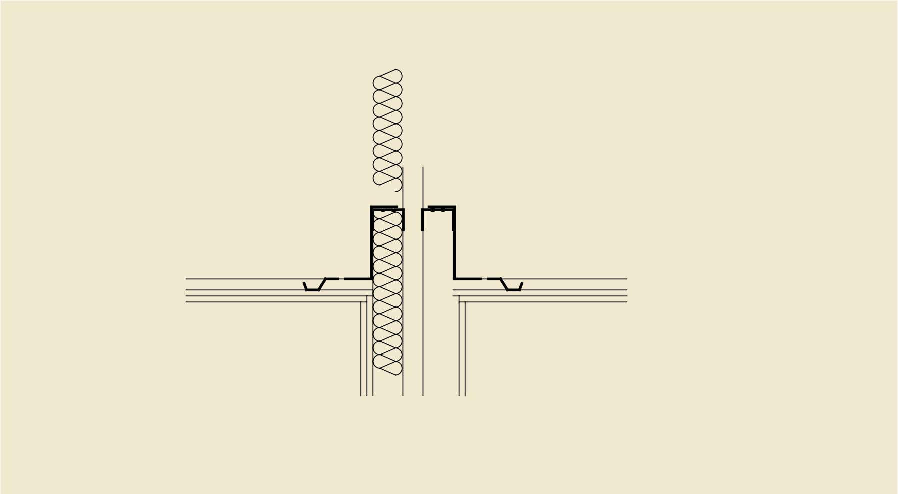
Best Practice in Steel Construction

RESIDENTIAL BUILDINGS

Guidance for Architects, Designers & Constructors

Research Fund for Coal & Steel



06 Modular Systems

This section describes the various forms of modular construction using 3 dimensional units. They can be designed independently, or as part of 'hybrid' steel construction systems, which are described in the following sections.

Modular construction uses load-bearing 3 dimensional units, which create self supporting structures up to 8 storeys high. The modules are manufactured in factory controlled conditions, and are repetitive units made in lengths and widths suitable for transportation and installation.

Modular construction has been used most effectively in hotels, student residences and social housing, as shown in Figure 6.1, where economy of scale in manufacture can be achieved.

There are three generic forms of modular construction:

- Fully modular construction using load-bearing modules.
- Modules supported by a separate steel structure or bracing system.
- Non-load-bearing 'pods' for bathrooms etc.

The structural use of these modules is presented, but 'pods' are not described, as they tend to be smaller and are non-structural.

Fully Modular Construction

Steel Frames and Modular Construction

Figure 6.1 Modular residential building with integral balconies, London
AHMA Architects & Yorkon

Fully Modular Construction

Figure 6.2 Module with load-bearing walls
Terrapin

Description

There are three generic forms of modular construction:

- Modules in which vertical forces are transferred through the side walls to the module below – see Figure 6.2.
- Modules with fully or partially open sides in which vertical forces are supported by edge beams and corner posts - see Figure 6.3.
- Non load-bearing modules supported on floors or a separate structure.

Many 'hybrid' forms of modular construction exist when modules are combined with other structural elements, such as:

- Modules supported on a steel or concrete podium which permits the open space beneath to be used for commercial use or car parking.
- Modules combined with 2 dimensional floor and wall panels.

Modules use light steel walls and floors with Square Hollow Sections or angles for the corner posts, which are similar to those described for walls and floors in Section 3.

Main Design Considerations

The main design considerations in the choice of modular construction are:

- Ability to use repetitive cellular units.
- Transportation and installation requirements.
- Ability to create open plan space where required.
- Building height and requirement for open space, particularly at the ground floor.

Modules are manufactured in widths of 2.7 to 4.2 m, which is the maximum for transportation on most major road networks. Internal dimensions of up to 3.6 m are more practical in residential applications (3.8 m external dimensions). Module lengths up to 12 m can be used, although 7.5 to 9 m is more practical.

The plan form of a typical modular building in which adjacent modules are combined to create larger rooms, is shown in Figure 6.3.

Figure 6.2 Module with edge beams and corner posts
Kingspan

Advantages	• Speed of construction (up to 60% faster than site-intensive construction). • Improved quality due to off-site manufacture. • Excellent acoustic insulation due to use of double skin walls and floors. • Economy of scale in manufacture of repetitive modular units. • Partially open-sided modules are more useful for apartments.
Fire Resistance	A fire resistance of 60 minutes is provided by using two layers of fire resisting boards to the walls and ceiling. It is also necessary to provide ‘fire stops’ between the modules to prevent passage of smoke and fire.
Acoustic Insulation	A high level of acoustic insulation (over 60 dB sound reduction) is achieved due to the double layer construction of the walls and combined floor and ceiling.
Loads and Deflections	Modular design is influenced by: • Load-bearing resistance of the wall studs. • Stability under wind action. • Robustness to accidental actions. For 4-sided modules, stability can be achieved by suitable bracing in the walls or by diaphragm action of the boards attached to the walls. For corner-supported modules, as shown in Figure 6.2, the design is influenced by the compression resistance of the corner posts and the spanning capabilities of the edge beams. Corner-supported or open-sided modules generally have to be stabilised by a separate structure. The modules are tied together at their corners so that they act together structurally.

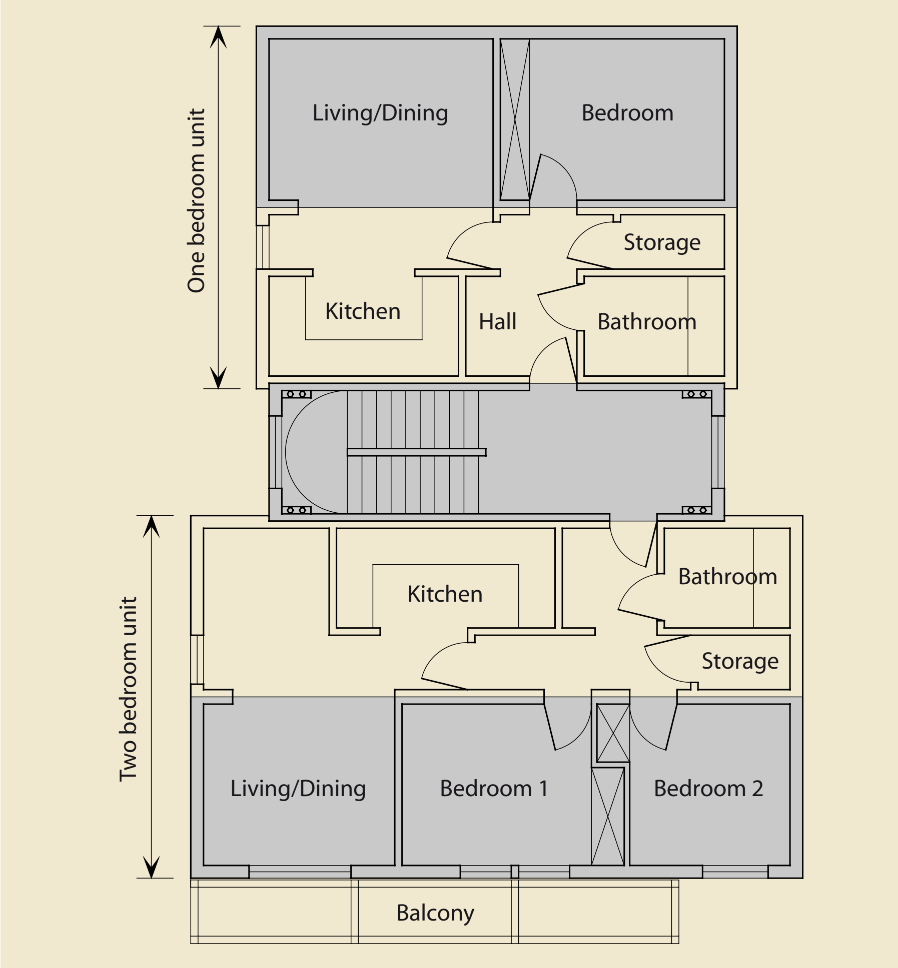


Figure 6.3 Plan form of modular residential building – alternate modules shown shaded

Overall Floor and Wall Zone

The overall floor zone is dependent on the combined depth of the floor and ceiling and may be taken for planning purposes as:

- 400 mm for smaller modules (< 3.6 m wide);
- 500 mm for larger modules (< 4.2 m wide);
- 600 mm for open sided modules with edge beams.

