ANNEX 4-A

Best Practice

INDUSTRIAL BUILDINGS

Contents

1 INTRODUCTION

In our industrial heritage halls are very common and present in nearly every business park. The urbanistic and architectural quality is influenced by many factors, i.e. the development plan, the heterogeneity of usages, up to the quality of the single building. Steel is offering numerous possibilities in order to fulfil the task of pleasant design with unrestricted functionality.

In most cases an industrial hall is no solitary structure. If office and administration units, garages as well as adjoining rooms and canopies are not designed uniformly with the hall itself, they can influence the clear construction of the hall. However, good examples show that these elements can be designed in such a way, that they fit the hall construction.

For industrial halls the economy of the structure plays a decisive role. With increasing spans it becomes more important to design in an optimised way and to minimise the use of materials, costs and assembly effort.

Industrial buildings use steel framed structures and metallic cladding of all types. Large open spaces can be created, which are efficient, easy to maintain, and are adaptable as demand changes. Industrial buildings are a "core" market for steel. However, the use of steel in this type of construction varies in each European country. Competition with other materials has become tougher, which means that steel has to defend its position on economic grounds, as well as other aspects such as fire and architectural quality.

In the general part this publication describes the common forms of industrial buildings that may be designed and their range of application in Europe. Regional differences may exist depending on practice, regulations and capabilities of the supply chain. These exceptions and differences can be found in the specific regional parts.

2 FORMS AND TYPES OF INDUSTRIAL BUILDINGS

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

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

The construction and appearance of an industrial hall allows the consultant engineers great latitude in configuration in order to realise the architectural ideas besides the functional requirements. In the standard case an industrial hall has a rectangular floor space with longish orientation. The design of the hall can be carried out variably, coordinated with functional requirements and the illumination concept.

The following forms of industrial halls represent only an overview of the possible architectural and constructional solutions. In recent years for exhibition halls, railway stations, airports and sports arenas many projects have been realised, spanning almost any ground plans. Those kinds of objects are almost always special structures. The following general issues are restricted to “standard” ground plans.

In Figure 2.1 different structures consisting of beam and columns are presented. If no purlins and bracings in both directions are used diaphragm action of the roofing is required in order to provide stability for horizontal loads.

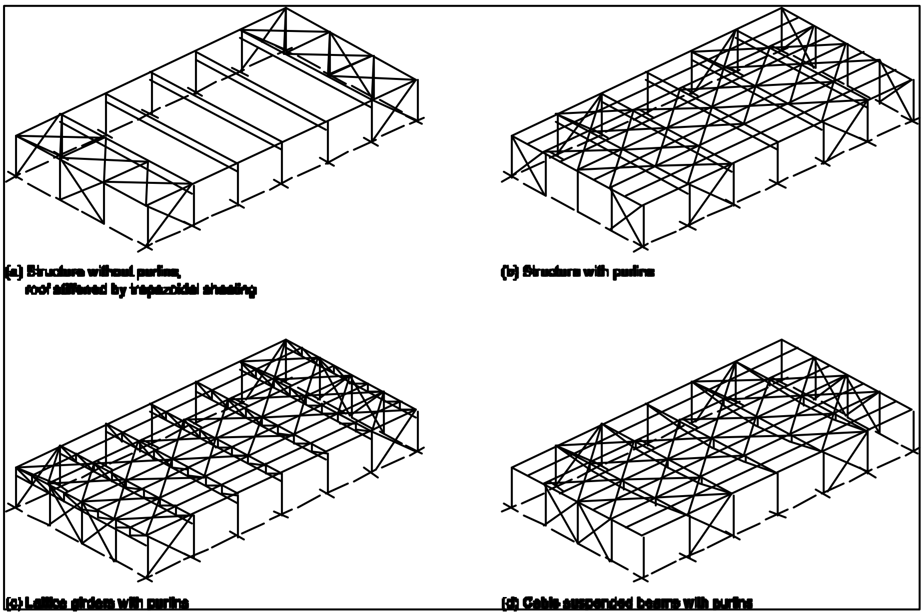


Figure 2.1 *Column and beam structures*

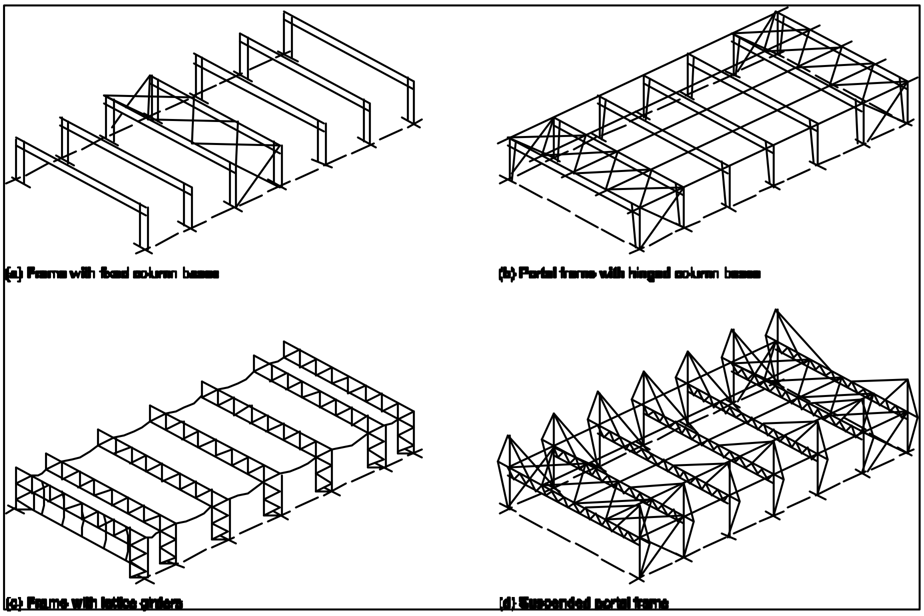


Figure 2.2 *Portal frames*

Figure 2.2 shows portal frames with fixed (a) or hinged (b) column bases. For examples (c) and (d) with structures lying partly outside the building, the details concerning the piercing of the envelope have to regarded especially.

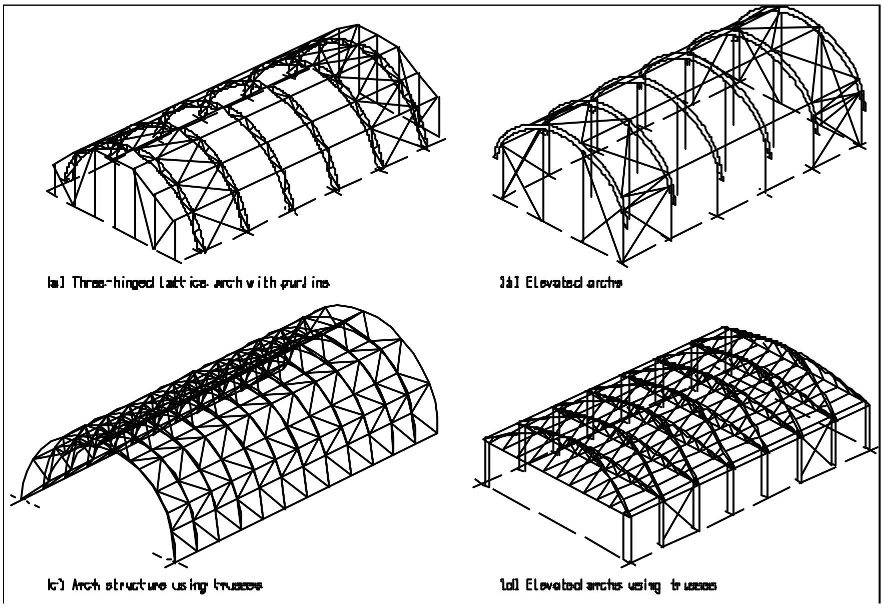


Figure 2.3 *Arch structures*

Besides the shapes with cubic or prismatic appearance arch structures offer advantageous load-carrying behaviour as well as a pleasant visual appearance. In Figure 2.3 (a) for example a hall with a three-hinged arch reaching to the ground is shown. Alternatively, the arch structure can be elevated on common columns or integrated in a truss structure, as in Figure 2.3 (d).

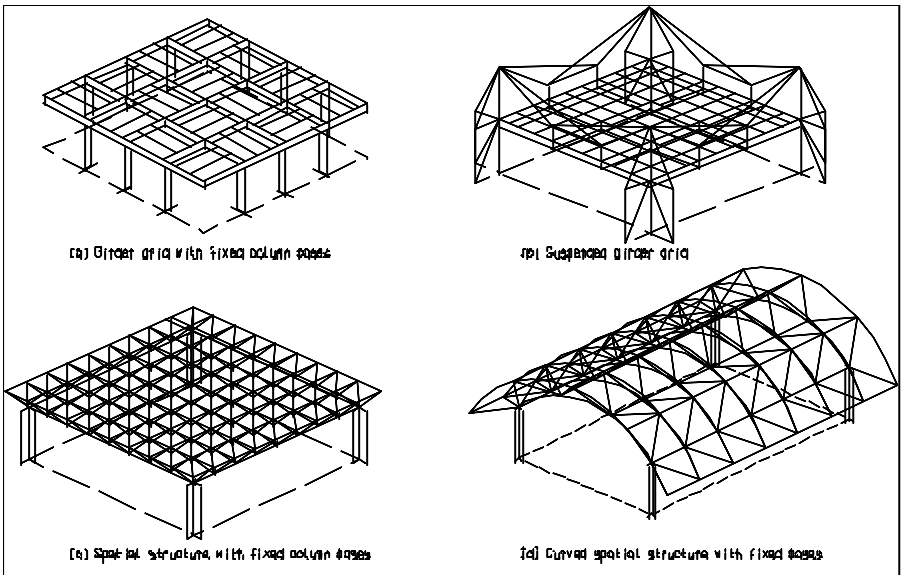


Figure 2.4 *Spatial structures*

The forms of halls with primary and secondary structural elements described above are all directional structures, for which the loads are carried on defined loading paths. Spatial structures and space trusses are non-directional structures. Figure 2.4 shows some examples.

3 SUPPORT STRUCTURES

3.1 Portal frames

3.1.1 General issues

Steel portal frames are widely used in the most of the European countries because they provide structural efficiency with functional application. Various configurations of portal frames can be designed using the same structural concept as in Figure 3.1.

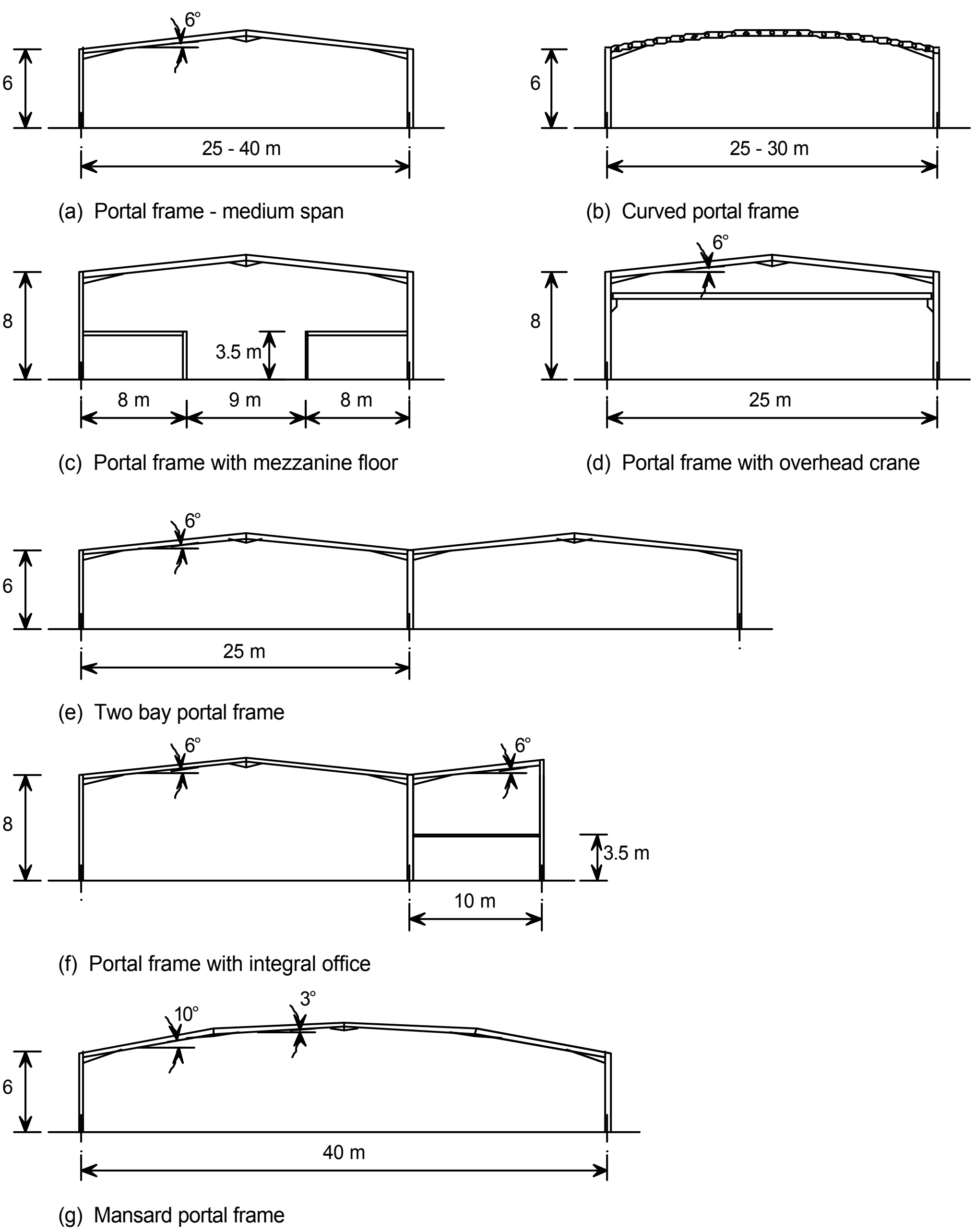


Figure 3.1 *Various forms of portal frame*

In addition to the primary structure a wide range of secondary components has also been developed, such as cold formed steel purlins, which also provide for stability of the framework (see Figure 3.2).

Figure 3.2 *Typical portal frame and secondary components*

These simple structural systems can also be designed to be architecturally more interesting by use of curved members, cellular or perforated beams etc. (see Figure 3.3 and Figure 3.4). Innovative structural systems have also been developed in which moment resisting connections are replaced by articulations and ties, as in Figure 3.5. Multi-bay frames can also be designed, as in Figure 3.1 (e) and (f), either using single or pairs of internal columns.

Figure 3.3 *Cellular beam used in portal frames*

Figure 3.4 *Curved beam used in portal frame*

Figure 3.5 *Innovative moment-resisting connections in an industrial building*

Long span industrial buildings can be designed with lattice trusses, using C, H or O sections. Various configurations of lattice trusses are illustrated in Figure 3.6. The two generic forms are W or N-bracing arrangements. In this case, stability is generally provided by bracing rather than rigid frame action (see Figure 3.7). However, columns can also be constructed in a similar way, as illustrated in Figure 3.8, in order to provide in-plane stability.

