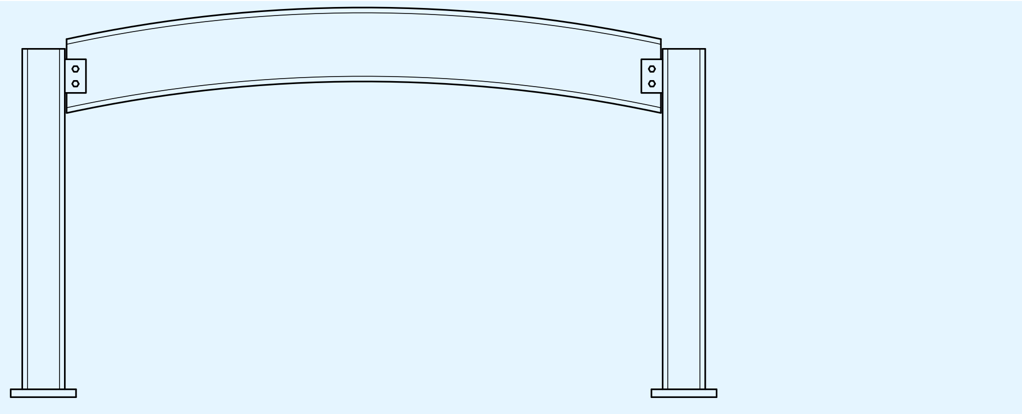


Figure 5.1 Simple beam and column frame

Frame stability for this form of structure is provided by bracing in each orthogonal direction. The beam is designed as simply supported, and the columns as simple struts, with a nominal moment applied by the beam connection. It is common to assume that the shear force from the beam is applied 100 mm from the face of the column.

6 BUILT-UP COLUMNS

Heavily loaded columns, or columns in tall industrial buildings may be in the form of built-up sections. Built-up columns often comprise HE or UPE sections in which battens (flat plate) or lacing (usually angles) are welded across the flanges, as shown in Figure 6.1.

Built-up columns are not used in portal frames, but are often used in buildings supporting heavy cranes. The roof of the structure may be duo-pitch rafters, but is more commonly a truss, as illustrated in Figure 1.4.

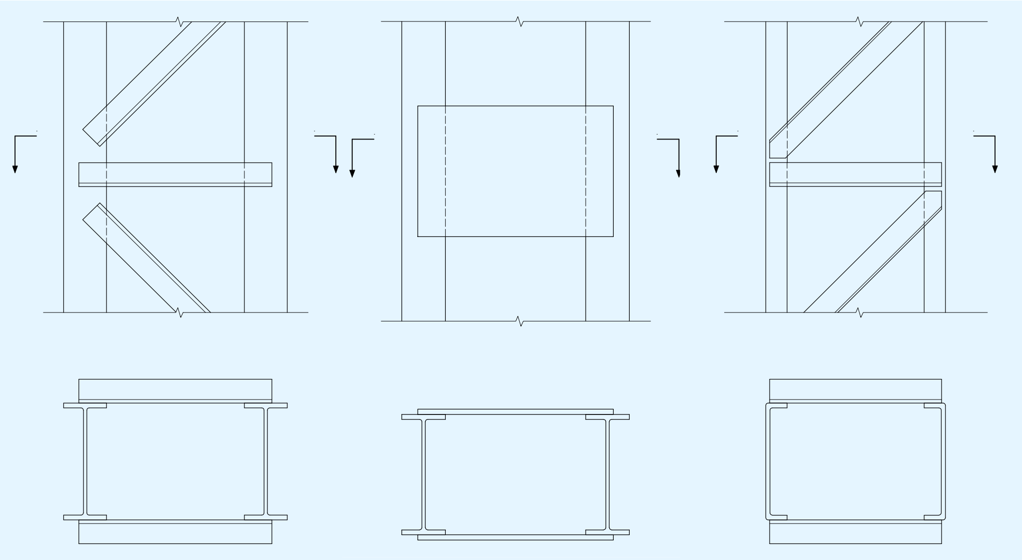


Figure 6.1 Cross-sections of built-up columns

To support the roof above the level of the crane, a single member may project for several meters. This is often known as a "bayonet" column. The projecting member may be a continuation of one of the two primary sections in the built-up section, or may be a separate section located centrally to the built-up section. Examples of built-up columns are shown in Figure 6.2. Buildings that use built-up columns are invariably heavily loaded, and commonly subjected to moving loads from cranes. Such buildings are heavily braced in two orthogonal directions.