The combined width of the adjacent walls of modules may be taken as:

- 250 mm for low-rise modules;
- 300 mm for multi-storey modules with corner posts.

The space between the modules allows for installation tolerances. Balconies can be created within the module, as shown in Figure 6.1, or by attaching projecting balconies to the corner posts of the modules. Stair modules may also be introduced as part of the modular concept, which may influence the overall floor zone. In this case, it is recommended to use a 500 mm floor and ceiling zone for planning purposes.

Steel Frames and Modular Construction

Figure 6.6 Modular building supported on a podium level and stabilised by a braced steel structure around the stairs

Description

Many types of buildings require more open plan space and in this case, modular units can be combined with a primary steel frame. Three generic forms of combined use of steel frames and modules exist:

- Modules supported on a steel podium, in which the locations of the columns in the podium are aligned with multiples of the module dimensions above.
- Modules with fully or partially open sides supported by a steel framework at every floor level.
- Modules that are stabilised by a braced steel or concrete core.

Where the modules are stabilised by a core or supported on a podium level, their design is similar to that described earlier. Where supported by a separate steel framework, the modules can be designed as non load-bearing. An example of a podium structure and a braced stair core is shown in Figures 6.6 and 6.7.

Main Design Considerations

Where supported by a separate steel framework, the modules are of similar size to the load-bearing modules described earlier. The beams of the supporting structure are located below the load-bearing walls of the modules. For efficient car parking at ground or below ground, two 3.6 m wide modules with a supporting beam span of 7.2 m are efficient for use of 3 car parking spaces below. Cellular beams or fabricated sections are effective in providing open plan space below podium level.

The combined use of modular units and planar floors is advantageous when modular units are used for the highly serviced areas, such as bathrooms and kitchens, as illustrated in Figure 6.8.

Advantages

- No limitation on building height.
- Podium level creates open plan space and car parking below.
- Suitable for mixed residential and commercial use.

Fire Resistance

The steel frame should be fire protected conventionally. The preferred protection system is likely to be intumescent coatings in order not to increase the dimensions of the steel sections. Use of Square Hollow Section columns is advantageous.

Figure 6.7 Completed modular building in Figure 6.6

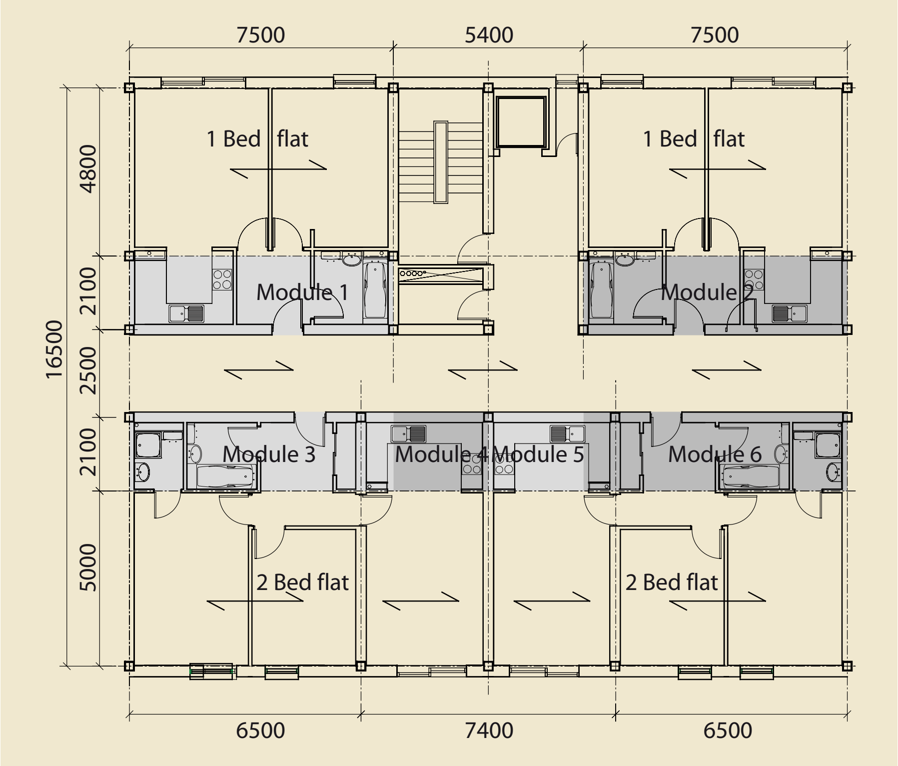


Figure 6.8 Combined use of modules with a steel framework

Acoustic Insulation	Acoustic insulation is independent of the use of the steel support structure when using modular construction.
Loads and Deflections	The steel beams should be designed for combined bending and torsion when loaded unequally by adjacent modules. Asymmetric steel sections may be advantageous.

07 Façade & Roof Systems

This section reviews the various forms of cladding that can be used in combination with light steel walls. The characteristics of the cladding systems are presented, particularly in relation to thermal performance. Roof systems based on steel components are also reviewed.

Façade systems are supported by light steel external walls, which themselves are load-bearing or alternatively, are infill walls within a primary steel or concrete frames. The same principles and details apply to both systems. Three generic forms of cladding are considered:

- Brickwork, which is usually ground supported and laterally restrained by the walls.
- Metallic or board-type cladding.
- Insulated render bonded through insulation to a rigid backing board.

The principle design requirements are those of weather-tightness, thermal insulation and air-tightness. The details of these cladding systems are presented.

Roofs can also be designed in steel in the form of roof trusses, purlins, composite panels and roofing sheeting with insulation. Open roof systems can be created, which provide habitable space efficiently.

Façade Systems

Roof Systems

Figure 7.1 Residential building in light steel framing and with metallic cladding in Glasgow
Peck and Reid Architects & Metsec

Façade Systems

Figure 7.2 Insulated render combined with clay tiles attached to light steel infill walls

Description

There are two generic cladding types suitable for use within the external wall systems described earlier:

- Ground supported or floor supported cladding, such as brickwork.
- Lightweight cladding that is supported by the light steel wall.

In multi-storey buildings, brickwork requires support by stainless steel angles attached to the perimeter beams. Lightweight cladding is of various forms, such as:

- Insulated render.
- Clay tiles or brick slips attached to horizontal ribs.
- Metallic cladding, such as composite panels.
- Boards of various types.

Where glass panels are used, they are often integrated into the wall itself or attached directly to the floor on a separate sub-frame.

Prefabricated light steel wall panels can be designed with pre-attached cladding, and in this case the joints are crucial to the design concept. Examples of prefabricated wall panels using light steel framing are shown in Figures 4.1 and 4.5.

Main Design Considerations

The main design considerations in the choice of the façade system are the:

- Means of vertical and lateral support to the cladding.
- Provision of the required level of thermal insulation with minimal ‘cold bridging’.
- Provision of openings (windows and doors) and attachments.
- Opportunities for prefabrication of the façade panels, with attached cladding.

When using light steel framing to support the façade, insulation is normally placed externally to the light steel elements and is supplemented by additional mineral wool between the wall studs.

Brickwork is attached by wall ties to vertical ‘runners’ that are screw fixed through the external insulation to the wall studs at nominally 600 mm centres, as shown in Figure 7.3. The wall ties are fixed every fifth course (or at 375 mm vertically) leading to 2.5 ties per m^2 area. Additional ties are required around openings. Brickwork is self supporting up to 12 m high (4 storeys) but taller buildings require additional vertical support at every or alternate floors. This is only practical with a steel framework and not with light steel framing.

