Modular Construction using Light Steel Framing

Design of Residential Buildings

M T GORGOLEWSKI Bsc, MSc, PhD, Dip Arch RIBA

P J GRUBB BSc(Hons), CEng, MICE

R M LAWSON BSc(Eng), PhD, ACGI, CEng MICE, MIStructE

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Published by:

The Steel Construction Institute
Silwood Park
Ascot
Berkshire SL5 7QN

Tel: 01344 623345
Fax: 01344 622944

Why use modular construction?

Modular construction uses pre-engineered volumetric units that are installed on-site as fitted-out and serviced 'building blocks'.

Modular construction uses galvanized cold formed steel sections as its main structural components. These sections are widely used in the building industry and are part of a proven technology. Modular construction extends the range of steel framed options available for residential construction and similar buildings.

The Egan Task Force report called for improved quality, increased use of off-site manufacture, and reduced waste in construction, and the Egan principles have been adopted by The Housing Corporation and other major clients in the residential sector. Modular construction satisfies these Egan principles and it combines the benefits of a reliable quality controlled product with economy of scale in manufacture and speed of construction on-site.

Modular construction is inherently re-usable and robust in performance. There is an established infrastructure of manufacture that is well covered by British Standards, type approvals and publications.

Architects and specifiers are now able to extend the successful application of modular construction as an economic and rapid form of construction for residential buildings, particularly in urban locations.

This publication provides guidance on the design and detailing of modular construction in modern residential buildings in ways which comply with the Building Regulations in England and Wales.

Front cover illustration: Murray Grove, Hackney, London
Clients: The Peabody Trust

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FOREWORD

This publication is one of a series on modular construction using light steel framing. It gives information suitable for use by all parties at the design and specification stage of modular construction in residential buildings. The publication has been prepared by Dr M Gorgolewski, Mr P J Grubb and Dr R M Lawson of The Steel Construction Institute.

Detailed assistance has been provided by the Modular Framing Group (MFG), particularly in reviewing the technical information. At the time of publication, the members of the MFG are:

Mr K Blanshard	Yorkon Limited
Mr J Blyde	(Representing Volumetric Limited)
Mr R J Colver	Ayrshire Metal Products plc
Mr M Goss	M Tech Services Ltd
Mr A Horncastle	Britspace Modular Building Systems Ltd
Mr R Marshall	Kajima UK
Mr J Mason	Alan Baxter & Associates (representing DETR)
Dr J Miles	Ove Arup & Partners
Dr R Pedreschi	University of Edinburgh
Mr D Phillips	Corus Colors
Mr J Prewer	John Prewer Associates
Mr J A Robinson	Corus Colors
Dr A L Rogan	Consultant
Mr P Sidey	MACE Limited
Mr P Trebilcock	AMEC Ltd
Mr A Trinick	Tritone Partnership (representing DETR)
Mr N Whitehouse	Terrapin International Group

The other publications in the series on modular construction are:

- Case Studies in Modular Steel Framing (SCI P271)
- Modular Construction using Light Steel Framing: An Architects' Guide (SCI P272)
- Value and Benefits Assessment of Modular Construction (SCI P278 *to be published*).

Further information on residential buildings is given in:

- Light Steel Framing in Residential Construction (SCI P301).

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CONTENTS

SUMMARY

The publication provides information and guidance on the design of modular construction in residential and similar buildings. A previous publication, *Modular Construction using Light Steel: An Architect's Guide* presents general information for use at the early stages in the planning of a project. This new publication extends the guidance at a technical level, and gives information for use by specifiers which may be used in detailed discussions with the modular manufacturers.

It covers the requirements of the Building Regulations (England and Wales) and presents design methods and details which satisfy these requirements. The particular requirements that are covered are: structure and loading, fire safety, acoustic performance, and thermal performance. Although the detailed design of the modules is the responsibility of the manufacturer, the interface with the foundations, cladding, roofing and services is often the responsibility of the overall building designer and is therefore given special attention in this publication. Typical details are presented to assist specifiers.

Details of the procurement process, construction on-site, and information relevant to in-service performance are also included. A value-benefit assessment and a review of sustainability indicators are presented. Architectural opportunities using modular units are described in outline. Sources of other information are given, including contact details of manufacturers of modular units using light steel framing.

Construction modulaire utilisant des ossatures legeres en acier: Dimensionnement des immeubles residentiels

Résumé

Cette publication fournit informations et guidances relatives au dimensionnement de constructions modulaires pour immeubles résidentiels ou similaires. Une publication précédente "Construction modulaire utilisant des ossatures légères en acier : un guide de l'architecte", a présenté les informations générales qui sont nécessaires au stade du projet. La nouvelle publication étend cette guidance au niveau technique et donne les informations nécessaires pour rédiger des demandes d'offres auprès des fabricants.

Elle couvre les aspects réglementaires (Angleterre et Pays de Galles) et propose des méthodes de dimensionnement ainsi que des détails de réalisation qui satisfont ces réglementations; en particulier les aspects liés à la structure et son chargement, la protection incendie, les performances acoustiques et thermiques. Le dimensionnement détaillé des modules est de la responsabilité du fabricant. Toutefois les interfaces avec les fondations, les recouvrements des parois et des toitures et les services sont souvent laissés à la responsabilité du designer général. Ces différents aspects sont couverts par la publication. Des exemples typiques sont également présentés.

Modulares Bauen mit Stahlleichtbau – Berechnung von Wohngebäuden

Zusammenfassung

Diese Publikation vermittelt Information und Anleitung zur Berechnung von modularen Bauten im Wohnungsbau und ähnlichen Gebäuden. Eine frühere Publikation,"Modulares Bauen mit Stahlleichtbau – Ein Leitfaden für Architekten" stellt allgemeine Informationen für die frühe Planungsphase eines Projekts vor. Diese neue Publikation erweitert die Anleitung auf einem technischen Niveau und gibt Informationen, die in ausführlichen Diskussionen mit den Herstellern der modularen Bauteile verwendet werden können.

Sie behandelt die Anforderungen der Bauvorschriften (England und Wales) und stellt Berechnungsmethoden und Details vor, die diese Anforderungen erfüllen. Insbesondere werden folgende Anforderungen behandelt: Tragwerk und Belastung, Brandsicherheit, akustisches und thermisches Verhalten. Obwohl die genaue Berechnung der Module in der Verantwortlichkeit der Hersteller liegt, wird dem Zusammenspiel mit Gründung, Fassade, Dach und Installationen besondere Aufmerksamkeit gewidmet, da dies oft in der Verantwortung des für das Gesamtgebäude zuständigen Tragwerksplaners liegt. Typische Details werden vorgestellt um den Anwender zu unterstützen.

Details über den Beschaffungsprozess, die Montage auf der Baustelle und Informationen zum Verhalten im Endzustand sind ebenso enthalten. Eine Wertbeurteilung und ein Überblick über Indikatoren zur Unterhaltung werden vorgestellt. Architektonische Möglichkeiten mit Modulbauteilen werden in Umrissen beschrieben. Andere Informationsquellen werden angegeben, einschließlich Details zur Kontaktaufnahme mit Herstellern von modularen Bauteilen im Stahlleichtbau.

Construcción modular mediante el uso de entramados ligeros de acero: Proyecto de edificios residenciales

Resumen

La publicación describe y ayuda al proyecto de construcciones modulares en edificios de tipo residencial y semejantes. Una publicación anterior "Modular Construction using light steel: An Architect's Guide" ofrece información general para ser usada en anteproyectos. Este nueva obra extiende los consejos al nivel técnico y da información utilizable por los proyectistas en sus discusiones con los fabricantes de los módulos.

Describe los requisitos de las Building Regulations (Inglaterra y Gales) y presenta métodos de proyecto y detalles que los cumplen. En particular se tratan: estructura y cargas, seguridad al fuego, acústica, funcionamiento térmico. Aunque el proyecto detallado del módulo sea responsabilidad del fabricante, la interfase con los cimientos, revestimientos, techado y servicios es, a menudo, responsabilidad del proyectista global del edificio y por ello la publicación le presta atención especial. Como ayuda complementaria se incluyen detalles típicos.

También se incluyen detalles del proceso de preparación, construcción in situ e información relevante para el funcionamiento en servicio. Se presentan una *evaluación coste-beneficio y una revisión de los indicadores de sostenibilidad.*

Se bosquejan las posibilidades arquitectónicas del uso de unidades modulares. También se dan otras fuentes de información incluyendo detalles de contacto con fabricantes de unidades modulares que usen entramados ligeros de acero.

Costruzioni modulari realizzate usando telai leggeri in acciaio: Progettazione di edifici residenziali.

Sommario

Questa pubblicazione fornisce informazioni e una guida sulle costruzioni modulari in edifici residenziali e su edifici similari. Una precedente pubblicazione, "Guida architettonica alle costruzioni modulari realizzate mediante sistemi intelaiati leggeri in acciaio", presenta informazioni generali per un uso negli stadi iniziali della pianificazione di un progetto. Questa nuova pubblicazione estende la guida ad un livello tecnico e fornisce informazioni utili, nelle interazioni con i produttori di moduli, nella fase di pianificazione del progetto.

Questa pubblicazione copre i requisiti all'interno delle esplicite finalità del Regolamento per gli Edifici (in vigore in Inghilterra e Galles) e presenta metodi di progetto e dettagli utili allo scopo. I particolari requisiti che sono coperti sono relativi alla sicurezza al fuoco, alle prestazioni acustiche e a quelle termiche. Sebbene la progettazione di dettaglio dei moduli avvenga sotto la responsabilità del produttore, la responsabilità delle interfacce con fondazioni, tamponamenti, copertura e servizi è spesso di pertinenza del progettista dell'edificio completo e quindi nella pubblicazione viene prestata particolare attenzione a questi aspetti. In aggiunta, si precisa che sono proposti i dettagli più significativi con la finalità di assistere gli specialisti in questo settore.

Nella pubblicazione vengono riportati i principali dettagli sul processo di approvigionamento e sulla fase costruttiva in situ, unitamente alle più importanti informazioni sulle prestazioni garantite durante il normale esercizio. Sono considerati i vantaggi associati alla tipologia in esame con riferimento anche all'analisi degli indicatori sostenibili. Le possibilità architettoniche associate a questo tipo di costruzioni sono analizzate e vengono inoltre fornite le indicazioni per ottenere informazioni complementari, comprendendo anche i riferimenti dei i produttori di costruzioni modulari con telai leggeri in acciaio.

Modulbyggnader I Lättbyggnads med stål; konstruktionsdetaljer och utförande för bostäder

Sammanfattning

Denna publikation är en efterföljare till publikationen "Modular Construction using Light Steel An Architect's Guide" där projektering och planering av modulbyggnader vid ett tidigt skede diskuteras. Denna publikation kommer att vara en vägledning inom tekniska frågor vid modulbyggnad vilket kan användas vid ingåendes diskussioner med modultillverkaren.

Den täcker byggnormer i England och Wales inom moduldesign och utförande

av detaljer som tillfredställer dessa byggnormer. Denna publikation behandlar särskilt kraven för bandsäkerhet, bärandekonstruktion och olika last fall samt akustikegenskaper och termiska egenskaper. Andra tekniska frågor som behandlas i denna publikation är grundläggning, fasader, tak och installationer. Publikationen innehåller lämpliga detaljlösningar

1 INTRODUCTION

Modular construction is an emerging technology that uses light steel framing in factory-produced units that can be assembled on-site to form parts of, or even complete, residential and commercial buildings. Such units are internally lined and often fully fitted out in the factory, before delivery to site.

The residential building sector is a major area of interest for modular construction, where it offers the following benefits:

- Speed of construction on-site. This leads to business-related benefits to the client as a result of early completion and early return on capital invested.
- Less disruption due to construction operations. This is particularly important in inner-city sites.
- High degree of quality control in factory production.
- Economy of scale through repetitive production. There are considerable economies to be obtained on large projects, or through standardisation of room units.
- Off-site installation of services and complex equipment.
- Single-point procurement route.
- Relocatability. Units can be dismantled and re-used in the event of changing client or social requirements.

The motivation to use modular construction in the residential sector is strongly influenced by the building form, site location and the client and planning requirements. Modular construction is probably most appropriate for:

- Repeated projects, where some economy of scale in design and manufacture can be achieved.
- Regular or cellular building shapes with a high degree of repetition.
- Congested inner city sites, where there are constraints on the method of working and there is little space for other site facilities.
- Sites where noise and other pollution has to be minimised during the construction operations.
- Extensions to existing buildings, including roof-top extensions.
- Projects where some degree of relocation or extension is envisaged in the future.

In the residential sector, a typical example of modular room units combined to form larger apartments was in the Murray Grove project in central London, shown in Figure 1.1. Each apartment is accessed externally by prefabricated walkways.

An example of a pair of semi-detached houses, each constructed from four separate room-sized modular units, is shown in Figure 1.2. These were assembled and completed on-site in one week.

Figure 1.1 *Murray Grove in London for Peabody Trust using prefabricated steel framed modular units manufactured by Yorkon Ltd*

Figure 1.2 *Semi-detached modular houses constructed by Britspace Ltd*

It may be noted that the Japanese house-building market is dominated by modular construction; over 150,000 houses are produced annually in this form. The extremely high cost of land in Japan creates an economic imperative to build quickly and to achieve a rapid pay-back, which could not be achieved by traditional construction. Although land costs in the UK are not as high, many of the advantages of modular construction are common to both countries.

Modular construction has also established a niche market in renovation of existing concrete or masonry buildings, where modular units may be placed externally to provide new facilities.

Common to new build and renovation applications is the desire to maximise the benefit of speed on-site, and to have less reliance on-site activities and conditions, particularly the weather.

It is increasingly likely that in future, manufacturers of building components will be responsible for their disposal at the end of their life. In some European countries, the eventual disposal costs are already included in the life cycle cost of some building components. The disassembly of modular buildings provides great opportunities for refurbishment and reuse of modules or, alternatively, for the recycling of materials and components used in the modules.

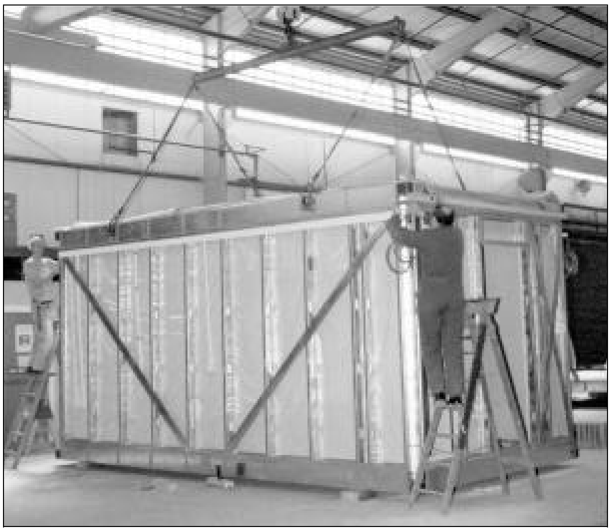
General information suitable for use by the design team at the early stages in the planning of a modular building project is given in the SCI publication *Modular construction using light steel framing: An architects' guide*[1]. Recent examples of this technology are presented in a further publication, *Case studies on modular steel framing*[2].

1.1 Forms of modular construction

Modular construction, in the context of residential buildings, uses one of three basic forms of modular unit, as illustrated in Figure 1.3:

- Modular room units, which are stacked together with connecting corridors, stairs and other communal facilities to form complete buildings.
- Modular bathrooms and kitchens, which are combined with separate wall panels and floors in more traditional on-site construction.
- Open-sided modular units, which are combined to form larger rooms. In this case, the open face of the unit may be braced during lifting and transport to provide temporary stability.

The light steel members used to form the framework of the modular units are usually of C section; the sections are roll-formed or brake pressed from galvanized steel strip of 1.0 to 3.2 mm thickness. The members are cut to length and assembled using various connection methods to form the framework of the modular units. Hot rolled steel sections (generally hollow sections) may be used at the highly stressed lifting points and at the corners of the units.



a) Modular room units

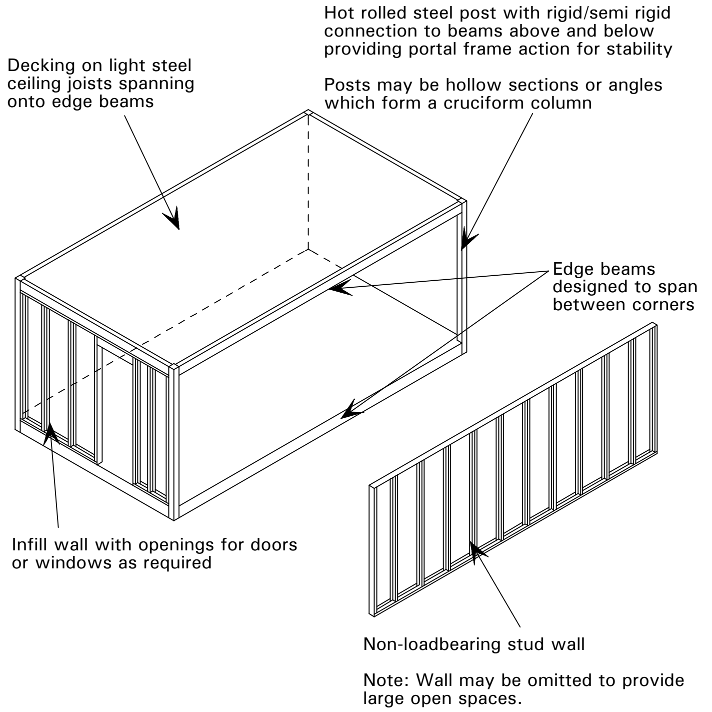
b) Modular bathrooms as external units

c) Open sided units used to form larger spaces (Portakabin Ltd)

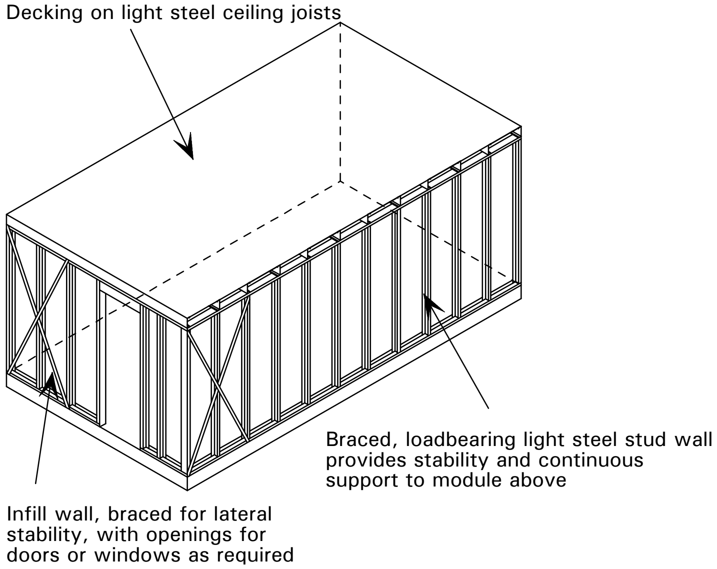
Figure 1.3 *Three basic forms of modular construction*

In terms of structural behaviour, there are also three basic forms of module:

- Corner supported modules, in which the sides of the units are braced and the units are designed to span between corner supports; (see Figure 1.4a).
- Continuously supported modules, in which the sides of the units are braced only for transportation and the longitudinal edge beams provide for continuous support (See Figure 1.4 b).
- Non-load bearing modules (often called 'pods'), which sit on floors of framed buildings. Toilets pods and highly serviced units are often used in commercial buildings.



a) Corner supported module



b) Continuously supported module

Figure 1.4 *Corner and continuously supported modules*

In load-bearing modules, hot rolled steel components can be introduced locally for strengthening, particularly for open-sided units and in high-rise applications.