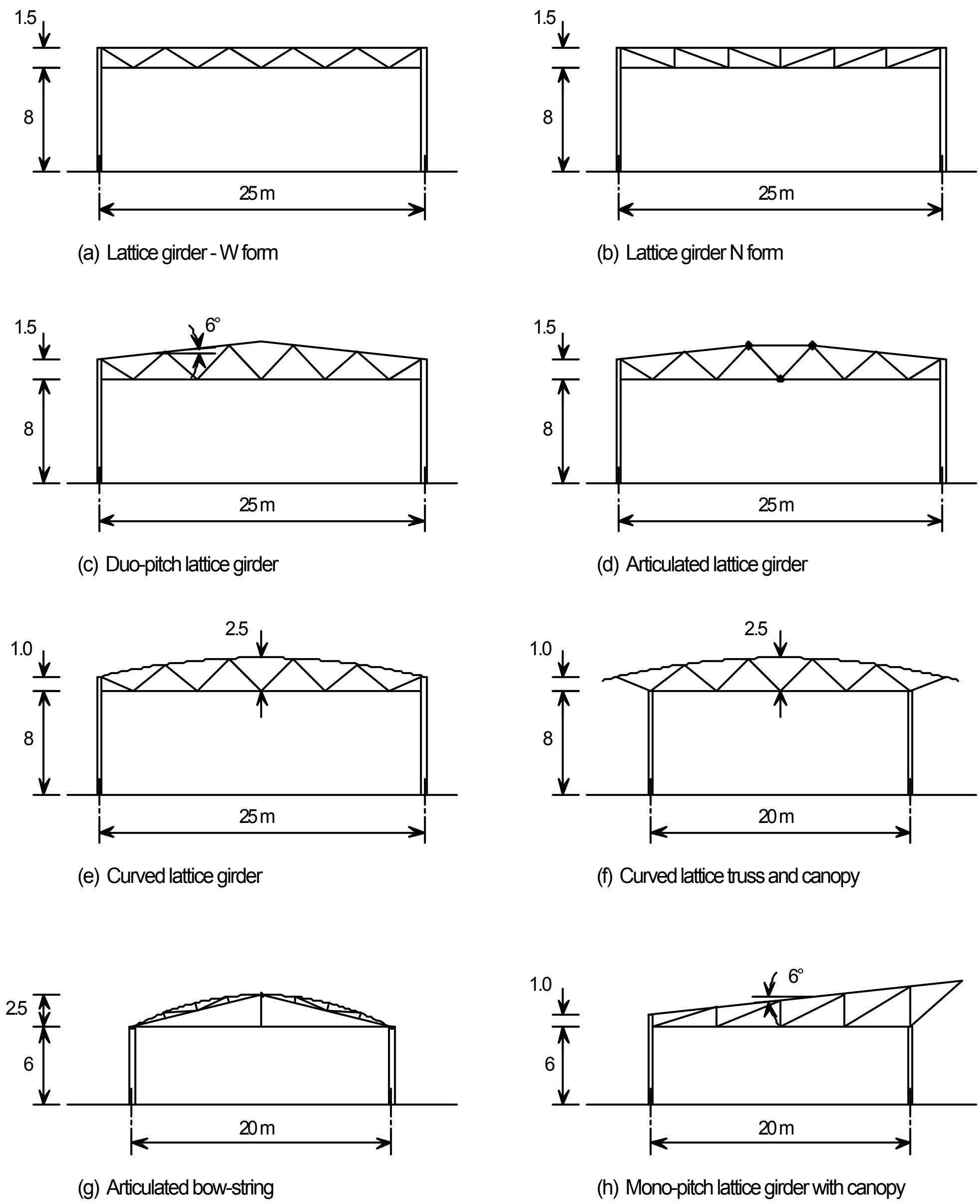


Figure 3.6 *Various forms of lattice truss used in industrial buildings*

Figure 3.7 *Lattice truss using tubular members*

Figure 3.8 *Lattice frame using lattice columns*

Suspended structures can be designed by extending columns outside the building envelope, as illustrated in Figure 3.9. Suspended structures achieve longer spans, although the suspension cables or rods also extend outside the building envelope, and can be obstructive to the use of the external space.

Figure 3.9 *Suspended structure used at the Renault Factory, Swindon, UK*

3.1.2 Structural behaviour

Portal frames are generally low-rise structures, comprising columns and horizontal or sloping rafters, connected by moment-resisting connections (see Figure 3.1).

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 large horizontal forces have to be considered. Yet hinged columns have the disadvantage of a higher steel consumption. The plastic reserve of the structural system is not as distinctive and reduced stiffness is provided.

The eaves regions are often stiffened by a suitable haunch or deepening of the rafter sections in order to make the material usage more efficient. This form of rigid frame structure is stable in its plane and provides a clear span that is unobstructed by bracing. Stability is provided by rigid frame action provided by continuity at the connections in the form of haunches.

Out-of-plane stability in most cases has to be provided by additional structural parts. Panels providing shear stiffness, cores as well as fixed columns provide sufficient stiffening. Rigid panels can be realised by massive elements or bracings. Also steel profile sheeting used in diaphragm action is able to realise sufficient out-of-plane stability. Some possible solutions for stiffening of the portal frame are shown in Figure 3.10.

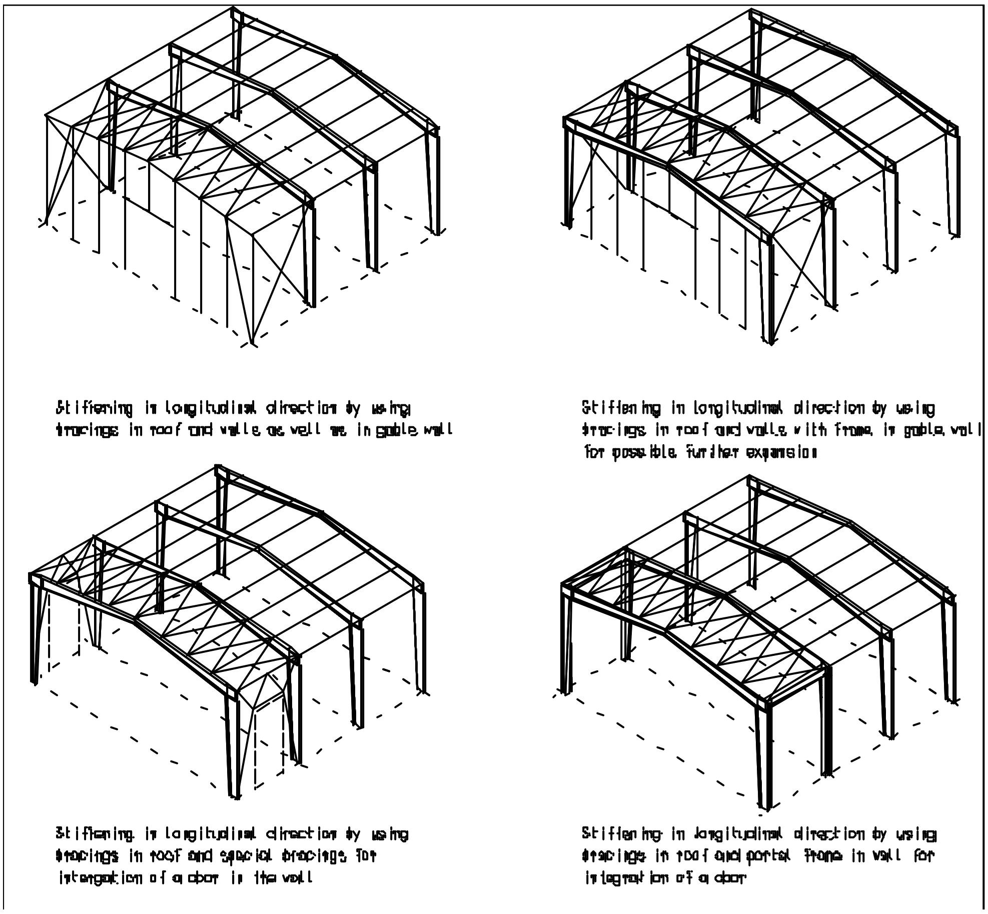


Figure 3.10 *Out-of-plane stiffening of a portal frame structure*

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 S355 steel. Use of high-strength steel is rarely economic in structures where serviceability (i.e. deflection) criteria or stability checks may control the design.

Sections should be at least *Class 2* at highly stressed points. If plastic hinge analysis is used, *Class 1* sections have to be provided. The effect of axial load on the classification of members should be considered. However, in many members, the axial force is so small compared with the bending moment that the classification is not affected.

3.1.3 Types of steel portal frames

Pitched roof portal frame

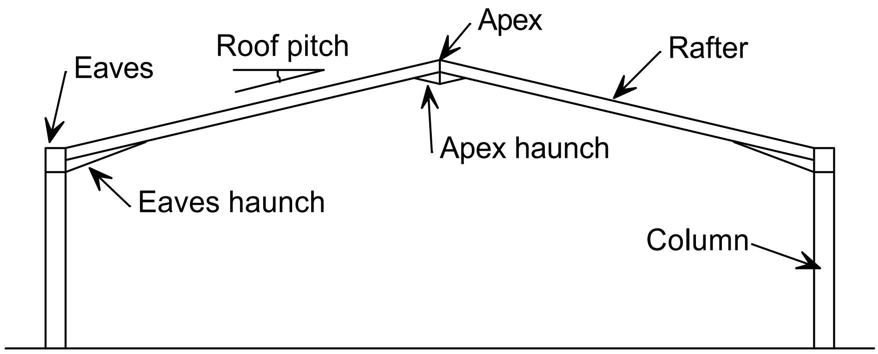


Figure 3.11 *Single-span symmetric portal frame*

A single-span symmetrical portal frame (see Figure 3.1) has typically:

- A span between 15 m and 50 m (25 to 35 m is the most efficient)
- An eaves height between 5 and 10 m (5 to 6 m is the most efficient)
- A roof pitch between 5° and 10° (6° is commonly adopted)
- A frame spacing between 5m and 8m (the greater spacings being associated with the longer span portal frames)
- Haunches in the rafters at the eaves and if necessary at the apex.

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

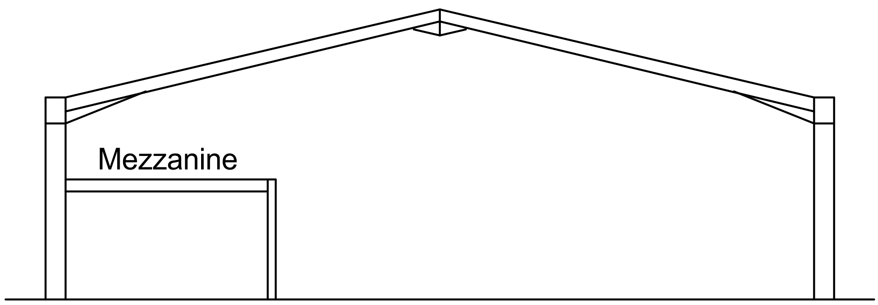


Figure 3.12 *Portal frame with internal mezzanine floor*

Office accommodation is often provided within a portal frame structure using a mezzanine floor (see Figure 3.12), which may be partial or full width. It can be designed to stabilise the frame, but often the internal floor requires additional fire protection.

Portal frame with external mezzanine

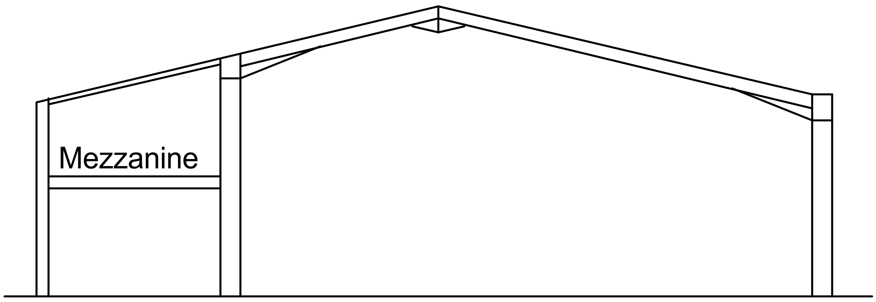


Figure 3.13 *Portal frame with external mezzanine*

Offices may be located externally to the portal frame which creates an asymmetric portal structure (as in Figure 3.13). 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 functionally needed, have an essential influence on the design and the dimensions of portal frames. They provide additional vertical loads as well as considerable horizontal forces, which may influence calculation.

Where the crane is of relatively low capacity (up to say 20 tonnes), brackets can be fixed to the columns to support the crane (see Figure 3.14). Use of a tie member or fixed column bases may be necessary to reduce the eaves deflection. The outward movement of the frame at crane rail level may be of critical importance to the functioning of the crane.

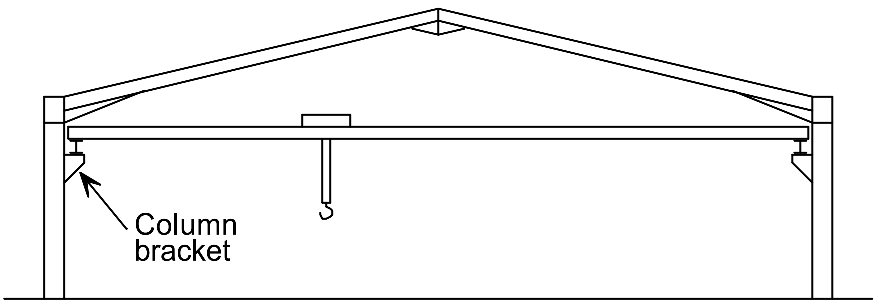


Figure 3.14 *Crane portal frame with column brackets*

For heavy cranes it is appropriate to support the crane rails on additional columns, which may be tied to the frame column by a bracing due to instability problems.

Propped portal frame

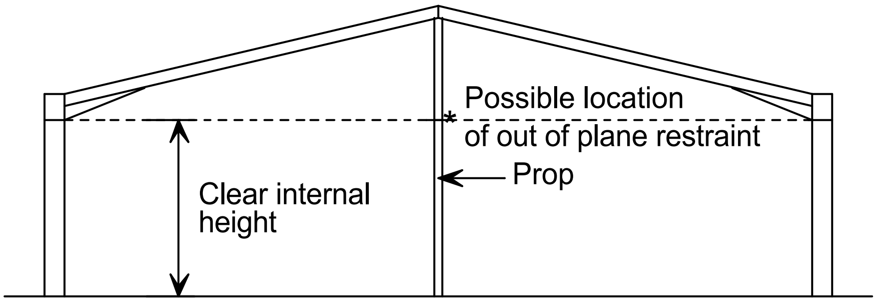


Figure 3.15 *Propped portal frame*

Where the span of a portal frame is greater than say 30 m, and there is no need to provide a clear span, a propped portal frame (see Figure 3.15) can reduce the rafter size and also the horizontal thrust at the base, giving economies in both steelwork and foundation costs.