Examples of cladding details using metallic cladding and insulated render are shown in Figures 7.4 and 7.5. In both cases, use of a sheathing board is recommended.

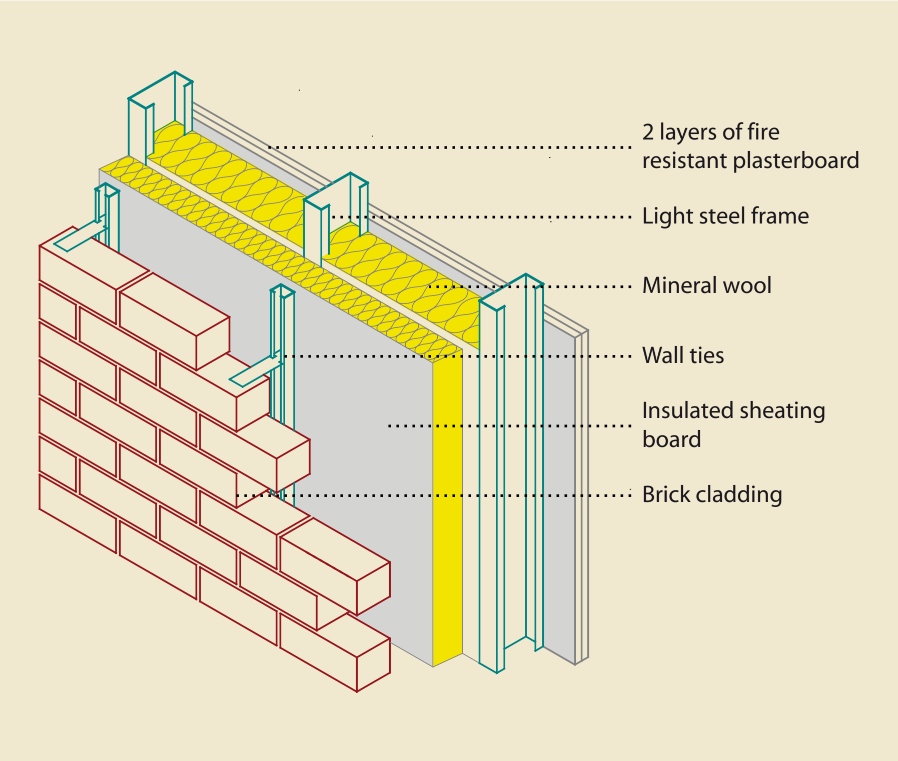


Figure 7.3 External wall with brick cladding attached to light steel framing

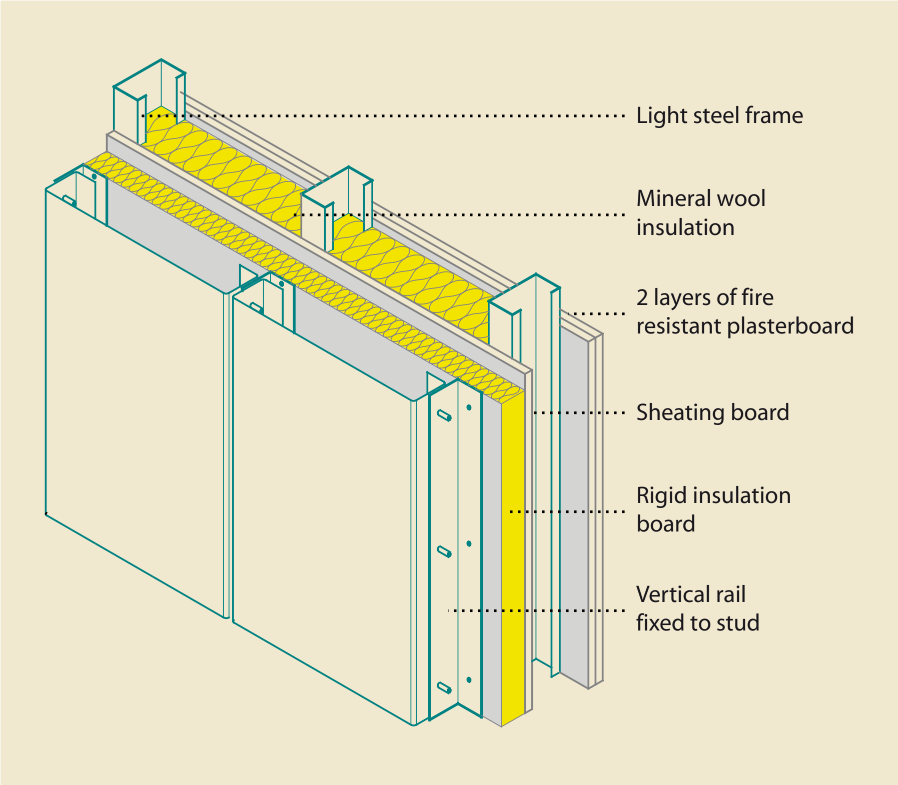


Figure 7.4 *External wall with metallic cladding attached to light steel framing*

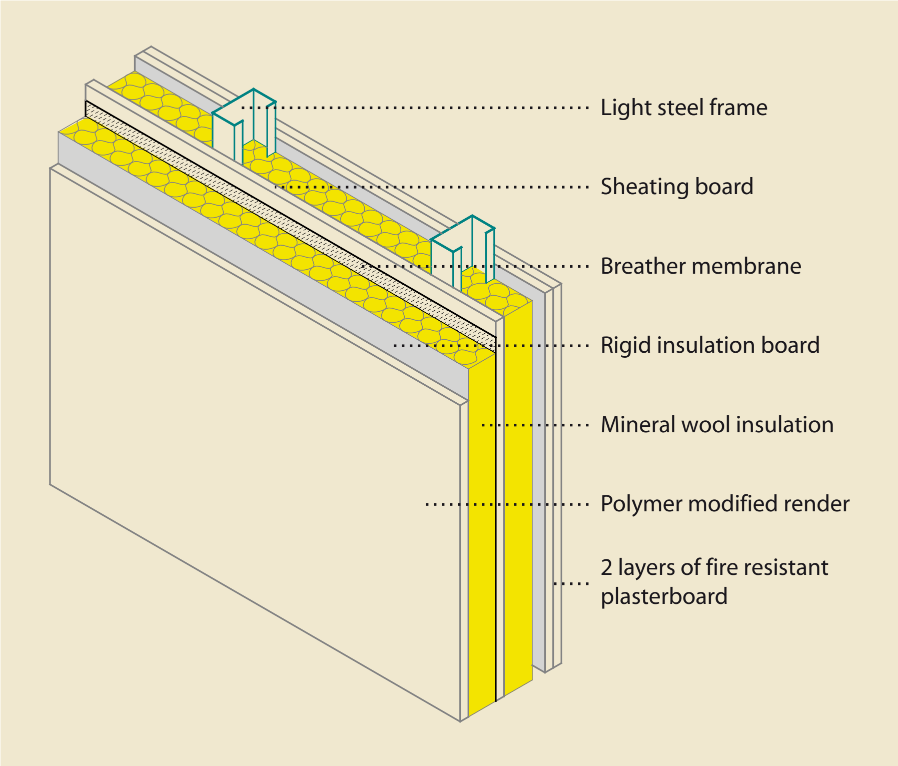


Figure 7.5 *Insulated render attached to light steel framing*

Advantages	• A wide variety of cladding materials may be used. • Lightweight cladding can be supported by the light steel walls. • Large panels can be prefabricated with their cladding attached. • High levels of thermal insulation (low U-values) can be achieved. • Walls are thinner than in blockwork or concrete construction.
Thermal Performance	U-values below 0.25 W/m^{2}K can be achieved for walls with brick cladding and below 0.2 W/m^{2}K for walls with insulated render. Slotted or perforated studs (Figure 7.6) reduce cold bridging and allow more insulation to be placed between the studs without causing condensation. For this reason, 150 mm deep slotted studs with 30 mm of external insulation board and 150 mm of mineral wool insulation between the studs can be thermally very efficient.
Acoustic Insulation	Acoustic insulation is rarely specified for cladding systems but most lightweight cladding providing a U-value less than 0.25 W/m^{2}K achieves an airborne sound reduction of over 30 dB. Brick cladding achieves a higher airborne sound reduction of over 35 dB.
Overall Wall Thicknesses	The overall wall thickness depends on the type of cladding used and the following dimensions may be used for cladding systems achieving a U-value of 0.25 W/m^{2}K: • Brickwork: 350 mm. • Insulated render: 250 mm. • Metallic or board cladding: 250 mm.