Module sizes are influenced by a variety of factors such as:

- ease of transportation
- site location and access
- efficient use of standard component dimensions, such as boarding.

The important rationale for modular construction is the repeatability of regular units of suitable height, width and length for transport. Manufacturers normally wish to use 'standard sizes' so that they can hold materials in stock and utilise standard jigs and machinery settings in production, which shortens the supply lead times.

For economic transportation, a commonly adopted maximum width is 3.5 m. Units up to 16 m lengths are possible, although 8-12 m lengths are more typical. Often, the structure is 'over-engineered' for its normal application because of the stability and stiffness required in the lifting and transport operations (see Section 5.2).

The most economic application of modular construction is in the production of a large number of similar room-sized units, which may be combined to form apartments. A good example was in the construction of the Murray Grove project in London for The Peabody Trust, which used 3.2 m wide × 8 m long room units (Figure 1.5).

Even though the modular units are of the same basic form (common plan dimensions and structural components), up to 12 different units may be required, taking account of left and right handed configurations, end units and roof top units.

Figure 1.5 *Installation of modules at Murray Grove, Hackney, London*

1.2 General performance and interface issues

The general performance issues to be addressed in the specification of modular construction are the same as those required for other construction methods for permanent buildings. However, the particular features of modular construction that have a greater influence on the performance of the completed building are as follows:

- Loading, which also includes requirements for lifting and installation.
- Fire safety, as influenced by the separating floors and walls, and passage of smoke.
- Acoustic insulation, which is improved by the air gap between the units.
- Thermal performance, as influenced by the type of cladding and level of insulation provided. Insulation between the modules provides good local control for rapid heating response.
- Robustness or resistance to accidental damage, which is largely affected by the inter-connection between the units.
- Interfaces with the cladding and roofing. A variety of roof shapes can be created, although the economic viability of complex shapes is dependent on the degree of repetition.
- Services and drainage (including service connections between the units).
- Maintenance requirements and ease of maintenance, particularly of the services.

The performance requirements are also dependent on the type of building. In this context, residential buildings are defined as those involving habitation, as opposed to leisure or work, and include:

- individual family houses in detached or terraced form
- multi-occupancy apartments
- sheltered accommodation and other care facilities
- student residences
- hotels and other short-stay accommodation
- health sector accommodation.

The manufacturers of modular units have addressed these performance issues and have developed strategies and details to deal with them. The manufacturers also provide their own performance data, based on full-scale testing.

It is intended that the standards and specifications described in this publication will prove to be acceptable and achievable across the whole industry. However, details of modular systems vary, and therefore specifiers are encouraged to discuss the opportunities for modular construction early in the design process, in order to optimise the benefits and to avoid any design or construction problems.

It is also recognised that the interfaces between the modular units and other building components are crucial to applications in the residential sector. These interfaces include:

- foundations
- wall cladding, including masonry
- roofs, where constructed conventionally
- services, including attachments between the units and to external services
- extensions to buildings.

Furthermore, modular units are relocatable, even if this is not envisaged or required in the original construction.

A particular benefit of modular construction is in the high quality of construction and finish that can be achieved due to production in a controlled workshop environment. In particular, the technology is suitable for highly serviced spaces with a high added value, such as kitchens and bathrooms. A typical mass production facility in Japan is shown in Figure 1.5. Although production in the UK is not at the same scale, the performance and quality levels are as high as in Japan.

Figure 1.6 *Modular units are produced in a controlled environment to high quality*

1.3 Scope of publication

This publication is aimed at providing general information to designers on how to specify and use modular construction, rather than giving detailed information on how to design the modular units themselves, which is the responsibility of the chosen manufacturer.

This publication addresses the design of modular units in residential buildings. It is presented in a form to reflect the requirements of the Building Regulations in England and Wales and gives design guidance and typical details, for common interfaces with other components. General design information on the use of light steel framing is given in the SCI publications *Building design using cold formed steel sections: Construction detailing and practice*[3] and *Building design using cold formed steel sections: Light steel framing in residential construction*[4].

Section 3 of this publication presents the relevant design criteria for the various Approved Documents of the Building Regulations, and gives:

- Building Regulation clauses and requirements
- Background information and supporting data
- 'Deemed to satisfy' solutions using modular construction
- Typical design details, where appropriate.

Other Sections present generic information on modular construction, such as transport and lifting, robustness, and maintenance issues.

1.4 Building Regulations 1991

Recent trends in new building legislation in the UK are leading to a combined approach where legislation forms one part of an integrated set of measures which include regulation, economic instruments, guidance, demonstration and performance targets.

Increasingly, many of the UK regulations arise as a result of the requirements of the European Union. These requirements generally take the form of 'directives' that result in the member countries of the EU modifying their own laws.

In England and Wales, a single set of Building Regulations applies. Different regulations apply in Scotland and Northern Ireland. This publication principally addresses the English and Welsh regulations.

The Building Act 1984 and the Building Regulations

The *Building Act 1984* forms the statutory framework for controlling the standards of building construction. The Act is implemented by means of the *Building Regulations 1991*[5], together with a number of formal amendments to the Regulations. The Building Regulations generally set performance requirements for building work, including the erection of new buildings and material changes of use of existing buildings. Practical guidance on ways of meeting these requirements is given in separate *Approved Documents*[6]. The Approved Documents (ADs) also refer to materials and product standards for technical requirements. There is no obligation to adopt the solutions shown in the ADs, if the designer wishes to demonstrate compliance in some other way.

The Approved Documents to the Building Regulations have been revised at various times since 1991. There are currently 13 'Parts'.

Part A*	Structure	1992
Part B*	Fire Safety	2000
Part C*	Site Preparation and Resistance to Moisture	1992
Part D	Toxic Substances	
Part E*	Resistance to Range of Sound	1992
Part F	Ventilation	1995
Part G	Hygiene	1992
Part H	Drainage and Waste Disposal	
Part J	Heat Producing Appliances	
Part K	Protection for Filling, Collision and Impact	1998
Part L*	Conservation of Fuel and Power	1995
Part M	Access and Facilities for Disabled People	1999
Part N	Glazing - Safety in Relation to Impact, Opening & Cleaning	1998

The date indicates the latest revision. The sections marked with an * are particularly relevant to the use of light steel framing in residential applications and are addressed in this publication.

2 DESIGN AND PROCUREMENT PROCESS

For the full benefits of modular construction to be realised, the implications of using this technology must be considered from the conceptual stage of the project. Decisions made at this stage are critical to the success of the project and the suitability of this technology. At the design stage, the various characteristics of the modular approach can be developed in detail, including the requirements for production, and the interfaces with other components of the building.

The typical procurement process for modular buildings reflects the aims of the Egan Report: *Rethinking Construction*[7]. This report highlights the benefits of prefabrication and partnering between suppliers and clients to improve construction efficiency. The benefits of modular buildings can be maximised by the client, designer and manufacturer working together at all phases of the project and especially over a series of projects.

2.1 Decision-making process

The decision-making process for modular construction differs from more traditional methods of construction because of:

- The close involvement of the client in assessing the business-related benefits provided by the method of construction.
- The direct involvement of the manufacturer in the design, costings and logistics.
- The need to make key decisions early in the procurement process (late decisions could result in be relatively expensive modifications).
- The important environmental and site-related benefits that can be achieved (such as reducing the impact on neighbouring properties and site traffic).
- The effect of transportation logistics on costs, and module sizes and a close working relationship with the main contractor in terms of site installation.

Since the benefits of modular construction are realised through pre-fabrication, the initial design phase, including the space planning and subsequent detailed design, service integration, and co-ordination, are critical. Prefabrication brings the decision-making process forward and requires commitment to a particular design solution at an earlier stage than conventional construction processes. Depending on the manufacturer's production flexibility, there may be less capacity for significant spatial, material or structural changes at a later stage. The design must be finalised prior to commencement of manufacturing.

The extent to which modules may be used within a project is also a key part of the decision-making process. At one extreme, most of the building may be constructed conventionally and only the highly serviced components, such as bathrooms, may be manufactured as modular units.

Often, clients choosing to use modular construction have had previous experience of its success, either with the same team, or with other UK or overseas modular projects. However, for clients to whom the technology is new, it is important and understand the decision-making process. Direct involvement of the client, manufacturer and main contractor (if different) is needed at the concept stage of the project.

2.2 Procurement process

The procurement process extends from completion of concept design to the successful commissioning of the assembly or building. It includes the process by which components are both manufactured off-site and installed on-site.

Procurement also includes the contractual and financial arrangements, although these are dependent also on the parties involved. In modular construction, the procurement process involves the specialist manufacturers who see the process in manufacturing terms. The process covers pre-ordering of materials, setting up of production line assembly, production efficiency by a suitable level of automation, and temporary storage and delivery to site on a ‘just-in-time’ basis.

There are several ways of procuring modular buildings:

- Traditional, in which an architect provides the design co-ordination and the general contractor provides the construction co-ordination. The modular manufacturer acts as a specialist subcontractor.
- 'Design and Build’ process, in which the modular manufacturer provides the detailed design and construction responsibilities. In this case, the client’s architect may carry out some of the outline design, and may be novated by the client to work for the contractor.

A Design and Build contract is often used for modular construction. In such cases, the role of the client’s architect will depend on the particular procurement process.

Some companies offer a complete ‘turnkey’ package, providing design, manufacture and erection services. However, in many projects, the client’s architect is responsible for the overall design and coordination of all the inputs from specialist manufacturers.

Two methods of specification by the architect are most commonly used:

- The architect may specify the manufacturer who will undertake the detailed design work. This will enable the parties to work together from inception to completion. The architect may select the manufacturer by competitive interview, tender, track record or reputation.
- Alternatively, the architect may draft a performance specification for the works, which is usually done in consultation with one or more modular manufacturer. This is then used as a basis for tendering, either through a main contractor or directly to the modular specialists.

It should be recognised that each manufacturer undertakes the construction of their modular units differently. They will be prepared to offer advice and provide detailed drawings, but may not wish to divulge commercially sensitive technical details at the tender stage.

Importantly, the 'lead-in' time required for prototype, design and manufacture of bespoke module units should be considered, although detailed design of the modular units can be carried out in parallel with other design activities. If the module configuration is repeated from other projects, then design and prototyping time is much reduced.

2.3 The role of the architect in modular construction

The roles of the various parties involved in modular construction projects may vary from those in traditional forms of procurement. The roles will largely depend on the procurement strategy adopted and the subsequent form of contract (see previous Section). Involvement of modular manufacturers in the design development helps to improve buildability and to ensure that the design and interface responsibilities are defined. However, most architects are often hesitant to nominate subcontractors. Contractual difficulties can be overcome by early tendering for the modular supplier, who might also act as the general contractor, or by including a shortlist of modular manufacturers from which a main contractor may select.

2.3.1 Roles and responsibilities

Table 2.1 identifies the areas of responsibility and interest which the architect, structural engineer, general contractor and modular manufacturer will generally undertake in a traditional contract. The general contractor is in overall control of construction on-site; modules are manufactured, supplied and often installed by the modular manufacturer, as a specialist subcontractor.

In certain cases, duties are shared between the various parties, hence careful coordination and definition of roles and responsibilities are required.

The key duties that an architect is likely to be required to undertake within each stage of the procurement process are summarised in Table 2.2.

The Table refers to 'traditional' and 'design and build' procurement methods and is divided into the stages of a typical construction project, as set out in the *RIBA plan of work*[8]. It explains the architect's role within each stage of construction of a modular building project.

2.3.2 Quality and planning issues

Modular construction achieves a high level of quality due to the nature of the manufacturing process, and the performance that is achieved is often better than traditional construction, for example, due to the use of double layer walls and floors. The performance should not be equated to that of relocatable or temporary buildings, which are designed to lower standards.

The use of modular construction offers certain planning benefits in terms of minimum disruption and speed of on-site construction. The finished appearance of the building can be defined to satisfy the client's and Planner's requirements, and does not need to reflect the repetitive nature of the modular framework. Architectural possibilities are reviewed in Section 6.

Table 2.1 *Responsibilities of the parties involved in a modular building project*

Item	Architect	Engineer	Contractor	Manufacturer
Design				
Specification of external/internal finishes	✓			✓
Specification of modular Construction details	C	✓		✓
Loading (including temporary conditions)	C	✓		✓
Co-ordination of structure and services	✓ (in building)	✓	C	✓ (modules)
Co-ordination of elevational dimensions	✓	C	C	C
Overall dimensions	✓	C	✓	✓
Integration of internal drainage	C		✓	✓ (modules)
Modular floor/ceiling construction	C	C		✓
Installation				
Requirements for lifting/installation		C	C	✓
Transportation requirements/arrangements			C	✓
Temporary site protection	C		C	✓
Foundations interfaces	C	✓	✓	✓
Cladding interfaces	✓	C	C	✓
Fire safety	✓	C	C	✓
External service connections	✓		✓	C
Foundation interfaces	C	✓	✓	✓
Maintenance requirements	✓		C	✓
Requirement for temporary propping stability		✓	✓	✓
Planning/Regulations				
Planning issues	✓			
Building Regulations applications	✓	✓		✓
Performance specifications	✓	✓	C	✓
CDM Regulations	✓	✓	✓	✓
Demonstration of compliance with performance specifications	✓	✓	C	✓
Monitoring production quality	✓	C	C	✓

✓ Duty   C Of interest

Table 2.2 *Duties of the architect in a modular building project (as set out in the RIBA Plan of Work)*

Traditional Contract	Design and Build (D & B)
A FEASIBILITY and B BRIEFING PROCESS	
C Establish client's objectives and design brief. C Establish cost plan and overall programme. C Assess site constraints policy. C Consider planning requirements and statutory approvals. C Define preferred spatial relationships and orientation. C Discuss likely form of contract/method of procurement. C Advise client on the appointment of other consultants.	C Establish client's objectives and design brief. C Establish cost plan and overall programme. C Assess site constraints policy. C Consider planning requirements and statutory approvals. C Define preferred spatial relationships and orientation. C Discuss likely form of contract/method of procurement. C Agree with the client the scope and detail of the Employer's Requirements. C Advise on the appointment of a design and build contractor.
C OUTLINE PROPOSALS	
C Prepare outline design. C Obtain preliminary information from specialist subcontractors as necessary for the outline design. C Undertake necessary discussions with statutory and other bodies. C Advise client on the appointment of a planning supervisor to co-ordinate the pre-tender health and safety plan. C Co-ordinate work of other consultants. C Obtain cost plan and compare with client's budget. C Prepare and submit a planning application.	There are two alternative routes: **Alternative 1:** C The design team progresses the outline design proposals. C Obtain preliminary information from modular manufacturers, as necessary, for the outline design and tender price. C Undertake necessary discussions with statutory and other bodies. C Prepare a planning application. C Advise on the appointment of a D&B contractor, based on the outline design and Employer's Requirements. **Alternative 2:** C The client's design team prepare the Employer's Requirements and advise on the appointment of a D&B contractor who develops an outline design. The D&B contractor may be a module manufacturer, or a general contractor who will sub-contract the design and manufacture of the modules.

Traditional Contract	Design and Build (D & B)
D SCHEME DESIGN	
C Develop the outline proposals into a full scheme design with the design team. C Consider preliminary tender action for the specialist modular manufacturers. (They may be appointed as nominated subcontractors.) C If the procurement route does not allow the modular manufacturer to be appointed early, the architect should still seek advice from selected manufacturers. C Integrate and co-ordinate input from design team members and specialists. C Ensure that obligations under CDM regulations are satisfied. C Prepare draft preliminary specification. C Ensure that any specialist systems and components satisfy British Standards or other technical standards.	C The development of the design will be undertaken by the D&B contractor's design team. C The client's architect may be novated to the D&B contractor to develop the design. C Alternatively, the client's architect may be retained to act as employer's agent and advise on the suitability of the proposals and on compliance with overall architectural concept and employer's requirements.
E DETAIL DESIGN	
C Develop the scheme design into detail. C Co-ordinate design work by specialists, including the modular manufacturer. C Agree the critical interfaces and confirm the design/procurement responsibilities. C Review the requirements of the statutory authorities. C Submit for Building Regulations approval. C Where the modular manufacturer is not appointed, the architect will provide preliminary details from alternative modular manufacturers to convey the design intent. C Advise the client on the type of contract to be used.	C The detail development of the design will be undertaken by the D&B contractor's design team, who will also be responsible for making an application for Building Regulations approval. They will have to coordinate the specialist subcontractor design inputs. C The client's architect may be retained to advise on compliance with the overall architectural concept, and employer's requirements.
F PRODUCTION INFORMATION and G BILLS OF QUANTITIES	
C Translate the detailed design into precise technical instructions sufficient to allow for pricing and for construction of the proposed works. C Agree which information is to be provided by the modular supplier, which may include much of the detail design of the modular units. C Interview potential main contractors and modular manufacturers to verify tender list and confirm tenderers willingness/availability to tender.	C The D&B contractor will prepare production information and co-ordinate with specialist subcontractors. C The D&B contractor carries overall responsibility for design and detailing. C The client's architect may be retained to advise on the suitability of the proposals and on compliance with the employer's requirements.

Traditional Contract	Design and Build (D & B)
H TENDER ACTION and **J PROJECT PLANNING**	
C Advise the client throughout the tendering process. C Select appropriate tendering route. Note: Tendering is normally obtained by one of the following routes: ***1. Selective tendering*** - open to selected invitees only. This list is based on the track record and experience of the tenderer. ***2. Negotiated tendering*** - applicable where price is not the main criterion, for example where it forms the second step of a two-stage process. C When selecting the tendering route and in reviewing tenders, consider the following key questions: C Will the modular manufacturer act as the main contractor or subcontractor? C Does the client wish to nominate the modular supplier? C Are the performance requirements satisfied? C How will the coordination between the modular manufacturer and other trades on-site be managed?	C This is normally done earlier in a design and build contract. However the same principles apply, as listed in the column opposite.
Note: Preliminary tenders are often sought early in the design process so that the chosen modular manufacturer can assist in developing the detailed design. This philosophy in line with the EGAN Report which recommends that specialists are appointed early to integrate the design, production and construction processes.	
K OPERATING ON-SITE	
C Monitor both quality levels and progress against construction programme. C Review progress at regular meetings, and resolve technical/interface queries as necessary. C Obtain certificate(s) of warranty from the contractor and specialist. C Independent testing may be commissioned by the client to ensure the scheme complies with the performance requirements.	C The client usually appoints an employer's agent (who may be the client's architect) to monitor progress, and quality against the original employer's requirements and contractor's proposals. C Progress meetings usually take place as for a traditional contract. C On completion, the employer's agent will require certificates of warranty from the contractor and specialist.
Note: Because of the nature of production, major changes to the design and specification are not possible during manufacturer or site erection without time and cost	

Traditional Contract	Design and Build (D & B)
L COMPLETION	
On completion of the project, assemble documents for retention, and compile records. Such documentation may consist of: C Health and Safety file C Operation and Maintenance file C As-built drawings It is good policy to have a feedback session, involving the contractor, modular manufacturer, client and design team to discuss the success of the project, lessons learned, and to incorporate views of the occupants/users.	