This type of frame is sometimes referred to as a “single span propped portal”, but acts as a two-span portal frame in terms of structural behaviour.

Tied portal frame

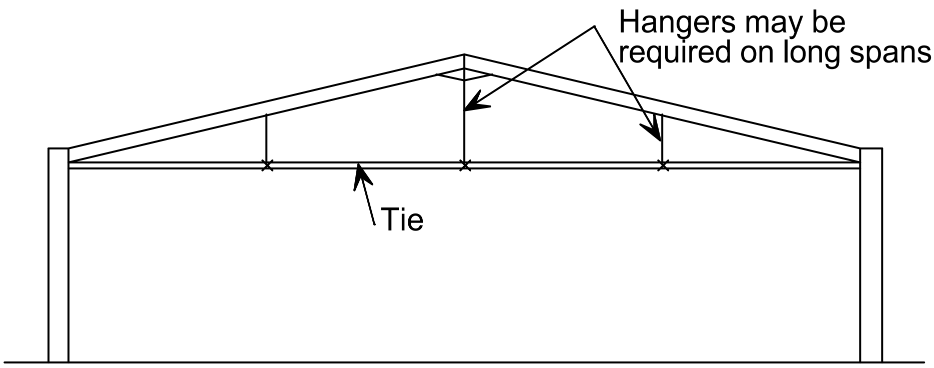


Figure 3.16 *Tied portal frame*

In a tied portal frame (see Figure 3.16), the horizontal movement of the eaves and the moments in the columns are reduced, but the available headroom is also reduced. For roof slopes of less than 15°, large forces will develop in the rafters and the tie.

Mansard portal frame

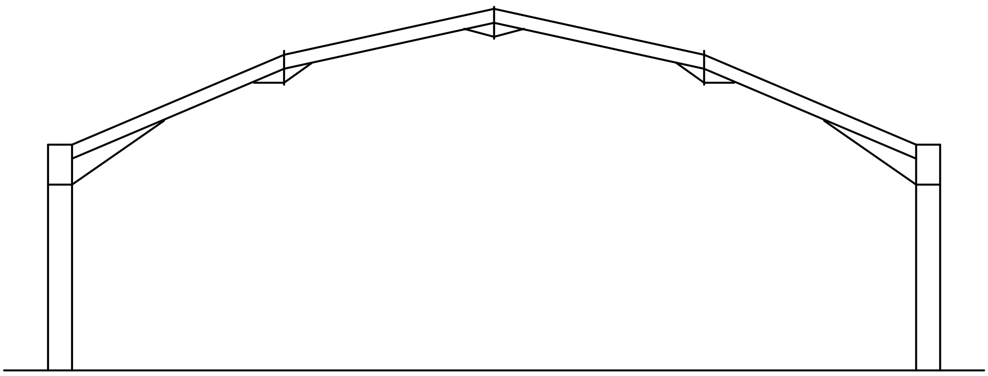


Figure 3.17 *Mansard portal frame*

A mansard portal frame consists of a series of rafters and haunches (as in Figure 3.17). 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 economic solution where there is a need to restrict eaves spread.

Curved rafter portal frame

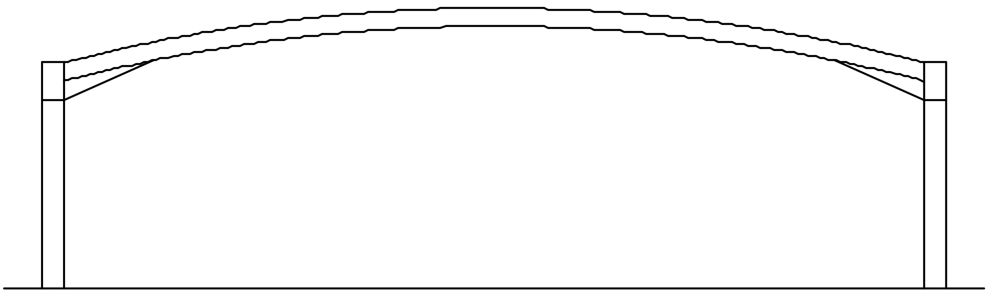


Figure 3.18 *Curved rafter portal frame*

Curved rafter portals (see Figure 3.18 and Figure 3.4) are often used for architectural applications. The rafter can be curved to a radius by cold bending, but for spans greater than 16 m, splices may be required in the rafter because of limitations of transport. These splices should be carefully detailed for architectural reasons.

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

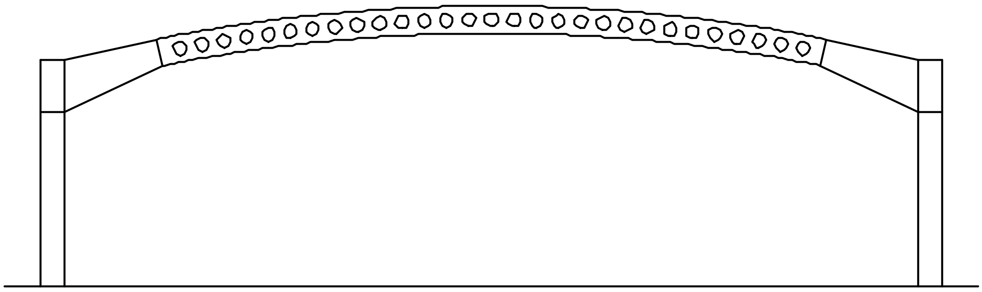


Figure 3.19 *Cellular beam portal frame*

Cellular beams may be used in portal frames (see Figure 3.19 and Figure 3.3), which commonly have curved rafters. Where splices are required in the rafter for transport, these should be carefully detailed to preserve the architectural features for this form of construction.

Gable wall frames

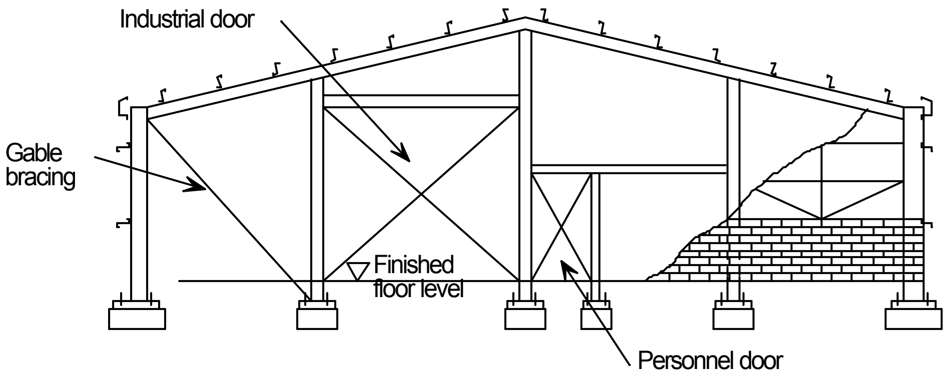


Figure 3.20 *Gable frame to a portal frame structure*

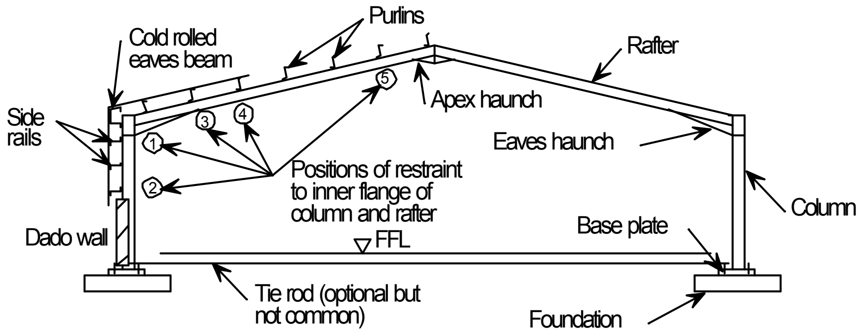
Gable wall frames are located at the ends of the building and may comprise posts and simply-supported rafters rather than a full-span portal frame (see Figure 3.20). If the building is to be extended later, a portal frame of the same size as the internal frames is preferred. In cases, in which the stability of the gable wall is not provided by a portal frame bracings or rigid panels are needed additionally, see also Figure 3.10.

3.1.4 Overall building form

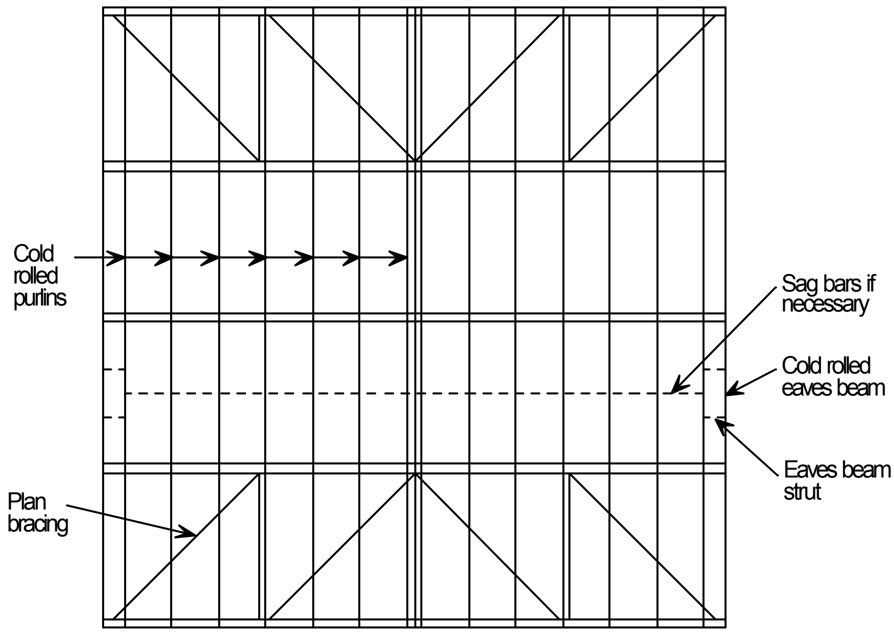
A typical steel portal frame structure with its secondary components is shown in Figure 3.21.

A portal frame is stable in its own plane, but it requires bracing out of its plane. This is generally achieved by bracing (generally tubular members) in the plane of roof between the outer frames. Purlins and side rails support the roof and wall cladding, and stabilise the steel framework against lateral buckling. Doors are often incorporated in the end gables.

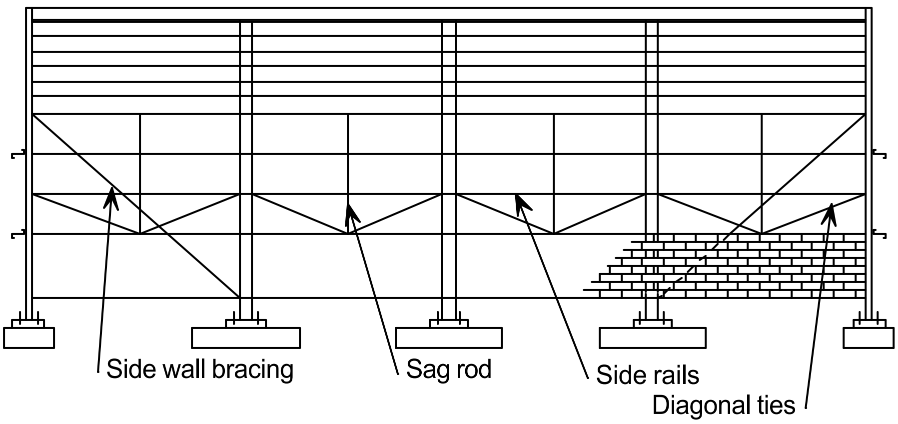
The installation process of the primary structure and secondary members, such as purlins, is generally carried out using mobile cranes, as illustrated in Figure 3.22. The spacing between the purlins is reduced in zones of higher wind and snow load, and where stability of the rafter is required, e.g. close to the eaves and valley.



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



(b) Roof steelwork plan



(c) Side elevation

Figure 3.21 *Overview of structural components in a portal frame structure*

Figure 3.22 *Installation process for a modern portal frame*

3.1.5 Purlins

Purlins have to bear the loads from the roofing to the primary structural elements, i.e. rafters of the portal frames. Furthermore they can act as compression member in bracings. For frame spacing up to 7.0 m it can be economic to span the profile sheeting between the rafters directly without the use of purlins. Larger frame spacing reduces the number of primary structural elements and foundations but requires the use of purlins. In industrial buildings hot-rolled I-sections as well as cold-formed profiles with Z-, C-, U- or custom made shape are used, see Figure 3.23.

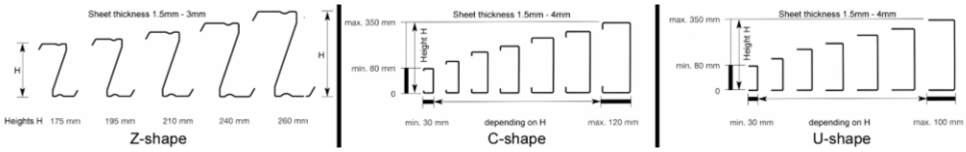
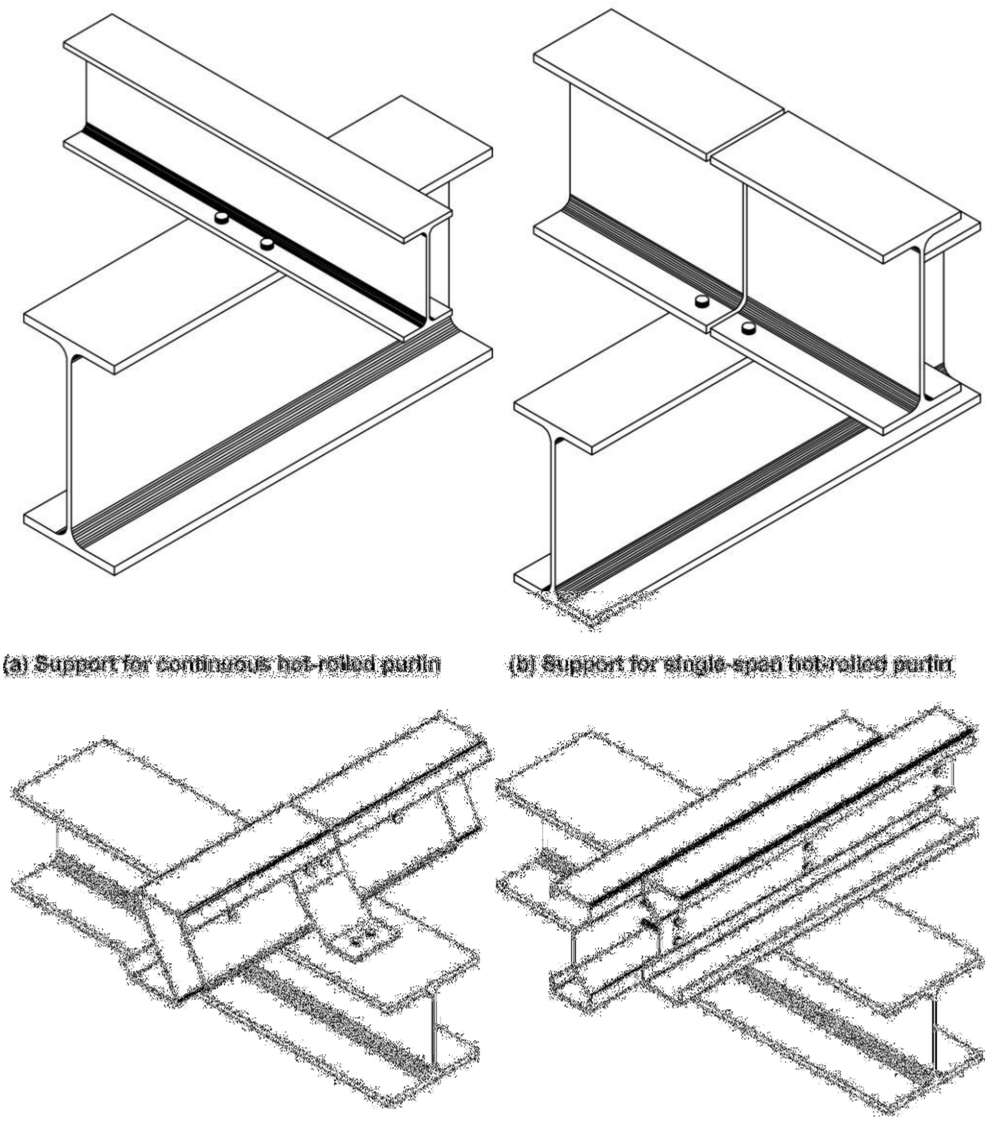


Figure 3.23 *Cold-formed sections typically used for purlins*

If cold-formed purlins are used, usually the grid is narrower at intervals of approx. 1.5 m to 2.5 m. Another aspect, which has to be considered, is that cold-formed sections provide only limited restraint against lateral torsional buckling of the rafter. Often manufacturers provide approved solutions for the connections to the rafter section using pre-fabricated custom steel plates, see Figure 3.24.