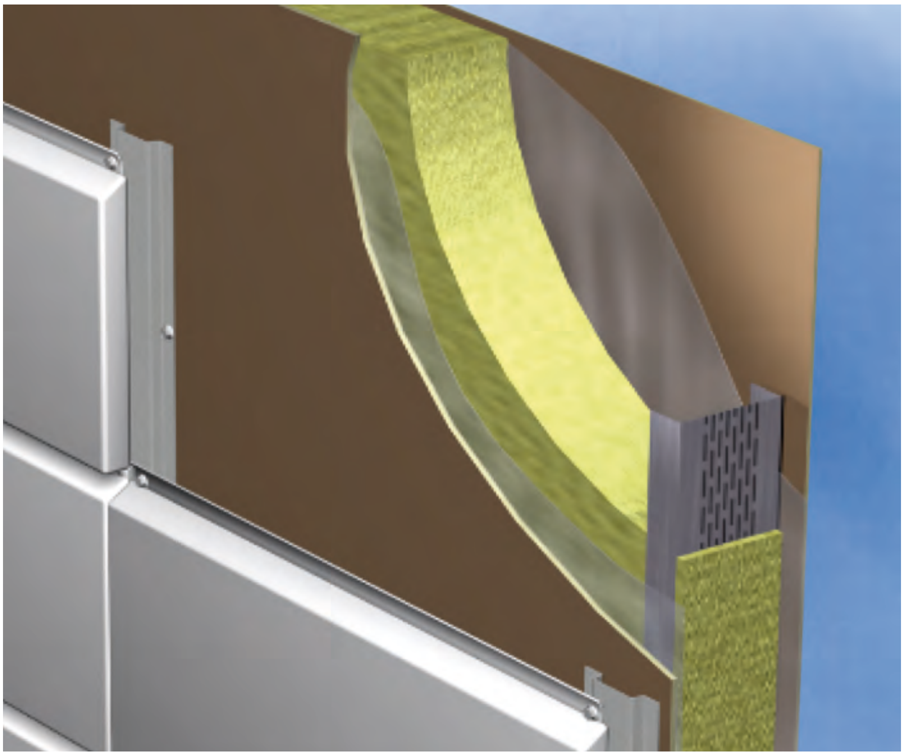


Figure 7.6 Slotted studs used with mineral wool and metallic cladding
Ruukki

Roof Systems

Description	Various roof options can be considered when using steel construction. These are: • Steel purlins spanning between structural frames or cross walls. • 'Open roof' system designed to create habitable space. • Prefabricated steel roof cassettes. • Composite panels (for spans up to 6 m). Steel roofs can be manufactured to a wide range of shapes including curved and hipped forms. Metallic cladding is suitable for shallow roofs and curved shapes.
Main Design Considerations	The two main considerations are; the span direction of the roof and the level of thermal insulation. Roofs can span either: • From façade to façade, with spans of 8 to 12 m, or; • Between cross-walls with spans of 5 to 8 m. In the first case, a traditional roof truss is preferred, but in the second case, purlins or other systems permit for use of the roof space. An 'open' steel roof system, which provides habitable space, is shown in Figure 7.7. For roofs, the required level of thermal insulation is usually high (U-values < 0.15 W/m²K) and so the total thickness of thermal insulation can be as much as 150 mm. The majority of the insulation is placed externally to the steel roof, i.e. trusses or purlins, but up to 30% of the insulation can be placed between the steel members without risk of condensation. Composite panels can be manufactured with a tiled appearance, as shown in Figure 7.8. Photovoltaic panels or thermal collectors can be easily attached to steel cladding and its sub-structure.

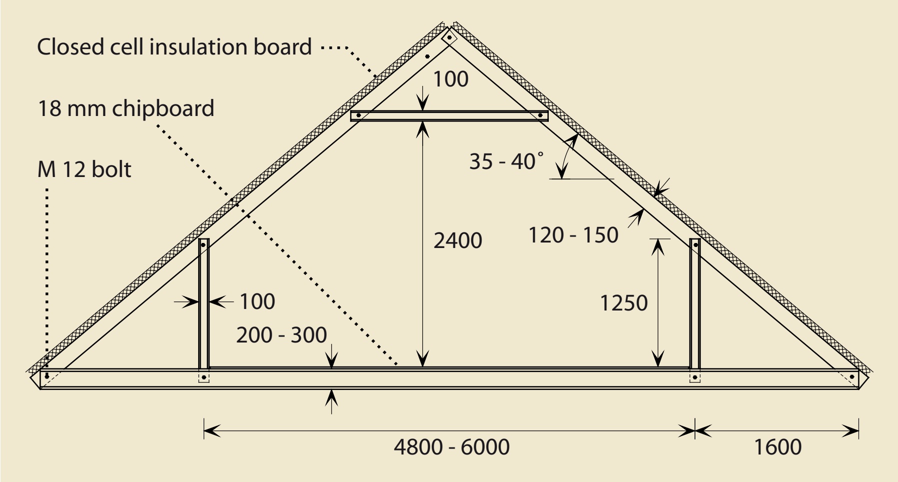


Figure 7.7 'Open' roof system using light steel C sections

Figure 7.8 *Tiled composite panel system being installed*
Kingspan

08 National Practice

In this section, national practices in housing and residential buildings are presented for several countries. These construction practices may follow or adapt the systems described in this Guide. Some new systems are presented which may be used more widely in Europe.

UK

The Netherlands

France

Sweden

Current Practice in the UK

In the UK, approximately 180,000 houses and apartments are built annually. The market for all steel technologies in the residential sector is good, particularly in the medium rise buildings and in single person accommodation. Overall, the market share for steel is about 7% in housing and residential buildings. All the forms of construction presented in this Best Practice guide are used, but the noticeable trends are in the use of:

- Light steel framing for 4 to 6 storey apartments.
- *Slimdek* and light steel infill walls for 6 to 15 storey residential buildings, requiring more flexible use of space.
- Modular construction for single person units, such as student residences, for buildings up to 10 storeys high.
- Mixed use of modular construction with a concrete core for stability in high rise applications, or with a supporting steel structure at podium level for 6-8 storey buildings.

The challenges for this sector are to build to higher density and more rapidly in urban locations, and to satisfy the Code for Sustainable Homes, which is now embodied in UK Regulations. More efficient construction systems are preferred from the point of view of speed of installation and thermal performance, which steel technologies can provide.

Figure 8.1 Housing project using light steel framing (Basingstoke)
HTA Architects

Figure 8.2 *Modular residential project in Basingstoke, UK*
PRP Architects & Vision

The following practices in the UK are described in more detail:

Light Steel Framing

Light steel framing uses the technologies presented earlier, but there are noticeable trends which should be recognised in the use of:

- single leaf load-bearing walls;
- mixed use of light steel floors and steel beams for longer spans;
- mixed use of composite slabs and light steel walls;
- mixed use of steel beams and light steel floors.

The market for infill walls in both steel and concrete framed buildings has also grown considerably.

Slimdek

Slimdek has achieved a wide market in the residential sector because of the need to provide flexibility in layout of rooms and to achieve the maximum useable area and minimum depth of floor without downstand beams. Light steel infill walls are also incorporated. *Slimdek* has been used in buildings up to 16 storeys (see Figure 2.2).

