

Best Practice in Steel Construction

INDUSTRIAL BUILDINGS

Guidance for Architects, Designers & Constructors



Contents



The Steel Construction Institute (SCI) develops and promotes the effective use of steel in construction. It is an independent, membership based organisation. SCI's research and development activities cover multi-storey structures, industrial buildings, bridges, civil engineering and offshore engineering. Activities encompass design guidance on structural steel, light steel and stainless steels, dynamic performance, fire engineering, sustainable construction, architectural design, building physics (acoustic and thermal performance), value engineering, and information technology.

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01 Introduction



02 Key Design Factors



03 Support Structures



04 Roof & Wall Systems



05 National Practice



06 Case Studies



01 Introduction

Large enclosures or industrial type buildings are very common in business parks, leisure and sports buildings. Their functionality and architectural quality are influenced by many factors, e.g. the development plan, the variety of usages and the desired quality of the building. Steel offers numerous possibilities to achieve both pleasant and flexible functional use.

For buildings of large enclosure, the economy of the structure plays an important role. For longer spans, the design is optimised in order to minimise the use of materials, costs and installation effort. Increasingly, buildings are designed to reduce energy costs and to achieve a high degree of sustainability.

Industrial buildings use steel framed structures and metallic cladding of all types. Large open spaces can be created that are efficient, easy to maintain, and are adaptable as demand changes. Steel is chosen on economic grounds, as well as for other aspects such as fire, architectural quality and sustainability.

In most cases, an industrial building is not a single structure, but is extended by office and administration units or elements such as canopies. These additional elements can be designed in a way that they fit into the whole building design.

This publication describes the common forms of industrial buildings and large enclosures, and their range of application in Europe. Regional differences that may exist depending on practice, regulations and capabilities of the supply chain, are presented in Section 5.

The same technologies may be extended to a range of building types, including sports and leisure facilities, halls, supermarkets and other enclosures.



Figure 1.1 Leisure building using a steel framed structure

02 Key Design Factors

The design of industrial buildings is affected by many factors. The following general guidance is presented to identify the key design factors and the benefits offered by steel construction.

Industrial buildings are generally designed as enclosures that provide functional space for internal activities, which may involve use of overhead cranes or suspended equipment as well as provision of office space or mezzanine floors.

Various structural forms have been developed over the last 30 years that optimise the cost of the steel structure in relation to the space provided. However, in recent years, forms of expressive structure have been used in architectural applications of industrial buildings, notably suspended and tubular structures.

A single large hall is the main feature of most industrial buildings. The construction and appearance of an industrial building provides the design engineer with a wide range of possible configurations in order to realise the architectural ideas and the functional requirements. Generally, an industrial building has a rectangular floor space, which is extendable in its long direction. The design of the building has to be coordinated with functional requirements and the energy-saving concept, including lighting.

The following forms of industrial buildings represent an overview of the possible architectural and constructional solutions. Exhibition halls, railway stations, airports and sports arenas tend to be special structures. However, the following general issues are restricted to 'standard' floor plans.

Forms of Industrial Buildings

The most elementary system used for an industrial building consists of two columns and a beam. This configuration can be modified in numerous ways using various types of connections between the beams and columns and for the column base. The types of structures most commonly used in industrial buildings are portal frames with hinged column bases. Portal frames provide sufficient in-plane stability, and thus only require bracings for out-of-plane stability.

Figure 2.1 shows a variety of rigid frames with fixed (a) or hinged (b) column bases. Fixed column bases may be considered when heavy cranes are used, as they deflect less under horizontal forces. Hinged column bases have smaller foundations and simple base connections. In examples (c) and (d), the structure is located partly outside the building, and so details concerning the piercing of the building envelope have to be designed carefully. The complex detail in these types of structure also serve architectural purposes.

In Figure 2.2, different structures consisting of beam and columns are presented. Figure 2.2 (a) shows an example of a structure without purlins, that is stiffened by diaphragm action in the roof and bracings in the walls. In Figure 2.2 (b), purlins are used, leading to a simple design of the roof cladding, which has reduced spans and only serves to support vertical loads. The roof is stiffened by plan bracing. The structure without purlins may offer a more pleasant

Forms of Industrial Buildings

Fire Safety

Building Physics

Loading

Concept Design Considerations

Floors

Service Integration

Lighting

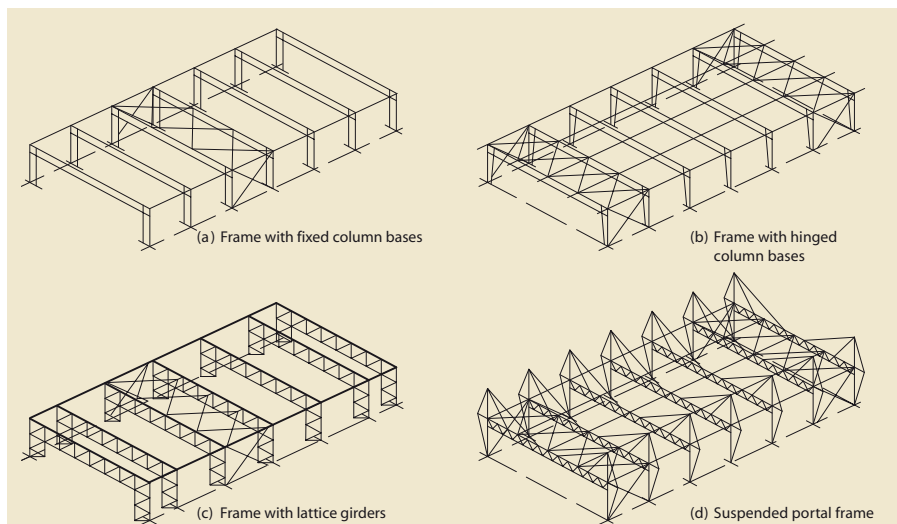


Figure 2.1 Examples of rigid framed structures

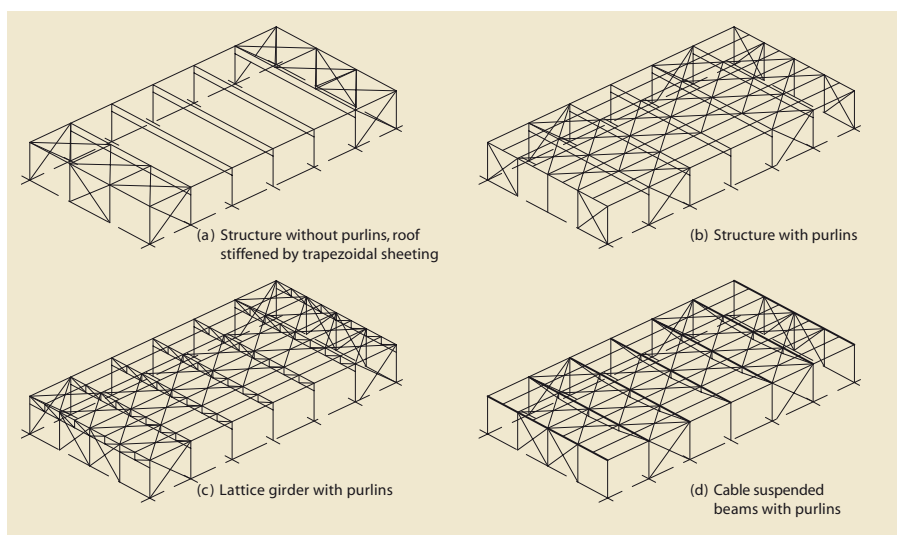


Figure 2.2 Examples of column and beam structures

appearance when viewed from the inside. Figures 2.2 (c) and (d) show lattice trusses and cable suspended beams, which may be beneficial to achieve larger spans, as well as desirable for visual reasons.

Arch structures offer advantageous load-carrying behaviour as well as having a pleasant visual appearance. In Figure 2.3 (a), a building with a three-hinged arch is shown. Alternatively, the structure can be elevated on columns or integrated in a truss structure, as in Figure 2.3 (d).

The forms of buildings with primary and secondary structural elements described above are all directional structures, for which the loads are carried primarily on

individual directional load paths. Spatial structures and space trusses are non-directional structures; they can be expanded, but would become heavy for long spans. Figure 2.4 shows some examples of spatial structures.

Portal frames

Steel portal frames are widely used in most of the European countries because they combine structural efficiency with functional application. Various configurations of portal frames can be designed using the same structural concept as shown in Figure 2.5. Multi-bay frames can also be designed, as in Figure 2.5 (e) and (f), either using single or pairs of internal columns.

In addition to the primary steel structure, a wide range of secondary components has also been developed, such as cold formed steel purlins, which also provide for the stability of the framework (see Figures 2.6 and 2.7).

These simple types of structural systems can also be designed to be architecturally more appealing by using curved members, cellular or perforated beams etc., as illustrated in Figure 2.8.

Innovative structural systems have also been developed in which portal frames are created by moment resisting connections using articulations and ties, as given in Figure 2.9.

Figure 2.3 Examples of curved or arch structures

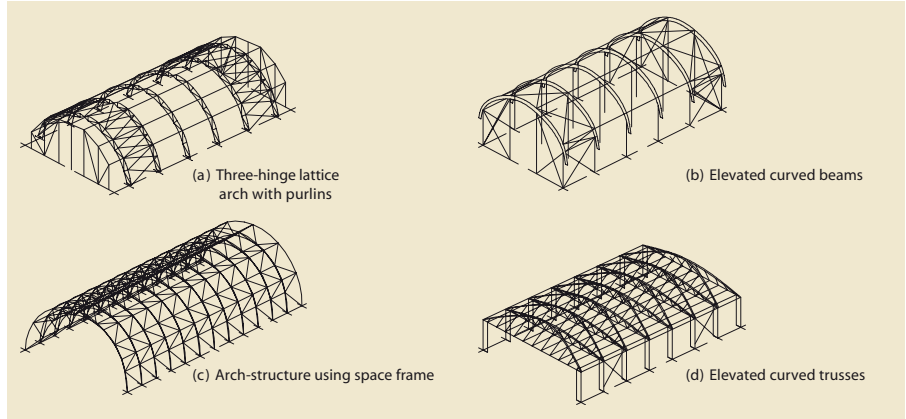


Figure 2.4 Examples of spatial structures

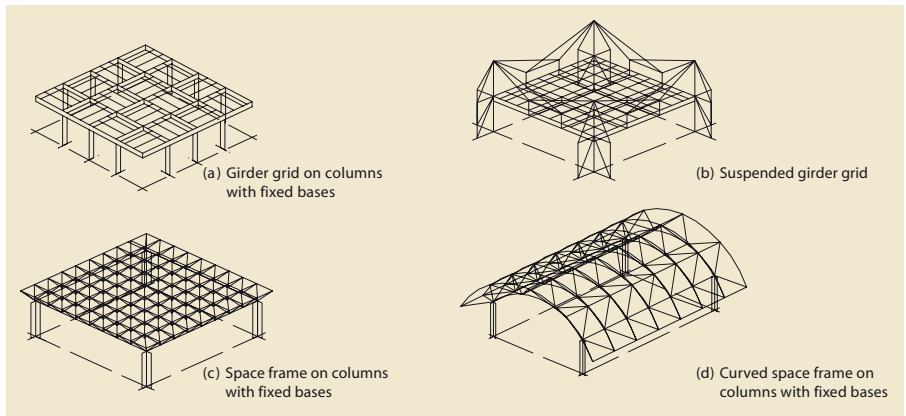


Figure 2.5 Various forms of portal frames

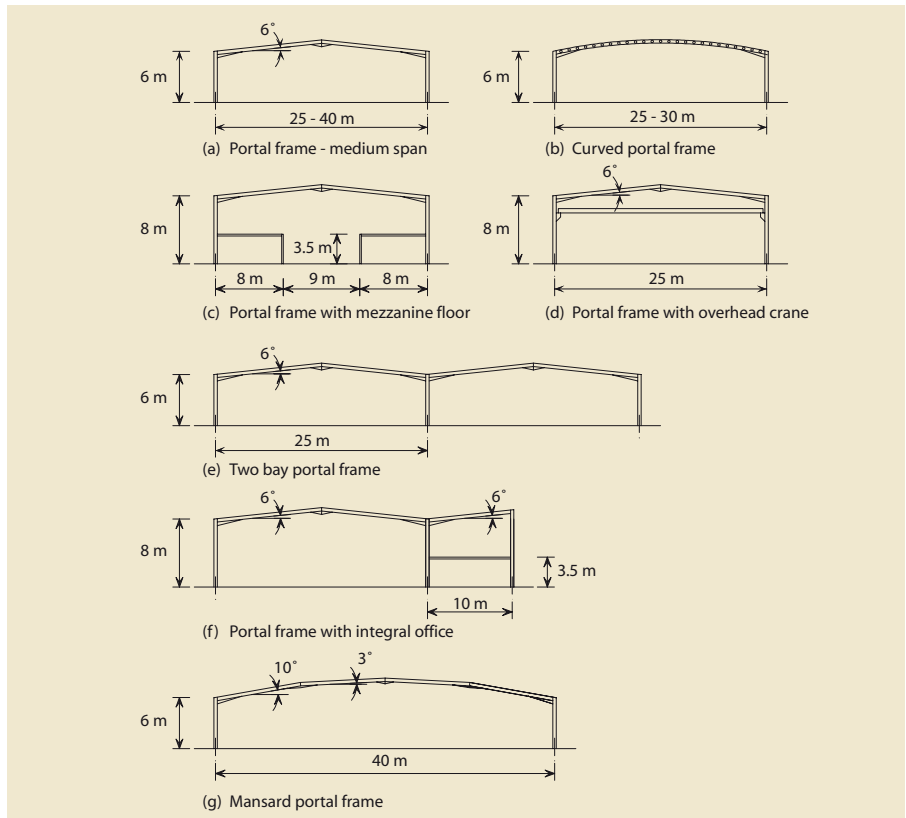




Figure 2.6 *Linked single bay portal frame*



Figure 2.7 *Two bay portal frame with purlins and roof bracing*
Kingspan Ltd



Figure 2.8 *Curved beams used in a portal frame structure*

Figure 2.9 Innovative moment-resisting connections in an industrial building



Figure 2.10 Installation process for a modern portal frame
Barrett Steel Buildings Ltd



The installation process of the primary structure and secondary members, such as purlins, is generally carried out using mobile cranes, as illustrated in Figure 2.10.

Lattice trusses

Long span industrial buildings can be designed with lattice trusses, using C, H or O sections. Lattice trusses tend to be beam and column structures and are rarely used in portal frames. Various configurations of lattice trusses are illustrated in Figure 2.11. The two generic forms are W or N bracing arrangements. In this case, stability is generally provided by bracing rather than rigid frame action.

However, columns can also be constructed in a similar way, as illustrated in Figure 2.13, in order to provide in-plane stability.

Using lattice structures, a comparatively high stiffness and load bearing resistance can be achieved while minimising material use. Besides the ability to create long spans, lattice structures are attractive and enable simple service integration.

A pinned structure is an idealisation used in design. Moment-resisting connections can be designed using bolted or welded connections. The resulting additional

internal forces are accounted for in the design of the lattice members, when the lattice truss acts to stabilise the building against lateral loads.

Suspended structures

By using suspended structures, long-span buildings with high visual and architectural quality can be realised.

The division into members that are predominantly subject to either tension or compression permits the design of lightweight structures. However, structures that save on materials use do not necessarily lead to economic solutions.

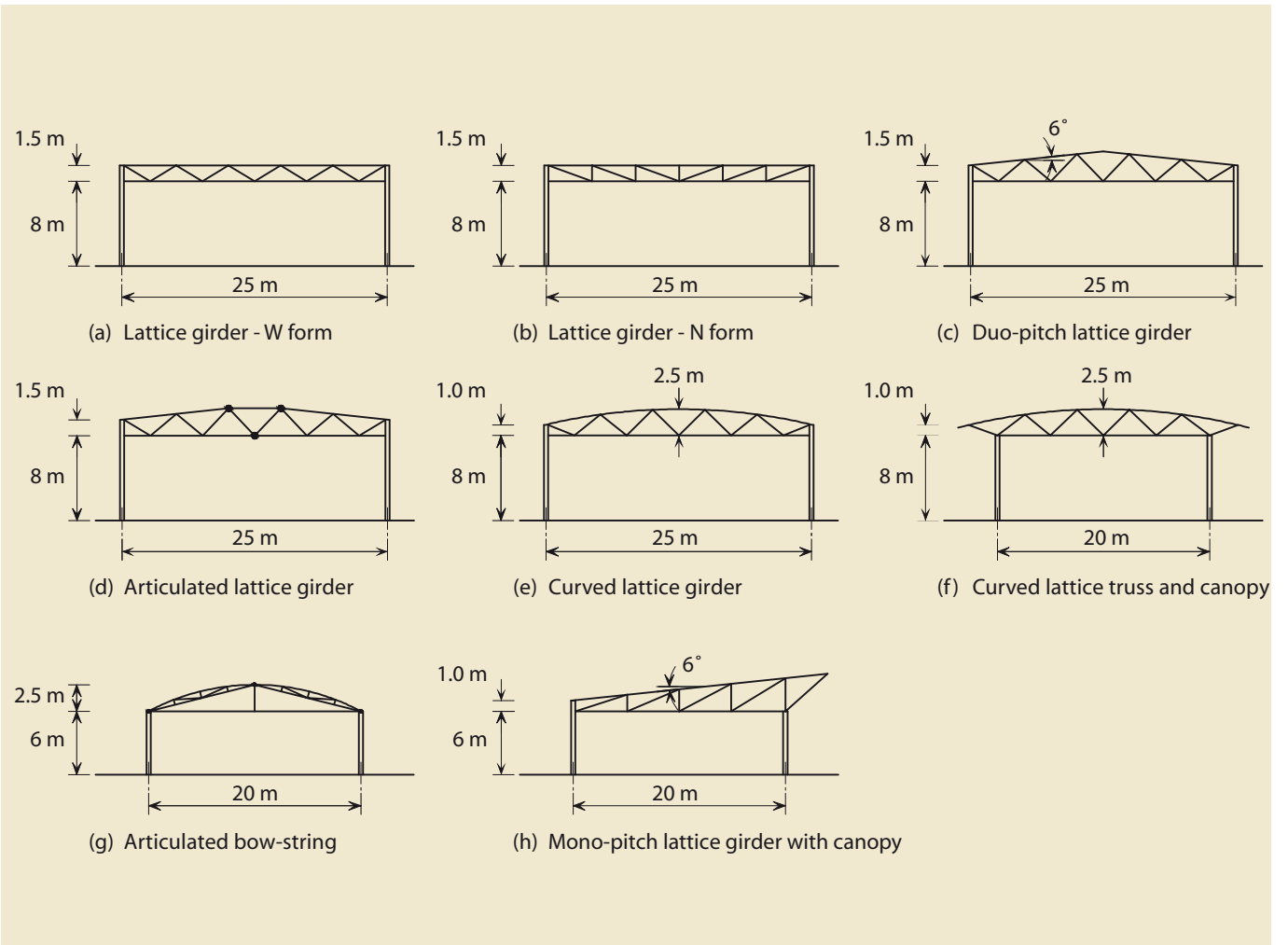


Figure 2.11 (Above) Various forms of lattice truss used in industrial buildings



Figure 2.12 (Left) Lattice truss using tubular members



Figure 2.13 Lattice frame using lattice columns

Particularly in space structures, the joints may be very complex and more time consuming to construct and install. Therefore, possible applications of this type of structure are industrial buildings that also serve architectural purposes rather than merely functional buildings.

Suspended structures can be designed by extending columns outside the building envelope, as illustrated in Figure 2.14. Suspended structures accomplish longer spans, although the suspension cables or rods also penetrate the building envelope, and can be obstructive to the use of the external space.

Lattice and suspended structures are complex and are not covered in detail in this Best Practice Guide.

Fire Safety

Even though the general context of fire safety regulations is the same throughout Europe, national differences do exist. For example a single-storey industrial building in the Netherlands with a compartment size of 50 x 100 m has no requirements concerning fire resistance, whereas in France, a fire resistance of 30 minutes is required in many cases, and in Italy the requirement is possibly as high as 90 minutes. At the design stage,

the following fire safety issues should be addressed:

- Means of escape (number of emergency exits, characteristics of exit signs, number of staircases, width of doors).
- Fire spread (including fire resistance and reaction to fire).
- Smoke and heat exhaust ventilation system.
- Active fire fighting measures (hand extinguishers, smoke detectors, sprinklers, plant fire brigade).
- Access for the fire brigade.