(a) Support for continuous hot-rolled purlin

(b) Support for single-span hot-rolled purlin

(c) Support for continous cold-formed Z-shaped purlin

(d) Support for continous cold-formed custom-shaped purlin

Figure 3.24 *Possible solutions for purlin-rafter connection*

4 CONCEPT DESIGN CONSIDERATIONS

4.1 General issues

Before the detailed design of the industrial building can begin it is necessary that a concept is developed for the building. Many considerations have to be taken into account. These include addressing the following:

- Space optimization
- Speed of construction
- Access and security
- Flexibility of use and space
- Environmental performance
- Standardization of components
- Specialist infrastructure of supply
- Services integration
- Landscaping
- Aesthetics and visual impact
- Thermal performance and air-tightness
- Acoustic isolation
- Weather-tightness
- Design life
- Sustainability considerations
- End of life and re-use

In the first instance, it is necessary to identify the size of the hall based on its required plan area. It is then necessary 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 will be dependent on the type of industrial building. For example, the requirements for a distribution centre will be different to a manufacturing unit. To enable an effective concept design to be developed, it is necessary to review these considerations based on the importance of each individual consideration based on the type of industrial building that is to be developed. Table 4.1 below 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 and hence relative importance may be changed. It is provided only as a general aid.

Table 4.1 *Important design factors for industrial buildings*

Type of single storey industrial buildings	Considerations for concept design															
	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 plants	✓✓	✓	✓	✓✓		✓	✓		✓	✓		✓	✓	✓✓	✓	✓
Distribution centres	✓✓	✓✓	✓✓	✓✓	✓	✓✓	✓✓		✓✓	✓	✓	✓	✓		✓	✓
Retail superstores	✓✓	✓	✓✓	✓✓	✓✓	✓✓		✓✓	✓✓	✓	✓✓	✓✓	✓✓		✓✓	✓
Storage/cold storage/Bonded cargo	✓	✓	✓✓	✓	✓✓	✓		✓	✓✓	✓		✓	✓✓		✓	✓
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

4.2 Compartmentation and mixed use

Nowadays larger industrial buildings are more and more often designed for mixed use, i.e. in most cases integrated office space and / or staff rooms for the employees. There are different possible locations for these additional compartments, see Figure 4.1:

- For single storey industrial halls inside the building, separated by internal walls being possibly two storeys high
- In an external building being directly connected to the hall itself
- For two-storey buildings at least partially on the top floor

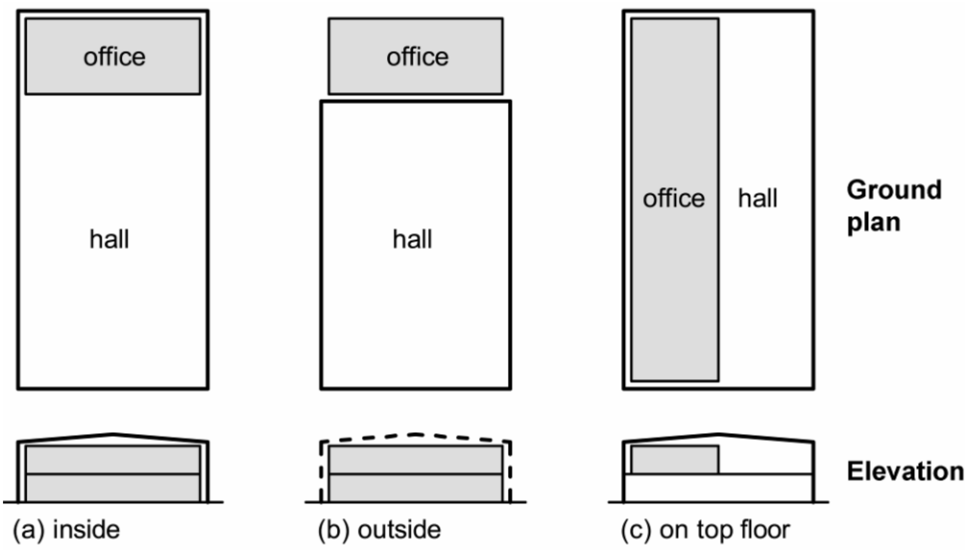


Figure 4.1 *Possible locations of office accomodation*

Independent from the location of the office compartment, this leads to special concept design requirements concerning the support structure and the building physics.

If the additional area is situated on the upper storey of the industrial hall, the consultant designer may design the support as a separate structure being enveloped in the global structure of the hall. In this case floor systems from commercial buildings can be used, often based on composite structures, e.g. slimfloor, integrated floor beams, etc. Another possible solution is to attach the office compartment at least partially to the global structure by using tension elements, which requires some particular attention on the stabilisation of the attached part.

Another important topic to be regarded is the building physics behaviour of the whole building. Some particular attention has to be spent on

- Fire-protection: Because office accommodation is designed for the sheltering of a larger number of people, stricter requirements on fire-safety are demanded by the authorities. If the offices are located on the top floor of the building additional escape routes and, if required, active fire fighting measures have to be considered. Additionally fire-spread has to be prevented from one compartment to another. A possible solution to provide an adequate separation between the production compartment at the ground level and the offices in the top storey is to use a composite structure for the slab above ground. Also two separate structures, one for the slab and one enveloping the whole building, are adequate solutions.

- Thermal insulation: As for fire-safety in many cases office compartments have higher requirements on thermal insulation. In numerous industrial buildings for storage purposes of non-sensitive goods no thermal insulation is provided because of only low demands on this topic. But if working places in office compartments are intended, a certain level of comfort is needed, which makes thermal insulation necessary. Therefore the interfaces between the cold and the warm compartment have to be carefully designed in order to provide adequate solutions.
- Acoustic performance: Especially in industrial buildings, where often noise-intensive production processes are performed, a strict separation between the production unit and the calm workspaces has to be realised. This requires sophisticated solutions to provide at least an adequate level of noise protection in the working areas.

For large industrial buildings compartmentation may play an important role in the design even if there is no internal office space. In order to prevent fire spread from one compartment to another the compartment size is limited to a certain value. This measure should prevent that the entire building will catch fire and additional fire load is activated. Therefore fire walls have to be provided for separation with a requirement of at least 90 minutes fire resistance. This is even more important if hazardous goods are stored in the industrial hall.

4.3 Service integration

Often for industrial buildings special requirements on building services are defined, because in industrial companies special services have to be considered for the operation of machines and manufacturing units.

The service integration should be taken into account in the early planning stages in order to prevent disturbances with the appearance of the building. Following this issue the arrangements of ducts has to be coordinated with the structure and natural illumination. The use of separated structures, like cellular beams, trusses, etc, can provide a modern integration of services providing coherent appearance of the building.

Besides the arrangement of ducts the design of the servicing rooms is of major importance. Centralisation of the technical services offers the advantage of easy maintenance. Figure 4.2 shows different possible solutions of the positioning of the service rooms.

Nowadays air-conditioning systems are usually installed in industrial buildings. They require large ducts and connected aggregates, like fans, filters, heating- and cooling-units, are of large volume as well.

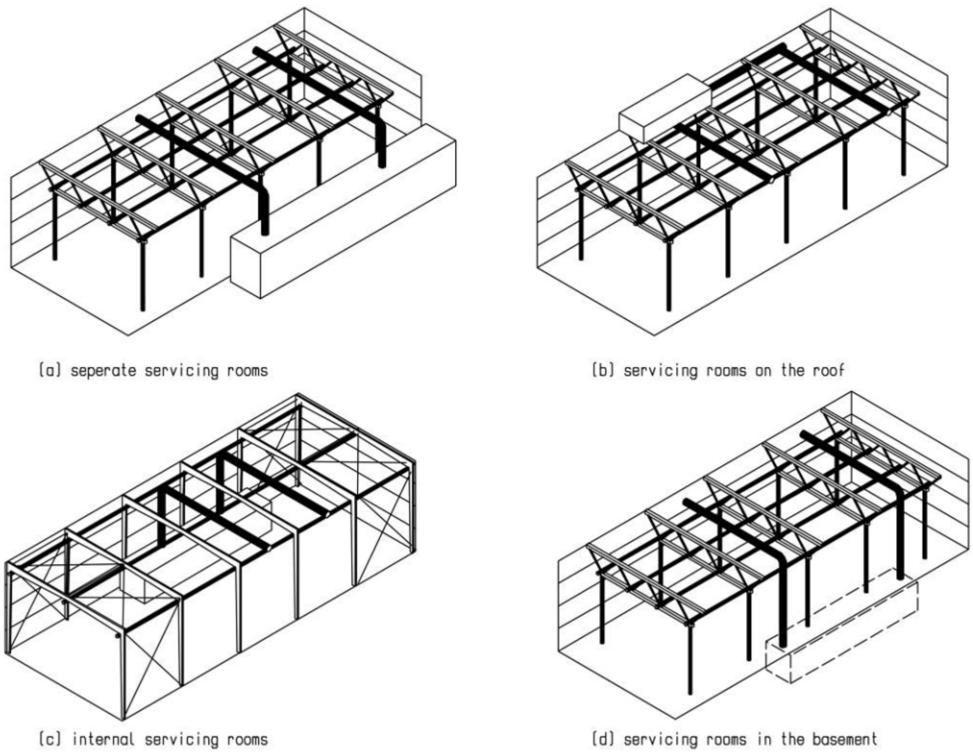


Figure 4.2 *Possible arrangements of the servicing rooms*

In many cases natural ventilation is sufficient for industrial buildings. With increasing size of the building it becomes more difficult to renew the used air and to conduct the heat out of the hall. Independent from the building height, a width of approx. 15 m is the limit for window ventilation.

The required air exchange can be supported by openings in the roof. Accurate arrangements of ventilation openings can make natural ventilation possible even in bigger halls. Furthermore, the following issues have to be taken into consideration:

- Elements for sun protection possibly constrain the air exchange.
- Possible sound- and smell inconveniences.
- Humidity of the external space cannot be influenced.
- Besides losses of comfort due to draught, heating loss is disadvantageous.

4.4 Illumination

Requirements on the illumination of industrial buildings depend on the type of use. Even if not explicitly demanded for working places it is preferable to provide natural illumination due to the physiological wellness of the employees.

The concept and the arrangement of openings to provide natural illumination permit diversity in architectural design, which has to be taken into account in the design of the structure also. In the roof domelights, shed constructions and gabled glazed roofs are common, whereas in the facades particular openings or vertical or horizontal light-bands are usual solutions. At the same time openings for natural illumination can function as smoke and heat outlets in case of fire.

The illumination of industrial buildings is very different. The achievable intensity of light of windows or light-bands in the facades depends on the distance to the external walls. By using openings in the roof a more uniform illumination is possible, see Figure 4.3

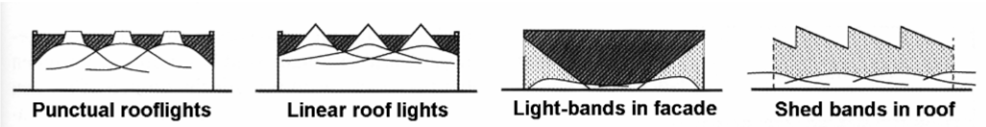


Figure 4.3 *Examples for the intensity of light of different illumination concept, [3]*

5 LOADING

5.1 General issues

The loads and load combinations described in this section should be considered in the design of a steel portal frame. Imposed, wind, and snow loads are given in Eurocodes EN 1991-1 and -3 and -4. Table 5.1 shows the relevant actions and structural components.

Table 5.1 *Actions and relevant structural components*

Nr.	Action	To apply on
1	Self-weight	Roofing, purlins, frames, foundation
2	Snow	Roofing, purlins, frames, foundation
3	Concentrated snow	Roofing, purlins, (frames), foundation
4	Wind	Walling, roofing, purlins, frames, foundation
5	Wind (increase on single elem.)	Walling, roofing, purlins, fixings
5a	Wind (peak undertow)	Walling, roofing, purlins, (fixings)
6	Temperature	Envelope, global structure
7	Attached loads	Dep. on specification: roofing, purlins, frames
8	Crane loads	Crane rails
9	Dynamic loads	Global structure
10	Sway imperfections	Wall bracings, columns
11	Bow imperfections	Roof bracings, purlins, rafter

5.2 Vertical loads

5.2.1 Dead loads

Where possible, unit weights of materials should be checked with manufacturers' data. The figures given in Table 5.1 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/m^2, expressed over the plan area.

Table 5.2 *Typical weights of roofing materials*

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)	0.1 - 0.15
Purlins (distributed over the roof area)	0.03
Steel decking	0.2
Three layers of felt with chippings	0.29
Slates	0.4/0.5

Tiling (clay or plain concrete)	0.6 - 0.8
Tiling (concrete interlocking)	0.5 - 0.8
Timber battens (including timber rafters)	0.1

5.2.2 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, air handling units, and runway and lifting beams.