Note: In the Traditional Contract, the architect acts as a consultant contracted to the client. In Design and Build contracts, the architect may be: the concept designer and employer's agent; the contractor's architect; or novated by the client to work for the contractor.

3 REQUIREMENTS OF THE BUILDING REGULATIONS AND ISSUES THAT AFFECT MODULAR CONSTRUCTION

This Section provides background detail for the specifier and the options available when using this technology, and how the Building Regulations are satisfied. The detailed design of modular units is generally undertaken by the modular manufacturers. The purpose of this Section of the publication is to inform the reader of the issues involved in the design of the modules and the typical structural solutions that are likely to be encountered.

A particular advantage of modular construction is that most standard systems are certified by LANTAC, the British Board of Agrément (BBA), or have Wimlas certification. This can speed up the process of obtaining Building Regulations approval.

3.1 Structure and loading

The structural design of the light steel modules is carried out by the modular manufacturers or their structural engineers. They have the experience of their own particular systems and have developed many local details, including connections between the modules, connections to foundations, and local strengthening at lifting points. Thus, the role of the consulting engineer will often be confined only to site-specific items such as foundations and the co-ordination of the complete structural package.

The arrangement of the modules in plan and elevation also influences the load paths and many alternative configurations are possible without compromising structural efficiency. Some architectural examples are presented in Section 6.

3.1.1 Building Regulations Part A: Structure

In Schedule 1 of the Building Regulations, Part A sets out requirements that buildings shall transmit dead and imposed loads to the ground safely and without excessive deformation that could impair stability.

Approved Document A gives guidance on the requirements for loading in buildings and provides information on acceptable designs in masonry and timber construction. There is currently no information in the Approved Documents that is specifically on modular construction.

The dead and imposed loads from wind and snow should be taken from BS 6399, *Loading for buildings*[9]. A typical dead weight for a timber boarded, light steel floor is 0.33 kN/m^2. The design imposed loads given in BS 6399:1:1996 are shown in Table 3.1.

Table 3.1 *Imposed loads as specified in BS 6399: Part 1*

Element	Loading
Roof	Distributed load 0.75 kN/m^2 or concentrated load 0.9 kN
Floors	
Above ground storey	Distributed load 1.5 kN/m^2 or concentrated load 1.8 kN
Communal areas	Distributed load 2.0 kN/m^2 or concentrated load 2.7 kN
Corridors, staircases, etc.	Distributed load 3.0 kN/m^2 or concentrated load 4.5 kN
Ceilings	Distributed load 0.25 kN/m^2 and concentrated load 0.9 kN

The Approved Document also lists Codes of Practice and British Standards for structural design and construction, which can be used to meet the requirements for structural stability. For light steel framing, the structural performance should satisfy BS 5950-5 [10].

Modules are often subject to their most onerous loading when in transit, or when being lifted and installed. In particular, high stresses will result locally at lifting positions and the adjacent members and their connections may need to be strengthened accordingly. In some situations, the light steel sections will be replaced by hot rolled steel components to strengthen these locations. Lifting techniques are described in Section 5.2.2.

3.1.2 Structural design of walls

Load bearing walls using light steel studs are subject to axial loads from floors and/or roofs and moments due to either wind pressure or to eccentric vertical load. Non-load bearing stud walls are subject only to wind loads, which are resisted by the bending of these members. Internal walls are designed to resist differential internal pressure, which is much less than for external wind pressure, and therefore the design of the external wall will control. All walls must be sufficiently robust to impact and lifting forces.

The deflection limits of external walls are generally more onerous than those for internal walls, since it is the external walls that provide the lateral support to the cladding. For example, the deflection of a stud wall offering lateral restraint to masonry is limited to a maximum of height/500. If steel cladding is used, the deflection limit can be relaxed to height/250.

For storey-heights up to 3 m, walls of modules will be constructed using 70 to 150 mm deep C section studs, usually at 400 or 600 mm centres. Examples of internal and external wall constructions are shown in the Figure 3.1. Additional insulation between the studs increases their acoustic insulation (see Section 3.3). The internal face of the walls is lined with one or two layers of plasterboard, or other suitable lining material, and the stud centres are chosen for compatibility with standard board sizes in order to minimise waste. Some wall lining materials are available in large sheet sizes, which reduces the number of joints and wet trades. This can considerably speed up the assembly process and improves quality.

In low-rise buildings, standard modules are designed for the worst-case loading. For buildings more than five storeys high, the loads on the lower modules may lead to heavier or more closely spaced studs than in the upper modules. Alternatively, strengthening measures can be introduced into the lower modules.

In modular construction, the internal walls are of double skin construction, which provides excellent acoustic insulation. Thicknesses of internal separating walls range from 225 mm to 330 mm (overall). Brick-clad external walls range from 275 mm thick (for 75 mm studs) to 330 mm thick (for 150 mm studs).

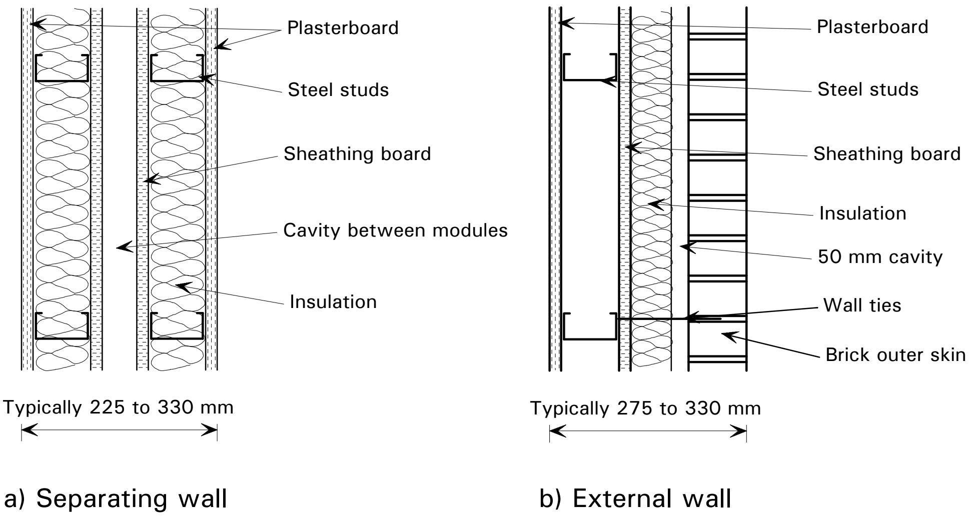


Figure 3.1 *Typical wall sections in separating and external walls*

3.1.3 Structural design of floors

The floor and the ceiling of the modules create a double-layer construction. The depth of floor and ceiling will vary depending on the span, as illustrated in Figure 3.2. In general, the floor will be approximately 150 to 200 mm deep and the ceiling will be 100 to 150 mm deep. However, for open-sided modules, the floor and roof zone may be as large as 500 mm because of the depth of the edge beams required to span over the open side. The resulting floor zone will be slightly deeper than in traditional construction but the separation of components will improve acoustic performance considerably.

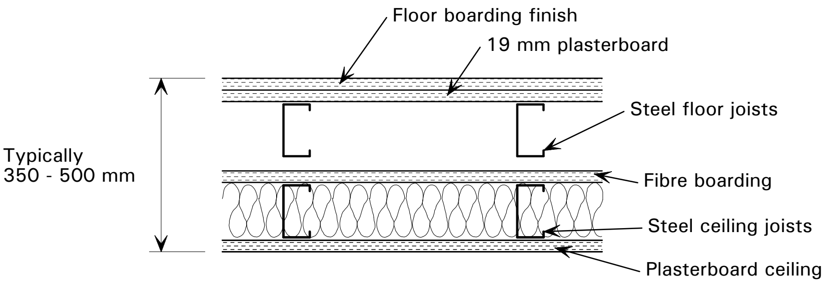


Figure 3.2 *Typical separating floor in modular construction*

The floors of the modular units are generally constructed using floor boarding supported by C section joists, or steel decking spanning between comparatively closely spaced edge beams. In the completed structure, the edge beams may be fully supported by load-bearing walls but, during construction, they are important in providing a torsionally stiff box. For corner supported modules, the floors and edge beams transfer the loads to the corners of the modules, which are stiffened locally.

Flooring materials

For domestic-scale buildings, moisture resistant type P5 chipboard to BS EN 312 [11] should be used for flooring. When improved moisture resistance is required, WBP grade plywood to BS EN 636 [12] or cement particle board to BS 5669-4 [13] should be specified. Installation should comply with the appropriate clauses of BS 5268-2 [14], BS 8000-5 [15] and BS 8201 [16].

To prevent squeaking, tongue and groove joints should be glued using adhesives complying with BS 4071 [17]. Square edge board should be supported at all joints on joists or noggins. Additional layers may be included in the floor build-up to enhance the acoustic insulation, as presented in Section 3.3.

Attachment of floors to walls

Joists may be built into the module walls, or alternatively be supported by joist hangers or cleats. Cleats should be attached to the web of the joists to minimise local bearing or buckling.

To provide large open-sided units, hot rolled steel or light steel spine beams may be used as edge beams to support shorter span joists. In this case, the spine beam is generally designed to be accommodated within the floor depth. The spine beam leads to concentrated end reactions that should be supported by discrete columns, often in the form of boxed C sections. For overall stability of the building, the spine beams can potentially be rigidly connected to external columns to provide portal frame action.

Bridging and blocking

Bridging and blocking in long span floors provides lateral restraint to the joists. Floor joists within modules generally span up to 3.5 m and, for these small spans, bridging and blocking will not be required. However, thinner C section joists have a tendency to 'roll' and some manufacturers reverse the orientation of the alternate joists to minimise this effect.

Manufacturers frequently join the bottom flanges of the C section joists together, either with steel or other rigid 'under drawing' or with steel runners or skids. These skids also protect the underside of the module from damage from the lorry bed during transit.

Joist design

The design of light steel floor joists with timber boarding is generally limited by serviceability criteria for control of deflection and vibrations. Although serviceability design criteria are not specified in the Approved Document, SCI has proposed the following design limits for lightweight floor constructions:

- Imposed load deflection < span/450.
- Total deflection (including self-weight) < span/350, but not > 15 mm.
- Natural frequency > 8 Hz (calculated using the self -weight of the floor plus 0.3 kN/m^2).
- Limit the deflection of the floor when subjected to a 1 kN point load. This is an alternative criterion. In modular construction, the floor joists may be assumed to resist this point load. The allowable deflection varies with span as shown in Table 3.2.

Table 3.2 *Serviceability criteria for floors subject to a 1 kN point load*

Span (m)	3.5	4.2	5.3	6.2
Max. deflection (mm)	1.7	1.5	1.3	1.2

For corner supported modules, the cumulative deflection of the floor joists and edge beams should be considered when assessing serviceability.

3.1.4 Connections in light steel framing

There are several techniques available for connecting light steel components; some of these are presented in Table 3.3. Guidance on the design and detailing of the most common connection types is given in BS 5950-5. Manufacturers use the method which best suits their manufacturing process and for which appropriate test data are available.

Structural connections between modules are required for integrity and robustness but details vary depending on the form of the module and the particular application.

Floor boarding, plasterboard and sheathing boards are attached using self-drilling, self-tapping screws.

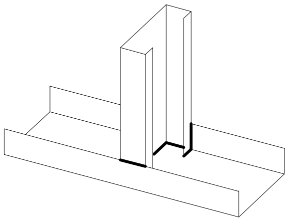
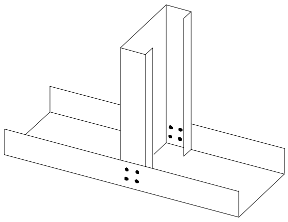
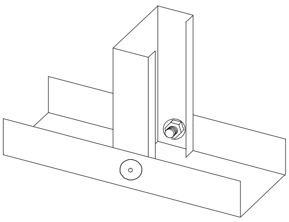
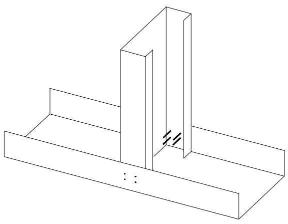
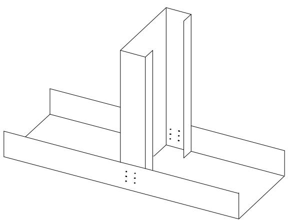
3.1.5 Overall stability

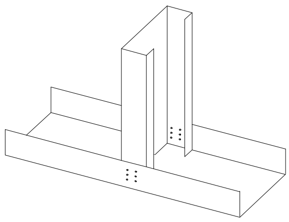
All load-bearing structures must be braced to prevent racking movement under horizontal loads. In the horizontal plane, the floor boarding is generally used as a diaphragm to provide bracing action. There are four principal means of providing stability in the vertical plane:

- K bracing - C sections are fixed diagonally between vertical studs within the depth of the stud walls. The diagonal bracing members must be securely connected to the vertical studs to ensure the transfer of their forces in tension and compression.
- X bracing - Crossed flat straps of strip steel are fixed on the external faces of the studs. These straps act only in tension and may be pre-tensioned during installation. The crossed flats should be fixed to every vertical stud.
- Diaphragm action - Effective diaphragm action is achieved by the use of suitable board materials (plasterboard and more robust boards) fixed to the light steel studs with self-drilling self-tapping screws, or equivalent, at a maximum spacing of 300 mm. A spacing of 150 mm is generally required at the edges of the panels.
- Rigid frame action - continuous joints between wall stud members and floor joists allow rigid frame or portal frame action to be developed which enhances the overall torsional stiffness of the module.

Some modules are constructed with large openings in the walls (as in Figure 1.3(c)). Two or more similar modules can then be installed adjacent to each other and form a large room. Such modules require special consideration for transport and installation and may require temporary bracing. This bracing should be positioned so that it can be easily removed after the modules have been located in their final position.

Table 3.3 *Typical connections used in light steel construction*

Welded connections	Typical shear capacity: by test (can be as great as shear strength of section)
	**MIG welding:** Light steel sections may be joined by continuous MIG welding. Care is required to ensure that the welding process does not cause damage to the components being connected, because the parent metal is very thin. The welding of galvanized steel requires special care (see Section 3.4.3). To maintain the durability of the steel, the affected areas should be protected after welding with a zinc rich paint.
	**Spot welding**: Spot welding is primarily used for workshop fabrication. An arc is created between the tips of the welding tool on either side of the steel elements to be joined. It is most appropriate where the welding tool can be supported and easily moved into position to form the weld. A minimum of 3 spot welds should be used for each connection.
Bolted connections	Typical shear capacity: 12 mm bolt: 8 -12 kN
	**Bolts** are a common choice for connecting light steel sections because of the ease with which holes in the sections can be punched during the roll forming process. The connections are usually arranged so that the bolts are primarily subject to shear and the capacity of the connection is generally governed by the bearing strength of the thinner material.
Screwed connections	Typical shear capacity: 5.5 mm screw: 5kN
	**Self-drilling, self-tapping screws** are commonly used for connecting light steel components. The drill part of the screw forms a hole in the steel section and the tapping part forms the thread in a single operation. This technique is commonly used to inter-connect either wall panels or stick built frames on-site, although care must be taken to ensure that the protruding head of the screw does not interfere with the finishes. Two or more screws should be used for each connection. Self-drilling self-tapping screws are also used extensively to attach finishing materials, such as plasterboard, sheathing, floor boarding, insulation and decking, to light steel structures. Stand-off screws, where the screw thread is discontinuous, may be used to fix cellular insulation boards to light steel components without the risk of crushing the insulation.
Riveted connections	Typical shear capacity: by test
	**Blind rivets** are fitted into pre-drilled holes and a mandrel is pulled by a special tool so that the rivet expands into and around the hole. These rivets provide a relatively robust form of attachment with good pull out resistance. They are useful for thin-thin attachments, such as the seams of profiled decking and sheeting.



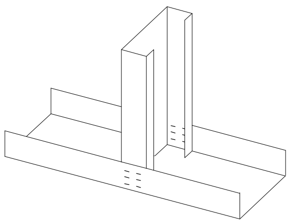
Self-piercing rivets do not require pre-formed holes in the components since the rivet is designed both to pierce and to form a permanent fastening within the materials being joined in one single operation. This requires a hydraulic operated tool with access to both sides of the fixing. The riveted connection is formed in two phases:

Piercing: The rivet shank acts as a shearing punch which cuts a hole through the top layers of material and partially through the lower layer until coming under the influence of the reacting die.

Flaring: During the final stages of punch travel in the lower sheet, the sheet material is displaced into the die and causes the shank of the rivet to flare out, locking itself into the material.

Press joining or clinching

Typical shear capacity: by test



Clinching is a combination of drawing and forming that locks two or more layers of thin gauge steel together. Clinching involves a hydraulically operated punch that drives the layers of metal into a die to make an impression. Additional force is then applied to spread the top layer of steel into the bottom layer. This prevents the top layer from being pulled out of the bottom layer.

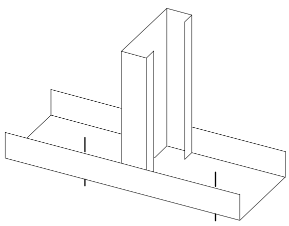
There are two basic **clinching** methods:

(a) Cut clinch: This type of clinch is formed by shearing the metal on two sides, drawing the top layer through the slits in the bottom layer and expanding the width to form a lock on both sides.

(b) Button or round clinch: This type of clinch is characterised by a "button" formed on one side of the metal. The layers of metal are simply formed by drawing them into a circular dovetail; the diameter is then expanded to lock the sheets together.

Powder actuated fastenings

Typical shear capacity: related to brick or concrete strength in typical applications.



Powder actuated fasteners are used to connect light steel members to concrete and masonry or to thick steel members. However, it is not possible to connect thin steel members, because of the flexibility of the connected parts to the driving force.

3.1.6 Robustness

The Building Regulations require that structures of five or more storeys should be designed to localise the effects of accidental damage. There is currently no published guidance on the 'robustness' of light steel frames against accidental effects, within the context of the Building Regulations. BS 5950-5 refers to BS 5950-1 [18], which requires that the design of hot rolled structures ensures robustness or structural integrity. The 'tying' option in BS 5950-1 requires minimum forces of 75 kN (floor) and 40 kN (roof) to be accommodated.

The direct application of this requirement to light steel structures would prohibit the economic use of light steel. Multi-storey modular structures have a very large number of regularly distributed structural elements, with a high degree of connectivity and structural integrity. In most applications, the provision of continuous ties between the components achieves robustness by preventing disproportionate collapse.

The following general rules for robustness have been established by SCI for light steel frames, and are consistent with the principles of BS 5950-1 and BS 5950-5.

Interpretation of the tying and continuity option for modular structures using light steel framing

Floors and roofs:

1. Horizontal tying arrangements, which are generally similar to those described in Clause 2.3.5.2 of BS 5950-5, should be arranged in continuous lines wherever practicable throughout each floor and roof level in two directions, approximately at right angles.