Fire resistance requirements should be based on the parameters influencing fire growth and development, which include:

- Risk of fire (probability of fire occurrence, fire spread, fire duration, fire load, severity of fire, etc.).
- Ventilation conditions (air input, smoke exhaust).
- Fire compartment (type, size, geometry).
- Type of structural system.
- Evacuation conditions.
- Safety of rescue team.
- Risk for neighbouring buildings.
- Active fire fighting measures.

The new generation of European regulations allow, in addition to

performing fire tests, three levels of fire design calculations:

- Level 1:** Classification of structural components by using tables.
- Level 2:** Simplified calculation methods.
- Level 3:** Advanced calculation methods.

Building physics Thermal insulation

The main purpose of thermal insulation in industrial buildings is to ensure an adequate indoor climate depending on the use of the building. During the heating season, one of the main functions of the building envelope is to reduce the heat loss by means of effective insulation. This is particularly true for buildings with normal indoor temperatures, such as retail stores, exhibition halls and leisure centres, it is true to a lesser extent for buildings with low indoor temperatures, such as workshops and warehouses.

For large panels, thermal bridges and airtightness of joints have a major influence on the energy-balance of the building. The thermal insulation has to be placed without gaps and the building envelope must be sealed and made airtight at longitudinal and transverse joints.



Figure 2.14 *Suspended structure used at the Renault Factory, Swindon, UK built in the 1980's*
Architect: Richard Rogers Partnership

In the summer, the role of the building envelope is to reduce the effects of solar gain on the interior space. The summer heat reduction depends on the total area and orientation of openings, as well as the effectiveness of solar protection measures.

Condensation risk

Thermal and moisture protection are linked closely, because damage arising from high local humidity is often the result of missing or improperly installed thermal insulation. On the other hand, lack of moisture protection can lead to condensation in the construction, which in turn affects the effectiveness of the thermal insulation.

In multi-skin roof or wall constructions, condensation risk has to be controlled by installing a vapour barrier on the inner skin of the structure. Wall constructions that are vapour proof on both sides, like sandwich panels, prevent diffusion. However, the humidity in the internal space also has to be regulated by air conditioning. Section 4 covers roof and floor systems.

Acoustic insulation

In all European countries, minimum requirements exist on the sound insulation of buildings. In addition,

for industrial buildings, it may be necessary to limit values of acoustic emissions from particular machinery.

In steel framed buildings, acoustic insulation is mainly achieved by the construction of the building envelope. All measures of acoustic insulation are based on the following physical principles:

- Interruption of transmission, e.g. by using multi-skin constructions.
- Sound absorption, e.g. by using perforated sheeting or cassettes.
- Reducing response by increasing the mass of a component.

For single sound sources, a local enclosure or isolation is recommended. In order to reach a high level of acoustic insulation, special sound-absorbing roof and wall cladding are effective. For multi-skin panels the level of sound insulation can be controlled by varying the acoustic operating mass. Due to the complexity of this issue, it is recommended to consult the specialist manufacturers.

Loading

The actions and combinations of actions described in this section should be considered in the design of a single-storey industrial building using a steel structure. Imposed, snow and wind loads

are given in Eurocodes EN 1991-1-1, 1991-1-3 and 1991-1-4. Table 2.1 shows the relevant actions and structural components and Figure 2.15 shows a typical load scheme.

Vertical loads

Self weight

Where possible, unit weights of materials should be checked with manufacturers' data. The figures given in Table 2.2 may be taken as typical of roofing materials used in the pre-design of a portal frame construction. The self weight of the steel frame is typically 0.2 to 0.4 kN/m², expressed over the plan area.

Service loads

Loading due to services will vary greatly, depending on the use of the building. In a portal frame structure, heavy point loads may occur from such items as suspended walkways, runway and lifting beams or air handling units. The following loads may be used for pre-design:

- A nominal load over the whole of the roof area of between 0.1 and 0.25 kN/m² on plan depending on the use of the building, and whether or not a sprinkler system is provided.

Imposed load on roofs

EN 1991-1-1 and -3 define characteristic

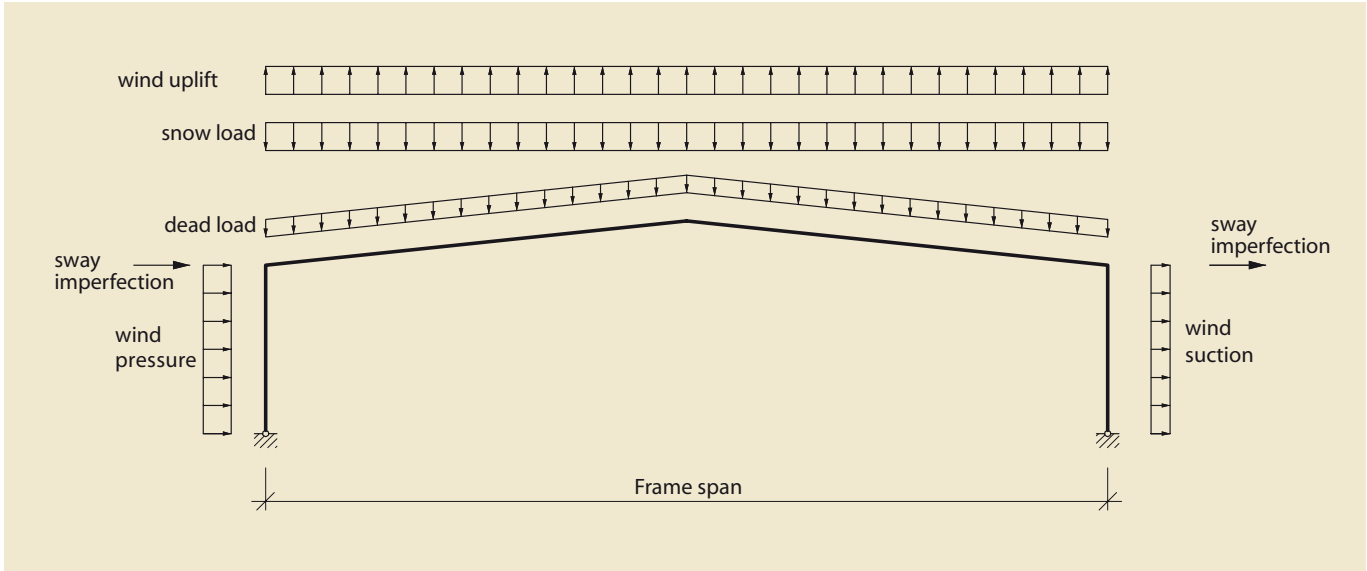


Figure 2.15 Loading scheme on a portal frame

Action	Applied to
Self-weight	Cladding, purlins, frames, foundation
Snow	Cladding, purlins, frames, foundation
Concentrated snow	Cladding, purlins, (frames), foundation
Wind	Cladding, purlins, frames, foundation
Wind (increase on single element)	Cladding, purlins, fixings
Wind (peak undertow)	Cladding, purlins, (fixings)
Thermal actions	Envelope, global structure
Service loads	Depends on specification: roofing, purlins, frames
Crane loads	Crane rails, frame
Dynamic loads	Global structure (Depends on building use and locality)
Second order effects (Sway imperfections)	Wall bracings, columns

Table 2.1 Actions and relevant structural components

Material	Weight (kN/m ²)
Steel roof sheeting (single skin)	0.07 - 0.20
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)	0.10 - 0.15
Purlins (distributed over the roof area)	0.03
Steel decking	0.20
Three layers of felt with chippings	0.29
Slates	0.40 / 0.50
Tiling (clay or plain concrete)	0.60 - 0.80
Tiling (concrete interlocking)	0.50 - 0.80
Timber battens (including timber rafters)	0.10

Table 2.2 Typical weights of roofing materials

values of various types of imposed loads on roofs:

- A minimum load of 0.6 kN/m² (on plan) for roof slopes less than 30° is applied, where no access other than for cleaning and maintenance is intended.
- A concentrated load of 0.9 kN - this will only affect the sheeting design.
- A uniformly distributed load due to snow over the complete roof area. The value of the load depends on the building's location and height above sea level. If multi-bay portal frames with roof slopes are used, the effect of concentrated snow loads in the valleys has to be considered.
- A non-uniform load caused by snow drifting across the roof due to wind blowing across the ridge of the building and depositing more snow on the leeward side. This is only considered for slopes greater than 15° and will not therefore apply to most industrial buildings.

Horizontal loads

Wind loading

Wind actions are given by EN 1991-1-4. Wind loading rarely determines the size of members in low-rise single span portal frames where the height : span ratio is less than 1:4. Therefore, wind loading can usually be ignored for preliminary design of portal frames, unless the height-span ratio is large, or if the dynamic pressure is high. Combined wind and snow loading is often critical in this case.

However, in two span and other multi-span portal frames, combined wind and vertical load may often determine the sizes of the members, when alternate internal columns are omitted. The magnitude of the wind loading can determine which type of verification has to be provided. If large horizontal deflections at the eaves occur in combination with high axial forces, then second order effects have to be considered in the verification procedure.

Wind uplift forces on cladding can be relatively high at the corner of the building and at the eaves and ridge. In these areas, it may be necessary to reduce the spacing of the purlins and side rails.

Imperfections

Equivalent horizontal forces have to be considered due to geometrical and structural imperfections. According to EN 1993-1-1 for frames sensitive to buckling in a sway mode, the effect of imperfections should be allowed for in frame analysis by means of an equivalent imperfection in the form of:

- initial sway deflections; and / or
- individual bow imperfections of members.

Other horizontal loads

Depending on the project, additional horizontal loading may have to be considered, such as earth pressure, force due to operation of cranes, accidental actions and seismic action.

Concept design considerations

General issues

Prior to the detailed design of an industrial building, it is essential to consider many aspects such as:

- Space optimization.
- Speed of construction.
- Access and security.
- Flexibility of use.
- Environmental performance.
- Standardization of components.
- Infrastructure of supply.
- Service integration.
- Landscaping.
- Aesthetics and visual impact.
- Thermal performance and air-tightness.
- Acoustic insulation.
- Weather-tightness.
- Fire safety.
- Design life.
- Sustainability considerations.
- End of life and re-use.

In the first instance, it is necessary to identify the size of the enclosure and to develop a structural scheme, which will provide this functional space taking into account all the above considerations. The importance of each of these considerations depends on the type of building. For example, the requirements concerning a distribution centre will be different from those of a manufacturing unit.

To develop an effective concept design, it is necessary to review these considerations based on their importance, depending on the type of building. Table 2.3 presents a matrix which relates the importance of each consideration to particular types of industrial buildings. Note that this matrix is only indicative, as each project will be different. However, the matrix can serve as a general aid.

Compartmentation & mixed use

Increasingly, larger industrial buildings are designed for mixed use, i.e. in most cases integrated office space and / or staff rooms for the employees are provided. There are different possible locations for these additional spaces and uses, as shown in Figure 2.16:

- For single-storey industrial buildings, creation of separate space inside the building and possibly two storeys high, separated by internal walls.
- In an external building, directly connected to the hall itself.
- For two-storey industrial buildings, partly occupying the upper floor.

This leads to special concept design requirements concerning the support structure and the building physics performance. If the office area is situated on the upper storey of the industrial building, it may be designed as a separate structure enclosed by the structure of the building. In this case, floor systems from commercial buildings can be used, often based on composite

Considerations for concept design																
Type of single-storey industrial buildings	Space optimization	Speed of construction	Access and Security	Flexibility of use and space	Environmental performance	Standardization of components	Specialist infra structure	Sustainability	End of life and reuse	Services integration	Landscaping	Aesthetics and visual impact	Thermal performance and air tightness	Acoustic isolation	Weather tightness	Design life
High bay warehouses	✓✓	✓✓	✓✓	✓✓	✓	✓✓	✓	✓	✓✓	✓	✓	✓	✓		✓✓	✓
Industrial manufacturing facilities	✓✓	✓	✓	✓✓		✓	✓		✓	✓		✓	✓	✓✓	✓	✓
Distribution centres	✓✓	✓✓	✓✓	✓✓	✓	✓✓	✓✓	✓	✓✓	✓	✓	✓	✓		✓	✓
Retail superstores	✓✓	✓	✓✓	✓✓	✓✓	✓✓		✓✓	✓✓	✓	✓✓	✓✓	✓✓		✓✓	✓
Storage / cold storage	✓	✓	✓✓	✓	✓✓	✓		✓	✓✓	✓		✓	✓✓		✓	✓
Small scale fabrication facilities	✓	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓	✓	
Office and light manufacturing	✓	✓	✓	✓	✓✓	✓		✓✓	✓✓	✓	✓	✓	✓✓	✓✓	✓	✓
Processing plants	✓	✓	✓✓		✓	✓	✓	✓✓	✓✓	✓			✓	✓✓	✓	✓
Leisure centres	✓✓	✓	✓	✓✓	✓✓	✓		✓✓	✓	✓	✓✓	✓✓	✓✓	✓	✓✓	✓✓
Sports hall complexes	✓✓	✓	✓	✓✓	✓✓	✓		✓✓	✓	✓	✓✓	✓✓	✓✓		✓✓	✓✓
Exhibition halls	✓✓	✓	✓	✓✓	✓✓	✓		✓✓	✓	✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓
Aircraft or maintenance hangars	✓	✓	✓✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Legend	No tick = Not important			✓ = important			✓✓ = very important									

Table 2.3 Important design factors for industrial buildings

structures, e.g. integrated floor beams. Another possible solution is to attach the office to the main structure. This requires particular attention to be paid to the stabilisation of the combined parts of the building.

Apart from structural issues, special attention has to be paid to:

Fire protection

For large industrial buildings, fire compartmentation may play an important role in

the design, even if there is no internal office space. In order to prevent fire spread, the compartment size is limited to a certain value. Therefore fire walls have to be provided for separation and should ensure at least 60 and often 90 minutes fire resistance. This is even more vital if hazardous goods are stored in the building.

Because the office is designed for use by a larger number of people, fire safety demands are stricter. If the offices are

located on the top floor of the building, additional escape routes are required and active fire fighting measures have to be considered. Fire-spread has to be prevented from one compartment to another, which can be achieved, for example by a composite slab between the office and industrial space.

Thermal insulation

As for fire safety, offices also have higher requirements on thermal insulation.

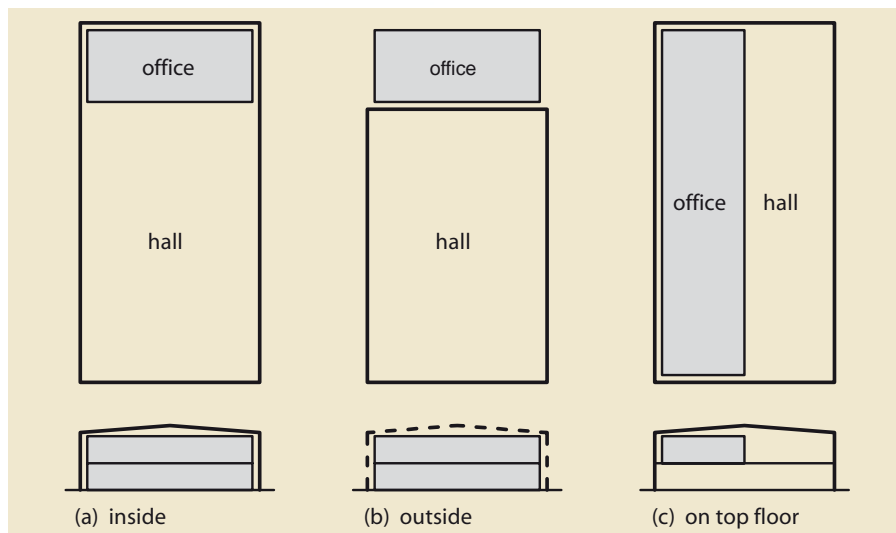


Figure 2.16 Possible location of an office attached to an industrial building

In industrial buildings used for storage purposes of non-sensitive goods, thermal insulation may not be required. In offices, however, a high level of comfort is needed, which makes thermal insulation necessary. Therefore the interfaces between the cold and the warm compartments have to be designed to provide adequate insulation.

Acoustic performance

Especially in industrial buildings with noise-intensive production processes, a strict separation between the production unit and the office areas has to be realised. This may require special measures for acoustic insulation, depending on the production processes.

Floors

In most cases, the floors for industrial buildings are used for vehicles or heavy machinery. They are designed to support heavy loads and have to be 'flat'. Concentrated loads due to vehicles, machines, racking and containers have to be considered, depending on the application.

Most industrial buildings have a concrete floor with a minimum thickness of 150 mm on top of a layer of sand or gravel, which is also at least 150 mm thick. For large floor areas, a sliding layer between the base layer and the concrete

is required, typically using two layers of synthetic material.

Service integration

For industrial buildings, special requirements for building services are often defined, which may be necessary for the operation of machines and manufacturing lines.

The service integration should be taken into account in the early planning stages. In particular, the position and size of ducts should be coordinated with the structure and provisions for natural lighting.

The use of structural systems, such as cellular beams and trusses, can facilitate integration of services and help to achieve a coherent appearance of the building.

The design of the servicing machinery and rooms can be of major importance in industrial buildings. **Centralisation** of the building services can offer the advantage of easy maintenance. Figure 2.17 shows different possible solutions of the positioning of the service rooms.

Natural ventilation reduces the reliance on air conditioning systems, which in turn means a reduction in the building's CO₂ emissions. The effectiveness of natural

ventilation depends on the size and orientation of the building. Roof vents are a common option for natural ventilation in buildings without suitably large openings, however these need to be carefully positioned so as to maximize their performance. Hybrid ventilation systems are now popular in industrial buildings. They use predominantly natural ventilation, but with mechanically driven fans to improve predictability of performance over a wider range of weather conditions.

Mechanical Heat and Ventilation Recovery (MHVR) systems use the heat from the exiting warm stale air to heat up the fresh cool air as it enters the building. The warm air is vented out of the building alongside the incoming fresh air, allowing heat transfer from the exiting to the incoming air. Although this heat transfer will never be 100% efficient, the use of MHVR systems can significantly reduce the amount of energy required to warm the fresh air to a comfortable level.

Further issues which may need consideration in services design include:

- The possible affect of elements for solar protection on air exchange.
- Odour extraction.
- Control of humidity.
- Control of airtightness.
- Acoustic insulation.

Lighting

Requirements for the lighting of industrial buildings depend on the type of use.

The concept and arrangement of openings to provide natural lighting permit diversity in architectural design. Rooflights and gable glazed roofs are common, along with lightbands in the façade (Figure 2.18). Openings for natural lighting can serve as smoke and heat outlets in case of fire.

Well-designed natural daylighting can have a significant impact on a building's carbon emissions. However, too much natural daylighting can result in excessive solar gain in the summer, leading to overheating, and increased heat loss through the envelope in the winter.

The decision to utilise natural daylight within a building and the type of daylighting selected have important implications for the overall building design.