The detailed design of built-up columns is covered in *Single-storey steel buildings. Part 6: Detailed design of built-up columns*[4] of this guide.

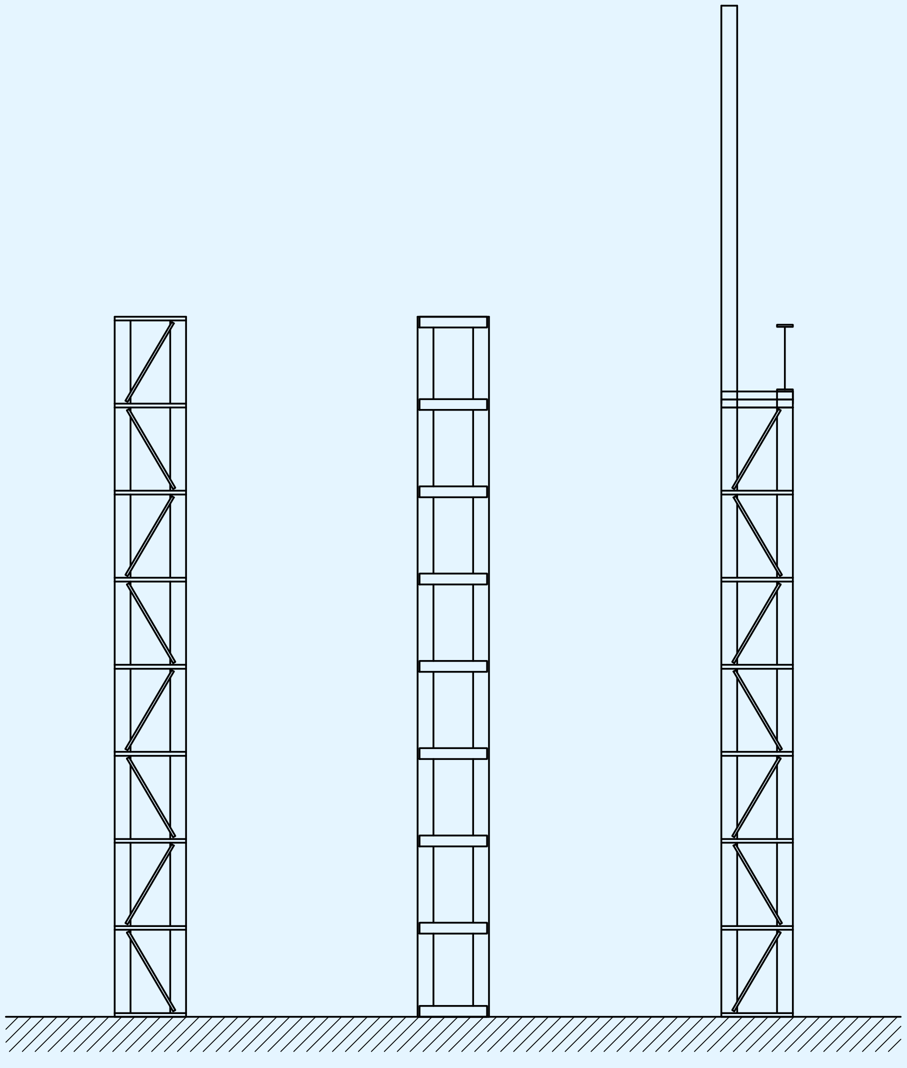


Figure 6.2 Examples of built-up columns in single storey buildings

7 CLADDING

There are a number of generic types of cladding that may be used in single storey buildings, depending on the building use. These fall into four broad categories, which are described in the following sections.