The following loads may be used for pre-design:

- Service loading over the whole of the roof area of between 0.1 and 0.25 kN/m^2 on plan depending on the use of the building, and whether or not a sprinkler system is provided.

5.2.3 Imposed roof loads

EN 1991-1-1 and -3 define various types of imposed roof load:

- A minimum load of 0.6 kN/m^2 (on plan) for roof slopes less than 30° is provided, where no access other than for cleaning and maintenance.
- A concentrated load of 0.9 kN - this will only affect 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 formation of concentrated snow loads at the low marks have to be investigated.
- 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 portal frame structures.

5.3 Horizontal loads

5.3.1 Wind loads

Wind loading is established according to EN 1991-1-4. It 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, 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. In addition to that the size of the wind-load can determine which type of calculation has to be provided. If large horizontal deflections at the eaves occur in combination with high axial loads, second order effects have to be considered in the calculation procedure.

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

5.3.2 Imperfections

Inner horizontal loads 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 on frame analysis by means of an equivalent imperfection in the form of an

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

5.3.3 Other horizontal loads

Depending on the object additional horizontal loads have to be applied due to earth thrust, mass force due to cranes, thrusts, explosions and earth quakes.

6 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 connections mostly bolted connections are used with continuous columns combined with beams having end-plates as shown in Figure 6.1. In some case the column with the haunched span of the beam is constructed as a whole and the section of the beam with constant height is connected with a bolted joint.

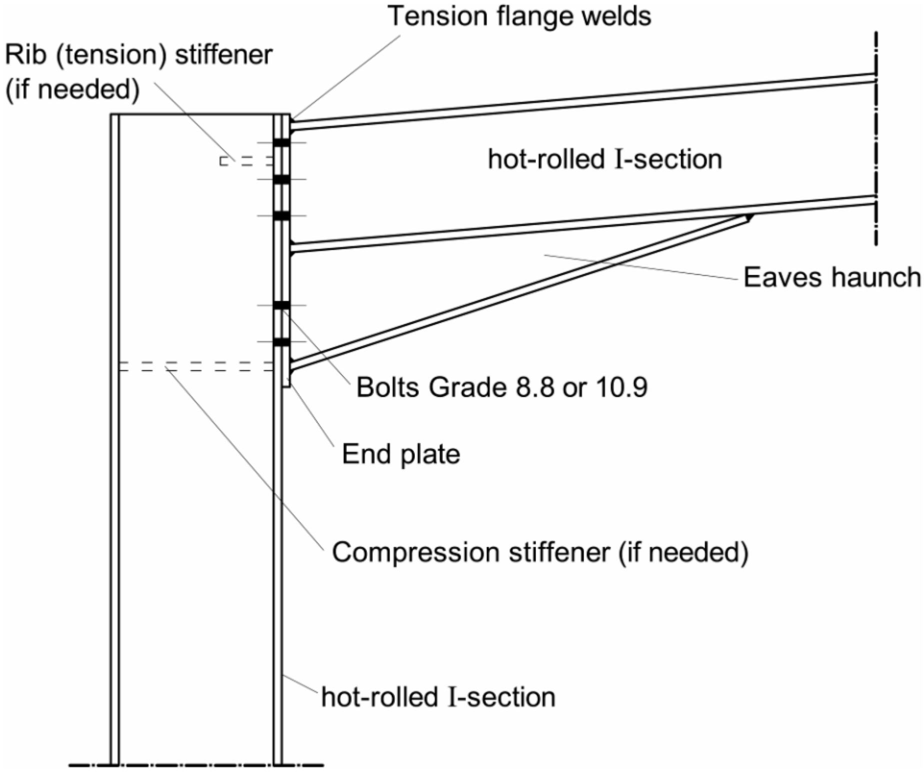


Figure 6.1 *Typical eaves connections in a portal frame*

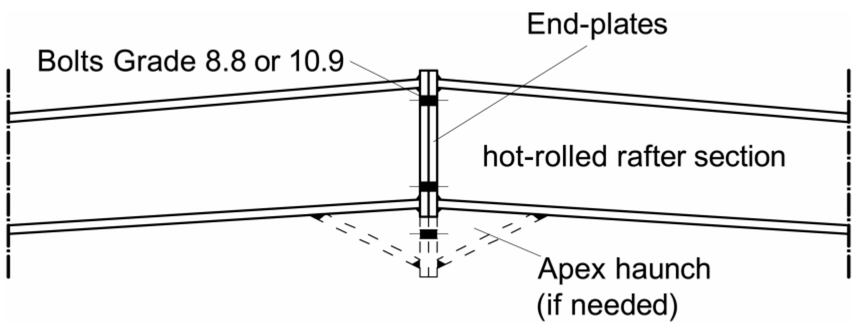


Figure 6.2 *Typical apex connections in a portal frame*

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

The apex connection is often designed similarly, see Figure 6.2. If the span of the frame does not exceed transportation limits, the on-site apex connection can be obsolete. The consulting engineer as well as the contractor should also avoid the apex haunch if possible, because of the increased fabrication costs.

The base of the frame column is often kept simple with larger tolerances in order to facilitate the interface between the concrete and steel workers, e.g. see Figure 6.3. In most case it is carried out pinned to keep the dimension of the foundation as small as possible. Only if comparatively large horizontal loads affect the structure fixed root points are provided.

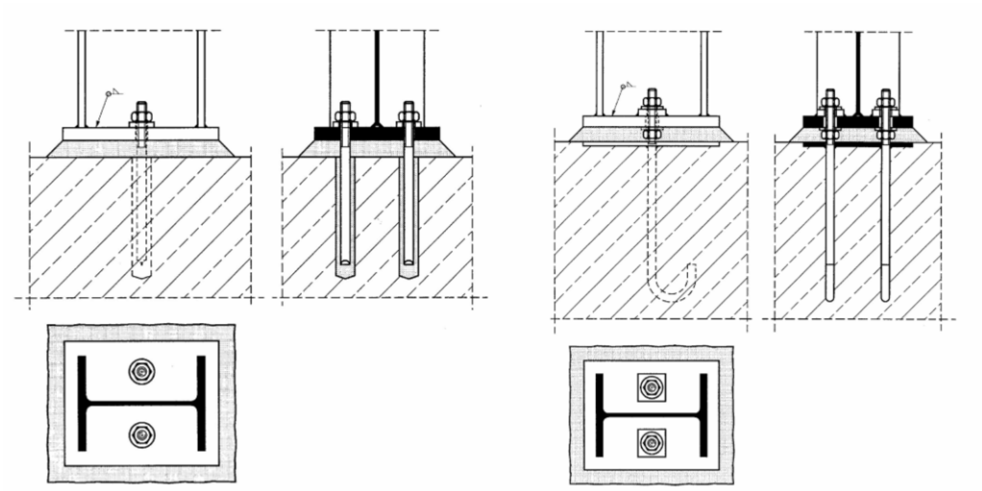


Figure 6.3 *Typical examples of pinned column bases in a portal frame, [2]*

The detailed design of the connections is generally carried out by the steelwork contractor. Sensibly proportioned haunches and columns can reduce the need for expensive stiffening.

7 BUILDING ENVELOPE

Because the building envelope encloses the structure completely in most cases, it is decisive for the appearance of the hall.

7.1 Building physics

7.1.1 Thermal protection

For industrial halls the floor space is relatively low compared to its volume. Hence, there are comparatively low requirements on thermal insulation of the building envelope. But nevertheless thermal insulation plays an important role even in the industrial sector due to matters of comfort as well as from the economic point of view with regard to the development of the energy costs in recent years.

Especially for large sized panels thermal bridges and air-tightness of joints have a major influence on the energy-balance of buildings. The thermal insulation has to be laid without gaps. Furthermore all heat transferring embracing areas have to be sealed at longitudinal and transverse joints air-tightly.

7.1.2 Moisture protection

Thermal and moisture protection are linked closely, because damages due to humidity are often the result of lacking or improperly installed thermal insulation. In multi-skin roof or wall constructions humidity penetration has to be prevented by installing a vapour barrier on the inner skin of the structure. Walling constructions being vapour proof on both sides, like sandwich panels, prevent the vapour diffusion. Yet for this reason the humidity in the hall has to be regulated by air conditioning measures.

7.1.3 Sound insulation

In all European countries minimum requirements exist on the sound insulations of buildings. In addition to that in industrial buildings limit values for the acoustic emissions have to be considered.

For single sound sources a local encapsulation is recommended, e.g. by using elements made of composite sheets. In order to insulate a general high level of sound impact sound-absorbing sidings of roof and wall are effective. For multi-skin walling constructions nearly any required sound insulation can be achieved by adjusting the respective acoustic operative masses. Due to the complexity of this issue it is recommended to consult the manufacturers in the design process.

7.2 Roof design

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.

7.2.1 Single-skin trapezoidal sheeting

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

Generally steel sheetings are made of galvanised steel grades FeE 280 G, FeE 320 G or FeE 275 G. Due to the diversity of product forms no standard dimensions exist. The steel sheets are usually between 0.50 and 1.50 mm thick (including galvanisation).

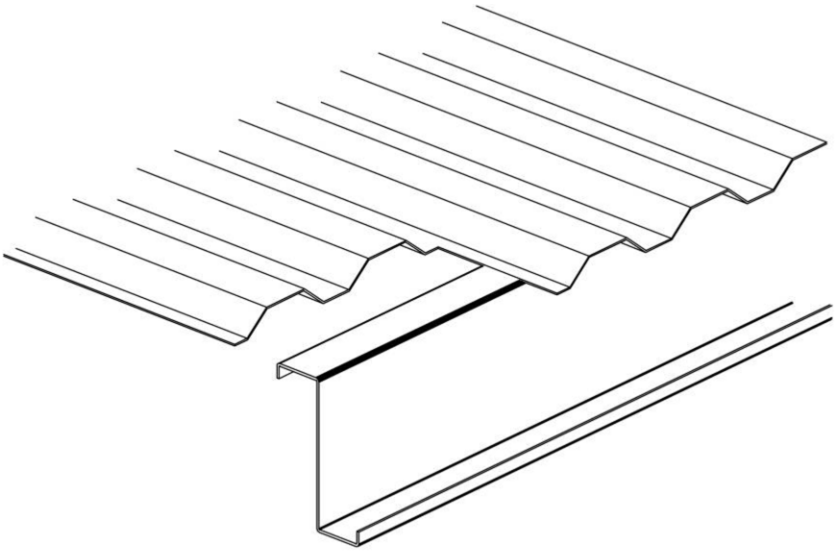


Figure 7.1 *Single-skin trapezoidal sheeting*

7.2.2 Double-skin system

These double skin or built-up roof systems usually use a steel liner tray that is fastened to the purlins, followed by a spacing system (plastic ferrule and spacer or rail and bracket spacer), insulation, and the outer sheet. Because the connection between the outer and inner sheets may not be sufficiently stiff, the liner tray and fixings must be chosen so that they alone will provide the level of restraint to the purlins. Alternative forms of construction using plastic ferule and Z or rail and bracket spacers are shown in Figure 7.2 and Figure 7.3.

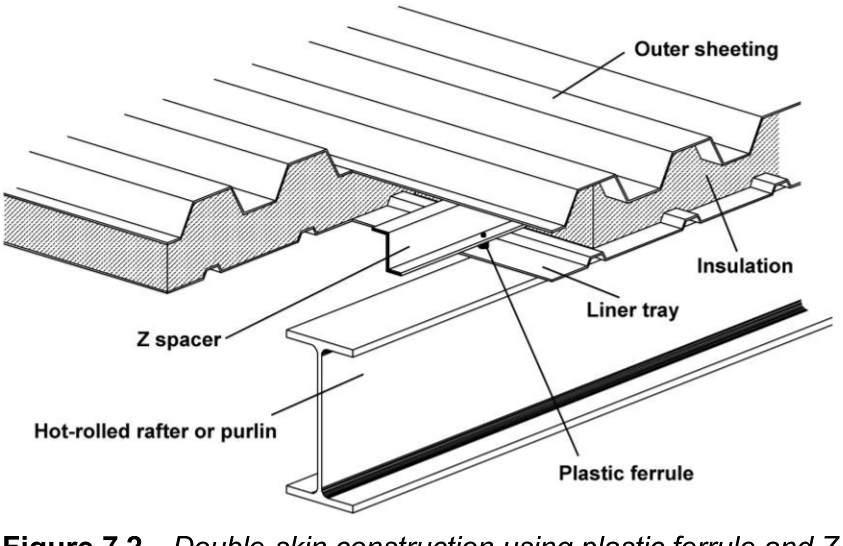


Figure 7.2 *Double-skin construction using plastic ferrule and Z spacers*

As insulation depths have increased, 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 should be provided.

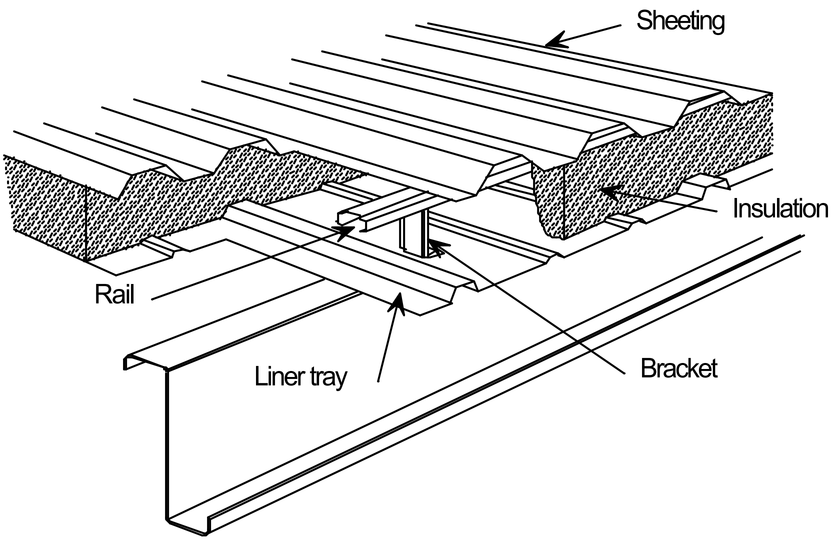


Figure 7.3 *Double-skin construction using 'rail and bracket' spacers*

7.2.3 Standing seam sheeting

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

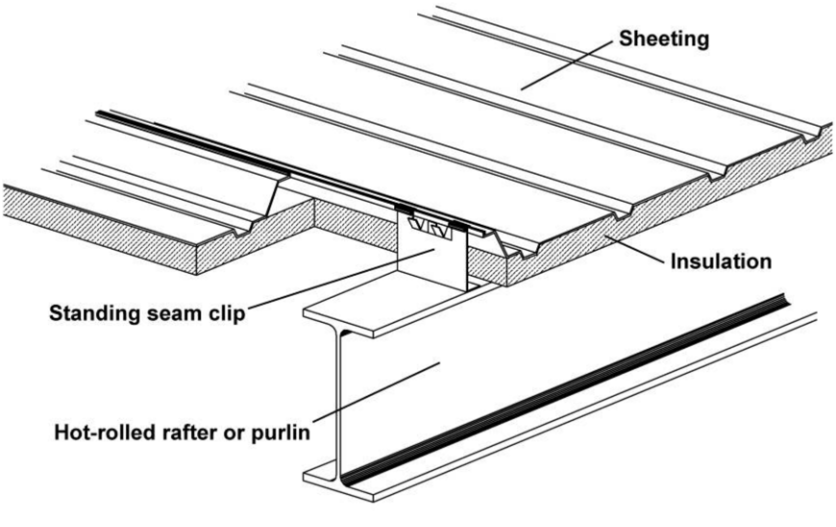


Figure 7.4 *Standing seam panels with liner trays*

7.2.4 Composite or sandwich panels

Composite or sandwich panels are formed by creating a foam insulation layer between the outer and inner layer of sheeting. Composite panels have good spanning capabilities due to composite action in bending. Both standing seam (see Figure 7.6) and direct fixing systems are available. These will clearly provide widely differing 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 these relatively thick elements, the self-weights from 11 kg/m² (40 mm thickness) to approx. 18 kg/m² (200 mm thickness) are comparatively low. Thus the elements are easy to handle and assemble. Possible element lengths of up to 20 m for roofs and walls allow constructions without or with only few joints. The basic material for the outer layers is usually galvanised coated steel sheeting with thicknesses of 0.40 to 1.00 mm.