2. Light steel members acting as ties and their end connections should be capable of resisting the following factored tensile loads, which need not be considered as additive to other loads acting on the members:

   - For floor ties (or joists as ties): $0.5\,(1.4g_k + 1.6q_k)L_a$ but not less than 5 kN/m (3 kN/m at roof level)
   - For internal ties: $0.5\,(1.4g_k + 1.6q_k)\,s_tL_a$ but not less than 15 kN (8 kN at roof level)
   - For peripheral ties: $0.25\,(1.4g_k + 1.6q_k)s_tL_a$ but not less than 15 kN (8 kN at roof level)

   where:

   g_k is the specified dead load per unit area of the floor or roof (kN/m^2)
   L_a is the average of any two adjacent spans between vertical supports (m)
   q_k is the specified imposed floor or roof load per unit area (kN/m^2)
   s_t is the mean transverse spacing of the ties (m)

   Note: The distributed tie force applies to the end connections of floor joists, roof trusses or rafters and should be multiplied by the spacing of the component to determine the end connection tie force. For example, the minimum tie force for floor joists placed at 400 mm centres is $5 \times 0.4 = 2$ kN.

Walls:

3. Tying members at the periphery of the building should be connected to the rest of the structure. If the vertical loads are supported by a distributed assembly of closely spaced elements, the tying members should be similarly distributed in order to ensure that the entire assembly is effectively tied. The forces required to anchor the vertical elements at the periphery should be based on the spacing of the elements and taken as 1% of the factored vertical load in the element.

   The floor to wall connections should be designed for the tying forces in 1 and 2, except that the minimum values of 15 kN or 8 kN for floor and roof ties do not apply to the wall studs.

4. If the main structural elements comprise discrete columns, the horizontal ties anchoring the columns nearest to the edge of a floor or roof should be capable of resisting a factored tensile load, acting perpendicular to the edge, equal to the greater of the load for an internal tie (given in 2), or 1% of the factored vertical dead and imposed load in the column acting at that level.

5. All splices in primary vertical elements should be capable of resisting a tensile force of not less than two-thirds of the factored design vertical dead and imposed load applied to the vertical element from the floor level(s) below the splice.

6. The system of bracing, providing resistance to horizontal forces, whether discrete members or diaphragm panels , should be distributed throughout the building such that, in each of two directions approximately at right angles, no substantial portion of the building is connected to a means of resisting horizontal forces at only one point.

Interpretation of the removal of columns option for light steel structures

7. If the conditions for *tying and continuity* in 1 to 6 above cannot be met, the designer should check each storey to ensure that disproportionate collapse would not be precipitated by the notional removal of vertical load bearing elements, considered one at a time.

   For *volumetric/modular* structures, the situation is considered to be similar to that of masonry; consideration should be given to the notional removal of a wall panel of 2.25 times the storey height. This length of panel is conservative because of the one-way spanning characteristics of the light steel components.

   In this check, as in BS 5950-1, only one-third of the normal imposed load need be considered, together with the dead load, except that in the case of buildings used predominantly for storage or where the imposed load is of a permanent nature, the full imposed load should be used. A reduced partial factor γ_f of 1.05 should be applied, except that, when considering overturning, the dead load supplying the restoring moment should be multiplied by a partial factor γ_f of 0.9.

   Volumetric/modular construction differs from other forms of construction in that there is far more connectivity, such that a stack of modules may tolerate the notional removal of a whole module. It is better to use a 'scenario-based' approach to review such cases, such as the removal of one support member. Eurocode 1: Part 2.7 [19] provides a method for this approach.

8. In all cases, the test for localisation of damage should be that the portion of the building at risk of collapse should not exceed 15% of the area of the storey or 70 m^2 (whichever is less) within that storey and the immediately adjoining storey above. A similar area of the floor immediately below could be loaded with debris from above. Hence, up to a total of 140 m^2 of floor area may be assumed to be at risk of collapse.

Interpretation of the key element option for modular structures

9. If the notional removal of a vertical load-bearing element would risk the collapse of a greater area than that specified in 8, then that vertical load-bearing element should be designed as a *key element*. For *key element* design, the following loading/assumptions should be adopted:

- A blast pressure of 34 kN/m^2 should be applied to the width of the stud or column.
- A reduced axial load (dead load + $^1/_3$ imposed load), may be taken from the floors above.
- No lateral restraint is provided by the plasterboard.
- No wind pressure is applied.
- No P-δ effects are considered as 'prescriptive equivalent' horizontal force.
- The design strength of the steel in the key elements may be taken as 1.2 times the nominal yield strength (P_y). This takes accounts of the actual strength that is normally achieved (as shown by mills certificates) and the high strain rate in the steel when exposed to blast pressures.

Requirements for modular structures clad with masonry

10. Special measures should be taken in the design of the masonry to ensure that, during an accidental event, disproportionate collapse of the masonry cladding does not occur. (In general, modular structures only offer lateral support to masonry cladding and the self weight of the masonry is transferred directly to the foundations.)

Strategies for robustness in modular buildings

Modular units differ from normal construction in that the units, although robust in themselves, are placed together so that the load path is through the walls or the stiffened corners of the units to the foundations. The possibility of the removal of this load path means that the walls should be designed either:

- to span horizontally over the damaged area as a deep beam or diaphragm
- to act in tension when supported by the adjacent units.

The latter alternative means that the units should be tied together horizontally in addition to being tied vertically. Tying action is illustrated in Figure 3.3 which, for clarity, shows only three-storeys of a multi-storey building. The manufacturers of light steel framed modules have prepared their own details of these horizontal attachments to satisfy 'robustness' requirements. A typical connection detail is shown in Figure 3.4.

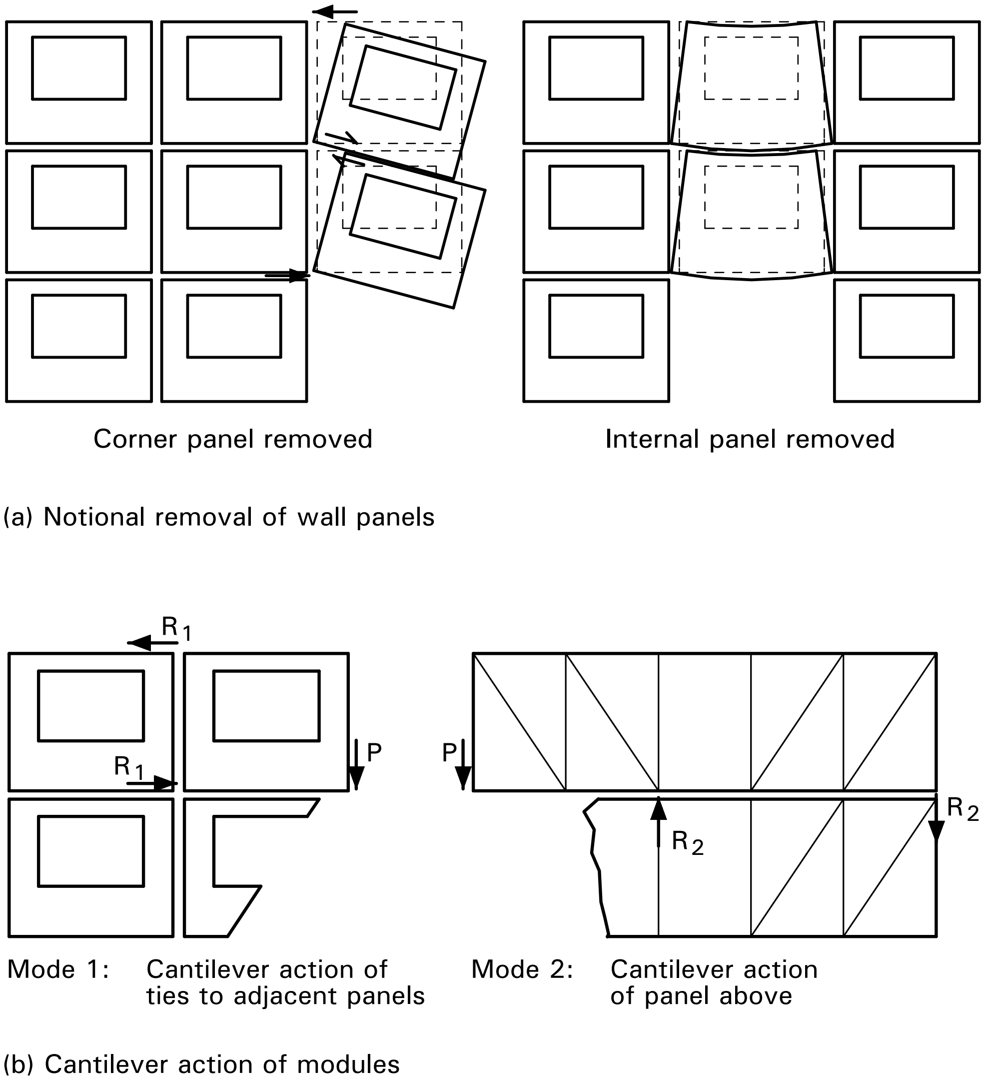


Figure 3.3 *Strategies to achieve robustness of modular construction*

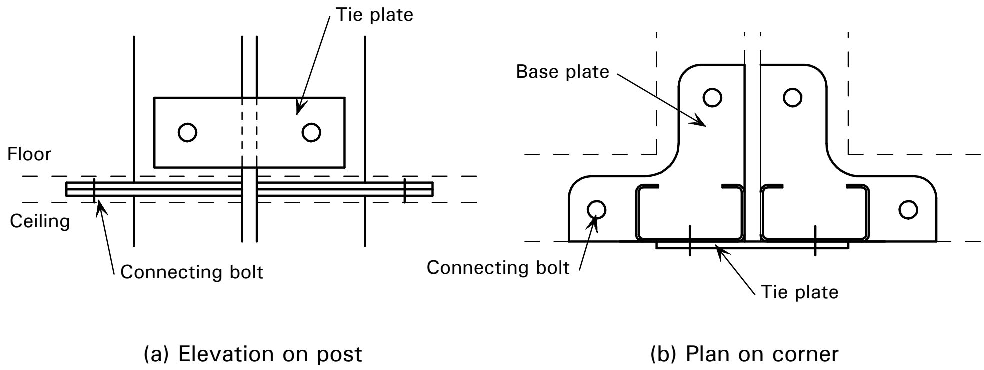


Figure 3.4 *Typical horizontal connection detail between units*

3.2 Fire safety

Fire safety is related to provision of adequate means of escape, to ensuring structural integrity, and controlling spread of fire across compartment boundaries. Fire resistance is expressed in terms of fire resistance periods, which require that structural stability, integrity to passage of smoke or flames, and insulation to a avoid combustion across compartment boundaries, are satisfied for this period.

Modular construction generally achieves these requirements by the use of fire resistant plasterboard. Alternative materials, such as cement particle board and gypsum fibre board, may be used and the fire rating of these boards is available from the manufacturers.

Mimimum periods of fire resistance are given in Approved Document B.

For houses and apartments of two storeys, 30 minutes fire resistance must be achieved for all elements of structure. This increases to 60 minutes for walls separating two dwellings. The structure of any house or apartment building with floors that are more than 5 m above the ground floor, should have at least 60 minutes fire resistance; separating walls must also be constructed of materials of limited combustibility. Taller buildings may require longer fire resistance periods. Any basement storey may require additional fire separation.

Each module is lined internally with one or two layers of fire resistant plasterboard as follows:

- For walls: 30 minutes fire resistance is achieved by a single layer of 12.5 mm fire resistant plasterboard on each face of a steel stud wall.
- For walls: 60 minutes fire resistance is achieved by one layer of 12.5 mm fire resistant plasterboard on a layer of 12.5 mm wallboard with staggered joints on each face of a steel stud wall.
- For floors: 30 minutes fire resistance is achieved with 18 mm tongue and groove boarding on light steel joists and 12.5 mm fire resistant plasterboard beneath with joints taped and filled.
- For floors: 60 minutes fire resistance is achieved with at least 18 mm T&G board floor finish and one layer of 12.5 mm fire resistant plasterboard on a layer of 12.5 mm wallboard with staggered joints beneath the steel joists.

Lining materials are constantly developing and individual manufacturers may use alternative, more economic materials and configurations to achieve the above levels of fire protection.

3.2.1 Provision of fire resistance

When the modules are assembled, the walls and floors effectively form a double layer construction with a cavity between, protected from both sides by layers of plasterboard, which achieves good fire compartmentation.

For fire resistance periods exceeding 60 minutes, refer to SCI publication *Building design using cold formed steel sections: Fire protection*[20]. Cement particle boards or gypsum fibre boards of 10 to 15 mm thickness can also be used to replace one or more of these layers. When multiple layers of board are used, their joints should be staggered to maximise integrity in fire.

The Approved Document requires that any proposed constructions must show, by test, that they are capable of achieving the required performance, or have been assessed by accredited fire consultants. The method of testing for fire resistance is defined in BS 476 [21] and the above constructions have been shown in tests to provide the required fire resistance.

3.2.2 Details of compartment walls and floors

In residential construction, each dwelling usually forms a separate fire compartment. All walls and floors that provide a separating function between compartments require 60 minutes fire resistance. In hotels and other residential buildings, each bedroom may form its own compartment. Double layer walls in modular construction are generally suitable for use as compartment walls.

Figure 3.5 shows a typical floor and wall construction used in modular construction which meets the current Building Regulations for compartmentation. In general, a compartment floor will also act as a separating floor for acoustic purposes, as the same measures will also achieve excellent acoustic insulation between rooms.

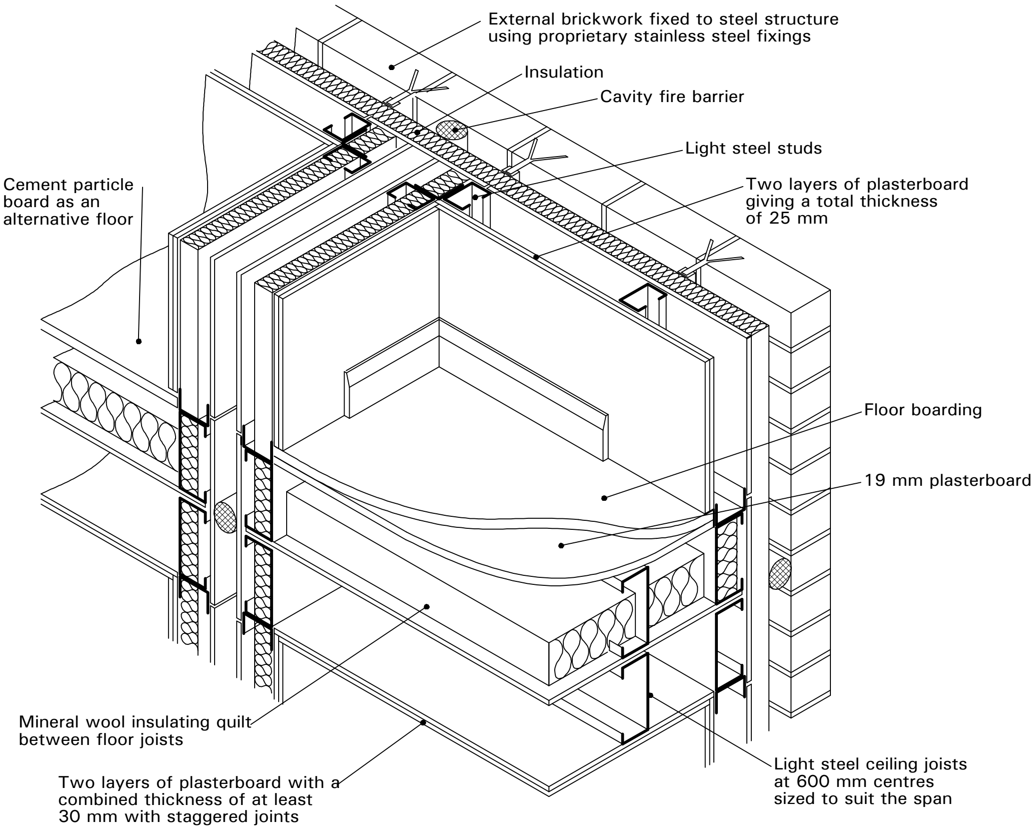


Figure 3.5 *Compartment floor at junction with external wall and compartment wall*

3.2.3 Avoiding spread of flame

Materials used for internal linings should have Class 1 (or below) for rate of flame spread (as measured in accordance with BS 476: Pt 7), other than in small rooms below 4 m^2 in residential buildings. Plasterboard, which is commonly used for internal finishes, will satisfy these requirements. Other materials are listed in Table 3.4.

Table 3.4 *Typical ratings for surface flame spread for commonly used cladding and lining materials*

Class	Material
Class 0	Brickwork Cement render Tile and slate hanging Cement particle board Gypsum fibre board Plasterboard Timber and wood based boards treated to class 0
Class 1	Timber and wood based boards treated to class 1
Class 3	Timber and wood based boards with density >400 kg/m^3

Furthermore, there are additional requirements to prevent passage of smoke and flame spread between the units (see Section 3.2.6).

3.2.4 External spread of flame

External cladding materials of limited combustibility, and Class 0 flame spread aterials (in accordance with BS 476: Part 7) are required for external walls within 1 m of a boundary and for buildings over 20 m tall. In such cases, there are also limitations on openings (unprotected areas in such walls). A variety of claddings can be used in modular buildings, as illustrated in Section 4.2. Many of these cladding types can be designed to satisfy the above requirements.

3.2.5 Means of escape

The Building Regulations require the provision of protected escape routes. These escape routes require at least 30 minutes fire resistance for buildings which have any occupied level more than 4.5 m above the ground.

Appropriate protected escape routes can be incorporated into the design of modular buildings. The inherent separation between modules provides an effective barrier to spread of fire. Spaces between modules, such as corridors in hotel developments, can easily be designed to satisfy the requirements for escape routes. Means of escape should be considered early in the scheme design in order to ensure that the module design and layout can satisfy these requirements.

3.2.6 Cavity barriers

Cavity barriers are required to prevent the spread of smoke or flame in concealed spaces. In modular construction, cavity barriers are required between modules in cases where the modules form separate compartments. Wire-reinforced (or polyethylene sleeved) mineral wool of 50 mm thickness is usually inserted when the units are positioned on-site. The mineral wool cavity barriers are installed in the spaces between modules around the floors and walls to seal each cavity between modules.

Cavity barriers are required within the cavity in the external wall between the module and the cladding at intersections with compartment walls. They are also required horizontally at junctions with floors and roof, and vertically at a maximum lateral spacing of 20 m (or 10 m where the material exposed to the cavity is not Class 0 or 1). Figure 3.6 illustrates location of cavity barriers to ensure that separating walls comply with the Building Regulations in terms of prevention of passage of smoke.

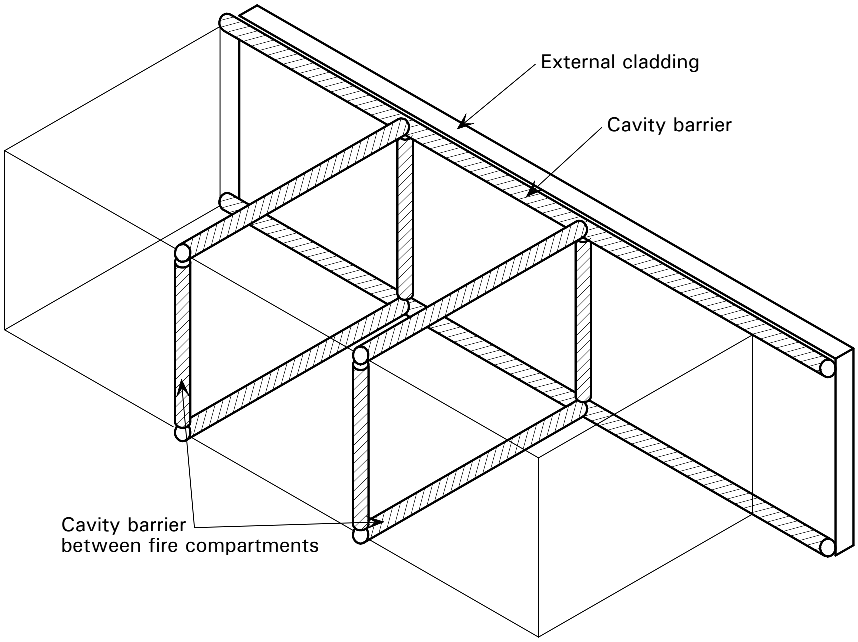


Figure 3.6 *Cavity fire barriers between modules*

Care should be taken in selecting materials in the cavity such that the performance of cavity barriers and cladding support is not compromised in fire conditions. Additional quilt may be needed to satisfy insulation requirements in fire, i.e. to prevent combustion of objects on the remote side of the wall or floor.