Modular Construction Stabilised by Concrete Core

Modules can be designed efficiently if the building is stabilised by steel bracing or by a concrete core, for example, as the 17 storey residential building, Paragon – see Case Studies. Other projects have also used modules and concrete floor slabs, as shown in Figure 8.2, in order to satisfy fire resistance and acoustic insulation requirements for taller buildings.

Modular Construction Supported by a Separate Structure

As described in Section 6, modular construction can be combined with a steel podium or platform level to create open plan space below for commercial or communal uses or car parking.

Modules can also be designed with an 'Exo-skeleton' as in the MOHO project in Manchester, shown in Figures 8.3 and 8.4. This technique is widely used to extend the range of application of modular systems and to create self-supporting balconies.

Current Practice in the Netherlands

Introduction

Over 70,000 houses are built every year in the Netherlands, and approximately 100,000 tonnes of steel are consumed per year in this sector. Additionally tens of thousands of tonnes of steel are used in the renovation sector, in which steel is a very popular building material.

The application of steel in the residential sector is very diverse. In housing developments with a 'modern look', profiled colour-coated steel sheeting is used for cladding and roofing. In the majority of Dutch houses, steel is used in

Figure 8.3 *Steel external framework combined with highly glazed modules, MOHO, Manchester*
Yorkon and Shed KM Architects

Figure 8.4 *Completed MOHO building*
Yorkon and Shed KM Architects

small elements, such as lintels above window openings and supporting beams above garage doors. However, steel frames are widely used in apartment buildings.

As in other European countries, lightweight prefabricated steel systems have advantages in urban projects. Many of the forms of construction presented in this Best Practice guide are used, but the noticeable trends in the Netherlands are:

- Light steel framing for roof top extensions to create apartments and maisonettes in renovated flat-roofed apartment buildings.
- Light steel framing for the transformation of non-residential buildings (offices, industrial buildings) into apartments.
- Steel frames using hot rolled sections with a variety of floors (precast concrete, composite and light steel joists) in apartment buildings.
- Variety of steel components in detached, semi-detached and terraced housing.

Roof top Extensions

Roof-top extensions have become a niche market for steel in the Netherlands. Many existing buildings with a concrete construction and a flat roof can be extended by adding one, two or even more floors and light steel framing is well suited for this purpose. There are many interesting projects, for instance: Leeuw van Vlaanderen in Amsterdam (Winner of the National Renovation Prize 2007) and recently Het Lage Land in Rotterdam (Figure 8.5) and De Bakens in Zwijndrecht.

The light steel frame elements are self-supporting, resulting in a very lightweight building method. Building physics and fire resistance requirements are easy to meet with layers of gypsum board. Heat loss through outer walls is minimised by insulation materials, such as mineral wool. Floor vibrations can be reduced by adding a gypsum screed.

Many disused buildings are in desirable locations such as harbours and city centres, and are being transformed into high quality apartments and commercial space. The renovation and roof top extension of the warehouses Nautilus and IJsvis in The Hague (Figure 8.6) is a good example. The additional penthouses in steel-and-glass architectural style offer a spectacular harbour view. The building method is a mix of structural steel and light steel framing.

Apartment buildings

In parallel with the increasing use of steel structures in commercial buildings, several multi-storey apartment buildings with steel frames have recently been completed.

A wide variety of floor systems are in common use: precast hollow core slabs (such as Het Baken in Deventer), solid concrete planks (Montevideo in Rotterdam), composite slabs (Schutterstoren in Amsterdam), inverted steel-concrete (La Fenêtre in The Hague - see Case Studies) and light steel framing (Linea Nova in Rotterdam).

Figure 8.5 Roof-top extension with maisonettes: Het Lage Land in Rotterdam

Figure 8.6 Transformation of an old warehouse with a spectacular view: Nautilus & IJsvis in The Hague (Winner National Steel Prize 2006, category Residential buildings).

Town houses

For nearly a century, private ownership of housing has been subsidised by the Dutch government. The desire for expressive architecture and large window openings has led to the use of structural steelwork and façade elements in detached, semi-detached and terraced housing. An example in a transparent architectural style using steel construction is shown in Figure 8.8.

The *Smart House* concept was developed by Architect Robert Winkel and uses Square and Rectangular Hollow Section beams and light steel floor cassettes and infill walls. It is based on a 5.4 m column grid. Although few buildings using this concept have been built, it is a very practical system for larger residential buildings and smaller office buildings (Figure 8.9).

Current Practice in France

The housing market in France is approximately 300,000 per year, of which approximately 50% comprises apartments. The social housing sector has always been active in France, and many social housing associations design and procure their own buildings.

Steel construction has reached a market share of 7%, mainly through the Maison Phénix system of house building. More recently, composite construction has achieved a break-through in the multi-storey residential sector. Modern building projects in France increasingly adopt the sustainability criteria according to the HQE system (Haute Qualité Environnementale).

PRISM

The PRISM (Produits Industriels et Structures Manufacturées) is a concept based on a steel structure suitable for residential buildings.

A variety of slab systems can be used with the PRISM concept, including plain reinforced concrete slabs, prefabricated reinforced hollow core concrete slabs and composite slabs.

PRISM generally uses external walls, which are light steel infill walls supported by the floor slabs. Thermal insulation is fixed externally to the wall and the light steel sub-frame forms the internal skin of the façade system. The sub-frame spans from slab to slab and thermal and acoustic insulation was provided by mineral wool and plasterboard (see Figure 8.10).

Figure 8.7 Multi-storey apartment building with a steel structure: Schutterstoren in Amsterdam.

Figure 8.8 Town houses: House De Kom in Oranjewoud.

Figure 8.9 (Above & right) Smart House, Rotterdam using Square & Rectangular Hollow Sections with light steel infill walls & floor joists

Two façades systems are used – one is for heavy weight elements such as terracotta, and the other is for lightweight elements such as insulated render. Both cladding systems use an adapted steel sub-frame, which provides for a wide range of design solutions.

Internally to the cladding elements, the wall is made up as follows:

- Two 13 mm thick fire resistant plasterboards providing 60 minutes fire resistance.
- A void of 60 to 100 mm permitting the inclusion of insulation to the slab edge and the steel columns.
- 70 to 100 mm thick mineral wool insulation.
- Light steel sub-structure wall which comprises horizontal rails and vertical studs.

The total thickness of the internal elements is about 160 mm. The slab edge and columns are thermally protected from outside by insulation, thereby avoiding thermal bridging. The total thickness of the wall can vary between 290 and 360 mm.

Separating walls and partitions are made of plasterboard fixed on an internal steel sub-frame and using mineral wool for acoustic insulation. This technique is widely used for building construction. It permits re-configuration of the floor layout after several years of use.

Cofradal slab system

Cofradal is a lightweight floor slab that uses a thin steel 'tray' into which rigid mineral wool is fitted and a thin concrete screed is placed on top. It is 200 mm deep overall, as illustrated in Figure 8.13, and may be used for both commercial and residential buildings. Composite action is achieved between the tray and concrete.

PCIS slab system

PCIS is a dry system for slabs used in residential buildings. Asymmetric beams are integrated into the slab depth. The sections can be fabricated or a steel plate may be welded under the lower flange of a HE section. The beams span up to 6 m and are simply connected to the columns. The overall slab depth is 320 mm.

The construction system is as follows (from bottom to top):

- The slab comprises galvanised profiled steel sheeting (1.5 mm thick) that is screwed to the supporting beams.
- Fibreglass layer, 3 mm thick (230 g/m^2), provides support for a triplex wooden panel, 12 mm thick. These panels are screwed onto the steel sheeting.
- 12 mm thick plasterboard with a hard finish provides the upper wearing surface.

Suitable ceiling materials are:

- Thermal and acoustic insulation: 45 mm thick mineral wool (30 minutes fire resistance) or 70 mm thick rock wool (60 minutes fire resistance).
- Two 12 mm thick plasterboard (30 minutes fire resistance) or two 12 mm fire resisting boards (60 minutes fire resistance).