The inner layers of sandwich panels are often lined or slotted, special designs are available plane as well. Close-pitch flutings have also been established, which are fully profiled, yet suggesting a plane surface from certain distance. Some types of patterns for sandwich panels are shown in Figure 7.5.

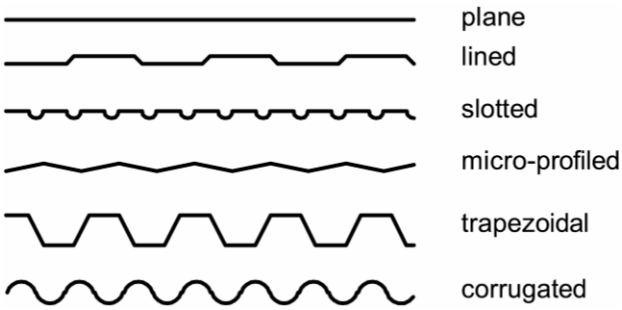


Figure 7.5 *Types of surfaces for sandwich panels*

Composite or sandwich panels generally designed according to Figure 7.6 offer numerous advantages:

- Pre-fabrication provides short construction time and cost-efficiency
- Without secondary treatment they are accurate concerning building physics
- Mountable in nearly all weather conditions.
- No sub-structure required due to high stiffness

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:

- PUR rigid foam
- Mineral fibrous insulating material
- Polystyrene (only in exceptions due to worse insulation behaviour)

The decking as well as the insulating foam are physiologically seen harmless, this means the handling during production and assembly as well as the permanent use in the building. The core insulation is odourless, rottenness- and mould-resistant. Furthermore they offer good recycling possibilities.

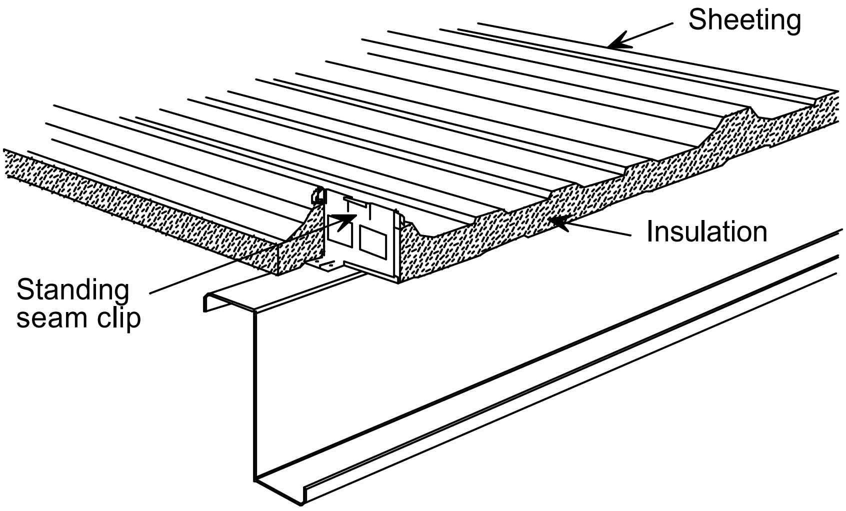


Figure 7.6 *Composite or sandwich panels with clip fixings*

One key issue which has to be taken into account for sandwich panels is the temperature difference. The separation of the inner and outer shell leads to heating and therefore extension of the outer sheeting due to solar radiation. For single span panels this results in a flexion of the panel without internal forces, which can influence the outer appearance of the envelope. For continuous panels constraint forces occur, which can lead to collapse of the panel. The darker the colour of the panel the higher the constraint forces. Therefore, for continuous panels checks including the loading cases “temperature in summer” and “temperature in winter” have to be performed, differentiating between the colour of the panel. On European level EN 14509 in the process of developing, which regulates the structural design as well as the production and quality assurance of sandwich and composite panels.

The manufacturers should be consulted for more information.

7.2.5 Fastening elements

The technique for joining parts covers the connections of the sheets to the sub-structure as well as the connection of the sheets among each other. For fastening of light-weight steel sheetings (self-tapping) screws, anchors or rivets are used. For profile sheetings at least every second rib has to be fixed to the sub-structure. If sheets are used for diaphragm action the joints have to be designed following the shear flow.

For light-profiled sandwich elements the designer has to consider the influence of the number of fastening elements on the ultimate load of the panel. Therefore the type and the number of fasting elements are part of the calculation of sandwich panels and have to be checked carefully. Figure 7.7 shows the different fastening elements depending on the substructure.

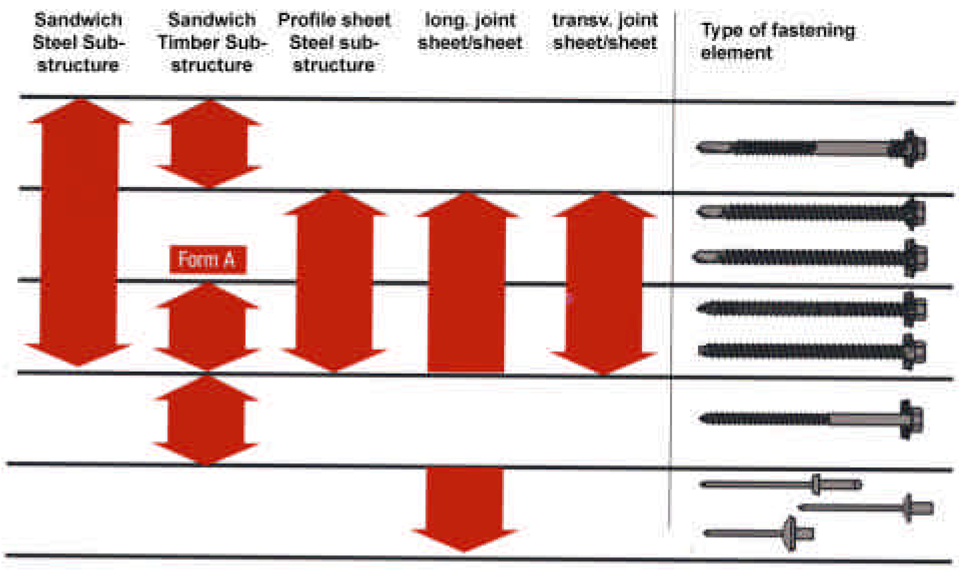


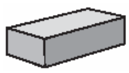
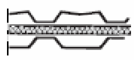
Figure 7.7 *Range of application for fastening elements, [4]*

7.3 Design of walls

7.3.1 General issues

For the design of external walls for industrial halls numerous possible solutions exist and the most common are shown in Table 7.1.

Table 7.1 *Possible designs of external walls in industrial buildings*

	Type / Properties	Gas concrete	Masonry	Steel sheeting (one layer)	Steel-Sandwich (insulated)	Steel sheets (two layers, insulated)	Coffered wall
Formats & Size	All dimensions in mm						
		Width 500 - 750 Thickn. 100 - 300 Length up to 7500, dep. on producer 2 property classes GB 3.3 / GB 4.4 Special profiles	Thickness 115mm	Width 700–1050 Prof.-height 10-206 Length up to 24000 Plate-thickness 0.63-1.5 Sizes up to 22 m²	Width 1000 Thickn. 40 - 200 Length up to 16000 Plate-thickness0.55 Sizes up to 16 m²	Width 700 – 1050 Plate-thickness 0.63-1.5 Length up to 24000 Insulation > 40 Thickness 90-300 Sizes up to 22 m²	Height 400 - 600 Webs 40-150 Plate-thickness 0.63-1.5 Length up to 7500
				Numerous special profiles	For sandwich-elements length more than 10m not recommended		
Building physics	Thermal insulation k [W/m²]	150 mm k=0.90 240 mm k=0.70	k = 3.08		40 mm k=0.60 120 mm k=0.20	40 mm k=0.87 140 mm k=0.33	
	Fire protection	>150mm F180-A >175mm Firewall	115mm = F90	Inflammable	Hardly combustible	Up to W90 / F30	Up to F30
	Acoustic insulation R´w [dB]	36 dB – 48 dB	44 dB+	20 dB – 25 dB	Up to 25 dB	Up to 46 dB	Up to 46 dB
Constructive	Surface	Porous, coatings required	rough	Plane	Plane	Plane	Plane
	Impact resistance	Suboptimal	Very good	Suboptimal	Suboptimal	Suboptimal	Suboptimal
	Self-weight	200mm=1.44kN/m²	115mm=1.95kN/m²	0.07-0.20 kN/m²	0.1-0.16 kN/m²	0.17-0.25 kN/m²	0.07-0.20 IN/m²

Due to high-quality standards, short construction time and cost-efficiency cladding types made of steel sheetings, i.e. the last four columns of the table above, are most commonly used. Generally 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
- 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 good examples are illustrated in Figure 7.8 to Figure 7.10. Brickwork is often used as a “dado” wall below window for impact resistance as in Figure 7.9.

Figure 7.8 *Horizontal spanning sheeting*

Figure 7.9 *Large window and composite panels with “dado” brick wall*

Figure 7.10 *Horizontal spacing composite panels and long corridors*

7.3.2 Sandwich panels

For walling constructions sandwich elements have widths of 600 to 1200 mm with thicknesses of 40 to 120 mm, even 200 mm for elements used in cold stores.

For a long time economic considerations pushed the use of composite and sandwich panels. But in order to achieve an aesthetical appearance of the building, nowadays other issues are gaining importance:

- Texture of the surface
- Choice of colours
- Design of joints
- Type of fixation

In addition, from a modern construction system the client expects technically immaculate fixations and transitions in the attic section and building's corners. Besides standard elements with bolted-through fixations, which are still commonly used, in ambitious facade systems invisible fixations have been established. These differentiate between hidden bolts and elements with additional clip fasteners; see Figure 7.6 and Figure 7.11. With the one last-mentioned slight dents at the bolts due to improper assembly or temperature influence can be avoided.

For the completion of sandwich facades, special formed components for the transitions between wall and roof are necessary. The manufacturers have developed special parts for recurrent details. Especially for premium facades manufacturers offer angled or rounded components for the attic or corner sections, which can be integrated similar to modular design principle. These special components have to be of the same quality as the adjacent elements to avoid corrosion problems.

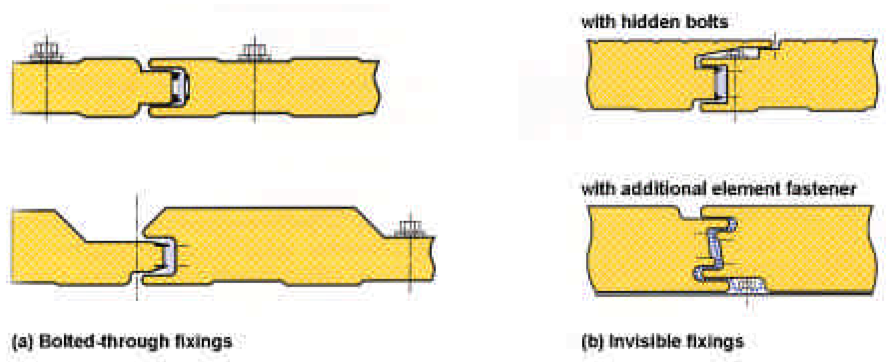


Figure 7.11 *Examples for the construction of fixings for walls made of sandwich panels, [4]*

7.3.3 Fire design of walls

Where buildings are close to a site boundary, the Building Regulations require that the wall is designed to prevent spread of fire to adjacent property. Fire tests have shown that a number of types of panel, can perform adequately, provided that they remain fixed to the structure. Further guidance should be sought from the manufacturers. Due to the construction used for the fire test specimens, it is considered necessary by some manufacturers and local authorities 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 (see Figure 7.12).

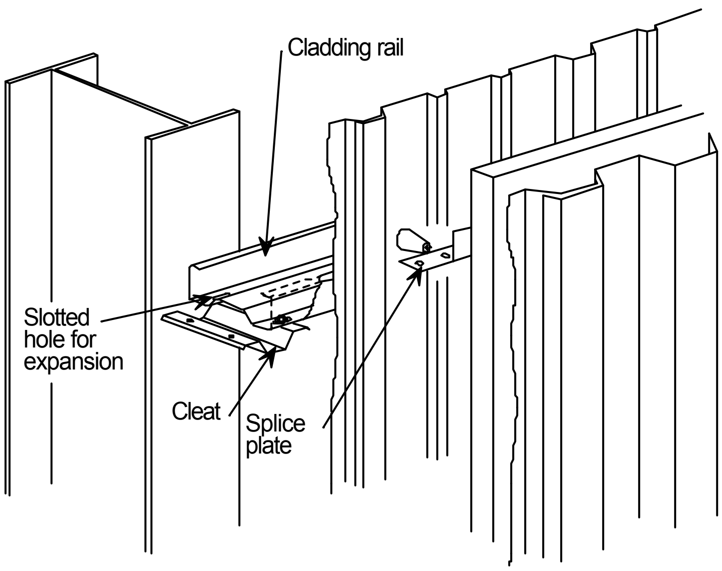


Figure 7.12 *Typical fire wall details showing slotted holes for expansion in fire*

7.3.4 Other types of facades

Not only steel sheeting is used for the facades of industrial buildings, glass as well found its way in the construction of production halls, see Figure 7.13.

Figure 7.13 *Example for an industrial building with glazed façade, (source: www.diemergmbh.de)*

The use of this architectural high-quality façade does not produce higher costs automatically. In the example above building costs are reduced by using hot-rolled sections for the structure as well as standardised façade-systems. By integrating solar gains into the thermal balance, maintenance costs are also reduced significantly. The structures supporting the façade and the detailing can be adopted from approved solutions from 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 the colouring of the façade. Whereas hitherto halls for industrial usage are often designed either in metallic shade or single-coloured, in the meantime architects try to integrate the building in the surrounding environment by using a suitable colour-concept, see Figure 7.14. Compatible with this, the various sheeting manufacturers offer steel sheetings in pleasing colours, often developed in cooperation with designers.