Cavity barriers or fire stops must be provided around any penetrations through fire resisting walls.

3.3 Acoustic performance

3.3.1 Building Regulations Part E: Resistance to the passage of sound

The requirements of Part E of the Building Regulations apply to floors and walls that separate one dwelling from another, or a dwelling from a communal space. There are currently no requirements for acoustic insulation of the external envelope, or for other walls and floors within dwellings.

The simplest way to satisfy the requirements is to follow one of the *'deemed to satisfy'* approved constructions that are identified in the Approved Document E. However, there is no information on modular constructions in this Approved

Document. Alternatively, it is possible to show by tests that a given construction meets the requirements presented in the Approved Document, or to repeat a construction that has been used previously and shown in tests to perform acceptably. The acoustic performance of a floor or wall will be acceptable if the values given in Table 3.5 are demonstrated in tests. These tests should be carried out in accordance with BS EN 20140-9 [22] (and the performance calculated in accordance with BS EN ISO 717 [23]).

Table 3.5 *Sound insulation values for separating floors and walls*

Separating Element	Individual Value (dB)	Mean (dB)
Separating wall - airborne sound insulation (D_{nTw})	>49	>53
Separating floor - airborne sound insulation (D_{nTw})	>48	>52
Separating floor - impact sound transmission (L_{nTw})	<65	<61

Most modular manufacturers have tested their own building systems to demonstrate compliance.

DETR has published proposals for revising the requirements of Part E of the Building Regulations. These require a higher level of performance and acoustic testing must be carried out at each site to prove that the requirements have been met. Standards are also proposed for walls within dwellings, external walls of dwellings, and walls in halls of residence, hostels, hotels and other rooms for residential purposes.

3.3.2 Acoustic separation in modular construction

Modular construction provides a high level of acoustic separation because each module has separate floor, ceiling and wall elements, which prevents direct transfer of sound. Modular units are often used in hotel buildings as they achieve excellent acoustic insulation between rooms.

A recent DETR-funded project, *Specifying dwellings with enhanced sound insulation* [24], has set standards for enhanced acoustic performance. These standards generally require a 3 dB improvement over current Building Regulations. Double layer light steel floors and walls as used in modular construction, are shown in the publication as meeting these improved requirements.

3.3.3 Acoustic insulation in lightweight modular construction

Traditionally, improving the resistance to the passage of sound has been associated with increasing mass of the separating wall or floor, but this is inefficient for light steel framing both constructionally and economically. In lightweight construction, the presence of a cavity and the isolation achieved by the multiple layers of materials, and the use of resilient layers provides excellent acoustic insulation. Further improvements can be achieved easily by insulating quilt and additional layers of board.

In modular construction, each unit has its own floor and walls, independent of the adjacent unit. This prevents direct sound transfer, as the units are only connected structurally at the corners or other discrete points. At these points, the local transfer of sound is reduced by the use of acoustic pads that prevent direct steel to steel contact.

Figure 3.7 illustrates the importance of acoustic separation. The acoustic insulation of individual elements within a double layer wall tend to combine together in a simple cumulative linear relationship, as long as the two layers are largely structurally separate. It is generally recommended that a distance of 200 mm is maintained between the external surfaces of the plasterboard finishes to adjacent rooms.

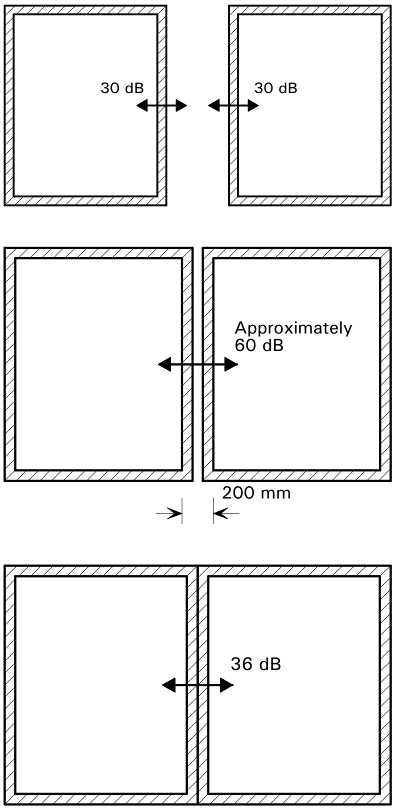


Figure 3.7 *Schematic showing the principle of double layer construction with associated acoustic benefits*

Lightweight construction uses dry assembly processes. Wet plastering will tend to seal cracks and joints. When using dry lining board, it is important to ensure efficient sealing of possible air paths, which can lead to local sound transfer. General guidance on acoustic insulation in light steel construction is given in SCI publication *Building design using cold formed steel sections: Acoustic insulation*[25].

3.3.4 Separating walls

The acoustic requirements for walls in the current Building Regulations are limited to airborne sound reduction. Typical data from modular buildings are given in Table 3.6; these exceed the Building Regulations limits by a significant margin.

Table 3.6 *Acoustic performance of separating walls*

Separating Walls	Airborne sound insulation (D_{nTw})
Requirements of Approved Document E	>53 dB
Measured in modular hotel - Peterborough	60 dB
Measured in prototype modular building	72 dB

Figure 3.8 shows a typical separating wall in modular construction. The essential requirements for good acoustic insulation are:

- a double layer construction
- an independent structure for each layer with minimal connections between
- a minimum weight of 25 kg/m^2 in each layer (two layers of 12.5 mm plasterboard, or equivalent)
- a cavity separation between the two walls of the modules
- good sealing of all joints
- a mineral fibre quilt within one or both of the layers or between the layers.

A layer of plasterboard fixed to the outside of the light steel members of each unit, as an external sheathing layer for weather protection also to improves acoustic insulation.

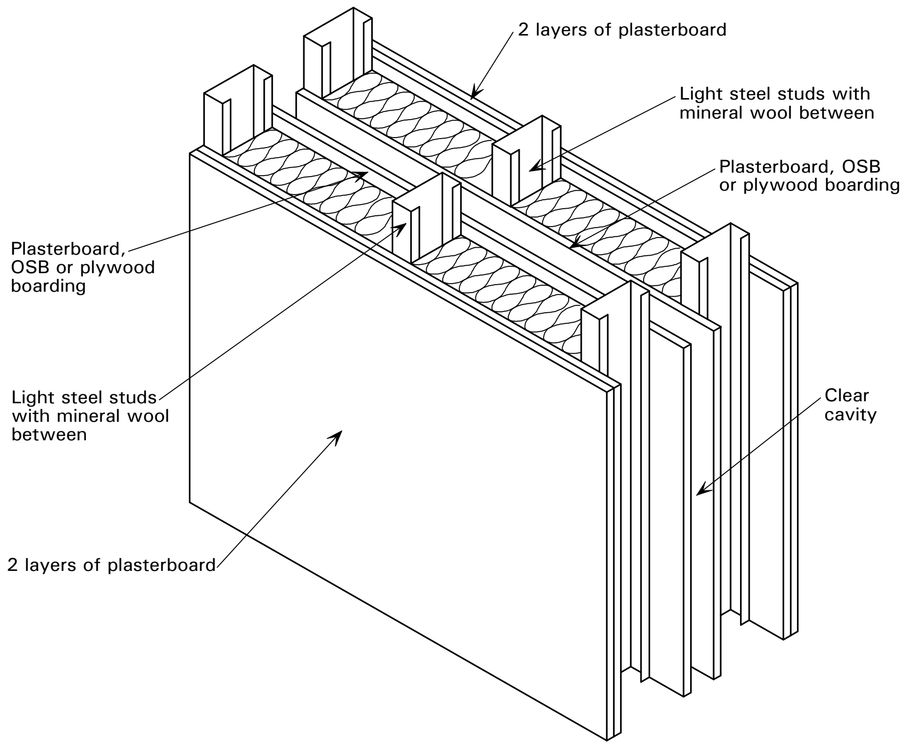


Figure 3.8 *Typical separating wall in a modular building*

3.3.5 Separating floors

For separating floor constructions between dwellings, both airborne and impact sound transmission must be controlled within the limits of Approved Document E (see Table 3.7). Typical data from modular buildings is also given in the Table; the values exceed the requirements by a significant margin, especially for impact sound reduction.

Table 3.7 *Acoustic performance of separating floors*

	Airborne sound insulation (D_{nTw})	**Impact sound transmission (L_{nTw})**
Requirements of Approved Document E	>52 dB	<61 dB
Measured in modular hotel - Peterborough	57 dB	48 dB
Measured in prototype modular building	62 dB	49 dB

Figure 3.9 shows a typical separating floor in a modular construction. As for walls, the separation of the floor and ceiling of adjacent modules provides excellent acoustic insulation. A mineral wool quilt between the floor or ceiling joists provides further acoustic insulation. Two layers of plasterboard on the ceiling and an appropriate walking surface for the floor (such as 22 mm cement particle board or 22 mm chipboard on a 19 mm plasterboard) provide sufficient mass. Such a floor can achieve airborne sound insulation above 60 dB and an impact sound transmission below 50 dB, without the use of resilient layers.

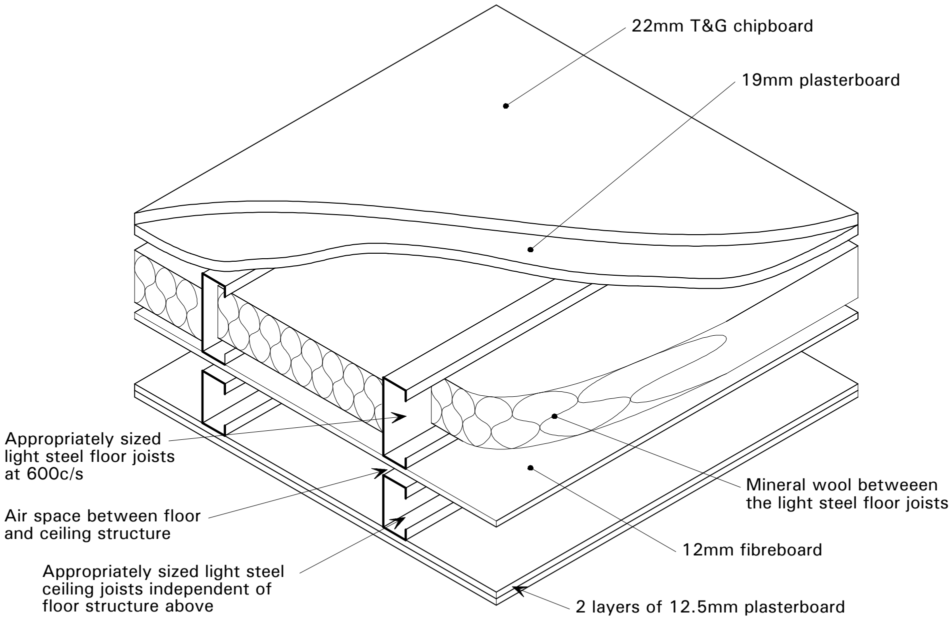


Figure 3.9 *Typical separating floor details in a modular building*

Further enhancement of acoustic performance of floors can be achieved by:

- Use of resilient bars to mount the plasterboard on the ceiling and the walls. This reduces the direct transfer of sound into the structure.
- Use of neoprene acoustic pads to separate the steel at structural joints, reducing transfer of sound at the structural connections. A typical detail is shown in Figure 3.10. However, the specific detail is dependent on the system used.

- A 'built-up' floor, consisting of several layers, including a resilient layer. Such a floor may consist of a base layer of OSB, plywood or chipboard with a 30 mm floating floor grade mineral wool (with a density between 60 and 100 kg/m^3) and 19 mm plasterboard below a 18 mm chipboard floor finish.
- An acoustic mat on the upper surface of the floor.

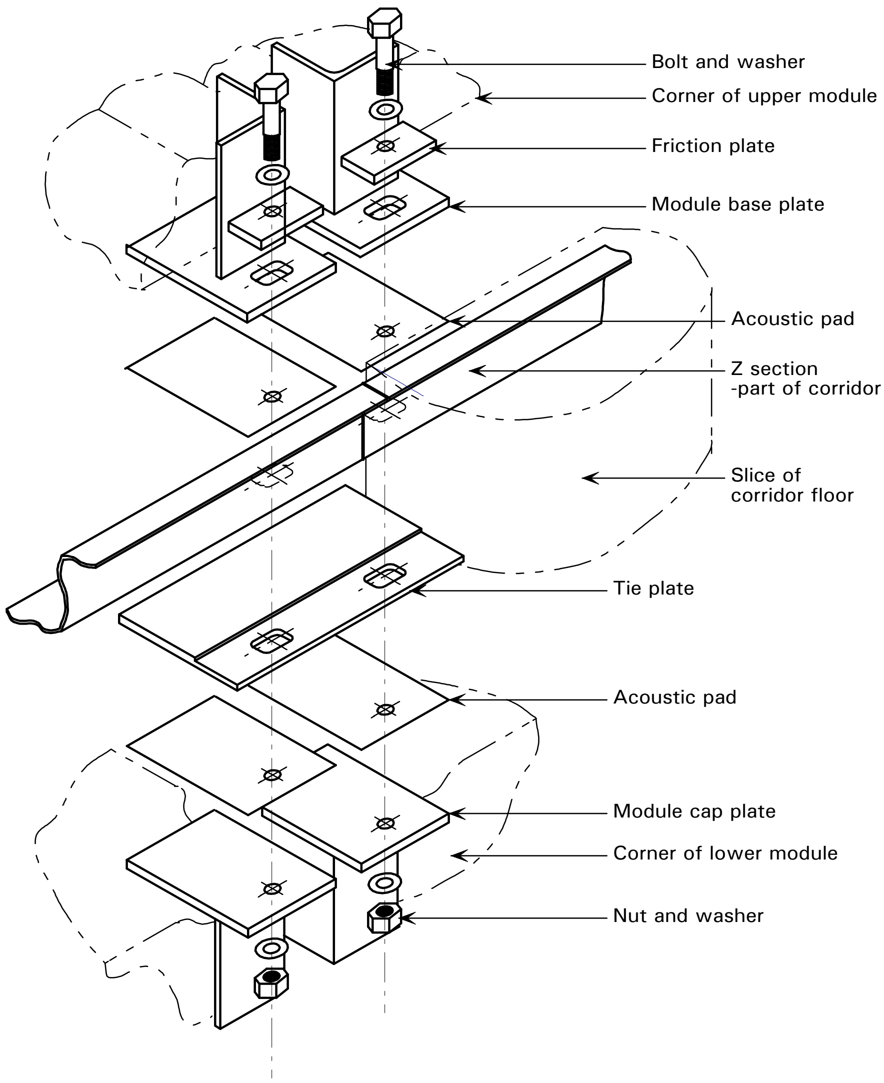


Figure 3.10 *Acoustic pad in structural connection to minimise sound transmission*

3.3.6 Flanking transmission

'Flanking' transmission occurs when airborne sound travels around the separating element of structure through adjacent building elements. Flanking transmission is difficult to predict because it depends on the particular configuration and the quality of construction on-site. Often flanking transmissions can add 3 to 7 dB to the sound transfer of similar constructions that are tested acoustically in the laboratory.

The separation of the structures of the modular units reduces the effect of flanking transmission significantly. However, it is also important to provide adequate sealing around any joints or service penetrations, including where walls meet other walls and floors, as even a small gap can lead to a marked deterioration in performance (see the following Section).

3.3.7 Penetration of linings

The Building Regulations allow wall linings to be penetrated so that services pass through the void, provided that fire and acoustic integrity is maintained. Since acoustic insulation can be particularly affected by air paths between spaces, special care is taken around openings for service pipes and other penetrations.

The following aspects related to penetration of linings should be noted:

- The location of electric sockets and switches should be carefully considered and back-to-back installations should be avoided, especially in separating walls.
- The joints of successive layers of boarding should not be coincident.
- Acoustic quilt or cavity barriers should be used, where appropriate, to seal air gaps and minimise flanking sound transmission, including that from floor to floor.
- There are no restrictions on the proximity of windows.
- If electric sockets in separating walls cannot be avoided, they should be backed by mineral wool, preferably with two layers of plasterboard (see Section 4.4).

Electrics are often installed in pre-formed ducts in the factory, which facilitates commissioning on-site and allows additional precautions to be made to ensure that they do not compromise acoustic performance.

3.4 Thermal performance

Part L of the Buildings Regulations requires that reasonable provision shall be made for the conservation of fuel and power in buildings by:

- Limiting the heat loss through the fabric of the building.
- Controlling the operation of the space heating and hot water systems.
- Limiting the heat loss from hot water vessels and hot water service pipework.
- Limiting the heat loss from hot water pipes and hot air ducts used for space heating.

Approved Document L sets out the minimum requirements for thermal insulation of new buildings and extensions that comply with Part L. The insulation properties are expressed in terms of U-values. Light steel constructions can achieve a high level of thermal insulation economically and without leading to excessive wall thicknesses. Walls with U-values below 0.2 W/m^{2}K are easily achievable.

Approved Document L is due to be revised in 2002, with further revisions planned in 2003 and 2005. It is expected that thermal performance requirements for buildings will be increased progressively. In particular, U-values are expected to be reduced significantly from the current 0.45 W/m^{2}K for external walls to 0.31 or 0.35 W/m^{2}K, in 2001 and later to 0.27 or 0.3 W/m^{2}K in 2003 (depending on the type of heating system used). Requirements for control of air infiltration may be introduced into the Regulations.

3.4.1 Insulation of the building fabric

The Part L requirements for the building fabric can be met either by meeting the maximum U-value requirements which are set out in the Approved Document or by achieving a SAP energy rating (see below).

Elemental method

The *Elemental Method* in Approved Document L specifies the maximum U-values of the elements of the building fabric. In the proposals for the revision to Approved Document L, the maximum U-values are different for buildings with efficient gas heating from those with electric heating and inefficient gas or oil heating. The U-values achieved by light steel framing systems generally exceed the existing requirements and can readily meet the proposed new requirements.

Table 3.8 provides guidance on the typical U-values of external walls that can be achieved with various forms of modular construction.

Table 3.8 *U-values of external walls in modular buildings*

Wall construction	Insulation	U-value (W/m^{2}K)
Light steel frame with external insulation and brickwork	45 mm polyurethane 90 mm polyurethane	0.41 0.25
Light steel frame with insulation between the studs and brick work	100 mm mineral wool between the studs and 25 mm insulated sheathing	0.31
Light steel frame with insulation between the studs and externally finished with render or cladding	100 mm mineral wool between the studs and 50 mm mineral wool on the outside of the studs	0.26

Target method

A more flexible *Target Method* sets out a calculation procedure that defines a target U-value for the whole dwelling, which should not be exceeded. This allows more flexibility of trade-off between elements. The resulting target will give a heat loss for the whole building close to that which would be achieved if complying by the Elemental Method.