Maison PHÉNIX

Maison Phénix is the leader in the French market with about 6,000 houses delivered per year and with 50 years of

Figure 8.10 The PRISM system during construction: Steel frame, roof and external light steel walls ready to receive external skin

Figure 8.11 PRISM system: Example of external envelope with stone cladding
Architect: P Sartoux

Figure 8.12 Example of building constructed using the PRISM system

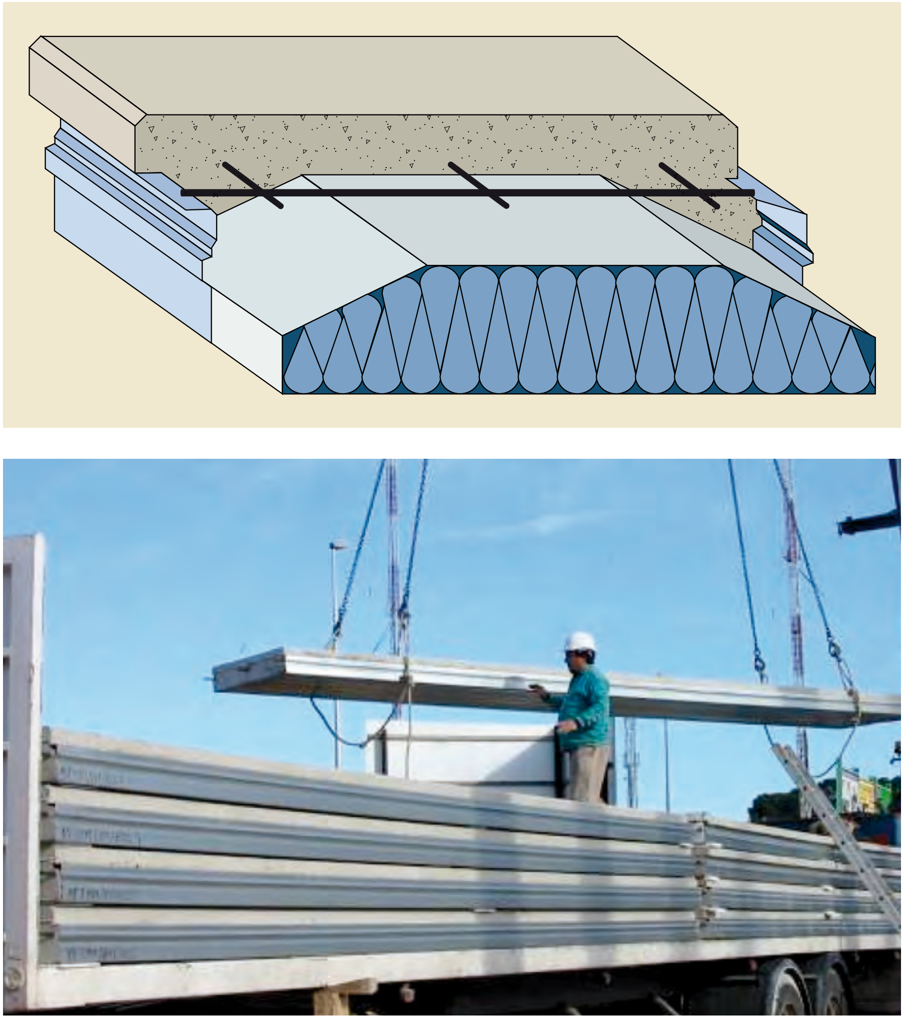


Figure 8.13 Cofradal lightweight slab units – typical cross section and panels during installation

experience. The steel frame is made from IPN / IPE or angle sections. The adaptability and the customisation of products create a wide range of housing forms with a variety of façades.

Details of this housing system used mainly for single storey houses is shown in Figure 8.14.

Current Practice in Sweden

Introduction

In Sweden, the main application of steel is in slim floor construction (offices and housing) and in light steel walls, often using slotted or perforated C sections. It is possible to create very shallow floor structures, which is important in Sweden. Labour costs are a large part of the total cost of the finished construction and reduced construction time on site is also very important.

Slim Floor Systems

Slim floor systems have shallow beams, whose long spans achieve flexibility of apartment layout. The low height depends not only on the floor itself, but also on the edge beams and internal beams that are designed with wide bottom flanges. The junction between the supporting beam and the hollow core slab are filled with concrete. The steel beams are then protected by the surrounding concrete. In residential buildings, it is common to build a secondary floor system. Horizontal services can then be installed between the upper and the lower floor elements.

Light Steel Construction

A light steel floor consists of load-bearing cold formed steel profiles and slabs, as described in Section 3. It can be built on site, or prefabricated in the form of cassettes or elements which are then installed on site. A common floor construction consists of C profiles at a spacing of 600 mm. The section height of the joists is between 150 and 300 mm, depending on the span. Trapezoidal decking is fixed to the upper flange and can also transfer load in the horizontal plane. The maximum floor span is about

Figure 8.14 Maison Phénix during construction, showing the roof details for a single storey house

Figure 8.15 Example of 7 storey residential building using slim floor construction in Sweden

8 m when using 300 mm deep C sections. The current experience is that light floor structures with a span of 4 to 4.5 m are most economical in housing and effective detailing ensures good acoustic insulation.

Light steel constructions are used as load-bearing systems in residential buildings of up to three storeys. It is common that light steel buildings are combined with other stabilising systems such as rolled or welded steel sections. The total floor weight is less than 150 kg/m^2 floor area.

Modular Construction

The *OpenHouse* modular system has been used in Annestad in Malmö and is based on a 3.9 m column grid. The application of *OpenHouse* is presented in the Case Studies.

09 Case Studies

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

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

- *Paragon*, London. A series of residential buildings comprising 4 to 17 storeys of modules clustered around concrete cores.
- *Social Housing*, Evreux. 4 storey residential building using a dry construction system.
- *La Fenêtre*, The Hague. Multi-storey residential building supported on inclined steel columns.
- *Bioclimatic Towers*, Vitoria-Gazteiz. Four highly sustainable 16 storey towers constructed in steel.
- *OpenHouse*, Malmö. Modular housing system for 4 storey apartments.

Paragon, London

Social Housing, Evreux, France

La Fenêtre, The Hague, NL

Bioclimatic Towers, Vitoria-Gazteiz, Spain

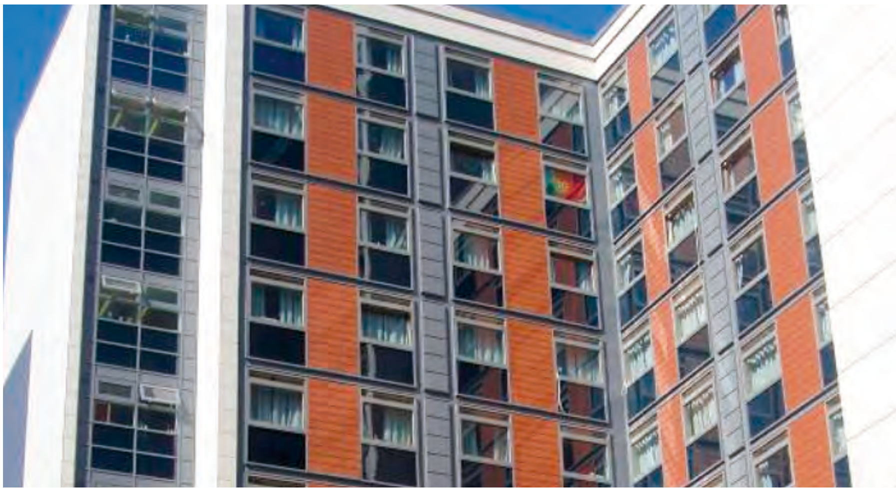
OpenHouse, Malmö, Sweden

Paragon, London

Britain's tallest modular building has been completed for developer Berkeley First, and provides affordable accommodation in West London. This project uses 17 storeys of modules clustered around a concrete core.