7.1 Single-skin trapezoidal sheeting

Single-skin sheeting is widely used in agricultural and industrial structures where no insulation is required. It can generally be used on roof slopes as low as 4° providing the laps and sealants are as recommended by the manufacturers for shallow slopes. The sheeting is fixed directly to the purlins and side rails, as illustrated in Figure 7.1 and provides positive restraint. In some cases, insulation is suspended directly beneath the sheeting.

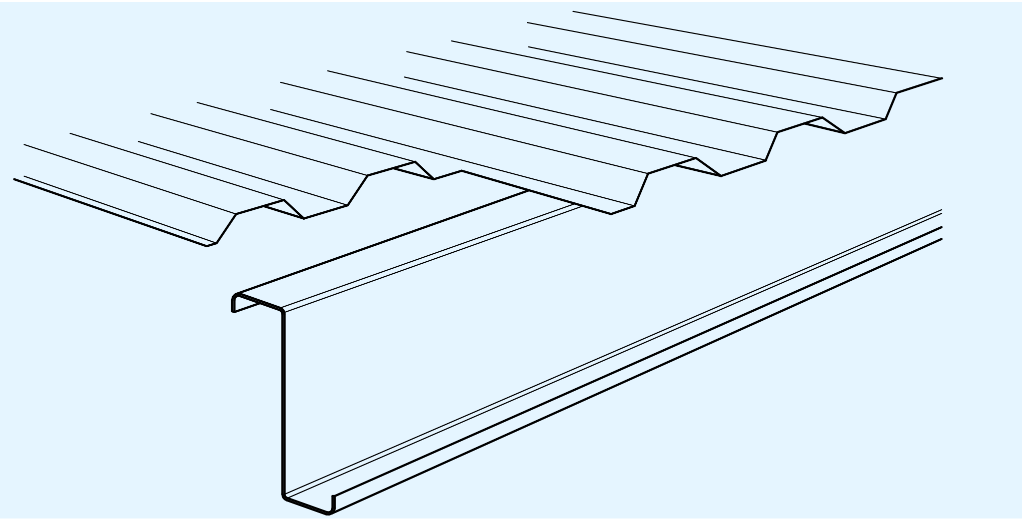


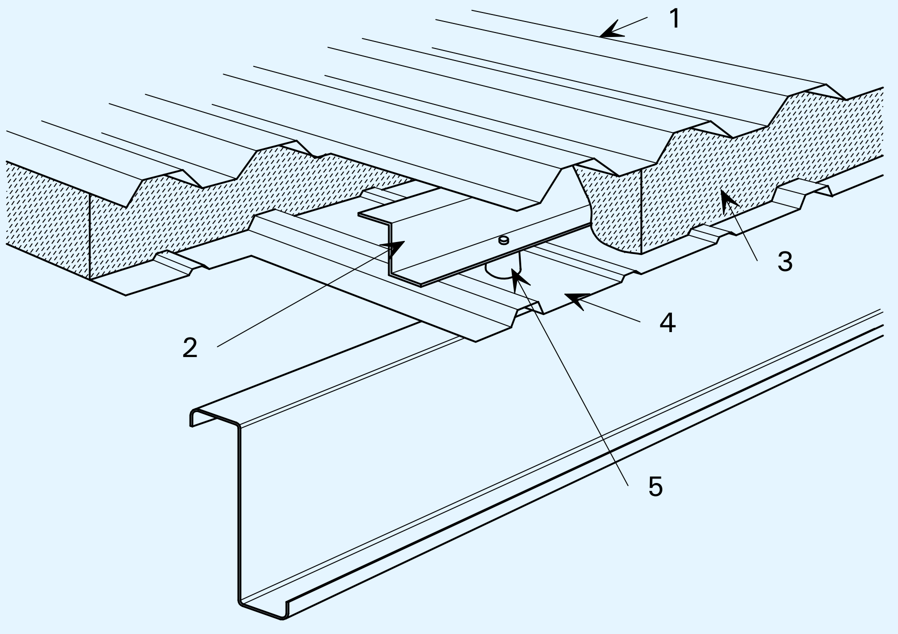
Figure 7.1 Single-skin trapezoidal sheeting

7.2 Double-skin system

Double skin or built-up roof systems usually use a steel liner tray that is fastened to the purlins, followed by a spacing system (plastic ferrule and spacer or rail and bracket spacer), insulation and the outer profiled sheeting. Because the connection between the outer and inner sheets may not be sufficiently stiff, the liner tray and fixings must be chosen so that they alone will provide the required level of restraint to the purlins. This form of construction using plastic ferrules is shown in Figure 7.2.