SAP rating of buildings

The *Standard Assessment Procedure* (SAP) [26] is an energy rating method for new dwellings. A rating of 1 (poor) to 100 (good) is awarded. The SAP rating can be calculated by computer program or manually. SAP energy ratings of 80 to 100 are readily achievable using light steel framed constructions.

In future, when the Approved Document L revisions come into effect, the SAP will be converted to a Carbon Index, which will be used as one method of satisfying the requirements of Part L of the Regulations.

The SAP calculation considers the insulation and glazing levels and the efficiency of the heating system and fuel used. Typical light steel frame constructions achieve good standards of insulation and, with a standard gas central heating system, will have little difficulty in exceeding the SAP requirements.

The National Home Energy Rating (NHER) assessment method [27] is a commonly used alternative energy rating to SAP. This provides an energy rating of 0 (poor) to 10 (good). Light steel frame dwellings can readily achieve NHER scores of between 8 and 10.

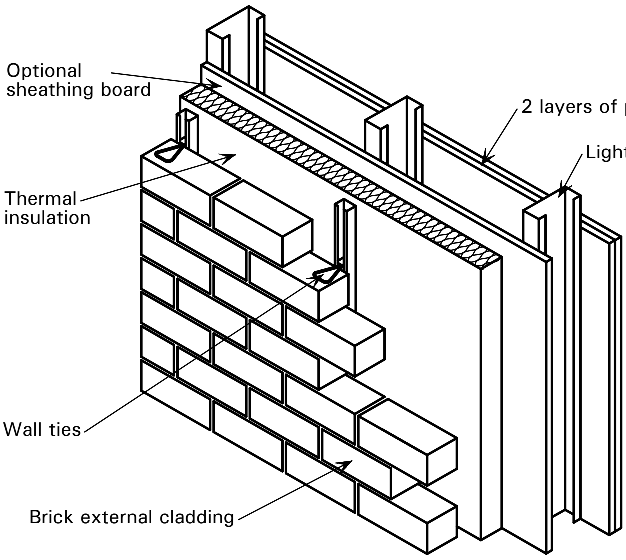
3.4.2 Location of insulation

The effect of thermal bridges through the envelope should be considered in the U-value calculation. In framed construction, it is important to minimize the thermal bridging that may occur as this can increase heat loss significantly and cause local surface condensation and staining of the interior surface (ghosting).

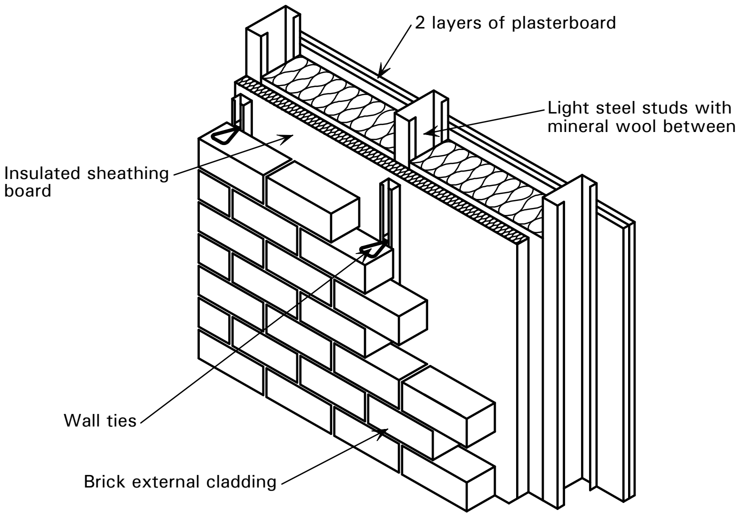
Modular units using light steel framing generally adopt the 'warm frame' approach, where most or all of the insulation is placed on the outside of the structure (see Figure 3.11a). This reduces the effect of the steel acting as a thermal bridge through the insulating layer. Supplementary insulation can be placed between the studs but the amount of insulation should be less than that used externally, unless measures are taken to control humidity within the building. Alternatively, where condensation risk is low, insulation can be placed between the steel studs together with an insulating sheathing board on the outside of the frame (See Figure 3.11b). Some modular manufacturers also use steel furring runners as spacers on the inside of the steel studs. The plasterboard is fixed to these furring runners, which also act as a thermal break (Figure 3.11c).

Some modular unit manufacturers may not wish to fix insulation on the outside of the frame in the factory, unless the cladding is also to be factory-fitted. This is because the insulation can be damaged during transport of the module. Ideally, factory fitting of all insulation is preferable.

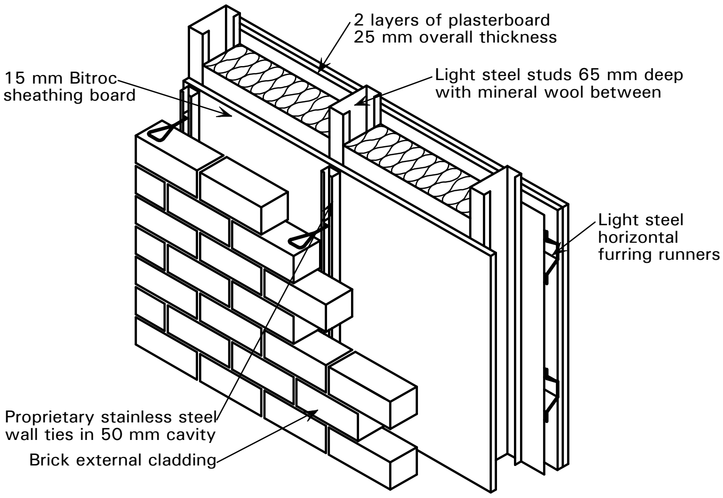
Detailing around openings should minimise thermal bridging. In traditional construction, thermal bridges commonly occur around window and door openings and at the junction of walls with floors and roofs, and can significantly increase heat loss. The 'warm frame' principle ensures the insulation in a module to be continuous right up to the window or door frame. This avoids the cooler wall surfaces that may occur around openings.



a) Warm frame construction



b) Insulated sheathing and insulation between the studs



c) Insulation between the studs and furring runners as a thermal break

Figure 3.11 *Alternative configurations of insulation in external walls*

3.4.3 Airtightness

Approved Document L does not give specific targets for air infiltration. The proposed revisions require that buildings should achieve a nominal maximum air change rate of $10m^3/m^2/hr$. However, air leakage testing will not be required for residential construction. Other countries, such as Sweden and Canada, already have strict air infiltration standards and regular testing. Space heating demand is significantly affected by infiltration of cold outside air through cracks and gaps in the building envelope. Air movement within a construction assembly also increases the risk of interstitial condensation.

Many of the potential air-leakage paths can be eliminated at the design stage by careful consideration of the details. Airflows through the structure can be prevented or reduced by means of a continuous barrier, which can be the vapour barrier or some other element of the envelope such as plasterboard. This air barrier should be effectively sealed at all junctions, and penetrations should be avoided.

Modular construction has the benefit of factory assembly, where attention is paid to ensuring a good quality of workmanship. Thus, the correct installation of an effective air barrier and sealing of cracks and gaps in the construction can be given careful attention. This is also helped by good quality control and inspection procedures.

Many modular manufacturers install a protective polythene sheeting around each unit to prevent damage during delivery and installation (Figure 3.12). After it is positioned on-site, this wrapping should be removed, particularly from the faces of the module which form the external face of the building. This is to avoid interference with moisture migration through the external envelope.

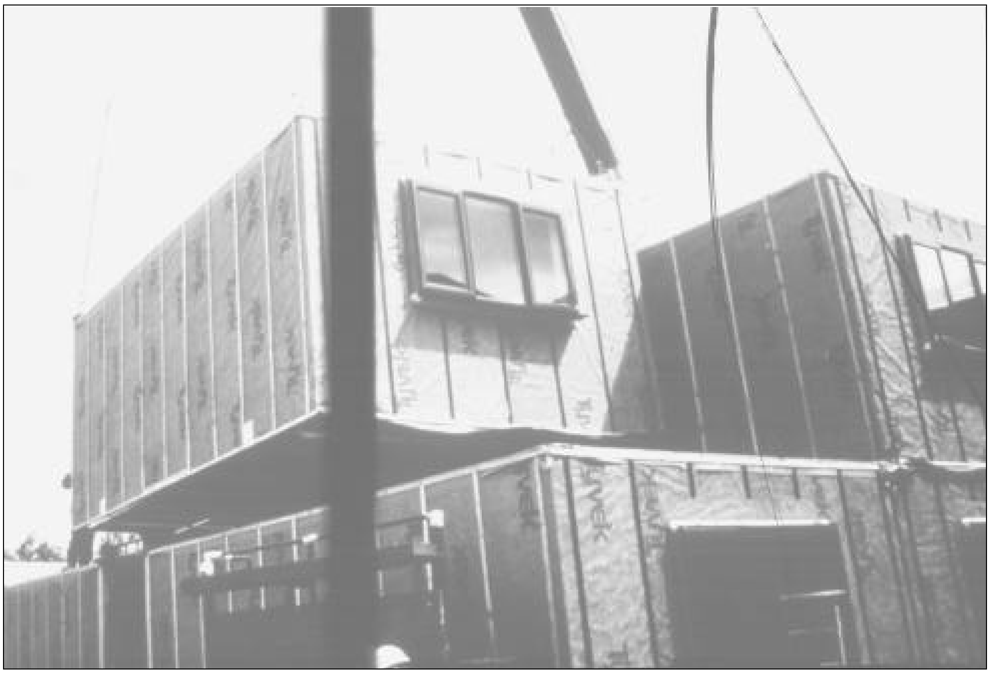


Figure 3.12 *Installation of a module with its protective covering*

3.4.4 Control of condensation

It is implicit in the requirements for thermal insulation that condensation is avoided both within the construction elements and on the internal surfaces. Condensation within the thickness of the wall can be more serious if it goes unnoticed, as it can damage the fabric of the building.

'Warm frame' construction ensures that the internal surface temperatures on the walls along the steel framing elements do not fall to below the dew point temperature. This prevents 'ghosting', where local condensation causes discolouration of the wall surface along the lines of the studs. Alternatively, insulated sheathing boards can be used with some insulation between the studs. Building Research Establishment guidance [28] suggests that, in order to avoid ghosting, internal surface temperatures should not fall below 15.5°C.

In modular construction, interstitial condensation on the steel elements is avoided by locating the steel frame within the insulated cavity, or ensuring that there is an effective vapour control layer to prevent water vapour reaching the colder part of the wall. Where insulation is placed between the studs, the increased thermal conductivity of the steel studs means that the temperature of the steel along the web and at the outer flange is greater than in the adjacent insulation. This reduces the likelihood of condensation on the studs.

Off-site construction also ensures that vapour barriers are correctly fitted, reducing the risk of interstitial condensation.

3.5 Durability

Galvanizing zinc protection alone provides adequate durability of light steel frame construction in internal applications not directly exposed to moisture for long periods. The standard coating is G275 (275 grams/m^2 summed over both faces).

As for traditional construction, attention to design and construction details is essential. Control of moisture ingress and condensation, including the correct positioning of thermal insulation and the use of damp proof courses (DPC), damp proof membranes (DPM), vapour control layers and flashings, ensures good performance.

The connection of the light steel frame should be isolated from the foundations by the use of DPC and DPM, as this is a particular area that requires care to avoid contact with moisture. Furthermore, when a brick cavity wall is used, it is important to ensure that a clear cavity is maintained and correctly detailed to avoid moisture bridging the cavity.

When using galvanized steel, damaged areas of corrosion protection, e.g. at weld zones, must be reinstated by treatment with an appropriate zinc-rich paint. For this treatment to be fully effective, these areas must be thoroughly cleaned by wire brushing, primed and coated with two coats of a zinc rich paint having a zinc content of at least 96%, or with an equally effective alternative protection system.

In the following situations, sacrificial loss of zinc coating occurs in local areas, protecting the exposed edges of steel against corrosion. No further attention is required for:

- Member ends, which have been cut in the factory.
- Holes for bolts or services that have been punched in the factory.
- Penetrations made by self-drilling self-tapping screws.

In 'warm frame' or modular construction, the frame components achieve a design life of over 100 years, provided that the building envelope is properly maintained. Guidance on these applications is given in *Durability of light steel framing in residential building*[29].

Special consideration should be made to semi-exposed or fully exposed applications such as:

- Supports directly in contact with the ground.
- Suspended ground floors.
- Exposed components, such as balconies.

Bitumen coating may be used for steel elements, as contact with the foundations, although the structure should be insulated by a DPC.

In the case of light steel joists used in suspended ground floors, it is recommended that the soffit below the joists should be insulated to create a 'warm frame', and the ground should be protected by a concrete covering or other impervious layer (see Section 4.1.4).

4 INTERFACES WITH FOUNDATIONS, CLADDING AND SERVICES

This Section describes the various interfaces between modular units and other components in the building that may not be under the control of the modular manufacturer. The responsibility for design and coordination usually lies with the building designer (see Section 2).

4.1 Foundation interfaces

4.1.1 Foundation types

A variety of foundations can be used, including strip, trenchfill, pad and piled foundations, some of which are illustrated in Figure 4.1. Precast concrete pile systems are often used and they extend the prefabrication process. They are applicable to most ground conditions and can speed up the groundworks phase of the work. Further inspirations on pile foundations is given in *Composite ground floors and piling for housing*[30]. However, strip or trenchfill foundations are most common.

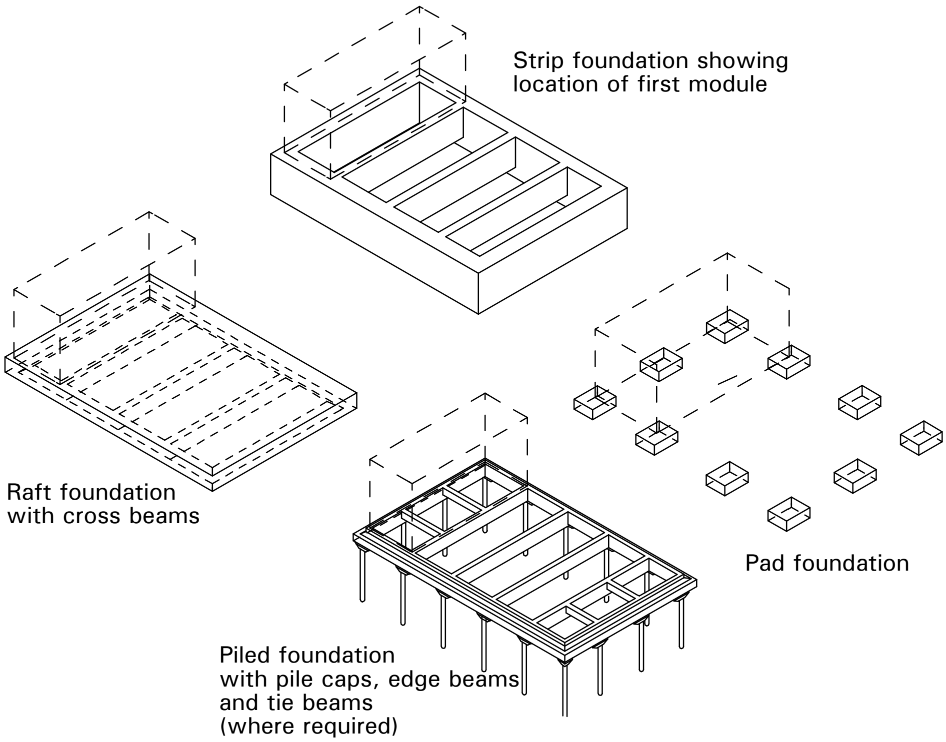


Figure 4.1 *Alternative foundation options for modular units*

Modular units are lightweight and therefore foundations may be smaller than in conventional construction. Nevertheless, the cladding options and building height may dictate the foundation design.

With strips, rafts or ground beams, the modular units can be designed to be continuously supported around the perimeter of each unit or to be supported at four points only, in which case the walls or spine beam are designed to span between the support points.

The simplest form of trenchfill foundation detail for a wall with brickwork cladding is illustrated in Figure 4.2. The required accurate level for the base of the units is provided by dense concrete blocks and cement particle board. The foundation also supports the brickwork cladding.

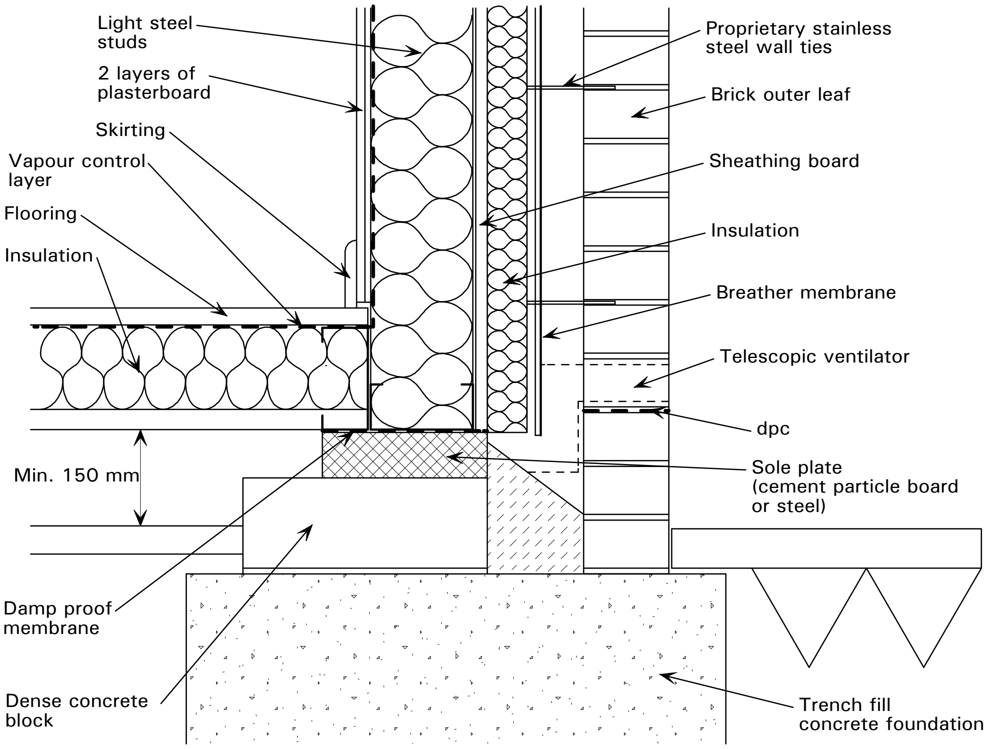


Figure 4.2 *Typical trenchfill foundation detail for masonry cladding*

4.1.2 Installation tolerances

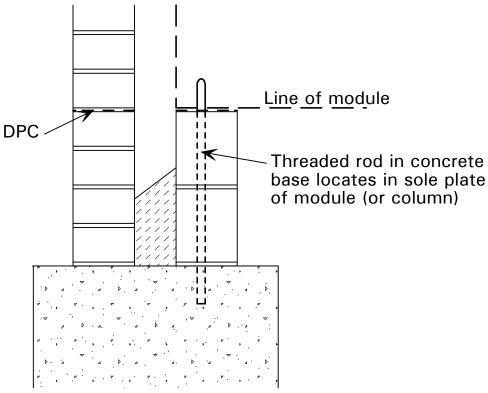
For installation of the modules, the maximum tolerances are listed below:

- Length of wall frame +/- 10 mm in 10 m
- Line of wall frame +/- 5 mm from outer face of plate
- Level of module sole plate +/- 5 mm over complete module.