As an additional feature high-effective photovoltaic modules may be integrated in the façade. Despite the fact that the angle to the sun is not optimal, the system's photovoltaic modules can achieve high performance values due to multi-layer coating, which makes the solar cells less dependent on the angle of incidence of the sun's rays.

Figure 7.14 *Example for an industrial building using coloured facade made of steel sheets with integrated solar panels, (source: www.reflectionsone.de), [1]*

7.4 Floors

In most cases the floors for industrial halls are driven on, so that they have to bear particular high loads and have to be preferably plane. Decisive for the design are the particular highly concentrated loads due to vehicles (fork-lift trucks 10-150 kN, trucks 10-40 kN, heavy trucks 50-100 kN), machines, racks and containers.

Therefore most industrial buildings have concrete floors with a minimum height of approx. 15cm. It is based on a base layer consisting of gravel sand or gravel, which is at least 15cm thick as well. For huge areas a sheet of drift between the base layer and the concrete is required, using mostly two layers of synthetic foil.

8 OTHER EUROPEAN PRACTICES

8.1 Current practice in Germany

8.1.1 Structure

As in most European countries in Germany the typical structure of industrial halls in steel is the portal frame with pinned column bases. The span of the girder varies from 12 m to 30 m when hot-rolled or welded I-sections are used. The standard is between 15 m and 20 m. By using lattice girders greater spans than 30m are possible. If there are no restrictions from the usage multi-bay portal frames of hot-rolled I-sections are used with each span varying between 15 m and 20 m. Other primary load-bearing structures, such as simply-supported beams on columns, arches, grids, shells, etc. play a rather subsidiary role and are used for more expressive buildings.

The grid usually ranges between 5 m and 8 m, 10 m are possible. In normal cases the eaves height of the frame is about 4.5 m to 8 m if cranes have to be provided.

The corners of portal frames made of IPE- or HE-sections are often designed haunched, because the material usage is reduced to the highly stressed regions. Mostly, bolted connections are used with continuous columns combined with beams having end-plates, as shown in Figure 6.1. In some cases the column with the haunched span of the beam is designed as one part and the section of the beam with constant height connected with a bolted joint. If the beam-span exceeds transportation limits another joint at the apex of the frame is provided, mostly as a bolted connection as well, see Figure 6.2.

Cold-formed as well as rolled purlins (see § 3.1.5) and trapezoidal sheeting spanning directly between the beams are used approximately to the same extent. By using sheeting only the stiffening of the roof can be obtained by stressed skin diaphragm action of the profile sheeting.

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. Current standard is DIN 18800, parts 1-5, which is almost identical with European standard EN 1993-1-1 and only shows differences in details. For a detailed design procedure according to both standards mentioned above, see ANNEX 4-D of this research project.

8.1.2 Building envelope

Roofing

The major part of the roofing in industrial halls in Germany is designed with a load-bearing shell of trapezoidal steel sheeting spanning between the portal frames or the purlins, if provided.

Currently the single-layer, upside insulated steel sheeting roof, as shown in Figure 8.1(a) is the most disseminated type of roofing in industrial halls in Germany. For this type of roofing the slope should be not less than 2° in order to ensure correct drainage. This type of roof is comparatively low in costs, but is sensible to mechanical damage of the sealing.

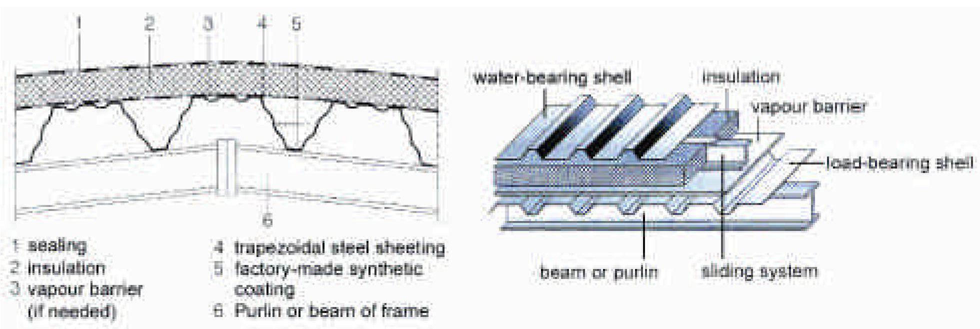


Figure 8.1 *Common roofing systems in industrial halls in Germany using trapezoidal steel sheeting, [3]*

Roofing constructions with two layers, see Figure 8.1(b), gain more and more importance because they are regarded easy to maintain combined with longer useful life. Further advantages are a higher resistance against environmental influences as well as the possibility to be involved in the concepts for acoustic insulation and fire resistance. It can be mounted nearly unaffected by weather conditions. Often the water-bearing shell is fixed to the load-bearing shell by a clamped joint with special sliding system, so that the water-bearing shell needs not to be penetrated.

External walls

For industrial halls in Germany diverse miscellaneous types of walls are used depending on the demands made by the building-physics behaviour, the use of the building as well as the surroundings, see Table 7.1

Due to lowered fire-protection requirements in the course of the “Muster-Industriebau-Richtlinie” systems of profiled, light-weight and large-sized sandwich panels are gaining importance, see § 7.3.2. These can be mounted easily, fast and not affected by weather conditions and offer also good behaviour for thermal insulation.

8.1.3 Non-structural requirements

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 these types of buildings only requirements concerning the heat transmission losses via the building envelope have to be satisfied. The heating installation has not to be considered.

For buildings with “lower internal temperature” there are fewer restrictions concerning the thermal insulation, which leads to smaller thicknesses of the insulation layer.

Fire-safety

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

It provides three calculation methods with increasing difficulty:

(1) Simplified calculation method

(2) More precise calculation method with determination of the fire-load –density basing 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 remarkable size (1800 m²) without having any active fire-fighting measures provided. By making available automatic sprinkler units the compartment size can reach 10000 m². If fire-walls are provided the size of the whole building can be enlarged by summarizing all compartments. Single storey halls used as shops feature similar low requirements on the fire-resistance of structural parts, if sprinklers are provided. The maximum size of the compartments is 10000m² also.

The more precise calculation method (2) bases on the German standard DIN 18230-1, which deals with determining an equivalent fire-duration. This value relates the parametric heating curve considering the specific parameters for the regarded project to the ISO-curve. It takes into account project-specific parameters like ventilation conditions, etc. By this compartment sizes up to 30.000m² are possible in unprotected steel.

In addition to the two simplified calculation methods mentioned above the methods of fire-engineering can be applied. The guideline formulates basic principles for making the appropriate checks to satisfy the aims of the legislator.

8.2 Current practice in Sweden

8.2.1 A typical Swedish hall

Open plan buildings like industrial halls are a very strong market for steel in Sweden (SBI 2004). Common sizes for light halls are spans between 15 and 25 meters with a room height of 5 to 8 meters. A building area of 1500-2000 m² is common. Of cause significantly longer spans are feasible. There are companies specialised on light hall systems and often the building, above ground, is delivered as a turnkey product.

Today new hall buildings usually are insulated with approximately 120 to 150 mm mineral wool. The hall often comprises some sort of office space in parts of the building where also an intermediate floor is used.

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, see Figure 8.2. The columns are considered as pendulum columns. Sometimes the wall sheeting is utilised as a stressed skin diaphragm too.

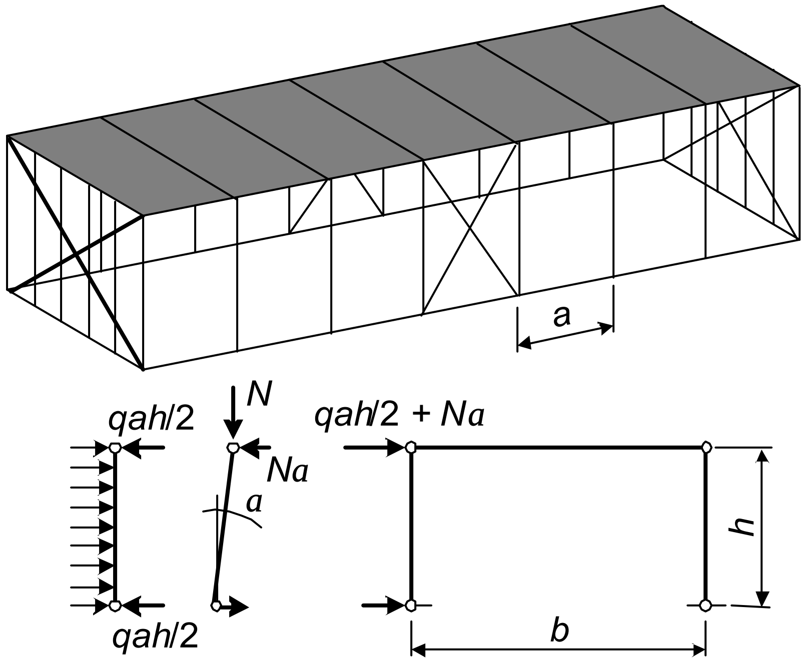


Figure 8.2 *Open plan building stabilised by wind bracing in the walls and diaphragm of trapezoidal sheeting in the roof (Höglund, 2002).*

A typical open plan building is shown in Figure 8.3. Often a gabled roof with an angle of 3.6° or 5.7° is used. The span between rafters is typically 6 to 10 m. The walls are composite panels or profiled sheeting on light gauge steel beams. The insulation is placed on top of the load bearing profiled sheeting and covered with roof material. A plastic foil is used as air and moisture tightening. Lattice beams are dominating for rafters. Spans up to 45 meters can be achieved with standard products but the cost increases significantly with span. The columns are typically HEA-columns, fastened with four anchor bolts on a base plate. Although the columns are considered as pin-ended, four bolts are recommended in order to have column stability during erection.

For non-insulated halls, the profiled sheeting is resting on purlins in order to orient the profiles on the sheeting. Z-profiles are often used as purlins up to 12 m.

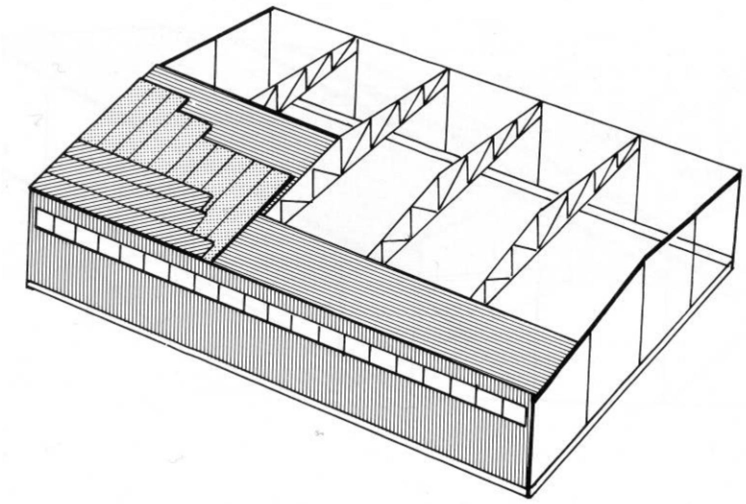


Figure 8.3 *A light insulated open plan building with profiled sheeting on rafters. A gabled roof with an angle of 3.6° or 5.7° is used. The span between rafters is typically 6 to 10 m. The walls are profiled sheeting on light gauge steel beams or composite panels. The insulation is placed on top of the load bearing profiled sheeting and covered with roof material (SBI 2004).*

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

8.2.2 Roofing & Cladding

There are several suppliers of roofing and cladding systems on the Swedish building market. A choice of systems is collected in this report. For more detailed information, please contact the suppliers listed in Chapter 4 Literature.

Roofing

Sheeting

There are a number of products for roofing on the market, mainly profiled sheeting and tiles. The profiled sheeting is design according to Figure 8.4 either as loadbearing with web stiffeners or as it is in the Figure. There are also roofing tiles in modules of one to ten tiles used for roof angles of 14° and more. The roofing tiles uses traditional colours and is significantly lighter than ceramic or concrete tiles.

Figure 8.4 *Example of different products on the market. The sinus profiled sheeting can be used either on roofs or on walls erected horizontally or vertically. The tiled sheet is developed for roofs.*

Load bearing profiles

There is profiled sheeting used for insulated roofs with spans up to approximately 11 m on the Swedish market. The longer spans are achieved with sheeting with corrugation in two dimensions. Shorter spans, up to 8 m, are achieved with more traditional grooved profiles.

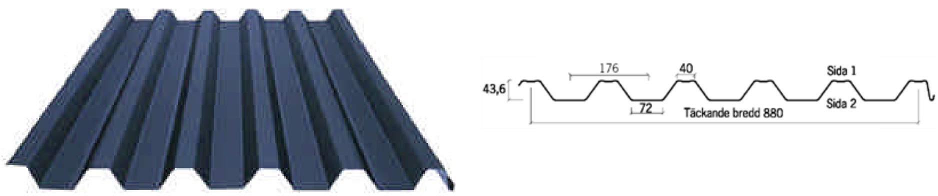


Figure 8.5 *The sheeting in the figure is commonly used in uninsulated loadbearing roofs that are built up with purlins. With a profile height of 45 mm it can manage heavy loading.*

The load bearing profile is usually dimensioned to also act as a stressed skin diaphragm. Stressed skin diaphragm design enables the roof to be constructed without bracing.

Insulated roofs

Profiled sheeting is used as load bearing structure. The height of the profile is chosen depending on the span. Insulation in form of rock wool in two layers with plastic foil as damp proof material as well as air tightening in between is used. Trapezoidal sheeting is used as external roof material. A minimum roof angle of only 3.6° is required. U-values (according to the Swedish building regulations) of 0.3 to 0.7 W/m²K can be achieved mainly dependant on the thickness of the insulation.