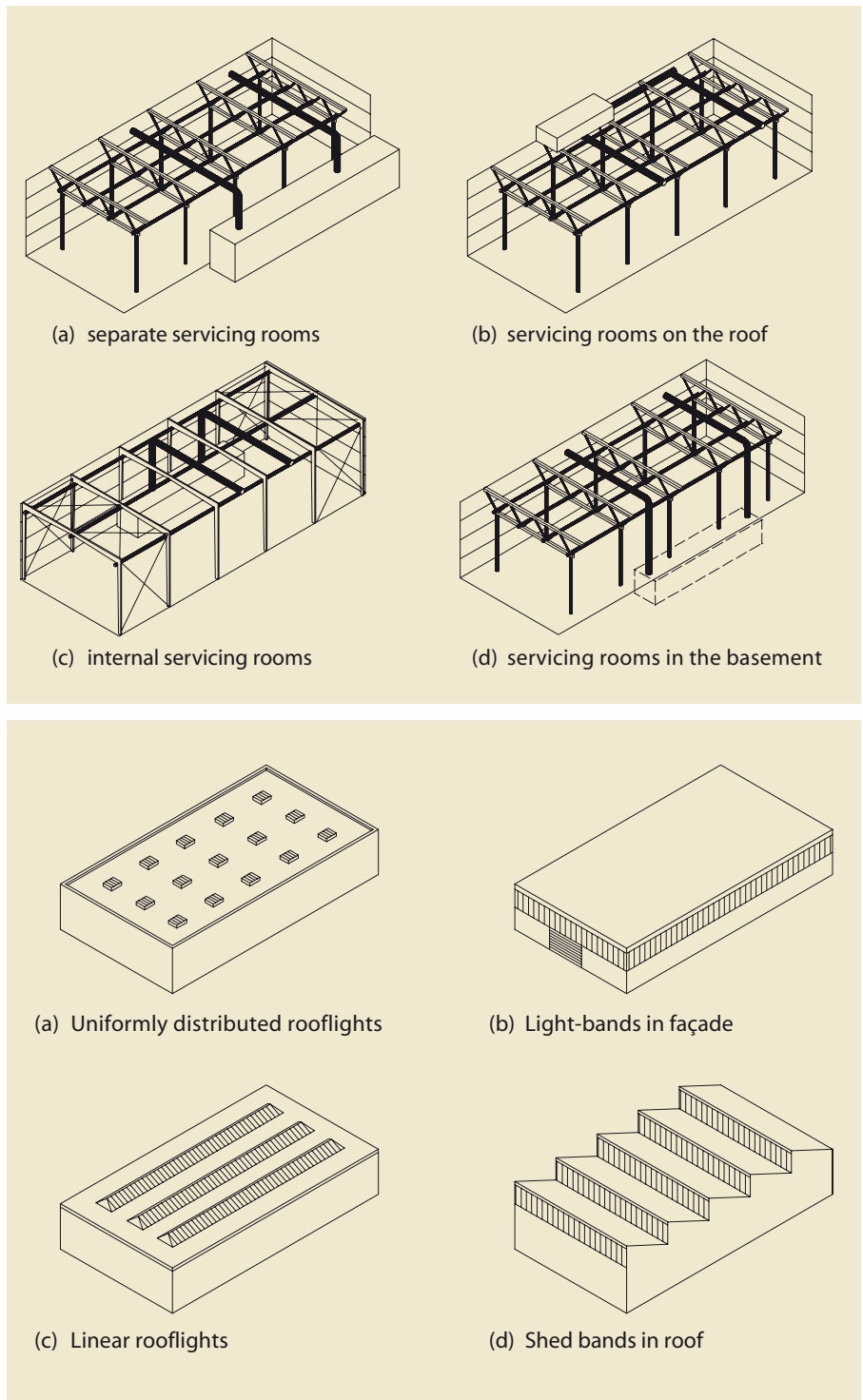


Figure 2.17 (Top right) Possible arrangements of the servicing rooms and service routes

Figure 2.18 (Right) Examples of ways of providing natural lighting in industrial buildings

03 Support Structures

This section describes common systems used for main support structures in industrial buildings. The characteristics of portal frames as well as column and beam structures are described, together with information on secondary components and connections.

Portal frame structures

Portal frame buildings are generally low-rise structures, comprising columns and horizontal or sloping rafters, connected by moment-resisting connections.

Portal frames with hinged column bases are generally preferred as they lead to smaller foundation sizes in comparison to fixed bases. Furthermore, fixed columns require more expensive connection details and therefore are predominately used only if high horizontal forces have to be resisted. However, pinned columns have the disadvantage of leading to slightly heavier steel weights due to the lower stiffness of the frame to both vertical and horizontal forces.

This form of rigid frame structure is stable in its own plane and provides a clear span that is unobstructed by bracing. Stability is achieved by rigid frame action provided by continuity at the connections and this is usually achieved by use of haunches at the eaves.

Out-of-plane stability in most cases has to be provided by additional elements, such as tubular braces and purlins (Figure 3.1). By using profiled sheeting, the stiffening of the roof can be obtained by stressed skin diaphragm action without additional bracing. Shear walls, cores and the use of fixed ended columns can also provide out-of-plane restraint to the portal frames.

A number of types of structure can be classified broadly as portal frames. The information given with regard to spans, roof pitch, etc. is typical of the forms of construction that are illustrated.

Steel sections used in portal frame structures with spans of 12 m to 30 m are usually hot rolled sections and are specified in grades S235, S275 or even S355 steel. Use of high-strength steel is rarely economic in structures where serviceability (i.e. deflection) or stability criteria may control the design.

Frames designed using plastic global analysis offer greater economy, although elastic global analysis is preferred in some countries.

Where plastic analysis is used, the member proportions must be appropriate for the development of plastic bending resistance.

Types of steel portal frames

Pitched roof portal frame

One of the most common structures for industrial buildings is the single-span symmetrical portal frame, as shown in Figure 3.2. The following characteristics emerged as the most economical and can therefore be seen as a basis at an early design stage:

- Span between 15 m and 50 m (25 to 35 m is the most efficient).
- Eaves height between 5 and 10 m (5 to 6 m is the most efficient).

Portal frame structures

Column and beam structures

Secondary components and bracing

Connections

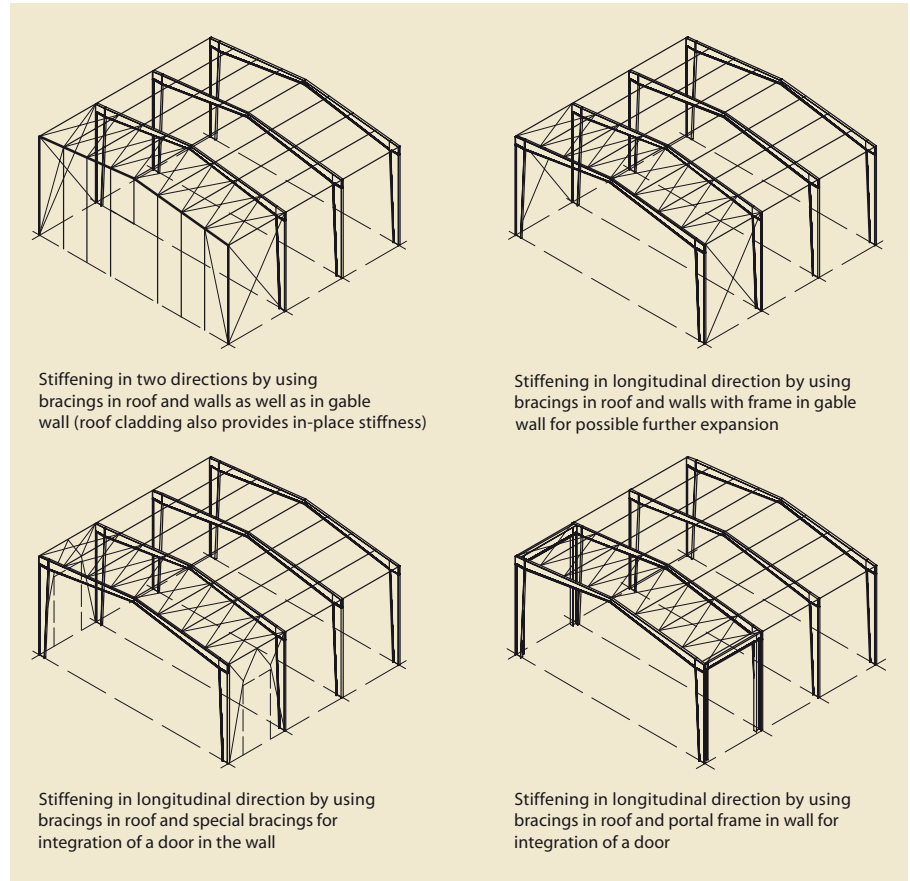


Figure 3.1 Examples of out-of plane bracing of a portal frame

- Roof pitch between 5° and 10° (6° is commonly adopted).
- Frame spacing between 5 m and 8 m (the greater spacings being associated with the longer span portal frames).
- Haunches in the rafters at the eaves and if necessary at the apex.

Table 3.1 can be used as an aid for pre-design of single span portal frames. The use of haunches at the eaves and apex both reduces the required depth of rafter and achieves an efficient moment connection at these points. Often the haunch is cut from the same size of section as the rafter.

Portal frame with a mezzanine floor

Office accommodation is often provided within a portal frame structure using a mezzanine floor (see Figure 3.3), which may be partial or full width.

It can be designed to stabilise the frame. Often the internal floor requires additional fire protection.

Portal frame with external mezzanine

Offices may be located externally to the portal frame, creating an asymmetric portal structure, as shown in Figure 3.4. 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.

Crane portal frame with column brackets

Cranes, if needed, have an important influence on the design and the dimensions of portal frames. They create additional vertical loads as well as considerable horizontal forces, which influence the size of the column section, in particular.

Where the crane is of relatively low capacity (up to about 20 tonnes), brackets can be fixed to the columns to support the crane (see Figure 3.5). Use of a tie member between haunches across the building or fixed column bases may be necessary to reduce the relative eaves deflection. The outward movement of the frame at crane rail level may be of critical importance to the functioning of the crane.

For heavy cranes, it is appropriate to support the crane rails on additional columns, which may be tied to the portal frame columns by bracing in order to provide stability.

Propped portal frame

Where the span of a portal frame is greater than 30 m, and there is no need to provide a clear span, a propped portal frame (see Figure 3.6) can reduce the rafter size and also the horizontal forces

Snow load [kN/m ²]	Span [m]	Eaves height [m]	Roof pitch [°]	Frame spacing [m]	Required cross-section	
					Column	Rafter
0.75	30.0	6.0	6.0	5.0	IPE 600	IPE 550
	25.0	6.0	6.0	5.0	IPE 500	IPE 500
	20.0	6.0	6.0	5.0	IPE 450	IPE 450
	15.0	5.0	6.0	5.0	IPE 360	IPE 360
	12.0	4.0	6.0	5.0	IPE 300	IPE 300
1.20	30.0	6.0	6.0	5.0	HEA 500	HEA 500
	25.0	6.0	6.0	5.0	IPE 600	IPE 550
	20.0	6.0	6.0	5.0	IPE 500	IPE 500
	15.0	5.0	6.0	5.0	IPE 450	IPE 450
	12.0	4.0	6.0	5.0	IPE 360	IPE 360
2.00	30.0	6.0	6.0	5.0	HEA 650	HEA 650
	25.0	6.0	6.0	5.0	HEA 550	HEA 550
	20.0	6.0	6.0	5.0	IPE 600	HEA 600
	15.0	5.0	6.0	5.0	IPE 500	IPE 500
	12.0	4.0	6.0	5.0	IPE 400	IPE 400

Table 3.1 Pre-design table for portal frames

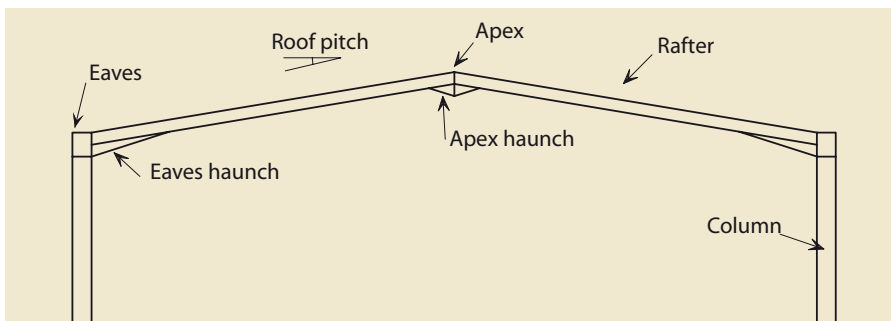


Figure 3.2 Single span symmetrical portal frame

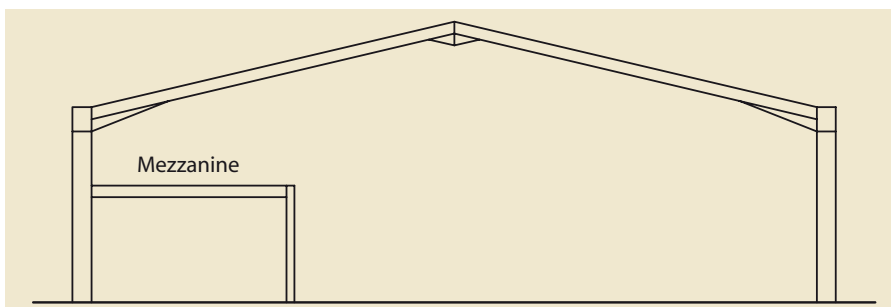


Figure 3.3 Portal frame with internal mezzanine floor

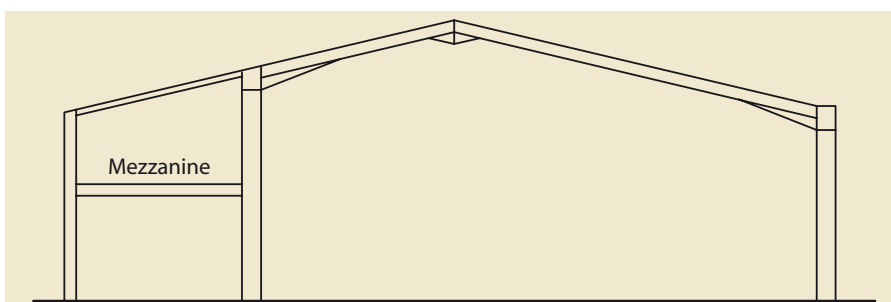


Figure 3.4 Portal frame with external mezzanine floor

Figure 3.5 Portal frame with column brackets

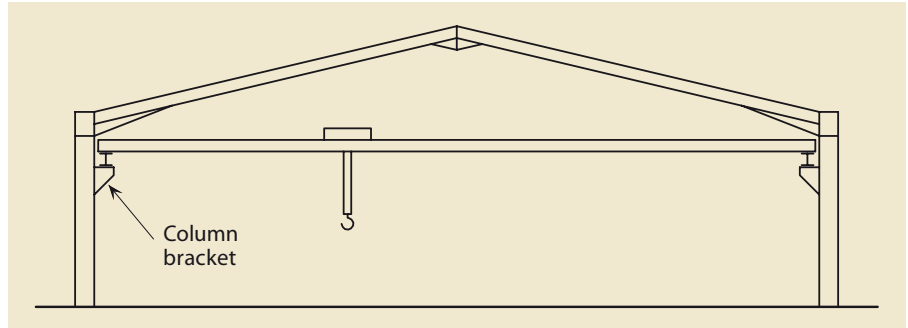
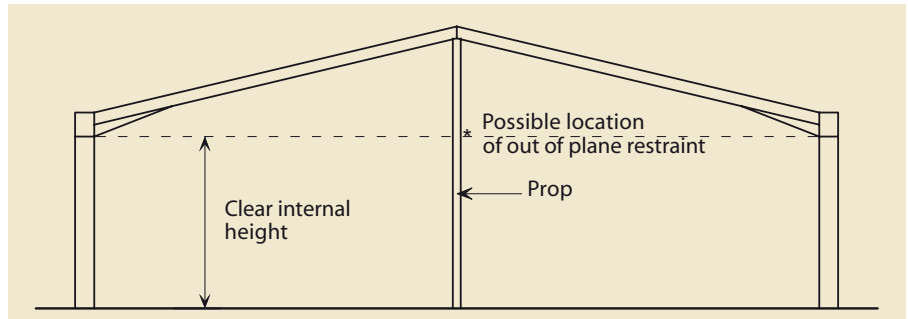


Figure 3.6 Propped portal frame



at the bases of the columns, thus leading to savings in both steelwork and foundation costs.

This type of frame is sometimes referred to as a 'single span propped portal', but it acts as a two-span portal frame in terms of the behaviour of the beam.

Tied portal frame

In a tied portal frame (see Figure 3.7), the horizontal movements of the eaves and the moments in the columns are reduced, at the cost of a reduction in the clear height. For roof slopes of less than 15°, large forces will develop in the rafters and the tie.

Mansard portal frame

A mansard portal frame consists of a series of rafters and haunches (as in Figure 3.8). It may be used where a large clear span is required but the eaves height of the building has to be minimised. A tied mansard may be an economic solution where there is a need to restrict eaves spread.

Curved rafter portal frame

Curved rafter portals (see Figure 3.9 and Figure 2.8) are often used for architectural

applications. The rafter can be curved to a radius by cold bending. For spans greater than 16 m, splices may be required in the rafter because of limitations of transport. For architectural reasons, these splices may be designed to be visually unobtrusive.

Alternatively, where the roof must be curved but the frame need not be curved, the rafter can be fabricated as a series of straight elements.

Cellular portal frame

Cellular beams are commonly used in portal frames which have curved rafters (see Figure 3.10 and Figure 2.9). Where splices are required in the rafter for transport, these should be detailed to preserve the architectural features for this form of construction.

Gable wall frames

Gable wall frames are located at the ends of the building and may comprise posts and simply-supported rafters rather than a full-span portal frame (see Figure 3.11). If the building is to be extended later, a portal frame of the same size as the internal frames should be provided. In cases in which the stability of the gable

wall is not provided by a portal frame, bracings or rigid panels are needed, as shown in Figure 3.11.

Column & beam structures

Column and beam structures require an independent bracing system in both directions. The beams may be I-sections or lattice trusses.

Column & beam structures with hinged column bases

For simple beam and column structures, the columns are loaded mainly in compression which leads to smaller columns. Compared to a portal frame, the internal moments in the beam are greater, leading to larger steel sections. Since pinned connections are less complex than moment resisting connections, fabrication costs can be reduced. Table 3.2 gives some indicative column and beam sizes for a hinged column base.

For this type of support structure, bracings in both directions are required in the roof as well as in the walls in order to provide stability for horizontal loads. For that reason, it is often used for predominantly enclosed halls (i.e. no substantial openings). This fact also has

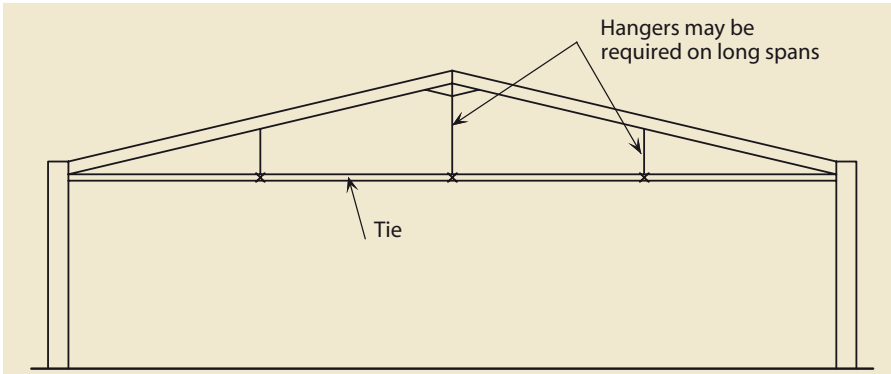


Figure 3.7 Tied portal frame

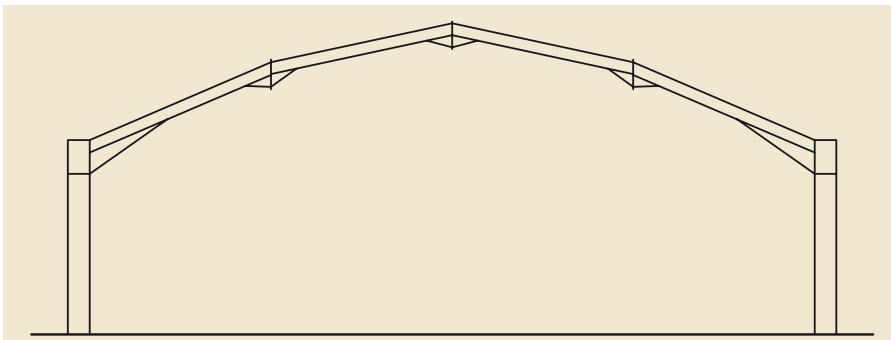


Figure 3.8 Mansard portal frame

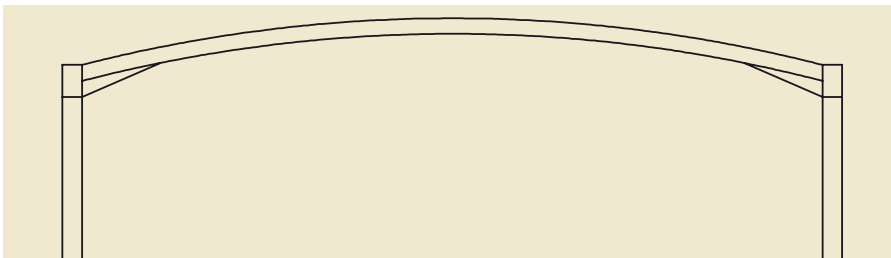


Figure 3.9 Curved rafter portal frame

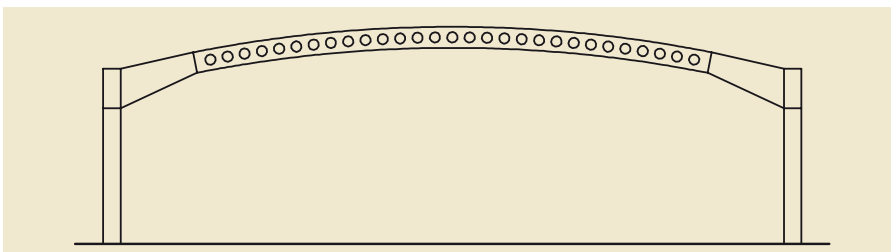


Figure 3.10 Cellular beam used in portal frame

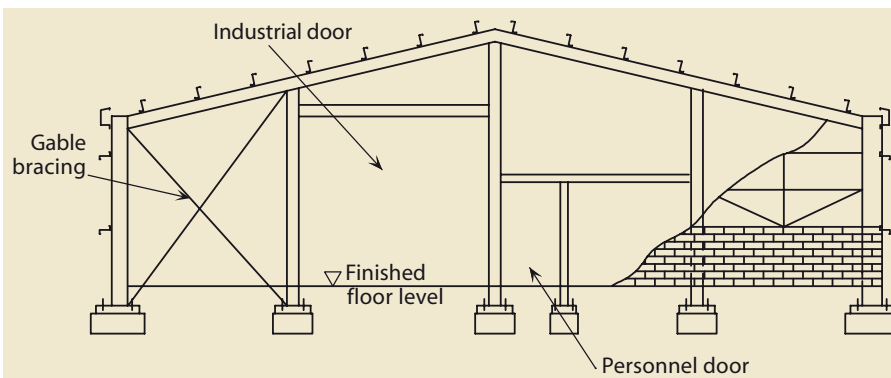


Figure 3.11 End gables in a frame structure

Snow load [kN/m ²]	Span [m]	Eaves height [m]	Roof pitch [°]	Frame spacing [m]	Required cross-section	
					Column	Beam
0.75	30.0	6.0	6.0	5.0	IPE 270	HEA 550
	25.0	6.0	6.0	5.0	IPE 270	IPE 600
	20.0	6.0	6.0	5.0	IPE 240	IPE 500
	15.0	5.0	6.0	5.0	IPE 200	IPE 360
	12.0	4.0	6.0	5.0	IPE 160	IPE 300
1.20	30.0	6.0	6.0	5.0	IPE 300	HEA 700
	25.0	6.0	6.0	5.0	IPE 300	HEA 550
	20.0	6.0	6.0	5.0	IPE 270	IPE 550
	15.0	5.0	6.0	5.0	IPE 220	IPE 450
	12.0	4.0	6.0	5.0	IPE 180	IPE 360
2.00	30.0	6.0	6.0	5.0	IPE 330	HEA 900
	25.0	6.0	6.0	5.0	IPE 300	HEA 700
	20.0	6.0	6.0	5.0	IPE 300	HEA 500
	15.0	5.0	6.0	5.0	IPE 240	IPE 500
	12.0	4.0	6.0	5.0	IPE 200	IPE 450