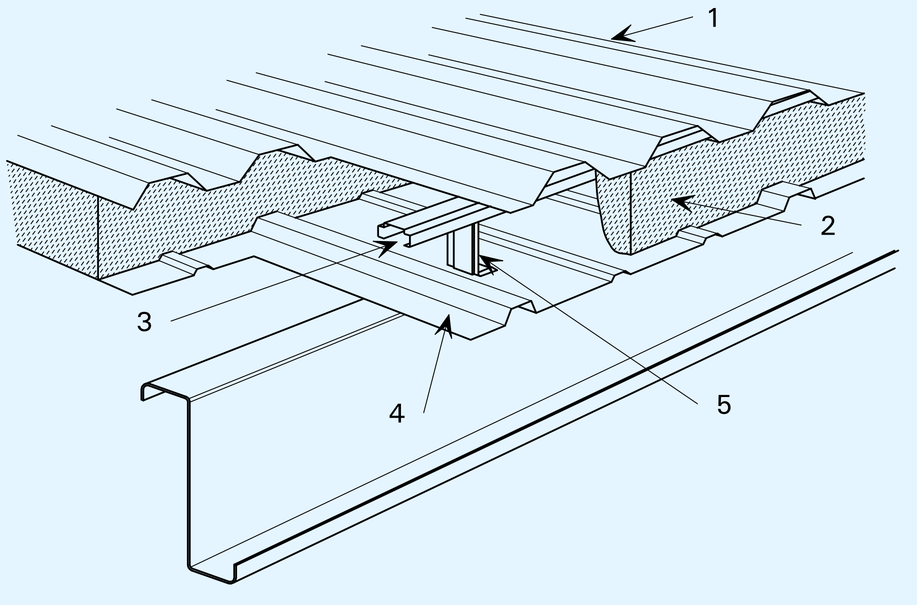
As insulation depths have increased, there has been a move towards “rail and bracket” solutions as they provide greater lateral restraint to the purlins. This system is illustrated in Figure 7.3.

With adequate sealing of joints, the liner trays may be used to form an airtight boundary. Alternatively, an impermeable membrane on top of the liner tray should be provided.