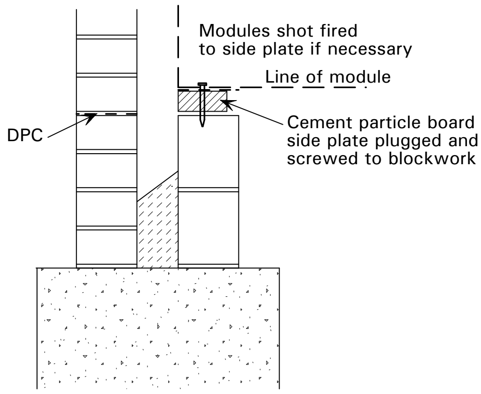
At foundation level, the deviation between the foundation and the sole plate at the ground floor module must be corrected by steel shims, or by levelling screws or other devices. A maximum depth of shims of 20 mm is permitted., the diagonals of a rectangular plan form will be equal.

4.1.3 Levelling of units

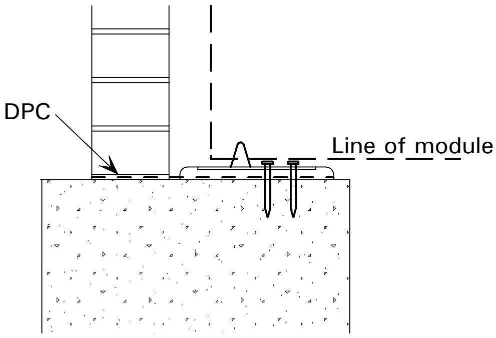
The levelling of the foundations or ground beams is crucial to the subsequent installation and alignment of the modular units. The modular manufacturers have developed their own proprietary locating and fixing mechanisms to aid the positioning of units on the foundations, as shown in Figure 4.3.



a) Vertical pins



b) Cement particle board pads



c) Steel plate (can be located on epoxy resin to provide tolerances)

Figure 4.3 *Typical locating arrangements*

Generally, base plates , strips of steel, or cement particle board are fixed to the foundations and grouted and levelled as necessary. They are used to take up any inaccuracies in the level of the top of foundations. A variation in level in the top of the foundations of up to 20 mm can be accommodated.

Generally, the shear attachment of the base plate to the foundations uses resin anchor bolts. In some cases, vertical pins cast into the base plate are used to locate the modules (Figure 4.3a). These pins prevent lateral forces due to wind loads. Alternative details are illustrated in Figures 4.3b and 4.3c.

The self-weight of the units is often sufficient that holding down of the modules is not necessary. However, where bolting down is necessary, this can be achieved through the base plates to the modules.

The trenchfill or strip foundation can also be used as support for brickwork. Other lightweight claddings can be supported directly by the light steel framework of the modular units (see Section 4.2).

4.1.4 Resistance to moisture

Particular attention must be paid to the details at the interface between the superstructure and the foundation to minimise the risk of corrosion. The light steel frame should be located entirely above the DPC level of the brickwork. In circumstances where this cannot be achieved, a thickness of corrosion protection equivalent to Z460 galvanizing, or a suitable bituminous coating should be applied to all steel components below DPC level.

Modular construction generally uses a suspended ground floor. For such floors, Approved Document to Part C of the Building Regulations requires a ventilated air space beneath the floor; this must be at least 150 mm from the top of the ground cover to the underside of the suspended floor structure and at least 75 mm to the underside of any wall plate (see Figure 4.2). There must also be a DPC between the steel and any material subject to ground moisture. The ground must be covered with a layer of suitable material to resist moisture and prevent plant growth. This is generally achieved by using either 100 mm of concrete or a polythene layer with 50 mm of concrete. The underfloor void is usually drained to prevent a build up of moisture.

To ensure cross ventilation, a free path must be maintained across the building and two opposing external walls should have ventilation openings, giving an open area of at least 1500 mm^2 per metre run of wall.

4.1.5 Radon gas infiltration

Part C2 of the Building Regulations requires that in certain areas of the UK, measures must be taken to protect against leakage of radioactive Radon gas from the soil into the building. Also, some sites, particularly brownfield sites, are affected by methane build up in the soil and this should be prevented from entering the building. The Building Regulations define which areas of the UK are required to investigate whether there is Radon present at any site. Guidance on the construction of buildings in Radon-affected areas is given in BRE publication *Radon: Guidance on protective measures in new dwellings*[31]. Similar precautions are necessary for methane affected sites.

The precautions focus on providing an airtight barrier across the underside of the building, including across any cavity in the external wall and between modules, and with the provision for ventilation beneath a suspended floor.

Generally in modular construction, two alternative approaches are possible:

- A Radon barrier can be included in the over-site concrete beneath the modular units. In a building clad in brickwork, the radon barrier must be taken across the cavity. With other forms of cladding, the radon barrier must be lapped with any vertical membrane.
- A Radon barrier can be incorporated into the floor of the modular unit. This must also be lapped with a vertical membrane in the wall and prevent Radon entering the vertical gaps between the modular units. Furthermore, the floor void beneath the modular unit must be ventilated sufficiently to vent away any build up of gas. Measures to achieve this will vary depending on the concentration of Radon at the site, but they may require mechanical ventilation or the provision of vertical suction pipes to the top of the building.

Attention should also be paid to:

- Detailing of joints between membranes to ensure they are well sealed.
- Service entries that penetrate the membrane should be avoided or, if necessary, well sealed.

- Service ducts that penetrate the membrane and may act as routes for the gas to enter the building, should be sealed internally.
- The connections between the modular units.

4.2 Wall cladding interfaces

The purpose of wall cladding is to provide weather resistance and to create the desired external appearance. Claddings for modular buildings can be self supporting vertically and only supported laterally by the units. Alternatively, they can be supported entirely by the modular structure.

Two generic systems of facade construction may be considered:

- Cladding that is placed entirely on-site using conventional techniques.
- Cladding that is completely or partially attached in the factory; infill pieces or secondary cladding may be fixed on-site.

Examples of cladding materials falling into the first category are:

- Brickwork, which is supported vertically by the foundations and laterally by the structure.
- Cementitious render applied to rigid insulation.
- Steel panels or sheeting attached to sub-frames or directly to the structure.

It is not normally practical to use brickwork for buildings over 12 m height because separate vertical support is required (see Section 4.2.1).

Examples of cladding that can be pre-attached to the modular units are:

- Cassette panels with infill pieces that are placed over the joints between the units.
- Panels with brick slips or tiles in which the joints between the units are either emphasised or concealed for architectural effect (see Figure 4.4).

Approved Document B requires the use of non-combustible claddings within 1 m of a site boundary and limits the size of openings and other ‘unprotected areas' on elevations near the boundary.

Cavity barriers must also be incorporated into any cavity that occurs between the external cladding and the modular structure. These must resist the spread of smoke and flame and are required between all separate dwellings or fire compartments (see Section 3.2.6 for details). Mineral wool is generally used.

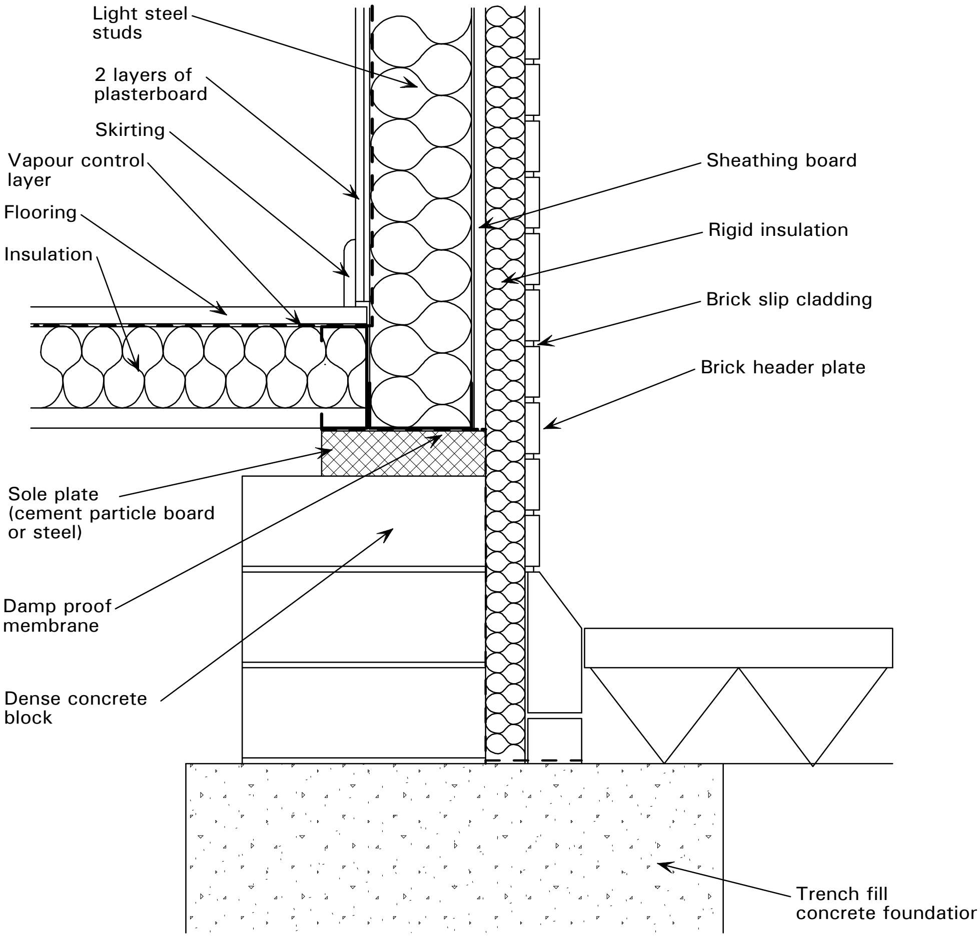


Figure 4.4 *Foundation details when using lightweight cladding*

4.2.1 Masonry cladding

Brickwork supports its own weight (on strip foundations) and transmits lateral loads to the modular structure via wall ties bonded into the brickwork and attached to the structure. The ties are placed at a density of 2.5 ties/m^2 of the facade. In light steel framing, this is achieved by 'Chevron' shaped ties attached to the structural sheathing, or by attaching vertical tracks through the insulation to the structure. These vertical tracks are usually placed at 0.6 m spacing and therefore ties should be attached every 5 or 6 brickwork courses, as shown in Figure 4.5.

Brickwork should comply with BS 5628 [32]; it recommends expansion joints in the brickwork to allow for lateral movement of 10 mm at 10-12 m centres (for clay bricks). Further guidance on brick cladding design is available from the Brick Development Association.

In general, the modular units only provide lateral restraint to the brickwork. However, for buildings over 12 m height, it may be necessary for the brickwork to be vertically supported by the modular units. Separate supports at each or alternate floor levels should be provided, and the modular units should be designed to resist these additional vertical loads, as illustrated in Figure 4.6. Lintels in the brickwork should be structurally independent of the modular structure.

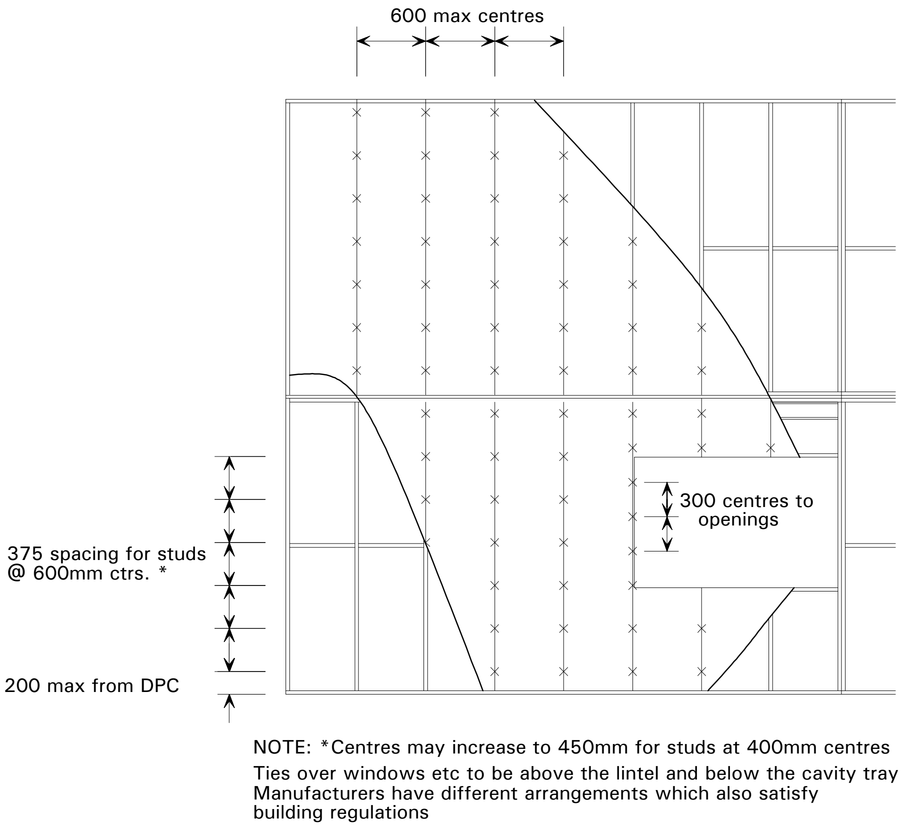


Figure 4.5 *Recommended brick tie spacings*

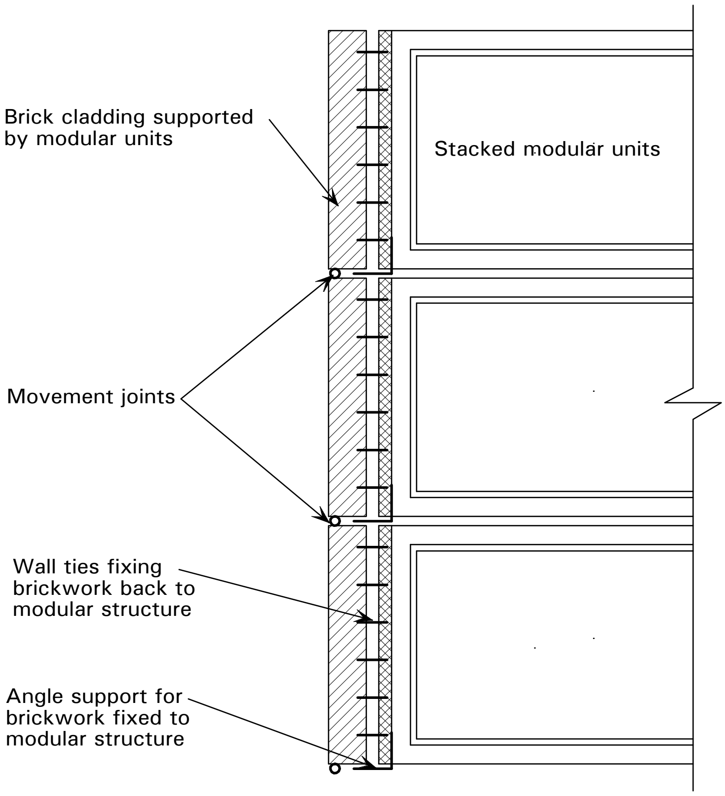


Figure 4.6 *Brickwork supported by the modular structure with additional movement joints*

The cavity between the modules and the external brickwork should be self-draining and openings should be provided for drainage along the bottom DPC and at any cavity trays over openings. Cavity barriers should be provided to prevent the passage of smoke (see Section 3.2.6).

Brickwork requires its own foundation and placing of brickwork is a site activity that can be slow. For tall walls, careful detailing around openings is required to accommodate differential vertical movement. Brickwork should comply with BS 5628 and a wide range of clay and calcium silicate bricks can be used.

Figure 4.7 illustrates the attachment of brickwork in 'warm frame' construction, and shows the vertical channels for attachment of the wall ties. The channels are screwed through the insulation to the steel studs using off-set screws. Figure 4.8 illustrates an alternative configuration of wall with an insulated sheathing board and additional insulation placed between the steel studs.

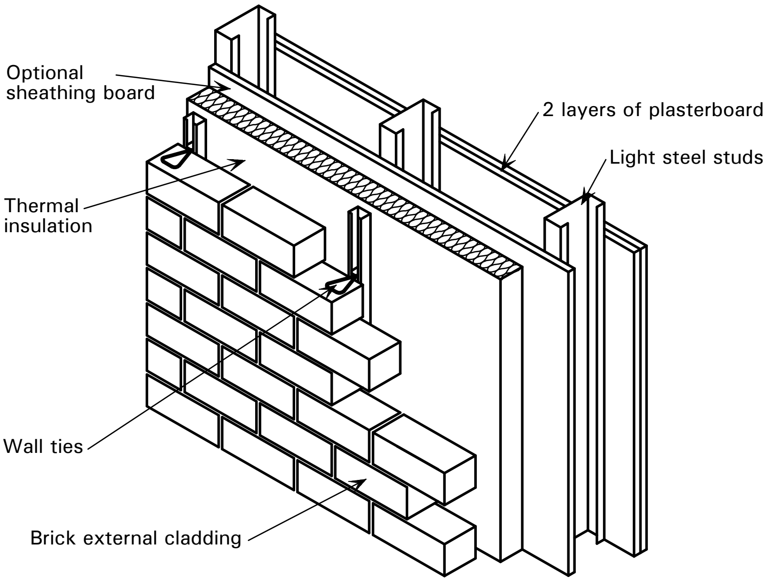


Figure 4.7 *Brick cladding in 'warm frame' construction*

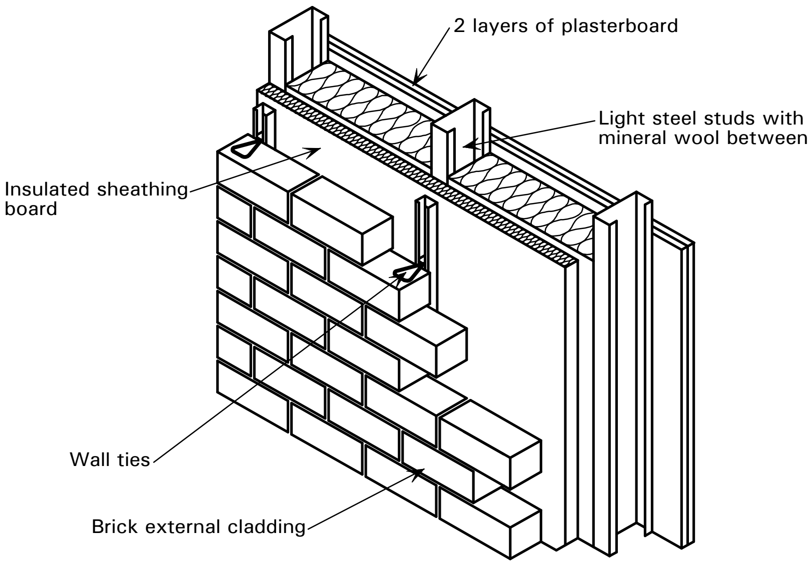


Figure 4.8 *Brick cladding on insulated sheathing board with insulation also located between the studs*

4.2.2 Lightweight cladding

Lightweight cladding is supported directly by the modular units and the additional loads should be considered in the design of the units. Lightweight cladding may be in the form of profiled sheeting, liner trays, cassette panels or composite panels. Profiled sheeting, liner trays and composite panels are linear elements, whereas cassette panels are discrete square or rectangular elements with typical dimensions between 600 and 1200 mm.