Table 3.2 Pre-design table for column and beam structures

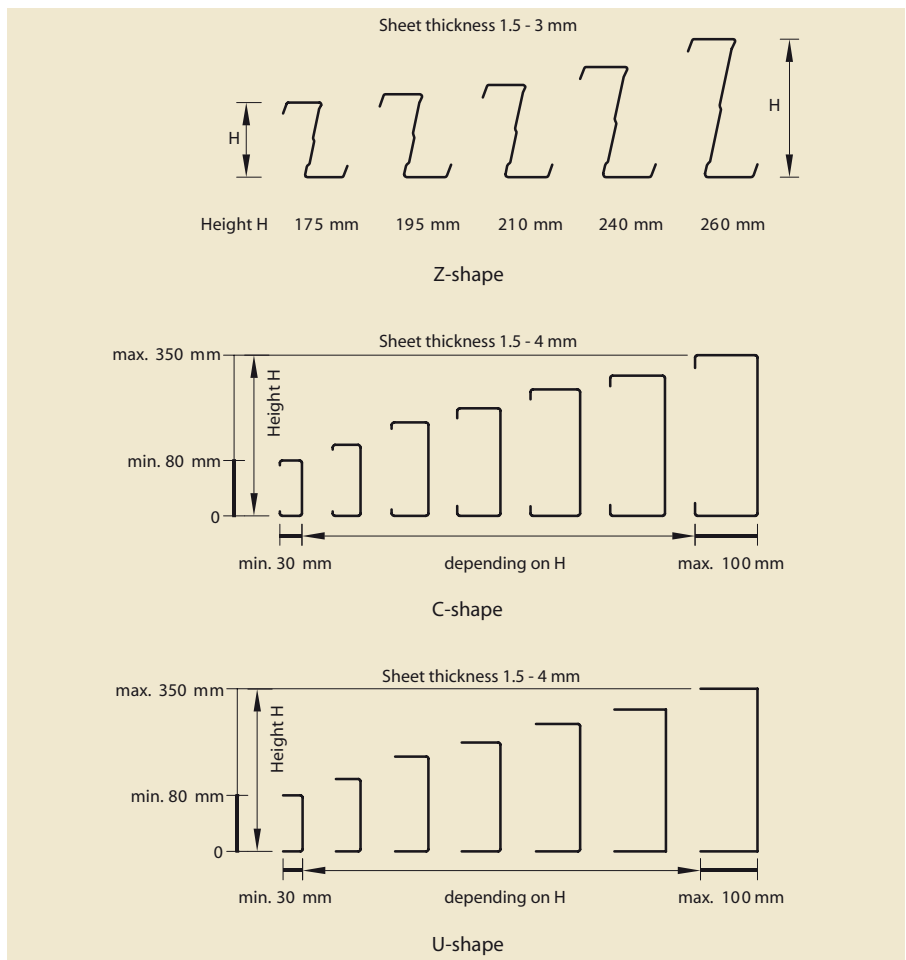


Figure 3.12 Cold-formed sections typically used for purlins

to be taken into account during the installation stage by providing temporary bracings.

Column & beam structures with fixed column bases

When using fixed-ended columns, larger foundations are required as a result of the additional bending moment. As the columns have low axial forces, the required size of the foundation will be large and possibly uneconomic. Large columns for industrial buildings with a crane may be designed as lattice structures.

Compared to portal frames, internal moments in the beams and lateral deformations are greater. The advantages of this system are its insensitivity to settlement and, in the case of the fixed supports, the base

stiffness acts in both directions, and the structure is stable after installation without additional bracing.

Secondary components & bracing

A typical steel portal frame structure with its secondary components is shown in Figure 3.14. Similar systems are provided for beam and column splices.

The bracing systems shown in Figure 3.1 are generally achieved by bracing (usually circular members) in the plane of the roof or wall. Purlins and side rails support the roof and wall cladding, and stabilise the steel framework against lateral buckling. Alternatively, panels providing shear stiffness or steel profiled sheeting used in diaphragm action can be used to provide sufficient out-of-plane stability.

Purlins

Purlins transfer the forces from the roof cladding to the primary structural elements, i.e. rafters. Furthermore, they can act as compression members as part of the bracing system and provide limited restraint against lateral torsional buckling of the rafter. For frame spacings up to 7 m, it can be economic to span the profiled sheeting between the rafters without the use of purlins. Larger frame spacings reduce the number of primary structural elements and foundations, but require the use of heavier purlins. In industrial buildings, hot-rolled I-sections as well as cold-formed profiles used in diaphragm action are used, as shown in Figure 3.12.

When cold-formed purlins are used, they are usually located at spacings of approximately 1.5 m to 2.5 m.

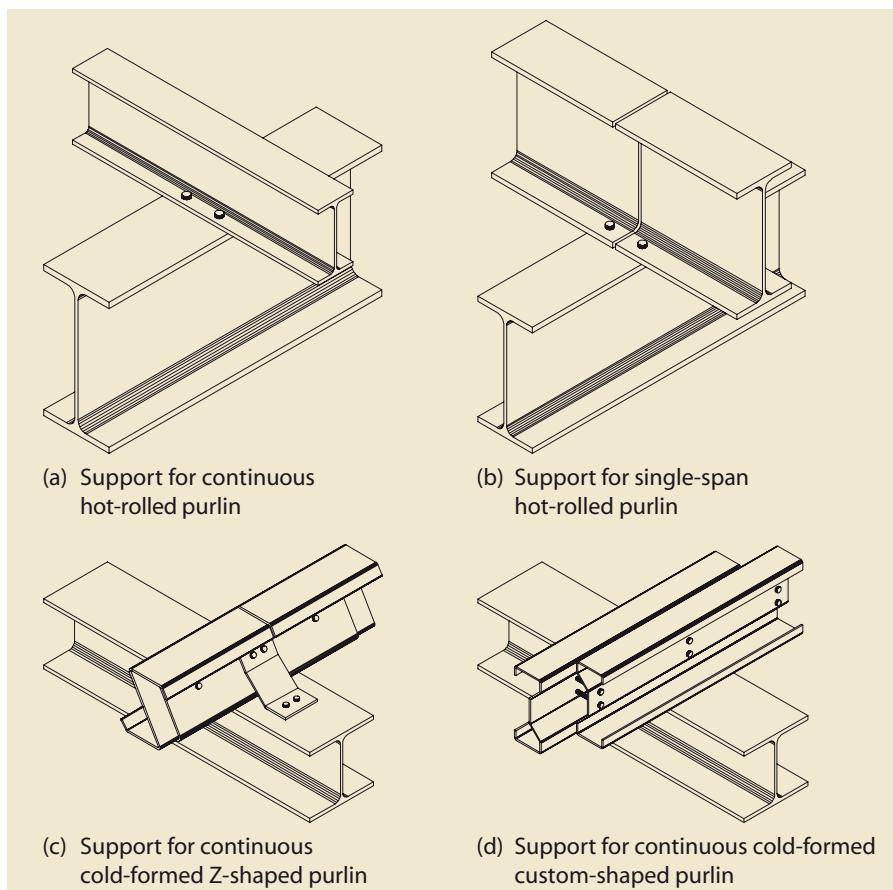
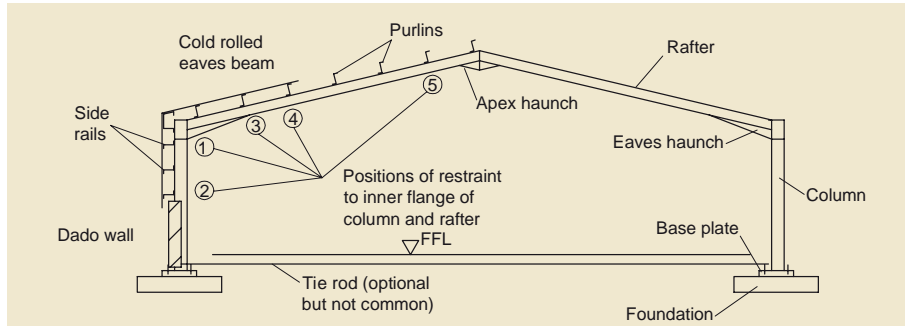
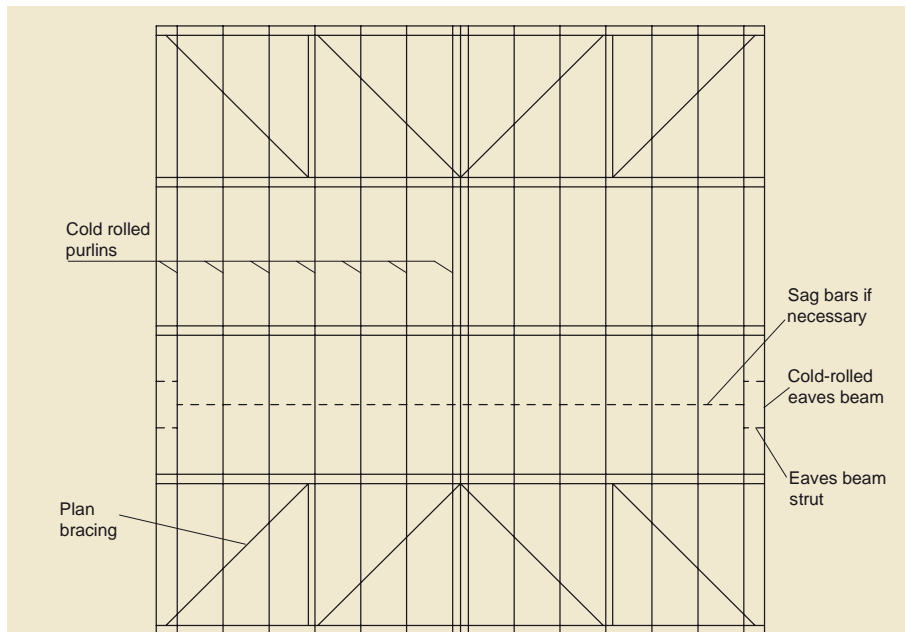


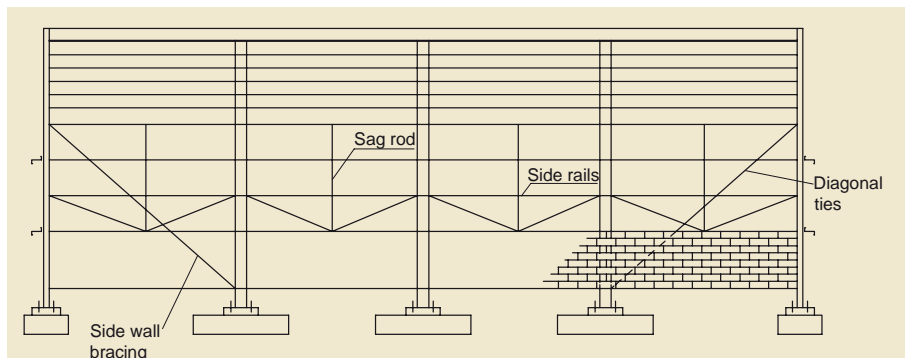
Figure 3.13 Possible solutions for purlin-rafter connections



(a) Cross-section showing the portal frame and its restraints



(b) Roof steelwork plan



(c) Side elevation

Figure 3.14 Overview of secondary structural components in a portal frame structure

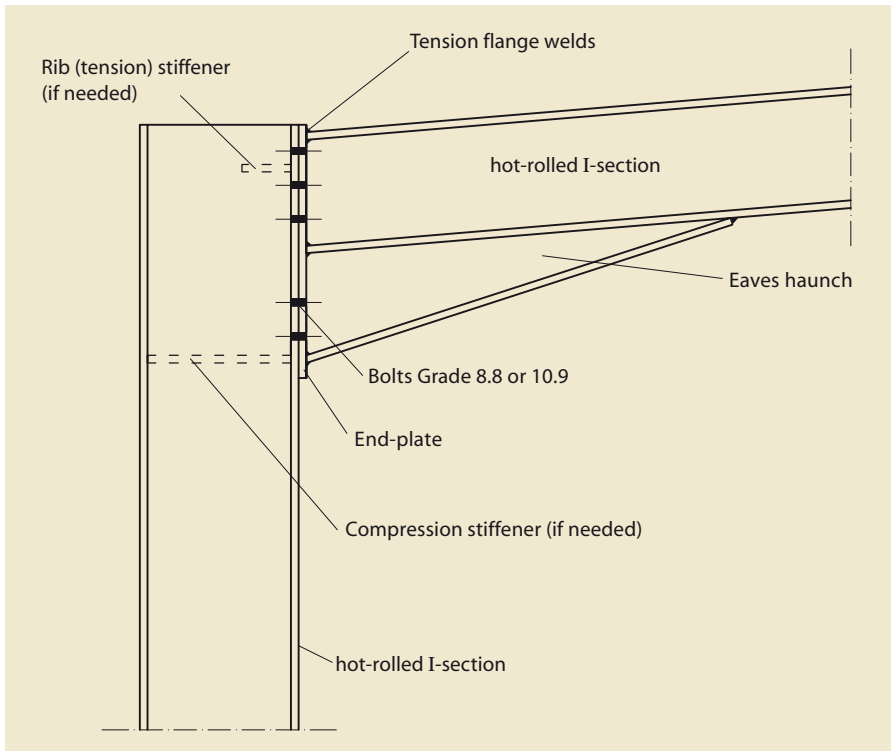


Figure 3.15 Typical eaves connections in a portal frame

The spacing between the purlins is reduced in zones of higher wind and snow load, and where stability of the rafter is required, e.g. close to the eaves and valley. Often manufacturers provide approved solutions for the connections to the rafter section using pre-fabricated steel plates, as shown in Figure 3.13.

Connections

The three major connections in a single bay portal frame are those at the eaves, the apex and the column base.

For the eaves, bolted connections are mostly used of the form shown in Figure 3.15. A haunch can be created by welding a 'cutting' to the rafter to increase its depth locally and to make the connection design more efficient. The 'cutting' is often made from the same steel section as the rafter.

In some cases, the column and the haunched part of the beam are constructed as one unit, and the constant depth part of the beam is bolted using an end plate connection.

In order to reduce manufacturing costs, it is preferable to design the eaves connection without the use of stiffeners. In some cases, the effects of the reduced joint stiffness on the global structural behaviour may have to be considered, i.e. effects on the internal forces and deflections. EN 1993-1-8 provides a design procedure, which takes these 'semi-rigid' effects into account.

The apex connection is often designed similarly, see Figure 3.16. If the span of the frame does not exceed transportation limits (about 16 m), the on-site apex connection can be avoided, thus saving costs.

The base of the column is often kept simple with larger tolerances in order to facilitate the interface between the concrete and steelwork. Typical details are presented in Figure 3.17. Pinned connections are often preferred in order to minimize foundation sizes although stability during construction must be considered. High horizontal forces may require the use of fixed based connections.

Figure 3.16 (Right) Typical apex connections in a portal frame

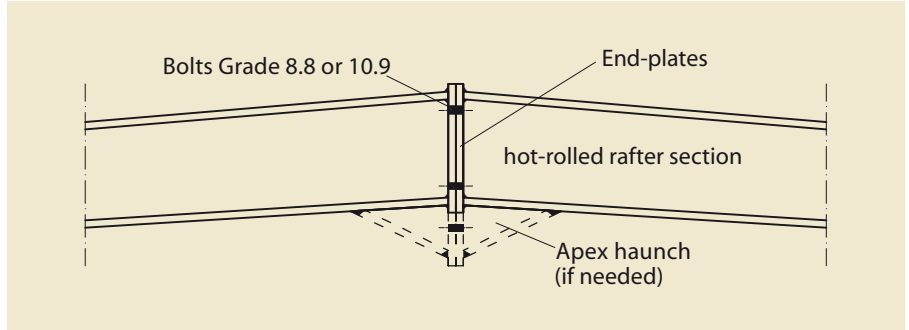
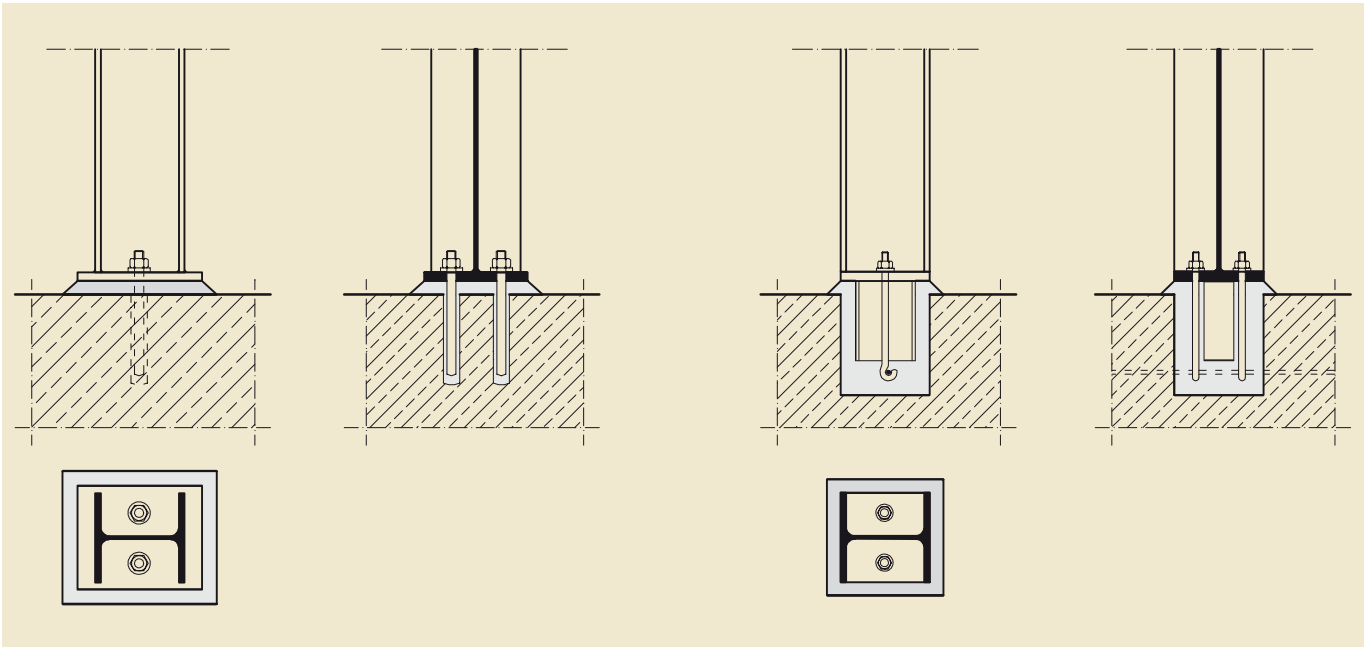


Figure 3.17 (Below) Typical examples of nominally pinned column bases in a portal frame



04 Roof & Wall Systems

This section describes common systems for roofing and cladding that serve as the building envelope and may at the same time provide stability for the main support structure. Also, mainly architectural aspects for industrial building such as service integration and lighting are discussed.