1 Outer sheeting
2 Z spacer
3 Insulation
4 Liner tray (inner sheet)
5 Plastic ferrule

Figure 7.2 Double-skin construction using plastic ferrule and Z spacers

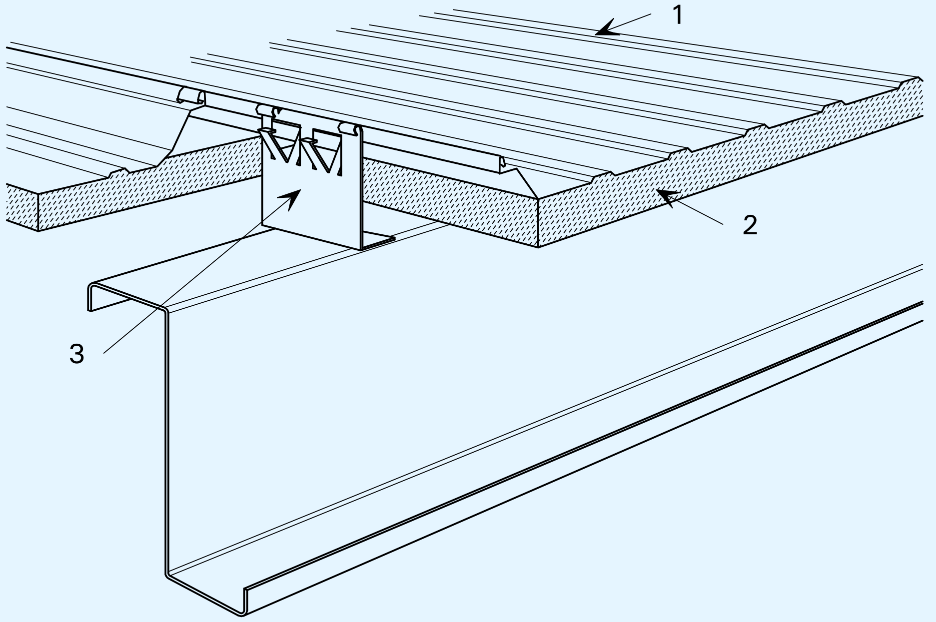


1 Outer sheet
2 Insulation
3 Rail
4 Liner tray (inner sheet)
5 Bracket

Figure 7.3 Double-skin construction using 'rail and bracket' spacers

7.3 Standing seam sheeting

Standing seam sheeting has concealed fixings and can be fixed in lengths of up to 30 m. The advantages are that there are no penetrations directly through the sheeting that could lead to water leakage and fixing of the roof sheeting is rapid. The fastenings are in the form of clips that hold the sheeting down but allow it to move longitudinally (see Figure 7.4). The disadvantage of this system is that less restraint is provided to the purlins than with a conventionally fixed system. Nevertheless, a correctly fixed liner tray should provide adequate restraint.



1 Outer sheet
2 Insulation
3 Standing seam clip

Figure 7.4 Standing seam panels with liner trays

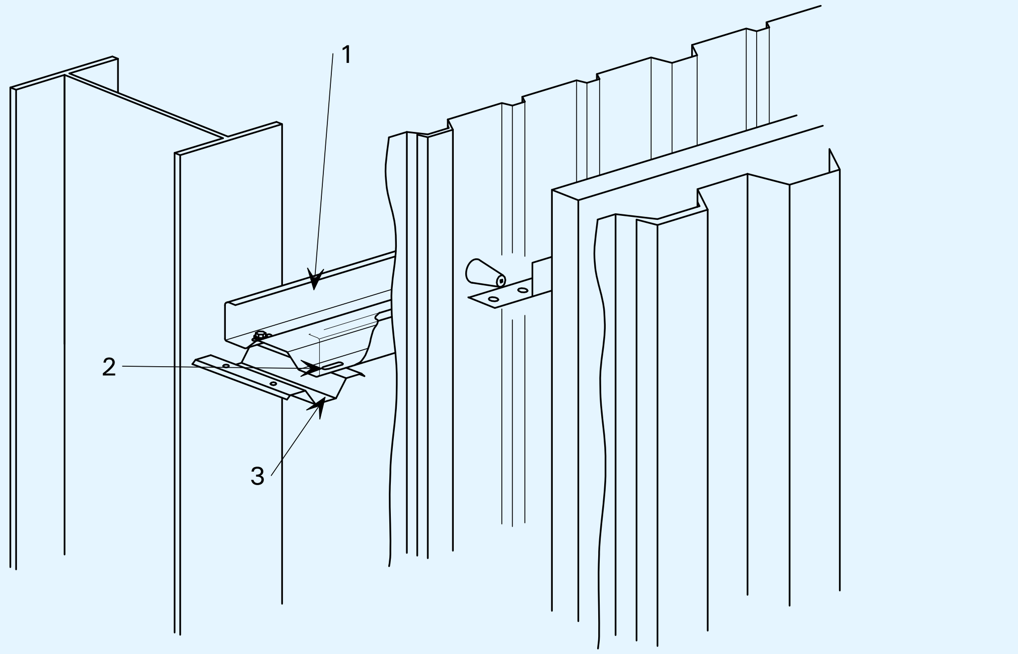
7.4 Composite or sandwich panels

Composite or sandwich panels are formed by creating a foam insulation layer between the outer and inner layer of sheeting. Composite panels have good spanning capabilities due to composite action of the core with the steel sheets. Both standing seam (see Figure 7.4) and direct fixing systems are available. These will clearly provide widely differing levels of restraint to the purlins. The manufacturers should be consulted for more information.

7.5 Fire design of walls

Where buildings are close to a site boundary, most national Building Regulations require that the wall is designed to prevent spread of fire to adjacent property. Fire tests have shown that a number of types of panel can perform adequately, provided that they remain fixed to the structure. Further guidance should be sought from the manufacturers.