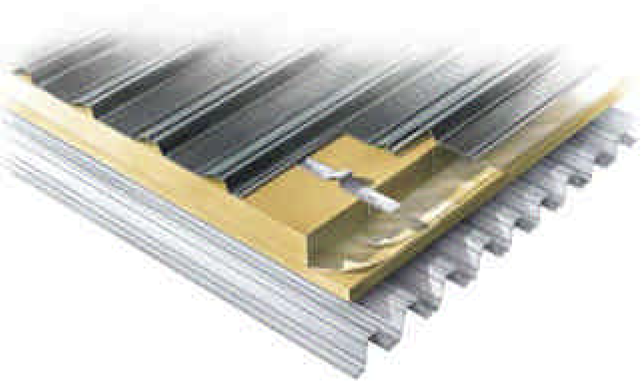


Figure 8.6 *An insulated roof with load bearing profiles for example Plannja 200 or Plannja 111. As surface profile a low Plannja 40 is used, especially developed for low sloping roofs, from 3,6 degrees. (Source: www.plannja.se)*

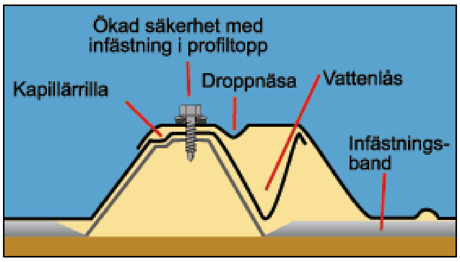


Figure 8.7 *The Plannja 40 sheeting has been developed to avoid water leakage.*

Cladding

Sheeting

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

Figure 8.8 *The sheeting has been developed The Fasetti facade lamella (cassette) is a metal sheet bent on two sides manufactured in length dimensions specified by the customer. Fasetti lamellas are generally manufactured object-made, they are not bent on ends; ends are finished with flashings. (Source: www.ruukki.com)*

Cassettes

Figure 8.9 *Cassettes of steel are used for cladding. Cassettes are not as convenient to manufacture as profiled sheeting and are somewhat more expensive. (Source: www.ruukki.com)*

Panels

Composite panels, sandwich constructions of steel and insulation, for exterior walls provide solutions with heat insulation, fire protection and aesthetics accounted for. Panels have sheeting on both sides with an insulation of mineral wool or EPS in between. Mainly depending on the thickness of the insulation, U-values typically vary from 0.18 (>200 mm) to 0.8 (50 mm) W/m²K. The systems include air and water tightening systems between panels. If rock wool is used the system provides good fire integrity and acoustic performance. The panels can be delivered as quite large units up to over 10 m. Also long spans can be used, as the panels themselves are strong constructions.

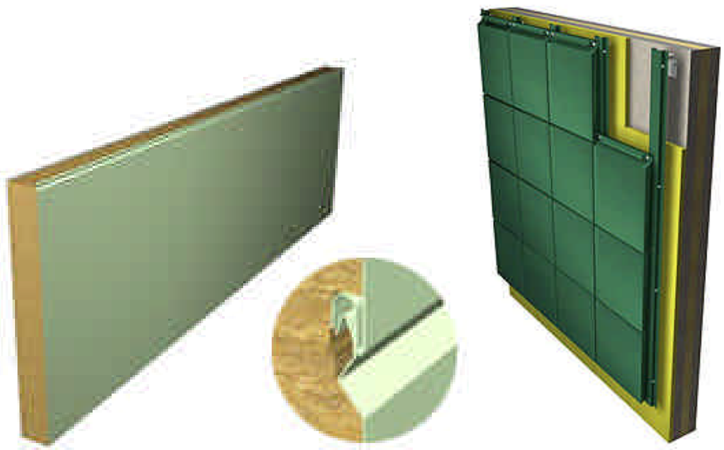


Figure 8.10 *Composite panel for e.g. industrial applications. To the left a Plannja panel (www.plannja.se). To the right a Liberta Grande facade cassettes. Cassettes made of sheet metal bent at all four sides with a stiffened backside, which enables creating larger and more plane-like surfaces. The details of the cassette system are based on the Liberta cassettes.*

This composite panel can be used for new production and for refurbishing old buildings. The steel panels are applicable to combine with other material as stone, timber, glass, stucco and concrete. The panel can be delivered with different surface finish, with deep and shallow profiling. The connection between two panels is the same and different panels can therefore simply be combined.

Figure 8.11 *Example of building using steel façade panels. (Source: www.plannja.se)*

Figure 8.12 *The panels can be used for interior applications as shown in the picture. (Source: www.plannja.se)*

Systems for refurbishment

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.

8.2.3 Impact of Regulations on thermal insulation

Current regulations on thermal insulation

Current standards are *Boverkets Byggregler BBR* (the Swedish Building Regulations).

Maximum average $F_{s,krav}$ for the total surrounding area including ground for non-residential premises is:

$F_{s,krav} \leq 0.22 + 0.95 \cdot A_f / A_{om}$ [W/m²·K]

Where: A_f = total window and door area, max 18% of heated floor area [m²]
A_{om} = total surrounding area including ground [m²]

This value may be exceeded by 30% if it can be proved that the energy consumption for heating, hot water and heat regain is not higher than for a house that fulfils the demands (shown with a trade-off calculation). The U-value is calculated regarding thermal bridges and also in a schematic way regarding possible imperfections depending on design, production and supervision. When calculating U for the ground the value is reduced with 25% taking heat storage into consideration. Also sun radiation through windows is taken into account.

The requirements do not apply to buildings:

- Which are used only for short periods or
- Where there is no heating requirement during a major part of the heating season.

Further: Buildings need not comply with the requirements where it is shown by special investigation that heat increments from processes cover a major proportion of the heating requirement.

Fulfilment of regulations

There are products on the Swedish market that can fulfil and exceed the Swedish building regulations as to heat insulation for industrial buildings. A construction with composite panels as façade and insulated roof can even fulfil the stricter requirements for residential buildings. Typical U-values for a 150 mm composite panel are 0.24-0.28 W/m²K. There are standard solutions for U-values down to 0.17 W/m²K.

8.3 Current practice in U.K.

8.3.1 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. Rising client expectations, Health and Safety regulations and Sustainability initiatives are impacting on this type of construction. Furthermore the technologies used to meet these requirements demonstrate a willingness to embrace innovation in design, manufacturing and detailing. Examples are the use of plastic design of portal frames, IT systems for design and manufacture, advanced cold formed components, such as purlins, and highly efficient cladding systems.

This single storey industrial sector in the UK has an annual value of approximately £ 1 billion for frames (1.5 billion Euros) and £ 1.5 billion (2.25 billion Euros) for associated envelope systems.

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. Obtaining approval for the structure is now routine and the focus of Building Regulation compliance is more on the envelope system.

This emphasis will increase further with the introduction of a revised Part L, with its more onerous requirements, and the European "Energy Performance of Buildings Directive" in April 2006. Key features will be:

- The need to achieve a saving of around 23 to 28% in CO2 emissions when measured against the equivalent building which would have complied with the 2002 regulations;

- The introduction of energy passports.

8.3.2 Selection of steel for UK single storey industrial buildings

Clients commissioning buildings must have a business case. They may be building it for their own use, to rent out, as an investment or to sell on. There are several criteria which can affect the value that the building brings to the clients and users. These are:

- Speed of construction
- Flexibility in use
- Maintenance
- Sustainability
- Value for money
- Supply chain

Speed of construction

Logistics or similar business may need the building urgently to service a new contract and therefore 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

Change is now a fact of life for most businesses, with the likelihood of substantial evolution in the activities for which the building provides shelter during its design life. The wide spans and minimal use of columns that are readily offered with steel construction offer the maximum opportunity for the building to be able to accommodate different processes efficiently.

The client may at some point wish to sell the building to an investment organisation. To facilitate this option, institutional criteria such as minimum height and higher imposed loads can be specified to maintain the asset value and provide flexibility for unknown 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 ones, where the owner carries maintenance responsibility. Any situation where the owner, who originally specified the building, has responsibility for maintenance, encourages the choice of better quality materials with a longer life expectancy in order to reduce maintenance costs. Increasingly, suppliers are providing guarantees and advice on necessary maintenance.

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 future, it is likely that planning permission will be easier to obtain with sustainable, environmentally friendly solutions. This is especially true in London. Many clients, potential clients and occupiers have sustainability policies against which their performance is monitored by share holders and the public.

Value for money

Steel has achieved a large market share in this sector because of responsiveness to client demand. This success has been achieved in very competitive national market places and demonstrates the value for money that steel construction provides.

Supply chain

In today's competitive environment, all members of the supply chain are under pressure in terms of the increased complexity of their own specific tasks and the reductions in time available to carry them out. In addition, with the increasing complexity there is also an increased interdependency between the various elements and a high degree of co-operation and co-ordination is needed in order to achieve an economic and high quality outcome. A key feature of any successful supply chain team is that it collectively understands how the whole building works and recognises the interdependencies between the various elements.

8.3.3 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 models used for detailing. In addition to driving the manufacturing process, the information in the model is also used for ordering, scheduling, dispatch and erection. Single storey construction at its best, with its highly integrated design and manufacture, represents levels of efficiency to which other sectors aspire. The key to realising the highest level of efficiency is to work in a way that enables the optimum use of this infrastructure.

Choice of primary frame

The most popular choice of structural form for single storey buildings with spans of 25 to 60m 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, as they do not fully utilise the capacity of the sections, 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.

Interdependence of frames and envelopes

The structural efficiency of portal frames is 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. The cladding sheets are profiled to provide the necessary strength to span between the purlins and provide the required restraint to these secondary members. 'Stressed skin' action may also be utilised.

The design methods for the steel structure are now well understood and accepted by all parties and the focus of attention has shifted to the envelope and how this is to be supported. There are three major reasons for this:

- The use of sheds is no longer restricted to industrial buildings and they are now used in a wide range of commercial applications. Examples include multi-functional headquarters, call centres, retail and leisure premises.
- 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 qualities of the envelope and the increased significance of the EU Energy Performance of Buildings Directive (EPBD) with its requirement for energy labelling. The cladding has become the most significant element in the building and the emphasis and culture have to reflect this by designing the building from the outside in, rather than the earlier approach of the structure first with basic cladding systems fixed to it. The choice of building envelope contractor has also become more significant, if economic compliance with regulations is to be reliably achieved.

Energy performance

Reductions in U-values over recent years have led to a considerable increase in insulation thickness, with implications for stability (of built-up systems), cladding weight and consequential handling requirements. There is a common perception that this trend will continue as future regulatory changes increase the demands on the building envelope. However, in reality the relationship between insulation thickness and energy efficiency is subject to diminishing returns as 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, the inclusion of roof lights is 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 in order to satisfy regulatory requirements.
A balance of all the factors is necessary to optimise the reduction of emissions in the operation of any building.

Airtightness

The introduction of airtightness 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 of buildings is $10m^3/m^2/hr$ at 50 Pascals, levels of airtightness down to a tested value of $2m^3/m^2/hr$ are possible with standard construction. However, achieving this level depends on an assured quality of construction and detailing. For buildings with floor areas less than 5,000 m^2 achieving good levels of airtightness becomes difficult to achieve due to the higher proportion of openings relative to the clad area. While a common view is that airtightness is the responsibility of the cladding contractor, in reality the necessary quality of construction can only be achieved if all contributors to the supply chain understand the requirements and the building design is well coordinated.

Design Coordination

Buildings are larger, higher and more highly serviced than they used to be. The contractor is responsible for the design, and it is important to select one who knows what constitutes a good design for the intended use, what they expect to see from the suppliers and how it can be achieved.

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 frame contractor is responsible for the design. To assist with the coordination, it is beneficial for the contractor to prepare a list of drawings that the architect is expected to produce, with the help of appropriate participants.

Building architecture

The focus for the design should be to provide clients and users with solutions that improve their business performance. In the pre-contract phase, the architect has a significant role in dealing with site-specific issues such as obtaining planning permission and dealing with abnormal situations such as wayleaves and flood risk. A prime task for the architect is the sizing of the building and the determination of how the elements are set out relative to grid lines. There are institutional standards for measuring lettable area, minimum height to underside of structure, floor loadings, durability of cladding etc. The advent of the EU Energy Performance of Buildings Directive in 2006, where buildings will have to have their energy rating declared on change of ownership or usage etc, will encourage standards to be set for this attribute too.

Developers and funders are clearly anxious that any investment is assured in the future in terms of its asset value. This generally means that flexibility for potential future tenants or owners is a significant criterion. Nobody wants to pay more than they need, but it is important to set appropriate quality and technical criteria (and see that these are maintained throughout the design and construction process), before going out to competitive tender.

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

- Overall geometry 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
- Selection of purlins and side rails
- Service loads on frame and deflections
- Imposed floor loads
- Cladding system and available guarantees
- Adequate access for possible future vehicle needs
- Tolerances of floor slab
- Potential for re-use / recycling of materials
- End of useful life liability
- Energy consumption and reduction of CO_2 emissions

Influences on structural design and costs

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 will be pin-based. Economies in the frame design in terms of weight of steel can be made where nominally fixed bases are used, but this approach will have implications for the cost of the foundations.

Particular attention should be given to ensuring that:

- The cladding system and frame design are based on the same wind loading criteria. Calculations should be requested from the envelope contractor showing the fixings that are required. It is recommended that the steelwork contractor also issues the relevant sections of his design information to the envelope contractor.
- The tolerances of the frame and chosen cladding system are compatible. This issue has become more important as aesthetics have assumed greater importance, leading to the selection of cladding systems with tighter tolerance requirements.
- Provisions have been set out for sprinkler systems and that these can be sustained in terms of both load capacity and space required, with pipes of up to 150 – 200 mm diameter. The sprinkler system is generally carried by the purlin system and the layout can affect bracing locations and arrangements. Larger pipes may need special provision.
- Loads on secondary members are adequate. Cladding systems and services have increased in weight over the years and assumptions may be lagging behind current practice.
- An adequate allowance has been made for the weight of the gutters. Insulated gutters weigh around 140 kg for a 3 m length and require specific design of the supporting steelwork. Gutters are often designed on the assumption that they will fill with snow, but it should not be forgotten that they can also fill with water, which is considerably heavier than snow. The supporting steelwork design should recognise these loads, but experience suggests that many designers have not updated their assumptions in line with changes in the construction. The location of overflow pipes affects the layout of the steel framing and the advent of symphonic drainage systems means that the tolerances and deflections of the support system can be critical for effective operation. The weight of the gutters is

such that cranage is necessary for erection and this may need to be provided by the steelwork contractor.

Sustainable construction

The need to consider sustainability is now recognised in all walks of life and the importance of the role played by construction is widely acknowledged. The requirement for sustainable construction is being encouraged in many ways, ranging from EU Directives on emerging 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 underpinned by the need to balance the triple bottom line of economic, social and environmental viability. Good construction should meet all three criteria and good steel construction certainly does.

8.3.4 SUMMARY OF INDUSTRIAL BUILDLING TRENDS IN THE UK

The following summary of trends in modern industrial warehouse design is adapted from a report by developer Gazeley, who is a key procurer in the area of logistics:

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 × 150 m plan area	
	15 m height to haunch	12 m height to haunch
	Portal frames of 30 – 35 m span with 6º roof slope	Steel portal frame with 2º 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 marshalling area
	U values of 0.35 $W/m^{2o}C$ for walls and 0.25 $W/m^{2o}C$ for roof	U values of 0.25 $W/m^{2o}C$ for walls and 0.20 $W/m^{2o}C$ for roof
	15% roof light area for natural lighting	15% roof lights (triple layer)
	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 PVs on roof
	Selective use of photovoltaics (PV) on roof	Wind turbines to generate primary energy

	Fire-wet suppression system	Greater use of solar thermal hot water
	Fit-out of services by end user	Sprinklers depend on client requirement
	Design life of 40 years – 25 years to first maintenance	Greater use of PVs on roof
	Pervious paviours in car park to assist drainage	
	Rainwater collection from roof	

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