Roof systems

There are a number of proprietary types of cladding that may be used in industrial buildings. These tend to fall into some broad categories, which are described in the following sections.

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 down to as low as 4° provided that the laps and sealants are as recommended by the manufacturers for shallow slopes. The sheeting is fixed directly to the purlins and side rails, and provides positive restraint (see Figure 4.1). In some cases, insulation is suspended directly beneath the sheeting.

Generally steel sheeting is made of galvanised steel grades S280G, S320G or S275G to EN 10326. Due to the wide range of product forms, no standard dimensions for sheeting exist, although there are strong similarities between products and shapes. The steel sheets are usually between 0.50 and 1.50 mm thick (including galvanisation).

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 an outer sheet. Because the connection between the outer and inner sheets may not be sufficiently stiff, the liner tray and fixings must be chosen

Roof systems

Wall systems

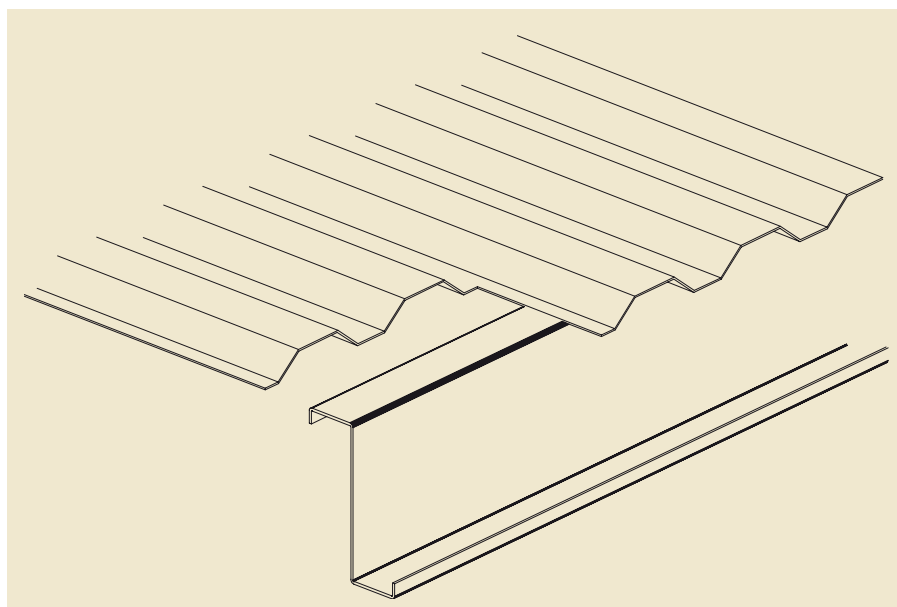


Figure 4.1 Single-skin trapezoidal sheeting

so that they provide the level of restraint to the purlins. Alternative forms of construction using plastic ferrule and Z-or rail and bracket spacers are shown in Figure 4.2 and Figure 4.3.

As insulation depths have increased to provide greater insulation performance, there has been a move towards 'rail and bracket' solutions, as they provide greater stability.

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 may be provided.

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 is rapid. The fastenings are in the form of clips that hold the sheeting down but allow it to move longitudinally (see Figure 4.4). The disadvantage is

that significantly less restraint is provided to the purlins than with a conventionally fixed system. Nevertheless, a correctly fixed liner tray will provide adequate restraint to the purlins.

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 in bending. Both standing seam (see Figure 4.5) and direct fixing systems

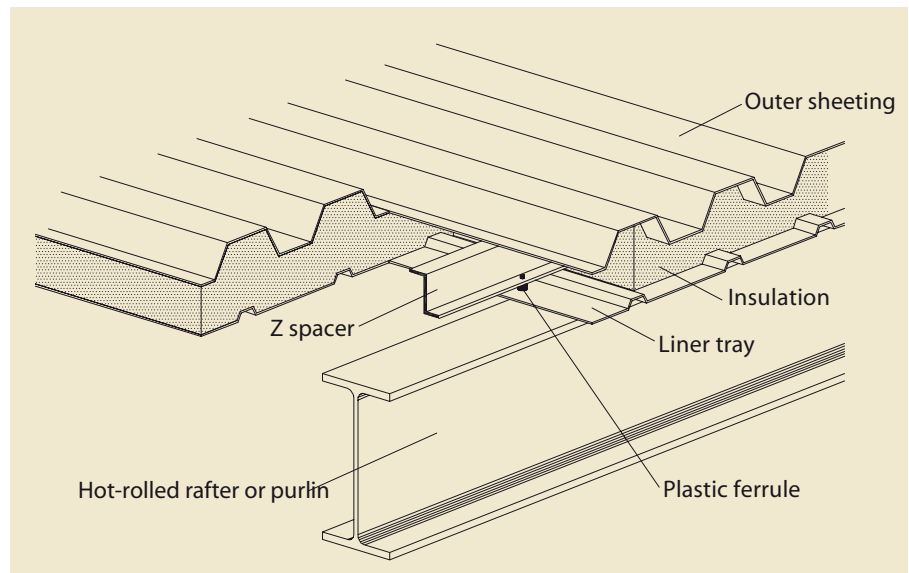


Figure 4.2 Double-skin construction using plastic ferrule and Z spacers

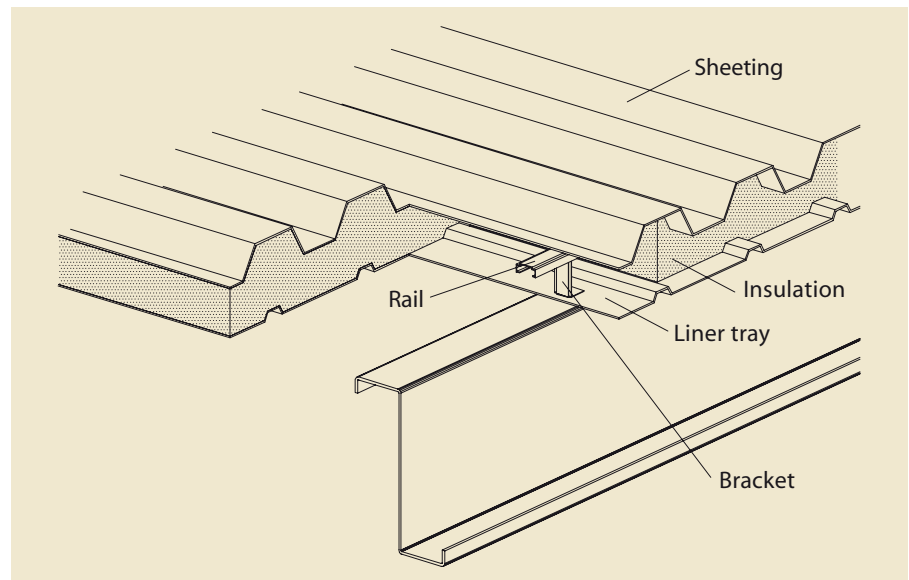


Figure 4.3 (Bottom right) Double-skin construction using 'rail and bracket' spacers

are available. These will clearly provide widely different levels of restraint to the purlins.

Sandwich elements for roofs generally have a width of 1000 mm with thicknesses between 70 and 110 mm, depending on the required insulation level and structural demands. Despite being relatively thick elements, the self-weights are comparatively low. Thus the elements are easy to handle and assemble. Component lengths of up to 20 m for roofs and walls permit constructions

without or with few joints. The basic material for the outer layers is usually galvanised coated steel sheeting with thicknesses of 0.4 to 1.0 mm.

The inner layers of sandwich panels are often lined or slotted; special designs are available with plane surfaces. Close-pitch flutings have also been established, which are fully profiled, yet appearing as a plane surface from a certain distance. Some patterns for external surfaces of sandwich panels are shown in Figure 4.6.

Requirements for corrosion protection of sandwich or composite panels are the same as for trapezoidal steel sheets. For foam insulation, the following solutions have been developed:

- Polyurethane PUR rigid foam;
- Mineral fibre insulating material;
- Polystyrene (only used in exceptions due to its lower insulation behaviour).

The steel skin and the insulating foam are physiologically harmless during production and assembly as well as in the permanent use in the building.

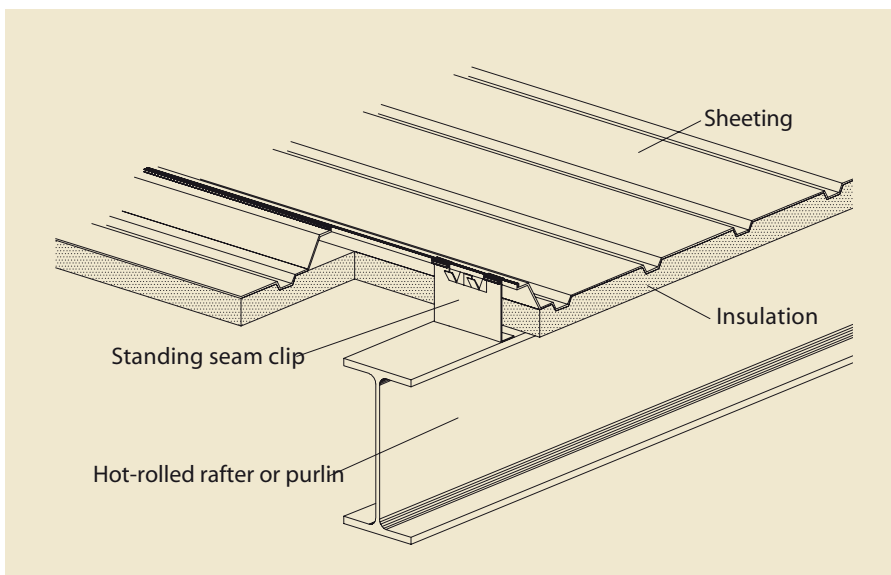


Figure 4.4 Standing seam panels with liner trays

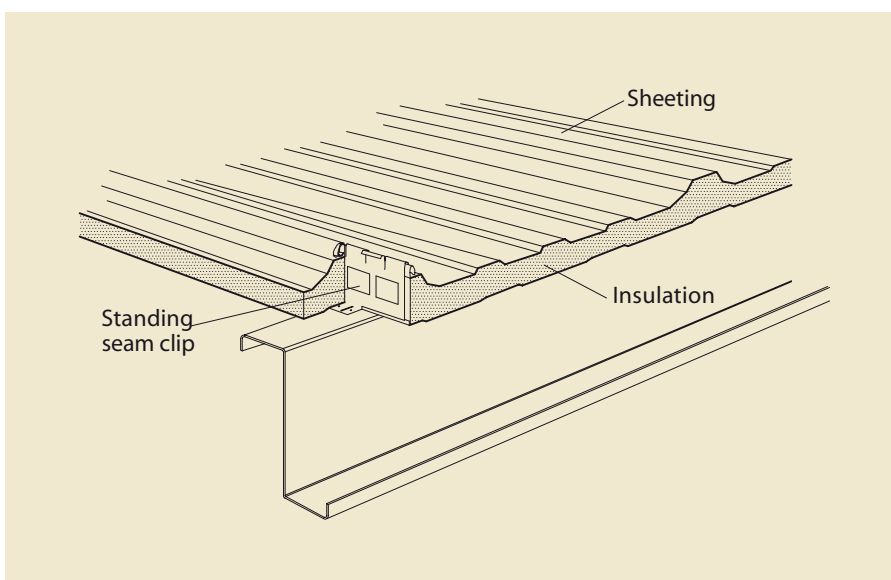


Figure 4.5 Composite or sandwich panels with clip fixings

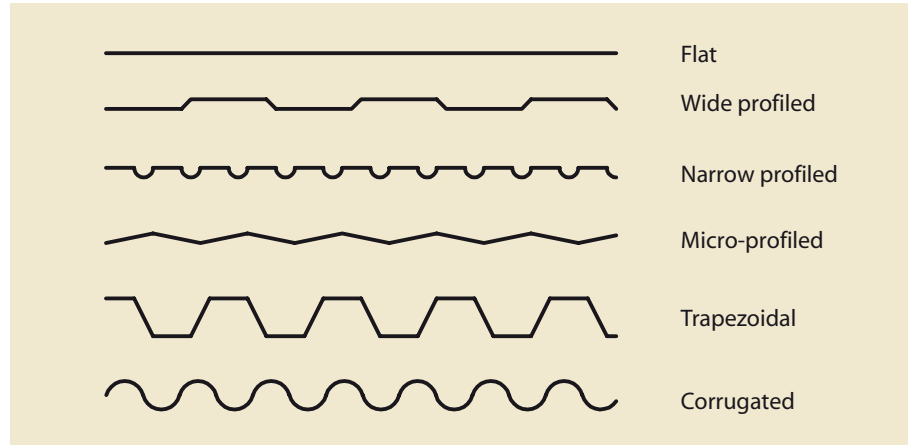


Figure 4.6 Types of external surfaces for sandwich panels

Composite or sandwich panels offer numerous advantages:

- Panel manufacturing provides short construction time and cost-efficiency
- Good building physics performance
- Can be installed in nearly all weather conditions
- Long-span capabilities which minimise the support structure

The core insulation is odourless, free from rot and mould-resistant. Furthermore it offers good recycling possibilities.

A key factor to be taken into account for the design of sandwich panels is the temperature difference across the element. The separation of the inner and outer skins leads to heating and therefore extension of the outer sheet due to solar radiation.

For single span panels, this results in a flexure of the panel. Even though this does not lead to additional internal forces, it might influence the appearance of the envelope.

For continuous panels, restraint of flexure leads to bending and to compressive forces in the skins, which can lead to

buckling of the panel. The darker the colour of the panel, the higher are the compression forces. Therefore, for continuous panels, checks for 'temperature in summer' and 'temperature in winter' design situations have to be performed, taking into account the colour of the panel. At a European level, EN 14509 (in preparation) defines the structural design method as well as the production and quality principles of sandwich and composite panels.

Manufacturers should be consulted for more information.

Special roofing systems

A flat roof of an industrial building spans a large area and is exposed to solar effects.

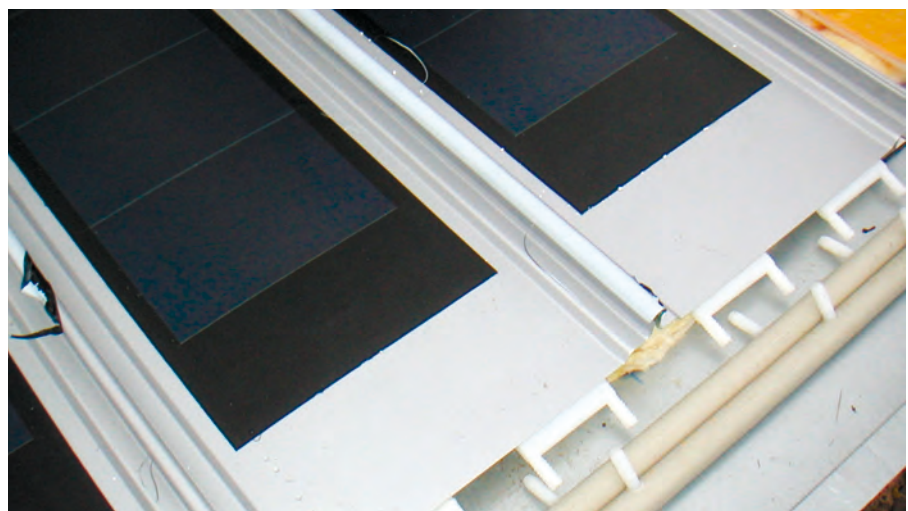


Figure 4.7 Solar cells and water cooling
Source: Corus

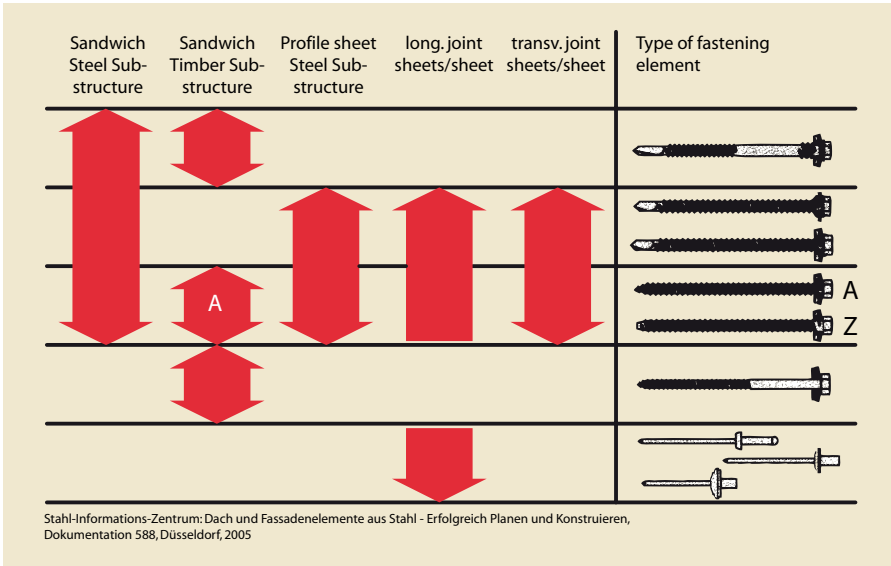


Figure 4.8 Range of application for fastening elements in various claddings

Advantage can be taken from this exposure by integrating a membrane with photo-conductive cells into the roof to capture solar energy. There are economic and easy to process products on the market.

Another steel roof cladding system has been developed with an integrated system of water channels in order to collect and use the heat (a solar thermal collector).

Fastening elements

Fastening techniques include the connections of the sheets to the supporting structure and the connections between sheets.

For the fastening of steel sheeting, (self-tapping) screws or rivets are used. For profiled sheeting, at least every second rib has to be fixed to the supporting structure. If sheets are used as a stressed skin diaphragm, the number of fixings have to be designed so that they resist the applied shear flow.

For sandwich elements, the designer has to consider the influence of the fastening method on the strength of the panel.

Figure 4.8 shows the different types of fastening elements depending on the support structure.

Wall Systems

Numerous systems exist for the design of external walls for industrial buildings. Cladding types made of steel sheeting are most frequently used, because they offer high-quality standards, short construction time and cost-efficiency. Generally, steel sheet wall cladding follows the same generic types as roof cladding, and the main types are:

- Sheeting, orientated vertically and supported on side rails;
- Sheeting or structural liner trays spanning horizontally between primary frame;



Figure 4.9 Horizontal spanning sheeting

Figure 4.10 Horizontally orientated composite panels and long 'ribbon' corridors.



Figure 4.11 Large window and composite panels with 'dado' brick wall



- Composite or sandwich panels spanning horizontally between the columns, eliminating side rails;
- Metallic cassette supported by side rails.

Different forms of cladding may be used together for visual effect in the same facade. Some examples are illustrated in Figure 4.9 to Figure 4.11.

Brickwork is often used as a 'dado' wall for impact resistance, as shown in Figure 4.11.

Sandwich or composite panels

Sandwich or composite panels are double skin continuously produced elements with various types of core insulation. They are the most common choice of wall cladding for industrial buildings in Europe. For walls, sandwich elements have widths of 600 to 1200 mm

with a thickness of 40 to 120 mm, and in some cases up to 200 mm for elements used in cold stores.

To achieve a good appearance of the building, the following aspects are important:

- Texture of the surface.
- Colour.
- Detailing of joints.
- Type of fixing.

In addition, for a modern construction system, the client expects practically invisible fixings and clean transitions at the building's corners. Nevertheless, through fixings are still commonly used. The details comprise either hidden fixings or elements with additional clip fasteners; as shown in Figure 4.5 and Figure 4.12. By the use of additional clip fasteners, slight dents that may occur at the fixings due to improper assembly or temperature influence can be avoided.

For the completion of the facades, special formed components for the transitions between wall and roof have been developed. For high quality facades, manufacturers offer angled or rounded components for the roof or corner sections. These special components have to be of the same quality and colour as the adjacent elements.

Fire design of walls

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

It is often considered necessary to 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. An example of this type of detail is shown in Figure 4.13.

Other types of façades

Many other types of façade materials may be used for industrial buildings, for example glass, as shown in Figure 4.14.