Application Benefits:

- Modular construction up to 17 storeys
- Rapid construction system
- Minimises logistical problems on site
- Excellent acoustic insulation
- Open sided modules provide for flexible space planning
- Modules supported by steel podium



Developer Berkeley First chose modular construction for its key worker and starter homes project called Paragon in Brentford, West London because it achieved the short construction programme of 22 months and minimised logistical problems on site.

Sandwiched between the M4 motorway, suburban housing and a local school, the site presented major difficulties for access, delivery, storage of materials and site facilities for workers and equipment. Modular construction solved many of these problems, and modules were delivered at an average rate of 8 per day in a 40 minute turn a round without requiring road closure.

The use of modular construction is conventionally limited to 8 to 10 storeys, but the extension of the technology to 17 storeys in this project was achieved by a concrete core, which provided overall stability. In this way the modules are required to resist vertical loading and to transfer wind loads to the core.

The first phases of the project were not originally conceived in modular construction, and for this reason the efficiencies of manufacture of repeatable modular units were not fully achieved. However, Caledonian Building Systems was able to manufacture a wide range of module types, many with open sides, so that two modules could be placed side by side to provide wider rooms.

The project comprises 6 buildings of 4, 5, 7, 12 and 17 storeys height. The total number of modules in the project is 827, and the 17 storey building consists of 413 modules. A typical module size is 12 m x 2.8 m, but some modules are manufactured up to 4.2 m wide, which is the maximum for motorway transport.

The project cost £26 million and was completed in September 2006.

Project Team
Developer:
Berkeley First
Architects:
Carey Jones
Structural Engineer:
Capita Symonds,
Alan Wood and Partners
Modular Contractor:
Caledonian Building Systems

Modules attached to concrete core

Construction Details

The Paragon project comprises 840 en suite student rooms, 114 en suite studio rooms, 44 one bedroom and 63 two-bedroom key worker apartments. Modules were combined to create larger apartments. The one or two bedroom apartments were constructed using 2 or 3 modules, each of 35 55 m^2 floor area.

The modules use light steel C sections in the floors and walls combined with Square or Rectangular Hollow Section posts, which resist the vertical loads. The posts were 80 x 80 SHS or 160 x 80 RHS in varying thicknesses depending on the building height. These posts fit within the light steel wall panels. The edge beams use 200 x 90 hot rolled Parallel Flange Channels (PFC) at floor level and 140 x 70 PFC at ceiling level in order to design partially open sided modules of up to 6 m span. The combined floor and ceiling depth was 400 mm and the combined width of walls was 290 mm. Both constructions achieved an excellent airborne sound reduction of over 60 dB, and a fire resistance up to 120 minutes.

Modules are attached to each other and to the concrete core by steel angles fixed to channels cast into the concrete core. The forces in these connections were established by consideration of wind forces and structural integrity. Construction of the slip formed cores was completed in advance of the modules being installed. In some areas, the modules were installed on a steel-framed podium in order to allow vehicular access below to the basement level.

Installation of module on steel podium

Social Housing in Evreux, France

A 4 storey residential building using a dry construction system led to fast track installation, flexibility in use and sustainability over its life.

Application Benefits:

- Fast track construction
- Intensive use of steel components using dry construction
- Lightweight construction and low foundation work
- Building can be re-configured in the future
- Flexibility in space use

This residential building was promoted by the Social Housing Agency and Public Development and Construction Service of Eure (OPAC de l'Eure) in cooperation with France's Ministry of Town Planning and Housing. The architects, Dubosc & Landowski, had been involved in the promotion of steel intensive use in building for many years, and proposed an innovative design concept for this 51 rental housing project, which included a district library.

The design was completely re-evaluated in favour of a steel-intensive dry construction approach with concrete limited to a minimum for basements and ground floor.

The project consisted of five 4 storey adjoining buildings, with 51 social housing flats ranging from 56 m² to 106 m², in two to five room configurations plus a 328 m² district library on two levels. The upper flats had two levels with terraces and large openings. A total of 22 covered parking spaces were also part of the building.

The structure consisted of a primary steel frame, deep decking and floor boarding, a curved metal roof and external steel stairs and X bracing. The whole building system is lightweight and potentially extendable or demountable in the future.

The project was part of a series of urban renovation initiatives in Evreux, Normandy. The total building cost was 775 €/m² floor area, of which 20% of the cost was the steel structure, floors and roof. The building was completed in 9 months, mainly due to the prefabricated nature of the construction process.

Project Team
Developer:
OPAC de l'Eure
Architect:
Dubosc & Landowski
Design Office:
Bohic
Contractor:
Quille

(Above) Mixed use of materials

Construction Details

The structural frame was made from hot rolled steel sections. The bracing was a flat cross bar system, integrated in partition walls and in the slab's depth for horizontal bracing. This structural frame is expressed from many points of the building, both outdoor and indoor showing the radical approach of design.

The envelope is a combination of wooden panels and steel sheeting giving an architectural contrast in colours and texture. The roof is made from arched steel sheeting supported on purlins.

The floor is a dry mixed system called PCIS "Plancher Composite Interactif Sec" from ArcelorMittal made from a combination of profiled deep steel decking, mineral wool for sound and thermal insulation, plywood panels and a floating screed. The beams were integrated in the slab depth to 320 mm and spanned up to 6 m for a live load of 1.5 kN/m^2 plus distributed load of 1 kN/m^2 (partitions and finishes).

All materials were all widely available and could be handled and installed by skilled workers in a fast track construction process. Large parts of the building elements were produced in the factory providing a high quality and fast track construction process.

A fire resistance of 30 minutes was achieved with two 13 mm plasterboards for the ceilings. Thermal and acoustic performances were better than required which led to the award of a quality label in France "EDF-Innov'elec".

Lightweight concrete was used in limited areas, mainly in the basement and ground floor. The use of lightweight concrete reduced the weight of the building and therefore the foundation sizes.

(Right) Intermediate floor showing wide open space for flexible arrangement of partitions and intensive use of steel elements

La Fenêtre, The Hague

A novel construction system was used to create a 16-storey apartment building in the city centre of Den Haag, Netherlands. The steel superstructure is supported on inclined tubular legs and the building is designed to be 'transparent'.

Application Benefits:

- Stability provided by inclined tubular columns
- Transparent façade with shallow floor zone
- Exposed concrete slab with embedded water pipes
- Fire resistance of 120 minutes
- Under-floor services distribution
- Excellent acoustic insulation

An exciting steel structure, called La Fenêtre forms a landmark at a busy road inter-section in The Hague (Den Haag) close to Rotterdam. Its 16-storeys of apartments are supported on inclined tubular legs. It uses a novel structural system called *Slimline*, which is based on a series of I beams at 0.6 to 0.9 m spacing, in which a concrete slab is precast around the bottom flange of the beam. The coverage of the inverted precast slab is 2.4 m, which is suitable for transportation and installation.

The inverted slab is typically 70 mm thick and is exposed on its underside. Services are located on the slab and also provide for under-floor heating and cooling. The flooring attached to the top flange spans between the beams, and can use a gypsum screed placed on floor boarding or shallow decking.

The construction system may also be used for offices and hospitals where there is a need for under-floor distribution of services. In this building, water pipes were also embedded in the slab to provide heating, and the inverted slab is able to radiate heat or 'coolth' to the space.

The façade is fully glazed and with its 20 m long tubular legs, the building appears to be transparent. The structure is braced internally and also consists of strategically located tubular members.

Fire tests were carried out at TNO in Delft to justify 120 minutes fire resistance of the otherwise unprotected steel beams due to the thermal insulation provided by the inverted slab. Excellent acoustic insulation was also achieved.

Construction started in early 2004 and was completed in late 2005.

Project Team
Client:
Latei projectontwikkeling
Architect:
Architectenbureau Uytenhaak
Steel structure:
Oostingh Staalbouw
Project Engineers:
Adams
Flooring Contractor:
PreFab Limburg BV
Services contractor:
Heijmans

(Above) Building during construction

Construction Details

A variety of steel beams can be used in the *Slimline* system, depending on their span and loading. Although the top flange of the beam is not laterally restrained, torsional restraint is provided by the slab cast around the bottom flange. A typical beam span to depth ratio is 20, and so a 450 mm deep I beam can span up to 9 m.