Some manufacturers provide slotted holes in the side rail connections to allow for thermal expansion. In order to ensure that this does not compromise the stability of the column by removing the restraint under normal conditions, the slotted holes are fitted with washers made from a material that will melt at high temperatures and allow the side rail to move relative to the column under fire conditions only. Details of this type of system are illustrated in Figure 7.5.



1 Side rail
2 Slotted hole for expansion
3 Cleat

Figure 7.5 Typical fire wall details showing slotted holes for expansion in fire

8 PRELIMINARY DESIGN OF PORTAL FRAMES

8.1 Introduction

The following methods of determining the size of columns and rafters of single-span portal frames may be used at the preliminary design stage. Further detailed calculations will be required at the final design stage. It should be noted that the method does not take account of:

- Requirements for overall stability
- Deflections at the Serviceability Limit State.

8.2 Estimation of member sizes

The guidance for portal frames is valid in the span range between 15 to 40 m. and is presented in Table 8.1. The assumptions made in creating this table are as follows:

- The roof pitch is 6°.
- The steel grade is S235. If design is controlled by serviceability conditions, the use of smaller sections in higher grades may not be an advantage. When deflections are not a concern, for example when the structure is completely clad in metal cladding, the use of higher grades may be appropriate.
- The rafter load is the total factored permanent actions (including self weight) and factored variable actions and is in the range of 8 to 16 kN/m.
- Frames are spaced at 5 to 7,5 m.
- The haunch length is 10% of the span of the frame.
- A column is treated as restrained when torsional restraints can be provided along its length (these columns are therefore lighter than the equivalent unrestrained columns).
- A column should be considered as unrestrained when it is not possible to restrain the inside flange.

The member sizes given by the tables are suitable for rapid preliminary design. However, where strict deflection limits are specified, it may be necessary to increase the member sizes.

In all cases, a full design must be undertaken and members verified in accordance with EN 1993-1-1.

Table 8.1 Member sizes for single-span portal frame with 6° roof pitch

	Rafter load (kN/m)	Eaves height (m)	Span of frame (m)					
			15	20	25	30	35	40
Rafter	8 8 8	6 8 10	IPE 240 IPE 240 IPE 240	IPE 330 IPE 330 IPE 330	IPE 360 IPE 360 IPE 360	IPE 400 IPE 400 IPE 400	IPE 450 IPE 450 IPE 450	IPE 450 IPE 450 IPE 450
Restrained column	8 8 8	6 8 10	IPE 300 IPE 300 IPE 300	IPE 360 IPE 360 IPE 400	IPE 450 IPE 450 IPE 450	IPE 550 IPE 550 IPE 550	IPE 550 IPE 600 IPE 600	IPE 600 IPE 600 IPE 750 × 137
Unrestrained column	8 8 8	6 8 10	IPE 360 IPE 450 IPE 450	IPE 450 IPE 550 IPE 550	IPE 550 IPE 600 IPE 600	IPE 550 IPE 600 IPE 750 × 137	IPE 0 600 IPE 750 × 137 IPE 750 × 173	IPE 750 × 137 IPE 750 × 173 HE 800
Rafter	10 10 10	6 8 10	IPE 270 IPE 270 IPE 270	IPE 330 IPE 330 IPE 360	IPE 400 IPE 400 IPE 400	IPE 450 IPE 450 IPE 450	IPE 0 450 IPE 0 450 IPE 0 450	IPE 550 IPE 550 IPE 550
Restrained column	10 10 10	6 8 10	IPE 360 IPE 360 IPE 360	IPE 450 IPE 450 IPE 450	IPE 450 IPE 550 IPE 550	IPE 550 IPE 550 IPE 600	IPE 600 IPE 600 IPE 600	IPE 750 × 137 IPE 750 × 137 IPE 750 × 173
Unrestrained column	10 10 10	6 8 10	IPE 400 IPE 450 IPE 450	IPE 450 IPE 550 IPE 600	IPE 550 IPE 600 IPE 750 × 137	IPE 600 IPE 750 × 137 IPE 750 × 173	IPE 750 × 137 IPE 750 × 173 HE 800	IPE 750 × 137 HE 800 HE 800
Rafter	12 12 12	6 8 10	IPE 270 IPE 270 IPE 270	IPE 360 IPE 360 IPE 60	IPE 400 IPE 400 IPE 400	IPE 450 IPE 450 IPE 450	IPE 550 IPE 550 IPE 550	IPE 550 IPE 550 IPE 600
Restrained column	12 12 12	6 8 10	IPE 360 IPE 360 IPE 360	IPE 450 IPE 450 IPE 450	IPE 550 IPE 550 IPE 550	IPE 600 IPE 600 IPE 600	IPE 750 × 137 IPE 750 × 137 IPE 750 × 137	IPE 750 × 173 IPE 750 × 173 IPE 750 × 173
Unrestrained column	12 12 12	6 8 10	IPE 450 IPE 450 IPE 550	IPE 550 IPE 600 IPE 600	IPE 600 IPE 600 IPE 750 × 173	IPE 600 IPE 750 × 173 HE 800	IPE 750 × 137 HE 800 HE 800	IPE 750 × 173 HE 800 HE 900