The use of this architectural high-quality façade does not automatically lead to higher costs. In the example shown in Figure 4.14, hot-rolled sections are used for the structure as well as a standardised façade-system. By integrating solar gains into the thermal balance, running costs are also reduced significantly. The structure supporting the façade and the detailing can be adapted from solutions for multi-storey buildings, where these kinds of building envelopes are common practice.

Another modern way of designing industrial buildings in an architecturally appealing way is of the use of different

colours for the façade. A variety of colours, including pastel shading and metallic finishes, are available from many sheeting suppliers. Figure 4.15 shows an example of a building well integrated with its surroundings by the use of coloured facades.

As an additional feature, photovoltaic panels may be integrated in the façade. Despite the fact that the angle to the sun is not optimal, the use of multi-layer coatings makes the solar cells less dependent on the angle of incidence of the sun's rays. An example of this technology is shown in Figure 4.16.

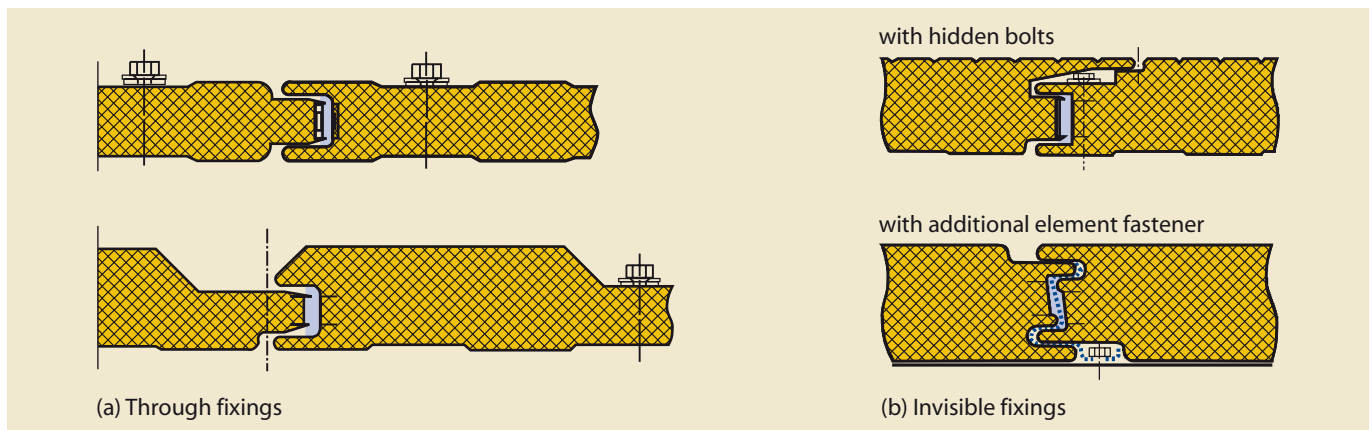


Figure 4.12 (Above) Examples of fixing methods for walls made of sandwich panels. Stahl-Informations-Zentrum: Dach und Fassadenelemente aus Stahl - Erfolgreich Planen und Konstruieren, Dokumentation 588, Düsseldorf, 2005

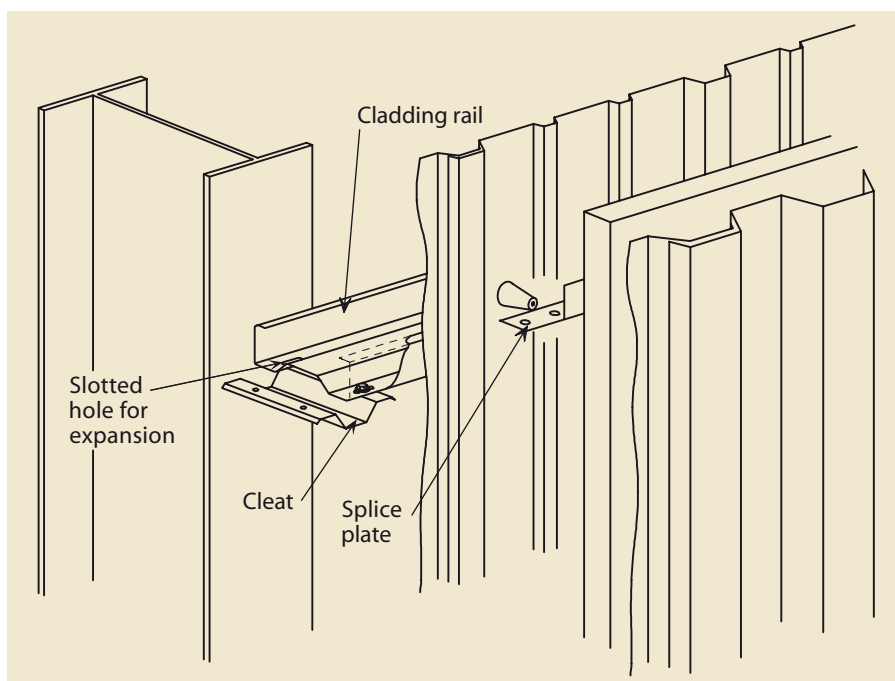


Figure 4.13 Typical fire wall details showing slotted holes for expansion in fire

Figure 4.14 Industrial building with a glazed façade
Bauen mit Stahl e.V.



Figure 4.15 Industrial building with a coloured façade
www.tks-bau-photos.com



Figure 4.16 Façade with integrated solar panels
www.tks-bau-photos.com



05 National Practice

In this section, some national practices are given for several countries. The construction systems have been identified as good practice in the countries concerned, although they may not be widely used in Europe.

Current Practice in Germany

Structure

In Germany, industrial buildings are typically constructed as portal frames with pinned column bases. The span of the frames varies from 12 m to 30 m when hot-rolled or welded I-sections are used, and spans are most commonly between 15 m and 20 m. Lattice trusses are a typical solution for spans greater than 30 m. If there are no restrictions in the building usage, multi-bay portal frames using I-sections are often used with spans of up to 20 m.

Other load-bearing structures, such as simply-supported beams on columns, arches, grids, shells, etc. are less often used, except for some architecturally expressive buildings.

The column spacing usually ranges between 5 m and 8 m, while up to 10 m is possible. The eaves height of the frame is about 4.5 m in standard cases, increasing to 8 m and more, if overhead cranes are provided.

The columns of portal frames made of IPE- or HE-sections are often designed with rafters which are haunched in the highly stressed regions. Bolted connections are mostly used with continuous columns combined with beams having end-plates, as shown in Figure 3.15. In some cases, the haunched part of the beam is attached to the column in the fabrication shop and the part of the beam with constant height is then connected on site using a bolted connection.

It is equally common for the sheeting to span between rafters and between purlins. About 40% of purlins are hot rolled and 60% are cold formed, with the cold formed proportion rising.

The design is almost exclusively carried out by using elastic calculation of the internal forces and moments, and comparing these with either elastic or plastic resistances of the cross section. The current design standard is DIN 18800, Parts 1-5, which is similar to European standard EN 1993-1-1.

Roofing

Roofs of industrial buildings in Germany are usually trapezoidal steel sheeting spanning directly between the portal frames or supported by the purlins.

Currently the single-layer, insulated steel sheeting roof, as shown in Figure 5.1 (left) is the most widely used type of roof cladding in industrial buildings in Germany. For this type of cladding, the slope should be not less than 2° in order to ensure sufficient drainage. This type of roof is comparatively low in cost, but is susceptible to mechanical damage of the weather-proofing layer.

Sandwich panel construction, as shown in Figure 5.1(right), has gained more importance, because it is easy to maintain and achieves longer useful life. Further advantages are a higher resistance to damage and good acoustic insulation and fire resistance. Often the waterproofing layer is fixed to the load-bearing layer by a clamped joint with

Germany

The Netherlands

Spain

Sweden

UK

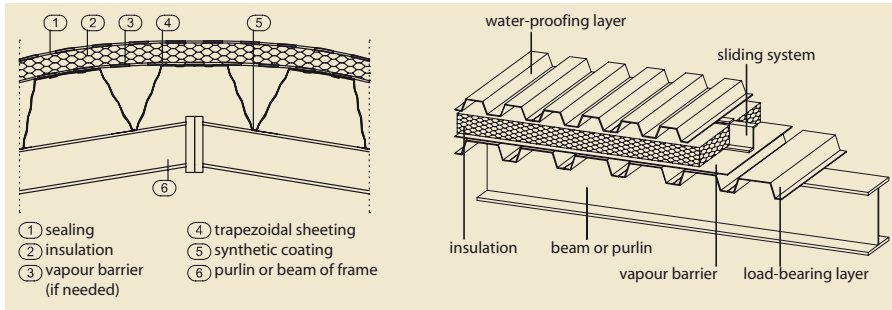


Figure 5.1 Common roofing system for industrial buildings in Germany using trapezoidal steel sheeting

special sliding system, so that the waterproofing layer does not need to be penetrated.

External walls

For industrial buildings in Germany, many types of walls are used depending on the building use, building physics requirements and the fire boundary conditions.

Systems of profiled, lightweight and large-sized sandwich panels are gaining importance as fire protection requirements are reduced with the introduction of the ‘Muster-Industriebau-Richtlinie’. These panels can be installed rapidly and easily and are not affected by weather conditions. They also offer high levels of thermal insulation.

Thermal behaviour

In Germany, the ‘Energy Saving Act’ (ENEV 2002) differentiates between buildings with ‘normal internal temperature’ and buildings with ‘low internal temperature’ (below 19°C) which can very often be found in the industrial sector. For buildings with low internal temperature, only the requirements concerning the heat

transmission losses through the building envelope have to be satisfied. The heating installation does not have to be considered. There are also fewer restrictions concerning the thermal insulation, which leads to smaller thicknesses of insulation.

Fire safety

In March 2000, a new guideline concerning the fire protection of industrial buildings came into effect, taking into account results of recent research projects dealing with natural fires. In combination with DIN 18230, it regulates the use of fire-protection in industrial buildings in terms of the fire resistance period of structural components, the size and arrangement of fire compartments, location and length of escape routes.

The guideline provides three calculation methods, of increasing level of complexity:

1. Simplified calculation method.
2. More precise calculation method with determination of the fire-load density, based on DIN 18230-1.
3. Fire-engineering methods.

The easier the calculation method, the more conservative is the result.

Using the simplified calculation method 1, single-storey industrial buildings can be designed in unprotected steel up to a plan area of 1,800 m² without providing any active fire-fighting measures. By use of automatic sprinkler units, the maximum compartment size can reach 10,000 m². If fire-walls are provided, the size of the building can be increased by adding all the compartments together.

Single-storey buildings used as retail premises also have similar low requirements in the fire resistance of the structural components, if sprinklers are provided. The maximum size of the compartments is 10,000 m² also.

The more precise calculation method 2 is based on DIN 18230-1, which determines an equivalent fire-duration. This value relates the parametric heating curve considering the specific parameters for the project to the ISO-curve. It takes into account project-specific parameters like ventilation conditions, etc. By this method,

Fire-fighting measures	No requirements	F30
No active fire fighting measures (K1)	1,800 m ² *	3,000 m ²
Automatic fire detection system (K2)	2,700 m ² *	4,500 m ²
Automatic fire detection system and plant fire brigade (K3)	3,200-4,500 m ² *	6,000 m ²
Automatic fire-extinguishing system (K4)	10,000 m ²	10,000 m ²

*Area of heat extraction surfaces ≥ 5% and width of building ≤ 40 m

Table 5.1 Allowable size of fire compartments for industrial buildings

compartment areas up to 30,000 m² can be designed using unprotected steel.

In addition to the two simplified calculation methods, fire-engineering analysis can also be used. The guideline formulates basic principles for appropriate checks to satisfy the aims of the regulations.

Current Practice in the Netherlands

For many years in the Netherlands, steel has been the most commonly used material for structural, roof and façade systems for industrial and agricultural buildings. The attributes of steel construction are beneficial to single-storey buildings with long spans:

- Speed of construction;
- Economic building cost;

- Lightweight;
- Pre-fabricated systems;
- Industrially produced components;
- Flexibility in use;
- Easily demountable;
- Reusability at three levels: material, element and building.

Construction

The vast majority of industrial buildings are single-storey, single-bay 'sheds'. These sheds are sometimes combined with offices. Multi-bay structures are a minority.

For single-storey buildings with a span up to approximately 25 m and a height up to approximately 6 m, portal frames with fixed connections are the preferred solution (Figure 5.2).

For single-storey buildings higher than 6 m, a steel frame with hinged connections and wind bracing is more economic. In this case, the connections are more complex but material use is more efficient.

A common industrial building in the Netherlands consists of portal frames of hot-rolled sections. The columns are HEA180 and the roof beams are IPE500 at 5.4 m spacing. Cold-formed profiled roof elements of typically 106 mm depth are popular. Wall elements are commonly 90 mm deep liner trays with cladding profiles fixed to the outside.

For single-storey buildings with spans longer than 25 m, trussed beams are preferred (Figure 5.3). Castellated and



Figure 5.2 For free spans up to 25 m, hot-rolled sections are preferred



Figure 5.3 For longer spans trussed beams are a popular alternative

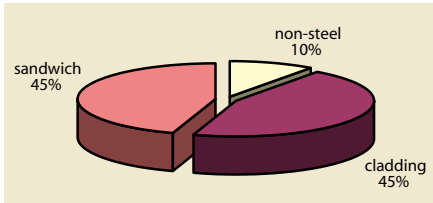


Figure 5.4 Market shares of steel façade systems in industrial buildings in the Netherlands (2006)



Figure 5.5 Trapezoidal roll-formed profiled sheet fixed to liner trays



Figure 5.6 Sandwich panels

Figure 5.7 (Right) The majority of industrial buildings are single-storey, single-bay sheds combined with offices. Most industrial buildings have flat roofs. Pitched roofs are common in agricultural buildings (Inset)

cellular beams are becoming a popular alternative to solid web sections.

Suspended and cable-stayed constructions can be economic for extremely long spans and for suspending heavy installations.

Façades

In the year 2007, Bouwen met Staal carried out a market survey of the use of façade and roof elements in industrial buildings in the Netherlands. It showed that steel cladding has a market share of approximately 90%. The remaining 10% comprise largely of masonry walls below the window sill.

Approximately half of the steel façades in industrial buildings consist of trapezoidal profiled sheet fixed to liner trays. The other half comprise steel sandwich panels. With respective outputs of 2 and 1.5 million m² per year, these two façade systems are, together with brickwork, the most commonly used products for exterior walls.

Roofs

Unlike other European countries, the vast majority of industrial buildings in the Netherlands have flat roofs. Pitched roofs are very rare in single-storey buildings in

the Netherlands, except for barns and stables in the agricultural sector.

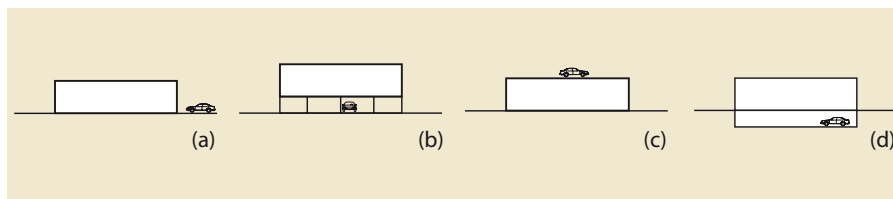
Approximately 80% of the roofs on industrial buildings consist of roll-formed profiled sheet fixed directly to the roof beams or to intermediary beams. About 15% are sandwich elements and 5% are non-steel.

Ponding on flat roofs

A point of interest is the ponding of large amounts of water on flat roofs. On one day in 2002, six roofs collapsed due to heavy rainfall. In response to these problems, the Ministry of Housing, Spatial Planning and the Environment set up a research team. One of the results is the practical guideline NPR 6773, which is published as an amendment to NEN 6702: *Technical principles for building structures. Loadings and deformations*. This simpler and more robust calculation method, in combination with more accurate supervision and control, has led to a significant decrease in problems caused by flat roofs.



Figure 5.8 (a) Parking next to the building, (b) Under the building, (c) On top of the building, (d) Below ground level



Fire protection

The main reason for the high market share of steel products in industrial buildings is the requirement for fire resistance. In the Netherlands, these requirements are relatively low in comparison to other European countries.

For single-storey buildings and most industrial buildings with a small office, there are no requirements for fire resistance from the construction. In some cases, 30 or 60 minutes is required for escape routes, for fire compartments or for prevention of fire spread between spaces and to adjacent buildings. These requirements are usually easy to meet with simple fire protection measures.

Parking

At the moment about 70,000 hectares of land is in use as an industrial development area. This is approximately 2% of the total area of the Netherlands. The Dutch government is trying to stop the rapidly increasing area zoned for economic activities. Increasingly, industrial and commercial buildings in these districts

will be renovated, and it is encouraged to find a parking solution inside the building envelope to decrease the pressure on public space (Figure 5.8).

Energy

In 2012, all new industrial buildings will have to be 'energy neutral'. This means that the energy consumption has to be equal to or less than the energy produced. In the town of Zaandam, an experimental 'zero-energy shed' has been built with promising results, and this technology is potentially useable more widely.

Current Practice in Spain

Structure

Most industrial buildings in Spain are constructed from built-up sections, although hot rolled sections are often used for bespoke shed designs. Construction components include structural systems, roof and wall cladding systems. The pre-engineered systems are delivered on site ready to be assembled. This complete process is quick, efficient and economic. The structural elements in many Spanish

industrial buildings can be identified as:

- Built-up 'I' shaped sections for the primary structure of portal frames (tapered columns and rafters from 750 mm deep to 1280 mm deep, usually from steel grade S275JR).
- Cold-formed 'Z' and 'C' shaped sections for the secondary structural members (roof purlins, side walls, etc.).
- Roof and wall cladding systems in compliance with new fire regulations.

Generally, tapered rafters have spans of 25-50 m but it is possible to design spans of 60-70 m without intermediate supports. On the other hand, the typical spacings between portal frames are 9-10 m, and columns are of 7-12 m height.

The complementary sub-systems consist of mezzanine floors, crane runway beams, crane beams, roof platforms, canopies, parapets, and all accessories needed for a complete and functional building.

The foundation requirements of these steel buildings are reduced significantly because of the open spaces provided by



Figure 5.9 Single portal frames with tapered columns and rafters under construction in Spain

Figure 5.10 Interior structure of an industrial building with tapered columns



Table 5.2 Regulations affecting the design of industrial buildings in Spain

Code	Description
EAE	Spanish Structural Steel Design Code (Instrucción de Acero Estructural). This regulation will be compulsory in 2009.
CTE	Spanish Technical Building Code (<i>Código Técnico de la Edificación</i>): Basic Documents: Basis of design (DB-SE), actions (DB-SE-AE) and design of steel structures (DB-SE-A).
EN 1993-1-1	Eurocode 3: Design of steel structures. Part 1-1: General rules and regulations for buildings.
EN 1993-1-3	Eurocode 3: Design of steel structures. Part 1-3: Supplementary rules for cold formed thin gauge members and sheeting.
RSCIEI	Spanish Regulation of Fire Security in Industrial Building (RSCIEI - <i>Reglamento de Seguridad Contra Incendios en los Establecimientos Industriales</i>) The RSCIEI is a compulsory document for the fire safety design of industrial buildings.

the clear span system, the longer bay lengths and the lower weight of the structure.

Steel industrial buildings use a variety of materials that satisfy a wide range of structural requirements. This flexibility provides an unlimited range of building configurations and applications.

Structural advantages

This structural system offers many advantages compared to traditional construction. Advanced design and fabrication methods help to reduce costs through faster construction and minimised labour on site.

Structural systems, walls, roofs and compatible accessories have the following advantages:

- The use of tapered built-up primary structural members (columns and rafters) results in up to a 40% weight advantage for the main rigid frames when compared to the use of conventional hot rolled sections.
- The use of 'Z' shaped secondary structural members (roof purlins and side rails), particularly the overlapping of the 'Z' shaped purlins at the frames, results in up to a 25% weight saving for the secondary members.
- Generally, all the components are factory-produced on automated production lines, saving many problems in installation.
- The steel scrap from the manufacture of built-up plate members and cold formed 'Z' sections is reduced.
- All steel is structurally efficient.

Public and private companies, contractors and designers benefit as a result of the cost savings and from the faster construction process.

Regulations

The main regulations affecting the design of industrial buildings in Spain are given in Table 5.2.

Fire safety engineering

The Spanish Fire Safety Regulation for industrial buildings (RSCIEI) requires an assessment of the fire resistance of the building according to the expected fire loads, compartment size and neighbouring buildings.