Services were passed through elongated openings formed in the web of the beams, and a floor of minimum depth of 600 mm was created.

The inverted concrete slab was designed to support its own weight and loads from services, and was typically 70 mm thick. The floor comprised a gypsum screed poured on floor boarding or shallow (20 mm) decking and was 60-80 mm thick. The structure was designed to support the imposed floor loading of up to 3 kN/m^2.

The *Slimline* precast floor panels can be supported by perimeter steel beams placed below the floor panels. The slab is cast 100 mm short of the edge of the beams. The supporting beams align with internal separating walls. Heating/cooling pipes can also be cast into the slab, depending on the application, and radiate into the space below.

In La Fenêtre, the inclined tubular legs were located below column positions on a 6 m x 9 m grid and were brought down to 8 discrete positions at ground level to optimise foundation requirements. Fire protection costs were minimised by the thermal insulation provided by the inverted slab, and the use of tubular members with high massivity. The building was stabilised by the tubular columns with internal tubular bracing.

(Right) Under-floor servicing in Slimline

Bioclimatic Towers, Vitoria Gazteiz

The Bioclimatic Towers in the Salburua Fens, Vitoria-Spain, are 4 similar towers of apartments, commercial space and offices, using 1,400 tonnes of steel. Control of solar radiation was achieved through a bioclimatic design.

Application Benefits:

- Outstanding architectural solution
- Sustainable and energy efficient with a bioclimatic approach.
- Prefabrication of the structure.
- Maximum flexibility concerning the use of the space.
- Recyclability of the building structure.
- Intensive use of steel components

Bioclimatic Towers under construction

Bioclimatic Towers

(Left) View of the completed steel structure

Salburua is a wetland area of international importance, situated on the edge of the city, forming part of the Green Ring of Vitoria-Gasteiz. Four towers comprising offices and social housing were built in the outskirts of the city. Critical design criteria for the towers were sustainability, structural efficiency, long-term usability and maintenance.

All the apartments in the towers have two orientations. The towers are highly sustainable, due to their optimum orientations, the energy efficient façade and the integration of renewable energy systems.

They were exhibited in the Museum of Modern Art (MOMA) of New York. The project was designed by the prestigious architects, Iñaki Abalos and Juan Herreros. Each tower has a floor area of 281.5 m^2 per storey and is 48 m high.

The 16 storey Bioclimatic Towers were built with a perimeter steel structure, reinforced concrete floors and internal columns (only 4 steel columns per floor). The structure of all the towers consists of 1,400 tonnes of steel. The total budget for the project of four towers was approximately 2.35 Million Euro. The buildings were completed in 2006.

Project Team
Client:
Ensnache XXI
Architect:
Ábalos & Herreros
Owner:
Jaureguizahar S.L
Steel frames:
Goros Construcciones Metálicas
Contractors:
Goros S.Coop (Vitoria-Gasteiz)

Off-site fabrication of the façade structural panels

Construction Details

The structure was made with four prefabricated panels for every two storeys of the building (approximately 6 m high). The main steel structure was completely fabricated in the factory, making the assembly phase on site much faster and more efficient.

The reinforced concrete floor (using concrete grade 25) was a solid slab of 250 mm depth, which achieved maximum spans of 7 m and was built totally on site.

The columns had mixed steel and concrete sections based on the particular tower and the height of the building. The steel sections were made from HEM200 to HEM600 or from HEB180 to HEB500 in S355 grade steel. In the majority of the columns, cross-pieces of steel section of HEM120, each approximately 3 m span, were encased with reinforced bars (steel B500S, 8 mm diameter at 200 mm spacing) and fixed into the concrete floor.

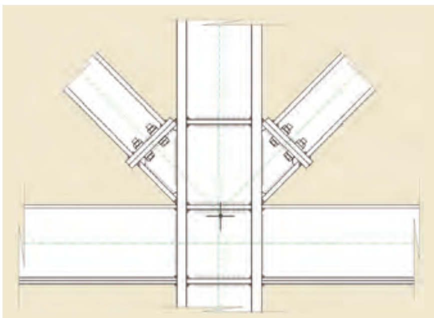
The structural panels were composed of plated girders of more than 1 m depth with variable spans in the perimeter of the towers from 2.3 to 2.9 m.

Welded connections were fabricated in the factory whereas on-site bolted connections were used because of their speed of installation and independence on the weather conditions.

A special transportation system was necessary to bring the prefabricated structural panels to site because they weighed more than 20 tonnes with a length of 30 m and width 6 m.

The structure was erected in record time, at an average rate of 1.5 days per floor. The time to fabricate and erect each tower was approximately 4 months, of which 2 months was manufacturing in the factory and 2 months assembly on site.

Floor with internal columns in the building works



Bolted connection between columns on first floor and bracing

Acknowledgements:

To the company GOROS S.Coop. from Vitoria (Basque Country, www.goros.net) and especially to Miguel Angel Zudaire (Technical Director), the foreman Raúl Etayo, Pedro Marchan (Site Manager) and Mikel Zudaire.

OpenHouse, Malmö

The aim of the OpenHouse system is to provide a cost-effective way to build apartments using modular construction. This project near Malmö provides 1200 apartments in a variety of plan forms.

Application Benefits:

- Adaptability in building use and form and future reuse of modules
- Sustainability by low materials use and wastage
- Risk minimizing and improved quality by industrialized processes, and dry construction on site
- Variety of cladding, roofing and balcony options
- High level of thermal and acoustic insulation

OpenHouse module during installation showing use of open sided modules with additional temporary posts

Annestad in Malmö, Sweden, is a large development by Swedish standards. A total of 1200 apartments were built during a period of four years. The development was divided into medium sized two to five storey blocks and completed in 2006. The development was a combination of rental apartments and tenant-ownership apartments. The rental cost of an apartment was approximately € 110 per m²/year.

The project used the OpenHouse system for the structural steel framing. The modules were based on a planning grid of 3.9 m with length a multiple of 3.9 m. They had recessed corners and Square Hollow Section (SHS) corner posts.

The size of the apartments varied from one room plus kitchen to four rooms plus kitchen. Façade materials used in this project were a combination of bricks, boards, insulated render and wood. Modules were positioned in an off-set configuration to create a variable façade line. Metallic roofs, façades and balconies were added to the fully equipped modules on site.

Project Team
Client:
Hyreshem Malmö /
OpenHouse Production
Architect:
Landskronagruppen /
OpenHouse Production
Main Contractor:
OpenHouse Production
Supplier of Modules:
OpenHouse Production

(Above) Module installation and completed façades

Construction Details

The modules were arranged within a framing system of SHS columns. The modules were supported by SHS columns at a spacing of 3.9 m. Each module was supported by six columns.

The internal dimensions of the modules were 3.6 m wide by up to 11 m long. The modules can cantilever 1.7 m from the exterior frame column. The typical finished weight of a module was 5 to 8 tonnes. The modules were constructed to transfer the horizontal loads to stabilising elements e.g. staircases using steel or concrete. The system can be used in eight storey buildings, although five storeys is the normal limit.

The modules used light steel framing in combination with mineral wool and gypsum boards. Exterior walls had slotted light steel studs, mineral wool and gypsum boards, providing good thermal performance. The roof and floor of the module used light steel beams, mineral wool, gypsum board and trapezoidal steel sheets. The modules are self supporting against vertical and lateral loads up to five storeys high.

Slotted steel studs with mineral wool in between provide a high level of thermal insulation to achieve a U-value close to 0.1 W/m^2K. Partially open sided modules were manufactured using intermediate posts, so that modules could be placed side by side to create larger room sizes.

Once lifted into position on site, the modules were connected to the SHS posts, the services linked up and flooring completed between open sided modules.

(Right) The Annestad project near Öresund, southern Sweden.

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