Table 8.1 (Continued) Single-span portal frame with 6° roof pitch

	Rafter load (kN/m)	Eaves height (m)	Span of frame (m)					
			15	20	25	30	35	40
Rafter	14 14 14	6 8 10	IPE 330 IPE 330 IPE 330	IPE 400 IPE 400 IPE 400	IPE 450 IPE 450 IPE 450	IPE 450 IPE 450 IPE 450	IPE 550 IPE 550 IPE 550	IPE 600 IPE 600 IPE 600
Restrained column	14 14 14	6 8 10	IPE 360 IPE 400 IPE 400	IPE 450 IPE 450 IPE 450	IPE 550 IPE 550 IPE 600	IPE 600 IPE 600 IPE 750 × 137	IPE 750 × 173 IPE 750 × 173 IPE 750 × 173	IPE 750 × 173 HE 800 HE 800
Unrestrained column	14 14 14	6 8 10	IPE 450 IPE 550 IPE 550	IPE 550 IPE 600 IPE 750 × 137	IPE 600 IPE 750 × 137 IPE 750 × 173	IPE 750 × 137 IPE 750 × 173 HE 800	IPE 750 × 173 HE 800 HE 800	HE 800 HE 800 HE 900
Rafter	16 16 16	6 8 10	IPE 330 IPE 330 IPE 330	IPE 400 IPE 400 IPE 400	IPE 450 IPE 450 IPE 450	IPE 550 IPE 550 IPE 50	IPE 550 IPE 600 IPE 600	IPE 600 IPE 600 IPE 600
Restrained column	16 16 16	6 8 10	IPE 400 IPE 400 IPE 450	IPE 550 IPE 550 IPE 550	IPE 600 IPE 600 IPE 600	IPE 750 × 137 IPE 750 × 137 IPE 750 × 137	IPE 750 × 173 IPE 750 × 173 HE 800	HE 800 HE 800 HE 800
Unrestrained column	16 16 16	6 8 10	IPE 450 IPE 550 IPE 600	IPE 550 IPE 600 IPE 750 × 137	IPE 600 IPE 750 × 173 HE 800	IPE 750 × 137 HE 800 HE 800	IPE 750 × 173 HE 800 HE 900	HE 800 HE 900 HE 900

REFERENCES

1 SANSOM, M. and MEIJER, J.
Life-cycle assessment (LCA) for steel construction
European commission, 2002

2 Several assessement methods are used. For example:

- BREEAM in the UK
- HQE in France
- DNGB in Germany
- BREEAM-NL, Greencalc+ and BPR Gebouw in the Netherlands
- Valideo in Belgium
- Casa Clima in Trento Alto Adige, Italy (each region has its own approach)
- LEED, used in various countries

3 Steel Buildings in Europe
Single-storey steel buildings. Part 5: Design of trusses

4 Steel Buildings in Europe
Single-storey steel buildings. Part 6: Design of built-up columns