Although it is possible to design industrial buildings without additional structural fire



Figure 5.11 (Above) Exterior appearance of industrial building in Spain

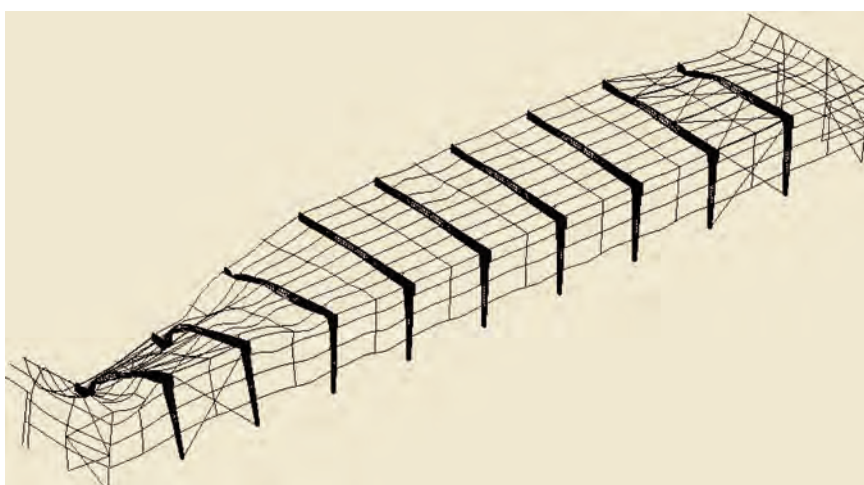


Figure 5.12 Full scale model in fire conditions showing collapse mechanism

resistance, i.e. detached sheds with low fire load, fire safety engineering offers a more competitive approach in the case of high fire loads or layouts requiring larger compartment sizes. An example of a model used to determine structural performance and time to collapse of a steel framed industrial building in fire is given in Figure 5.12.

Acknowledgements

The images shown have been provided by Prado Transformados Metálicos S.A. (www.pradotm.com).

Current practice in Sweden A typical Swedish industrial building

Open plan buildings, such as industrial buildings, are a very important market for steel in Sweden (SBI, 2004). Common dimensions for light industrial buildings are spans between 15 and 25 m with a height of 5 to 8 m. Building plan areas of 1500-2000 m² are common. Often companies specialising in these systems deliver the building as a turnkey product.

Modern buildings of this type are usually insulated with approximately 120 to

150 mm of mineral wool. The buildings often comprise an office space in parts of the building using an intermediate floor.

The most common and often most economic way of stabilising an open plan building is to insert wind bracing at the ends and in the long sides and to utilise the profiled sheeting in the roof as a stiff stressed skin diaphragm, as shown in Figure 5.13. The columns are designed as pinned. The wall sheeting may also be used as a stressed skin diaphragm.

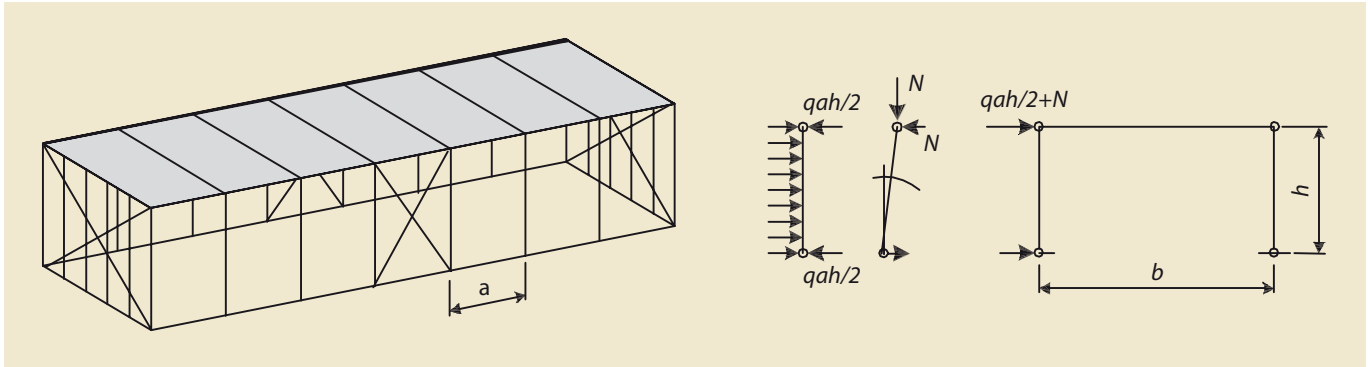


Figure 5.13 (Above) Industrial building stabilised by wind bracing in the walls and diaphragm of trapezoidal sheeting in the roof. SBI Publication 174, 2002

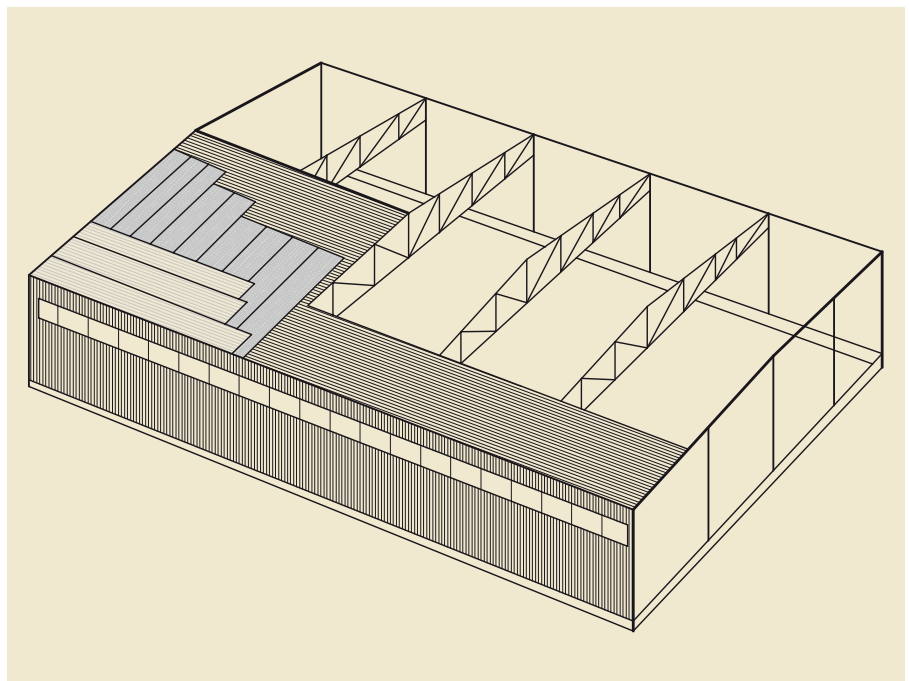


Figure 5.14 A light insulated industrial building. SBI Publication 130

A typical open plan building is shown in Figure 5.14. Often a gabled roof with an angle of 3.6° or 5.7° is used. The spacing between rafters is typically 6 to 10 m.

The walls are made from composite panels or profiled sheeting placed on light steel side rails. The insulation is placed on top of the profiled sheeting and covered with a suitable roof material. A plastic membrane is used for air and moisture-tightness.

Lattice trusses are generally used for the rafters. Spans up to 45 m can be achieved with standard sections. The columns are typically HEA-sections, fastened with four anchor bolts on a base plate. Although the columns are

considered as pin-ended at the base, four bolts are recommended in order to provide column stability during erection.

For non-insulated industrial buildings, the profiled sheeting is supported by purlins, and Z-profiles are often used as purlins up to 12 m span.

Using pinned columns, it is essential to stabilise the building during erection. It is often necessary to brace columns and sometimes the rafters too. As bracing of the columns is necessary during erection, it is common to design the bracing as permanent, thus not considering diaphragm action of the walls.

Roof cladding

There are a number of products for roofs, mainly profiled sheeting and tiles. The profiled sheeting is typically of the form shown in Figure 5.15. Roof tiles may be used for roof slopes of 14° and more. Roofing tiles use traditional colours and are significantly lighter than ceramic or concrete tiles.

Deep profiled sheeting may be used for insulated roofs with spans up to around 11 m and the longer spans are achieved with sheeting stiffened in both directions. Shorter spans, up to 8 m, are achieved with more traditional profiles.

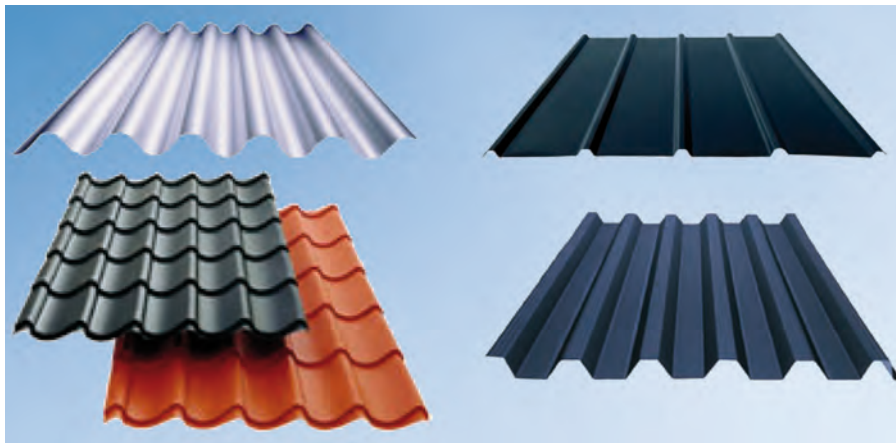


Figure 5.15 Example of different products on the Swedish market for roofs and walls

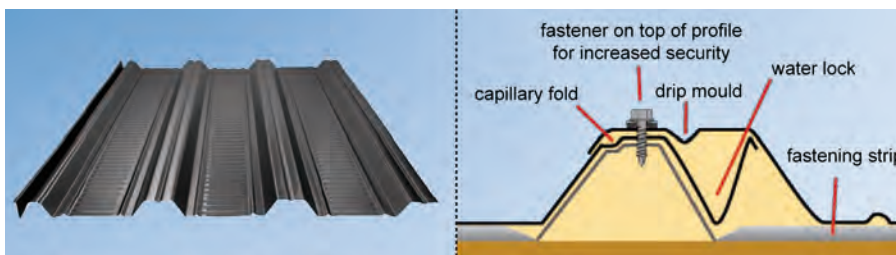


Figure 5.16 Plannja 40 roof cladding (for use on low sloping roofs from 3-6°) www.plannja.se



Figure 5.17 Fasetti façade lamella www.ruukki.com

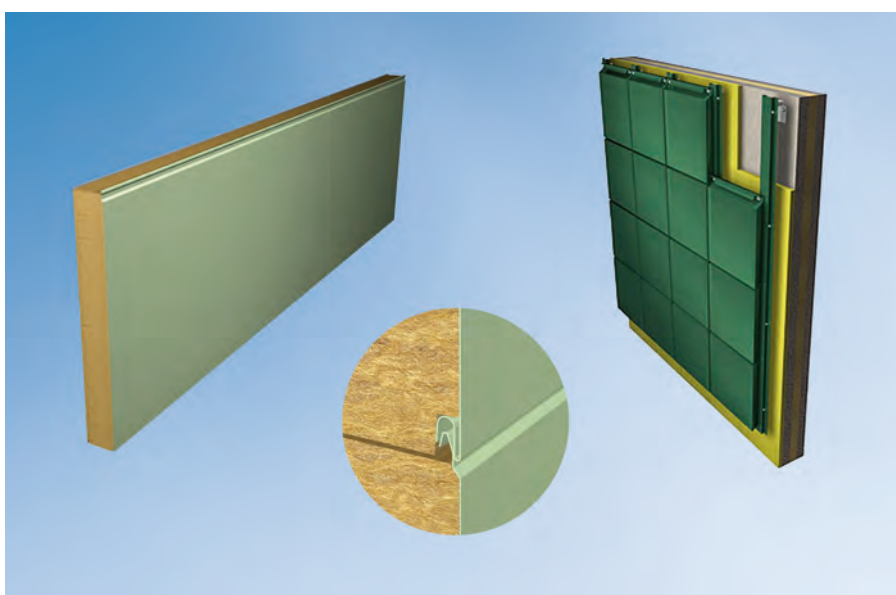


Figure 5.18 Composite panel
Left: Plannja panel
Right: Liberta Grande façade cassette
Ruukki

The roof is usually designed to also act as a stressed skin diaphragm which enables it to be constructed without bracing.

Profiled sheeting is used as load bearing elements for insulated roofs. The height of the profile is chosen depending on the span. Insulation in the form of mineral wool is used in two layers with plastic foil as a damp proof layer and an air barrier.

Trapezoidal sheeting is used as the external roof material. A minimum roof angle of 3.6° is required.

U-values of below 0.3 W/m²K can be achieved, dependant on the thickness of the insulation. This meets the Swedish building regulations.

Cladding

Profiled sheeting used as cladding is often the same as the sheeting used for roofing.

Composite or sandwich panels provide thermal insulation, fire protection and appearance. Panels have steel sheeting on both sides with an insulation of mineral wool or EPS in between. Depending on the thickness of the insulation, U-values can be typically from 0.18 to 0.3 W/m²K. The systems include air and water resisting systems between panels. If mineral wool is used, the system provides good fire integrity and acoustic performance. The panels can be delivered as large units up to 10 m long.

The steel panels may be combined with other material as stone, timber, glass, stucco and concrete. The panel can be delivered with different surface finish, with deep and shallow profiling.

There are systems for refurbishment of facades. The refurbishment is usually combined with an insulation of the façade. There are slotted separators for fastening of the profiled sheeting, allowing for mineral wool as insulation.

There are products on the Swedish market that can satisfy and exceed the Swedish building regulations as to the heat insulation of industrial buildings. Typical U-values for a 150 mm composite panel are 0.24-0.28 W/m²K and there are standard solutions for U-values down to 0.17 W/m²K.

Current Practice in the UK

General Issues

The construction of large single-storey industrial buildings, widely known as 'sheds', is a significant part of the UK steel construction sector. They are used as retail stores, distribution warehouses, manufacturing facilities and leisure centres.

Examples of innovations are the use of plastic design of portal frames, IT systems for design and manufacture, cold formed components, such as purlins, and highly efficient cladding systems.

The single-storey industrial sector in the UK has an annual value of approximately £1 billion for frames (1.4 billion Euros) and £1.5 billion (2.1 billion Euros) for associated envelope systems.

The architectural design of industrial buildings and other enclosures has developed considerably over the last 10-15 years, since major architectural practices have been involved in iconic buildings such as the Renault Distribution Centre, Swindon and the Schlumberger factory, Cambridge.

Steel portal frames, nevertheless, still account for the majority of the industrial building market. However, many variants of this simple manufacturing technique are employed, such as use of cellular beams or curved sections, as illustrated in Figure 5.19.

Today there are many more demands on envelope systems, in particular related to the energy conservation demands of Part L of the UK Building Regulations and

the high value activities for which these buildings are employed. The introduction of a revised Part L, with its more onerous requirements, and the European 'Energy Performance of Buildings' Directive in April 2006 have led to the following requirements:

- The need to achieve a saving of around 23 to 28% in CO₂ emissions when measured against the equivalent building to 2002 Regulations;
- The introduction of energy passports for many types of buildings.

Selection of Steel for Single-storey Industrial Buildings

The following criteria can affect the value that the building brings to the clients and users:

Architectural Design

Architects have a strong influence on the choice of building form and its appearance, as well as issues such as thermal performance. Although the structural form is still the province of the structural engineer and steel fabricator, the use of modern forms of structural systems is adopted by architects, who are increasingly involved in the industrial building sector. Examples of the architectural use of steel are illustrated in Figures 2.9 and 5.20.

Speed of Construction

For logistics or similar businesses, speed of construction is vital. This can affect the design in many ways, i.e. layout and components can be designed so that parallel rather than sequential construction can take place.

Flexibility in Use

The long spans and minimal use of columns typical of steel construction offer the maximum opportunity for the building to be able to accommodate different processes and change of use.

The client may at some point wish to sell the building to an investment



Figure 5.19 Curved steel sections used in a modern industrial building in the UK

organisation. To facilitate this option, criteria such as minimum height and higher imposed loads are often specified to maintain the asset value and provide flexibility for future uses.

Maintenance

Many buildings are constructed for owner occupation. Where a building is let, 'full repairing 25 year leases' (where the tenant is responsible for maintenance), are being replaced by shorter leases, where the owner carries maintenance responsibility. Where the original owner has responsibility for maintenance, the choice of better

quality materials with a longer life expectancy and reduced maintenance costs are encouraged.

Sustainability

Energy costs and the reduction of CO₂ emissions are becoming increasingly important and sustainability is now a key issue within the planning process. In the future, it is likely that planning permission will be easier to obtain with sustainable, environmentally friendly solutions. Many clients, potential clients and occupiers have sustainability policies against which their performance is monitored.

Value for money

Steel has achieved a large market share in this sector because of responsiveness to client demand. With the increasing complexity in design, there is also an increased inter-dependency between the various elements and a high degree of cooperation and coordination.

Design Issues

Steel construction is one of the most efficient sectors in the construction industry. Leading suppliers manufacture the components offsite, using computer controlled equipment driven directly by information contained in 3D computer



Figure 5.20 Curved cellular beams for a leisure centre Westok

models used for detailing. In addition to informing the manufacturing process, the information in the model is also used for ordering, scheduling, delivery and erection.

Choice of primary frame

The most popular choice of structural form for single-storey buildings with spans of 25 to 60 m is the portal frame because of its structural efficiency and ease of fabrication and erection. Portal frames may be designed using elastic or plastic analysis techniques. Elastically designed portal frames are likely to be heavier, but are simpler to design and detail using non-specialist design software.

For longer spans, lattice trusses may be used as an alternative to portal frames. Trusses are likely to be more efficient for spans over 60 m and in buildings of shorter spans where there is a significant amount of mechanical plant.

Inter-dependence of frames & envelopes

The structural efficiency of portal frames is achieved partly due to the provision of restraint to the rafters and columns by the purlins and side rails respectively. Similarly, the efficiency of the purlins is dependent on restraint provided by the cladding. 'Stressed skin' action may also be utilised in the design, if only to reduce deflections.

The design methods for the steel structure are now well understood and the focus of attention has turned to the building envelope. There are three major reasons for this:

- The use of steel structures is common in industrial and commercial applications.
- The need to promote client image and public access has meant more attention has been given to planning and aesthetics.
- The focus on the energy saving of the envelope and the increased significance of the 'Energy Performance of Buildings' Directive (EPBD) with its requirement for energy labelling.

Energy performance

Reductions in U-values over recent years have led to a considerable increase in insulation thickness, with implications for stability (particularly of built-up systems), cladding weight and consequential handling requirements. However, the point has now been reached where further increases in insulation thickness are unlikely to lead to significant improvements in energy performance.

For many applications, roof lights are important because they reduce the amount of artificial lighting that is needed and, consequently, the energy demands of the building. However, they also increase solar gain, which can lead to overheating in summer and increase cooling demand.

Heat loss through thermal bridging also becomes more significant as the insulation thickness increases, requiring the use of enhanced details and specialised components.

Air-tightness

The introduction of air-tightness testing has highlighted the importance of designing and delivering a building that is not subject to excessive heat loss. Recent studies have demonstrated that controlling airtightness is a very effective way of improving energy conservation.

As an example, while the current minimum standard for airtightness testing of buildings is 10 m³/m²/hr at 50 Pascals, levels of airtightness as low as 2 m³/m²/hr are possible with standard construction, but achieving this level depends on a high quality of construction and detailing. For buildings with floor areas less than 5,000 m², achieving good levels of airtightness becomes difficult to achieve, due to the higher proportion of openings relative to the clad area.

Design Coordination

A significant part of the design process of the actual building is the coordination of

the interfaces between the various specialist systems. This task is traditionally undertaken by the architect, but better coordination is achieved if the main contractor is responsible for the design.

Design process

Attributes that should be considered, in addition to those required by the Regulations, include:

- Overall geometrical considerations.
- Minimum height (clearance for crane beams, depth of haunch, etc.).
- Achieving maximum lettable area according to the conventions for measurement.
- Column layouts to give appropriate future flexibility of use.
- Loading and future loading requirements.
- Selection of purlins and side rails
- Control of deflections.
- Cladding system and available guarantees.
- Adequate access for possible future vehicle needs.
- Tolerances of the floor slab.
- Potential for reuse/recycling of materials.
- End of useful life requirements.
- Energy consumption and reduction of CO₂ emissions.

The effects of the site conditions on the structural solution, together with the engineering design of external works, will normally require the appointment of a consulting engineer to work alongside the architect prior to letting the Design and Build contract. The duties will include the selection and design of a suitable foundation system. In the majority of buildings, the structural frame has pinned bases.

Sustainable Construction

The requirement for sustainable construction is being encouraged in many ways, ranging from EU Directives on thermal efficiency to the increasing adoption of Corporate Social

Responsibility policies by companies. The ability to demonstrate a sustainable approach is becoming an essential part of obtaining planning permission. The concept of sustainability is under-pinned by the need to balance the 'triple bottom line' of economic, social and environmental viability. Modern steel construction should meet all three criteria.

Summary of Industrial Building Trends in the UK

Table 5.3 below shows a summary of trends in modern industrial warehouse design, which is adapted from a report by the Steel Construction Institute.

Table 5.3 Summary of trends in modern industrial warehouse design in the UK

Aspect of Design	Current Designs	Future Designs (in addition to current practice)
Building form and structure	Multi-span rectangular plan buildings of up to 90 m x 150 m plan area	8-12 m height to haunch
	15 m height to haunch	
	Portal frames of 30-35 m span with 6° roof slope	Steel portal frames with 2° slope
	6-8 m bay width with internal columns at 12-16 m spacing	
	Fibre reinforced 200 mm concrete ground slab	Post-tensioned concrete ground slab
	Adjoining steel framed office of 13.5 m depth in 6 and 7.5 m spans	
Cladding	Composite panels (sandwich panels) for roof and upper walls	Composite panels for roof
		'Green' roof in selective areas over marshalling area (approx 20 m)
	Precast concrete panels for lower part of walls	'Tilt up' precast concrete panels for walls
		Composite slab over distribution area
	U-values of 0.35 W/m ² K for walls and 0.25 W/m ² K for roof	U-values of 0.25 W/m ² K for walls and 0.20 W/m ² K for roofs
	15% roof lights (triple layer)	
	15% roof light area for natural lighting	
	Good air-tightness sought (10 m ³ /hr/m ² at 50 Pa)	Fibre reinforced plastic-timber beam and purlin system considered for 16 m span
Services and maintenance	Jet nozzle heating	Greater use of Photovoltaics (PVs) on roof
		Wind turbines to generate primary energy may be considered
	Selective use of Photovoltaics (PV) on roof	
	Fire-wet suppression system	Greater use of solar thermal hot water
	Fit-out of services by end user	Sprinklers to control fire spread, their installation depends on client requirement
	Design life of 40 years – 25 years to first maintenance	
	Pervious pavements in car park to assist drainage	
Rainwater collection from roof		

06 Case Studies

A series of Case Studies are presented in this Section to illustrate the design and construction principles discussed earlier. The Case Studies cover a range of building forms and locations throughout Europe.

The Case Studies and their structural systems are summarised as follows:

- *Cargo Hub, East Midlands Airport, UK.*
Two bay portal frame and cellular beams for mezzanine floor and adjacent office area.
- *Airbus Industrial Hall, Toulouse, France.*
Long-span lattice trusses for flexibility of space and fast-track construction.
- *Cactus Shopping centre, Esch/Alzette, Luxembourg.*
Portal frames using curved cellular beams for column free internal space and maximum transparency.
- *Netto Supermarket, Sweden.*
Lightweight column and beam structure using stressed skin action.
- *Distribution Centre, Waghäusel, Germany.*
Rack-supported storage system with cassette walls and a 'green' roof using steel sheeting for economical warehouse construction.

*Cargo Hub,
East Midlands Airport*

*Airbus Industrial Hall,
Toulouse*

*Cactus Shopping Centre,
Esch/Alzette*

*Netto Supermarket,
Sweden*

*Distribution Centre,
Waghäusel*

Air Cargo hub at East Midlands Airport, UK

A new distribution warehouse and office has been built for DHL at Nottingham's East Midlands Airport. The warehouse is constructed from 40 m span portal frames and the offices use 18 m span cellular beams. The total building cost was 45 million Euros.

Application Benefits:

- Simple portal frame solution provides efficient use of space
- Mezzanine floor using cellular beams supports handling equipment
- 3 storey office uses 18 m span cellular beams
- 18 aircraft stands provided
- 30 truck bays below a 22.5 m span canopy



DHL has operated at Nottingham East Midlands Airport in the UK for 25 years. With business volume increasing, the existing 'hub' was unable to cope and a new major facility was designed, capable of handling shipping volumes of over 1,000 tonnes per year. The 40,000 m² facility comprises two distinct parts: a warehouse distribution area and an office area.

The distribution area uses a structural grid that was dictated by the modular mechanical handling system and allowed for future expansion. A double bay steel portal frame was adopted with spans of 40 m. The mechanical handling system was placed on a mezzanine level which was constructed after the building envelope had been completed. The mezzanine level was constructed using cellular beams which allow for incorporation of services within the structure.

Due to the building size, a fire engineering strategy had to be adopted in order to extend the escape distance to

95 m by effective smoke control and by use of smoke vents and smoke curtains.

The office area provides 9,000 m² of additional space for 650 staff and is 3 storeys high. The structure also uses cellular beams spanning 18 m. All internal walls are lightweight and demountable, permitting flexibility in current and future use. The first floor office space also had to span over the service road and the second floor was suspended from the roof transfer trusses.

A 22.5 m span canopy was also included to give maximum flexibility in arrangement of the loading area.

A curved roof was chosen for visual reasons and used a standing seam cladding system based on an on-site rolling process to speed up installation.

The whole project was completed in only 18 months and provided DHL with efficient space that meets its current and future demands.

Project Team

Client:

DHL

Architect:

Burkes Green

Consultant:

Burkes Green

Contractor:

Howard Associates

Steelwork

Westcol

Services:

Couch Perry Wilkes**Construction Details****Roof and roof trusses**

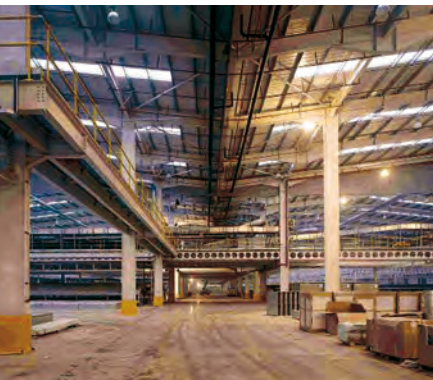
The two bay portal frame structures were designed plastically to achieve the most efficient solution for the 40,000 m² warehouse building. Mechanical handling equipment was supported by an independent mezzanine structure which used cellular steel beams.

The same technology was used for the 9,000 m² office building, which had to be flexible in its use, as the predicted lifespan in its current format was only 15 years. Cellular beams were chosen to provide services integration through the 600 mm diameter openings. The design of the office area was further complicated by the need to span over a service road, which necessitated supporting the floors from a long span truss of roof level.

The fire engineering strategy was also key to the whole building concept and the floor of the mezzanine was designed with an open steel grillage in order to allow for smoke extraction at high level.

The 2 bay portal frame was designed with a 'stiff' line of columns and was constructed before the design of the mechanical handling system had been completed. The flexible design of the steel structure made installation of this system easier in dry internal conditions.

The open sided canopy was also problematical, being 22.5 m span and 45 m wide between supports. The canopy projected at 45° and was connected to the portal frame structure for its stability. The roof of the office comprised curved steel beams of 150 m radius.



Airbus Industrial Hall in Toulouse, France

Steel construction provides efficient long span and low weight structural frame for large industrial halls that will produce the next generation A380 Airbus aeroplane for intercontinental flights.

Application Benefits:

- Fast track construction
- Efficient use of steel components
- Flexibility of space organisation
- Sustainable design approach
- High crane facilities



This industrial building covers 200,000 m² of floor space, is 45 m high and provides spans of more than 115 m. Criteria to be met were efficient space occupancy and flexibility in arrangement of the internal space.

- Two parallel industrial rolling cranes, 35 m span, 30 tonnes capacity for fuselage transportation.
- Two dual loads 2 x 4 suspended cranes for normal service.

Due to the expected change in the industrial process after several years of production, a reconfiguration/refurbishing approach design was considered, taking account of rapid financial return. Architectural and structural appearance were intended to be an attractive reflection of the company performance.

The wing-lifting cranes roll on rails suspended on the truss of the frame of the roof. Sliding doors provide a 117 x 32 m² opening. They are supported by their own structural frame. This huge structure was designed and installed economically using fabricated sections and a trussed upper beam.

The largest hall, which is 115 m long by 250 m wide, is equipped with the following heavy cranes:

- Two parallel industrial rolling cranes, 50 m span, 22 tonnes capacity for lifting of the wings.



Internal view of the building during construction

Project Team

Client:

EADS

Architect:

ADPI

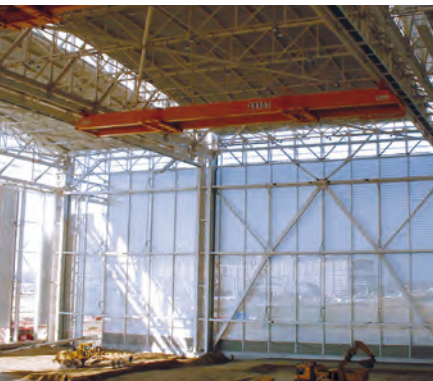
Design office:

Cooperation: ADPI & Jaillet-Rouby

Contractor:

**URSSA (Spain), CIMOLAI (Italy),
CASTEL et FROMAGET, JOSEPH
PARIS, RICHARD DUCROS (France),
BUYCK (Belgium)**

Control Office:

SOCOTEC and VERITAS**Construction Details****Roof and roof trusses**

The roof trusses span 117 m. The height of the trusses varies from 8 m at the supports up to 13.5 m at mid span.

The main roof elements are composed of two parallel truss frames of 33 m span along the building and made of rectangular hollow steel sections. Each roof element comprises a pair of front and rear trusses, roof structure, roof service equipments, fire safety network, etc., and when completed at ground level is lifted and positioned at the top of the columns in one piece.

Columns are rigidly fixed to the ground and have equal slenderness ratio in each direction to avoid any horizontal buckling phenomenon during lifting operations.

Assembly of the trusses at ground level has the advantage of achieving safe construction, limited use of scaffolding,

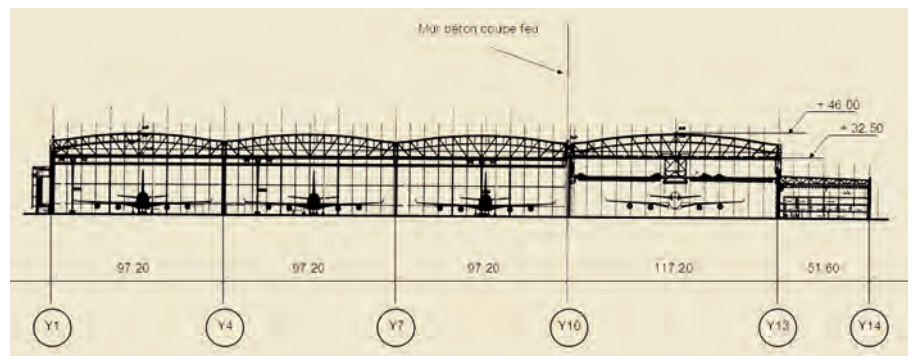
a simple operation and fast construction process. The joints between the truss elements and the top of the columns are pinned.

This simple method provides the following advantages:

- Rapid connection operations in a critical erection phase.
- No welding operation during assembly.
- The truss upper flange element is connected and simply sits on a short span beam on top of the column.

The vertical deflection of the trusses was limited to span/2000 due to crane operation requirements.

The elements of the main truss spanning across the building were I shape fabricated sections and bolted on joints. Each column was made of two separate fabricated sections jointed by a continuous truss web.

**Source of all images in this case study:**

Cabinet Jaillet-Rouby, France

Cactus shopping centre in Esch/Alzette

This urban project in Esch/Alzette, Luxembourg, provides a modern steel structure using curved cellular beams and a glazed façade. The building highlights the lightness of the exposed steel structure achieved by a modern fire engineering approach.

Application Benefits:

- Column-free internal space provides maximum flexibility
- Attractive appearance due to use of curved cellular beams
- Unprotected steel justified by a fire engineering approach



This medium size supermarket is situated in the city centre of Esch/Alzette and it replaces an older structure. The owner wanted to have a modern bright shopping centre and opted for an open space with huge glazed surface for two of the façades. It was a requirement that the steel structure, with its long span curved cellular beams, should be visible.

Due to the location of the supermarket in a city centre, the local authorities required a fire resistance of 90 minutes for the steel structure supporting the roof. The Natural Fire Safety Concept was applied to calculate the development of the fire in the supermarket. Using this concept, the opportunity for a building with a fully glazed façade and visible steel structure has been retained.

Project Team

Client:

Cactus S.A.

Architect:

Paczowski Fritsch Associés

Structural Engineer:

Schroeder & Associés S.A.

Contractor:

MABILUX S.A.

Fire Engineering:

ArcelorMittal**Building Facts**Construction period: **2003**Total height: **9.13 m**Ground-plan: **28.5 x 48.0 m****Construction Details**
Structure

The structure comprises a series of portal frames using steel columns and curved cellular beams. The frames are interconnected by means of steel roof purlins and a bracing system. The frame has a single 20 m span. The column height is 7.5 m and the maximum height in the middle of the curved beam is 9.1 m. The distance between adjacent main frames is 7.5 m.

Frames are connected by continuous purlins (IPE200). The roofing is made with a steel decking (HOESCH TR44A), insulation and waterproofing. The beams are ArcelorMittal Cellular Beams® made from HEB450 in S235 steel. The height of the beam is 590 mm, the diameter of the openings is 400 mm and the distance between the openings is 600 mm.

Natural Fire Safety Concept

ArcelorMittal was asked to perform the fire engineering of the structure and the authorities accepted the application of the Natural Fire Safety Concept. The fire design was based on the prescriptions of

EN 1991-1-2 (Characteristic fire load for office building 730 MJ/m²) and took into account active fire fighting measures (automatic alarm & transmission to the fire brigade, smoke exhaust systems, etc.).

No sprinklers were required due to the small size of the building. The fire temperature was calculated using the 2-zone software Ozone and localised temperatures were calculated using the Hasemi methodology. A set of simulations was performed to analyse the breaking of the glazed walls (front and back façades are completely glazed).

As the maximum resulting steel temperatures in the columns were 880°C, a 3-D finite element analysis was performed, taking into account the whole structure of the building at this temperature. One complete model of the building in 3 dimensions was analysed. All the simulations were made using the FE software SAFIR. The result of this fire engineering approach was the decision that the steel structure did not require any passive fire protection.



Netto Supermarket, Sweden

This is an example of a typical Swedish lightweight industrial building consisting of columns, roof-trusses and roof sheeting, designed for stressed skin action.

Application Benefits:

- Rapid building method
- High level of prefabrication
- Minimum size of load-bearing structure
- Few internal supports providing large open spaces with easy use for other activities



Lightweight single-storey buildings with a steel structure have a dominant position in Sweden among buildings used as industrial or warehouse facilities.

In Sweden, all Netto shops are designed in a similar way, which makes the building process exceptionally fast and very economical.

Netto's new store in Smålandsstenar demonstrates this simple and cost-efficient construction solution.

The small differences between the structures depend on the geographical location, which gives varying snow loads and wind actions. The snow load varies between 1 and 3 kN/m² and the wind speed between 21 and 26 m/s.

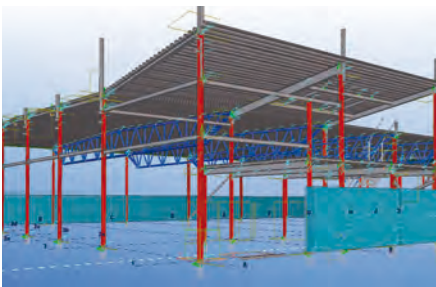
The structure consists of pinned columns, rafters and trapezoidal sheeting on the roof together with wind bracings in the walls for stability. The roof sheeting is designed as a stressed skin diaphragm, which transfers horizontal loads to the wind bracing.

Project Team

Client:
Netto Marknad AB
Architect:
GL Consult
Structural Engineer:
EAB AB
Steel Constructor:
EAB AB

Building Facts

Shopping area: **750 m²**
Steel use: **20 tonnes**
Roof sheeting: **1000 m²**
Total erection time: **5 weeks**
Total project time: **17 weeks**



(Above) 3D-model used for structural calculations

(Right) The construction site showing roofing and intermediate floors in place

Construction Details

The trapezoidal sheeting is between 0.65 mm and 1.2 mm thick. The sheeting transfers both vertical and horizontal actions, such as dead load, snow and wind loads, as well as inclined loads to the foundation through the columns and bracings, mainly HEA-profiles. HEA-profiles are also used as gable beams. For single span ceiling joists with a maximum span of 10 m, IPE-profiles are used.

When it is important to keep the building height to a minimum, or when it is not

possible to use vertical wind bracings in the walls, portal frames can be considered due to the use of smaller steel sections, and hence savings in steel cost.

The time needed to assemble columns, trusses and roof sheeting was about one week, which was done after the casting of the foundation. The next step was to assemble walls and to install the roofing. Finally, the services and the interior work were completed in a weather-proof building.



Distribution Centre in Waghäusel, Germany

The third distribution centre of dm-drogerie markt was completed in 2004 with a storage area of 20,000 m². By using the rack-supported building system, time and money was saved compared to traditional solutions.

Application Benefits:

- Maximum storage density
- Building use is unaffected by the structure
- Cheapest construction method for high-bay warehouse
- Short construction period
- Fast return of capital investment



Dm-drogerie markt – one of the leading drugstore chains in Europe – operates over 1,500 retail outlets and employs some 20,000 people. With a turnover of almost 3 billion Euros, dm-drogerie markt offers a range of some 12,000 product lines. In 2003, dm-drogerie markt decided to build a further logistics facility in Waghäusel, located in southern Germany between Karlsruhe and Mannheim.

The distribution centre is divided into four main parts. While the building for incoming and outgoing goods, servicing rooms, as well as offices, social rooms and canteen were built in reinforced concrete, the heart of the complex, the commission store, is built in steel. The commission store is 90 m long, 125 m wide and 20 m high and it provides space for 24,024 commissioning and storage bins.

The commissioning store was a rack-supported storage system, named because the construction of the steel racks also acts as the main support structure for roof and wall. Roof and wall cladding were rapidly attached to the racking construction parallel to the assembly. Compared to traditional solutions comprising a main support structure and racks that only support themselves, the construction period was significantly shorter, thus achieving an earlier return of the investment.

Apart from the short construction period and the comparatively low cost, the significantly shorter amortization period is an additional advantage. However, the racking system had to be designed taking into account the additional load cases due to the self-weight of the building envelope and imposed wind and snow loads.

Project Team

Client:

dm- drogerie markt GmbH & Co. KG

Architects:

**BFK + Partner Freie
Architekten BDA, Stuttgart**

General Contractor:

Swisslog AG, Buchs, Switzerland

Steel Construction:

**Nedcon Magazijnrichting B.V,
Doetinchem, Netherlands**

Fire Engineering:

Brandschutz Hoffmann, Worms

Building Services:

AXIMA GmbH, Karlsruhe**Building Facts**

Construction period:

2003-2004

Site area:

70,000 m²

Commissioning store:

200,000 m³

Hall for incoming/ outgoing goods:

4,500 m²**Construction details**

The steel construction of the rack-supported structure of the commissioning store was erected on a floor slab of reinforced concrete.

The wall cladding was designed using isolated cassette elements. The interior cassettes were attached to the gable columns and the columns of the longitudinal walls. The roof beams were arranged in accordance with the division of the racks in the longitudinal direction at a spacing of 3.14 m. An extensive 'green' roof was achieved using steel sheeting, 100 mm of thermal insulation, a sealant layer and soil covering.

There are a total of 5 stair towers in reinforced concrete with a fire resistance of 90 minutes. At the rear wall, external escape catwalks made

of steel serve as connecting bridges to the stairway towers.

Fire protection

The commissioning store, hall for incoming/outgoing goods and servicing rooms are separated by fire walls.

The fire walls reach up to 0.5 m above the roof of the ingoing/outgoing goods store. Furthermore, an impact resistant roof strip made of reinforced concrete was erected to prevent the fire spread between commissioning store and hall for incoming/outgoing goods.

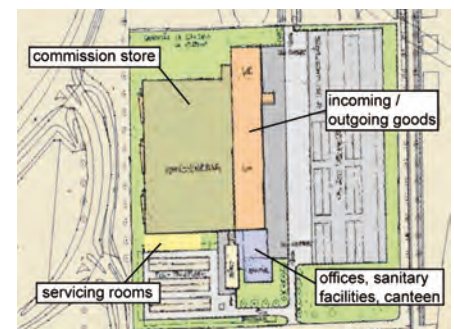
Both the commissioning store and the incoming/outgoing goods store are equipped with full sprinkler systems, with additional in-rack sprinklers in the commissioning store. In addition, an automatic fire alarm system was installed.



Inside view of commissioning store



Sectional elevation



Plan

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