In many cases, a secondary sub-frame, usually of steel or aluminum, is required to support these cladding elements. The sub-frame is isolated from the internal structure to avoid cold bridging. Some lightweight claddings can be fixed directly to the modular units in the factory and the joints between units sealed on-site. This requires a high degree of dimensional discipline during both the design and construction phases of the project.

A typical cladding detail for lightweight composite panels is presented in Figure 4.9.

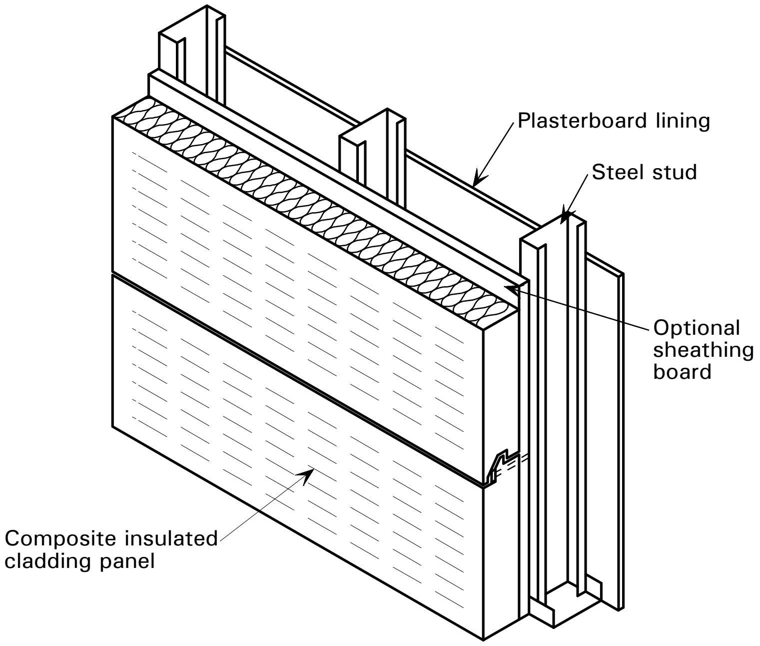


Figure 4.9 *Lightweight composite panels spanning horizontally*

The advantage of lightweight cladding supported directly by the modules is that differential movement between structure and cladding is negligible and movement joints are reduced or eliminated. In some cases, the cladding can be attached before delivery to site. Joints between the cladding panels are concealed by site flashings. This is possible when using cassette panels because small tolerances can be accommodated in the joints between the panels.

Tile or slate cladding

Vertical tile hanging, as shown in Figure 4.10, using concrete or clay tiles, or slates can be used in modular buildings and are supported by the modular structure. Such claddings are fixed to horizontal timber battens, nailed to vertical counter battens that are fixed back to the light steel framing. A breather membrane may be used behind the counter battens to prevent water ingress and ensure efficient drainage. The cavity behind the tiles should be closed by cavity barriers (usually mineral wool) (see Section 3.2.6).

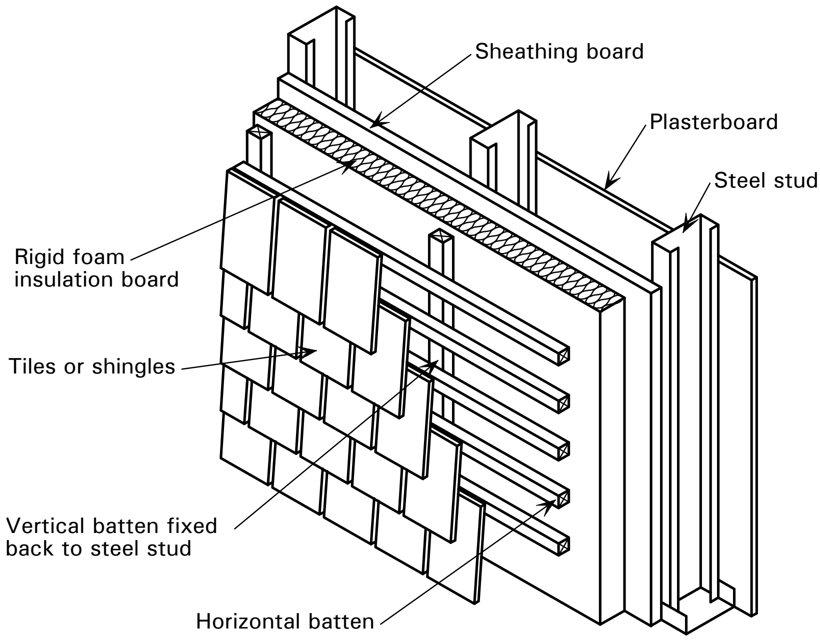


Figure 4.10 *Details of tile-hung cladding*

The detail design of the corners and junctions with other elements is important to the appearance and water resistance of tile-hung cladding. Attention should be given to window surrounds and building corners (as in Figure 4.11).

Rendered claddings

A variety of rendered claddings, supported directly by the modular structure, is now available for use on the external face of buildings (see Figure 4.12). These claddings offer a range of colours and surface finishes. They can be made to look very similar to other finishes such as brickwork or, alternatively, smooth finishes can be achieved. Patterns using different colours and textures are also possible.

Generally, renders can be divided into the traditional cement/sand based renders and newer polymer reinforced renders. Cement based renders are often 20 to 25 mm thick, and need regular maintenance. They require a solid sub-base or they can be applied to expanded stainless steel lathing fixed to timber battens. These renders require regular movement joints, particularly between adjacent modules.

Polymer reinforced renders are generally thinner (5 to 10 mm), lighter, tolerant to movement, and require less maintenance. These renders are usually reinforced by a polypropylene (or similar) woven mesh and can be applied to rigid insulation boards. The manufacturer's instructions should be followed with regard to installation, movement joints and all detailing around openings and at junctions. *BS 5262: Code of practice for external rendered finishes*[33] also provides further information on detailing of rendered claddings.

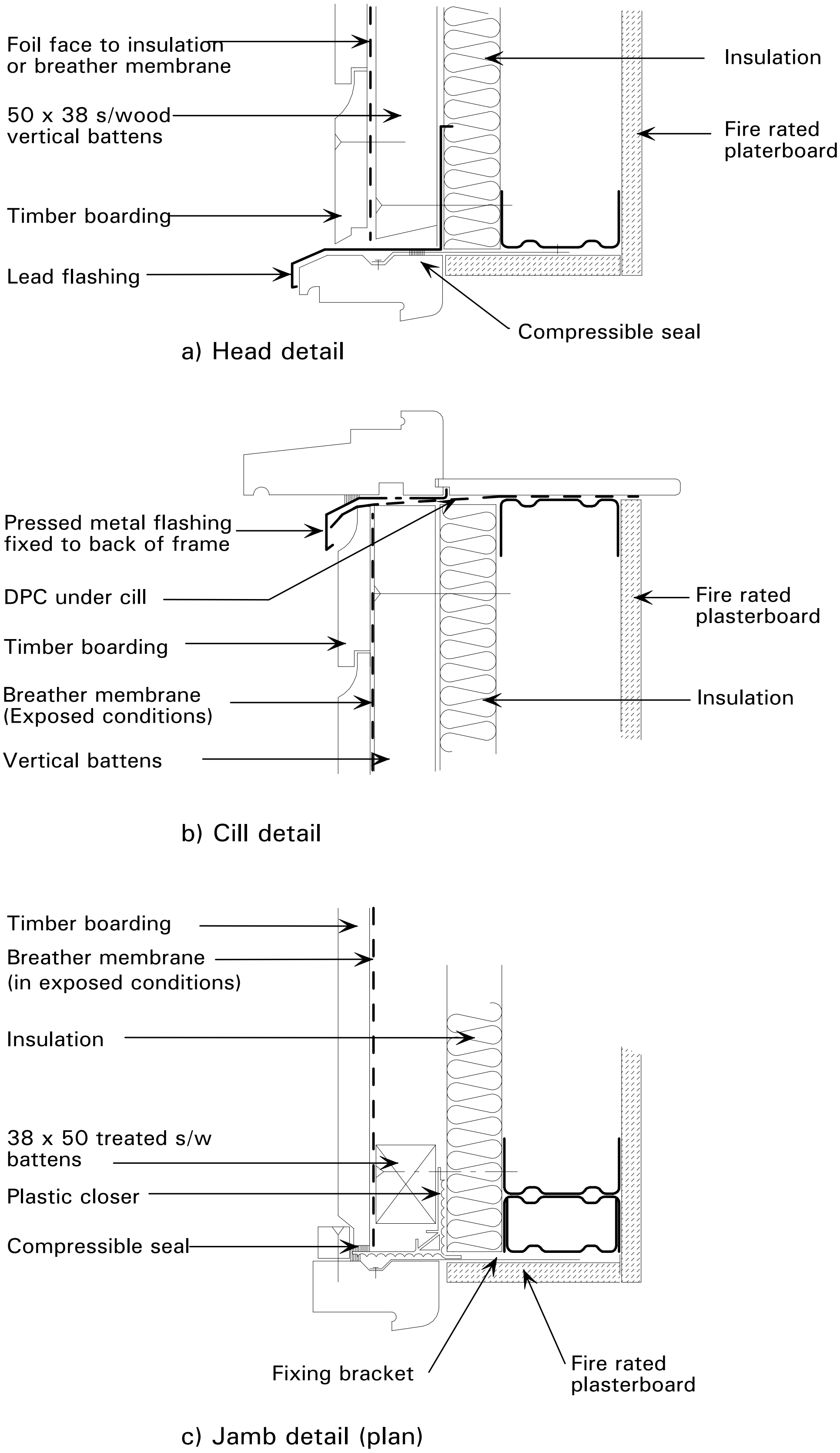


Figure 4.11 *Details of tile hanging at window and door openings*

Rendered claddings can be particularly suitable for use with modular construction, as it is possible to apply the cladding in the controlled environment of the factory and deal with the joints on-site after the modular units are in place.

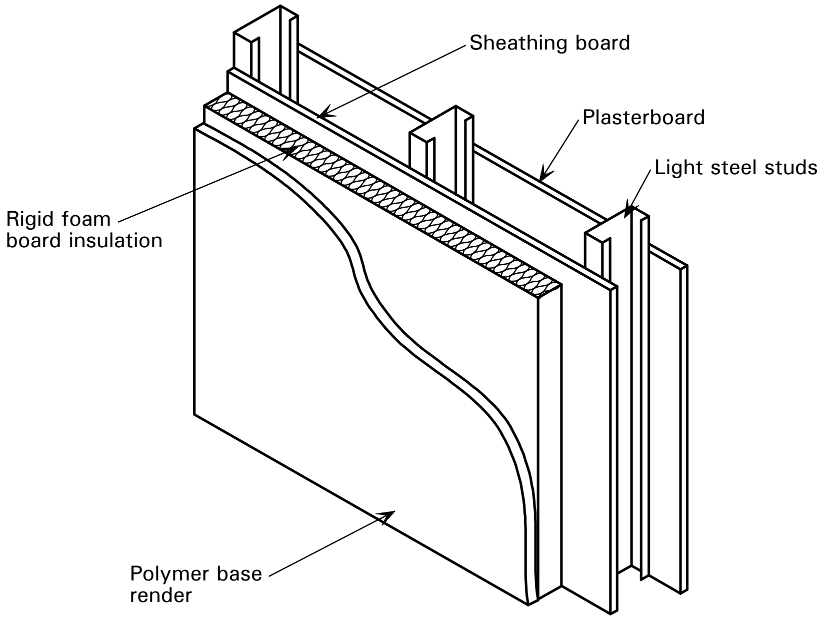


Figure 4.12 *Detail of polymer-based rendered cladding*

Timber based claddings

A variety of standard timber profiles is available for cladding. These can be planed or sawn, square edged or a variety of profiles such as tongue and grooved, shiplap, feather edged or waney edged boarding. They are supported directly by the modular structure, fixed using battens, counter battens (when necessary) and breathing paper fixed back to the light steel frame, as illustrated in Figure 4.13. Cavity barriers are also required (see Section 3.2.6).

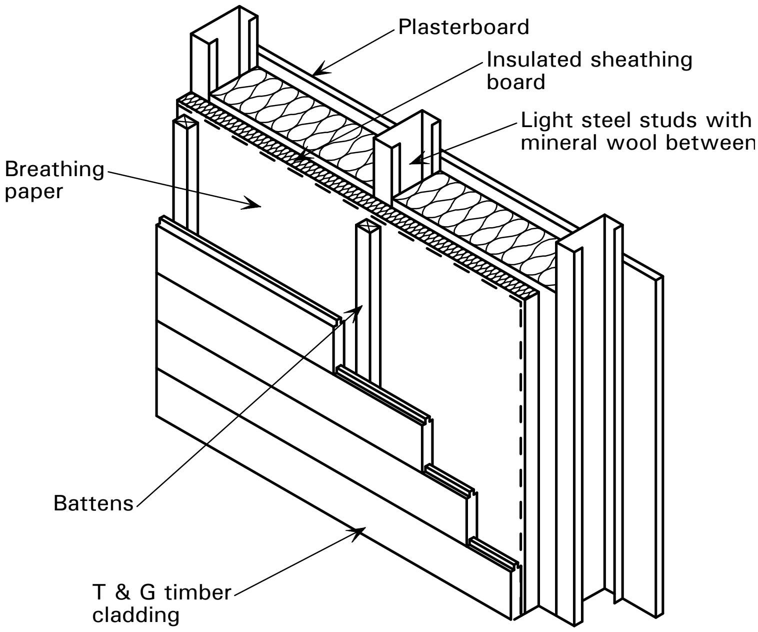


Figure 4.13 *Details of timber board cladding*

Such claddings are becoming more popular in residential buildings and are often used in conjunction with other forms of cladding, such as brickwork or renders. Some species of timber used for cladding, such as oak, cedar and larch, may not require any treatment or surface finish, and hence, little maintenance during their lifetime. Softwood claddings require preservative treatment and regular maintenance. BS 1186-3 [34] lists timbers and their treatments.

It is important to select a suitable profile for external use and to ensure that joints between the boarding do not trap water and to allow for seasonal movement. A minimum thickness of 16 mm is recommended by TRADA, and 19 mm is preferable. Galvanized or stainless steel nails should be used.

4.2.3 Openings for windows and doors

Window and door frames are generally fitted into the modular units in the factory and their detailing is generally similar to other forms of framed construction. The number of openings and area of glazing permitted in any one modular unit is limited only by structural requirements. If large openings are required, it may be necessary to incorporate some hot rolled steel elements into the structure of the unit.

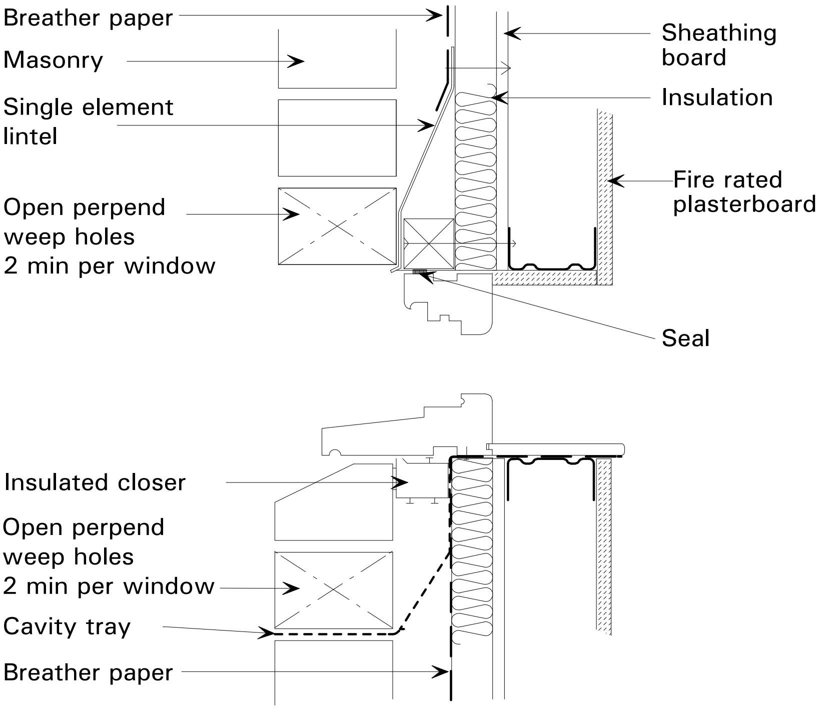
The external cladding must be detailed to fit around the openings with appropriate waterproofing details, as shown in Figure 4.14. Two alternative details are shown: a cavity brick wall and a tiled wall. The lintel provides support to the brickwork over the opening and is independent of the module.

4.2.4 Differential movements

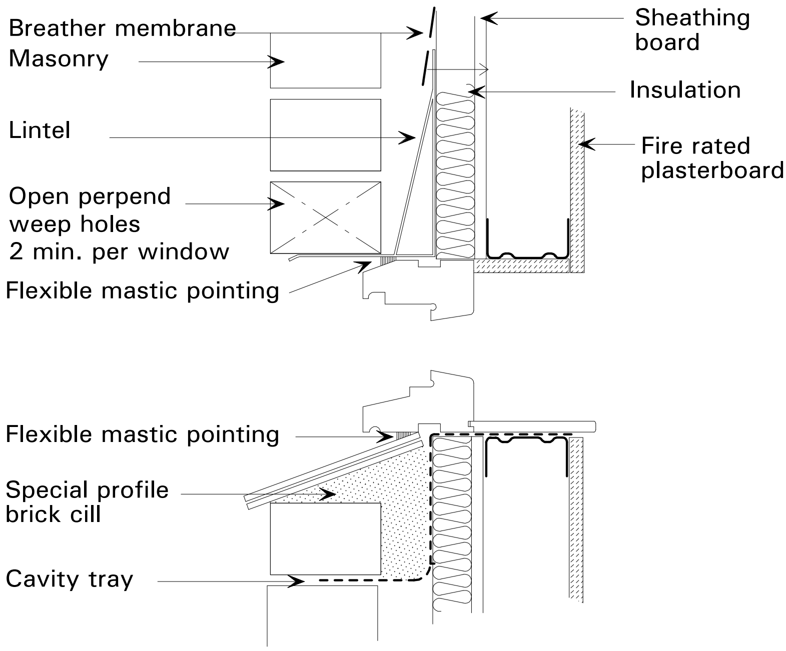
Although steel does not suffer from creep or shrinkage, adequate allowance should be made for differential movement between the cladding and modular structure. In particular, for self-supporting cladding such as brickwork, any component attached to the modular structure that protrudes into or past the external cladding, such as a window cill, vent or overflow pipe, must have an appropriate clear gap filled with sealant around it to allow for differential movement due to expansion of the brickwork (See Figure 4.15).

Movement between different types of cladding must be accommodated. For example, junctions between masonry cladding and lightweight claddings fixed to the modular units, must allow for differential movement, as illustrated in Figure 4.16.

For cladding materials such as cassette panels, timber boarding or tile hanging, movement is accommodated in the joints between components. However, more care must be taken to allow for movement joints in large areas of rendered cladding.



a) Cant brick cill



b) Tiled cill and head with lintel for wide openings

Figure 4.14 *Generic detail of openings in brickwork attached to modular units*

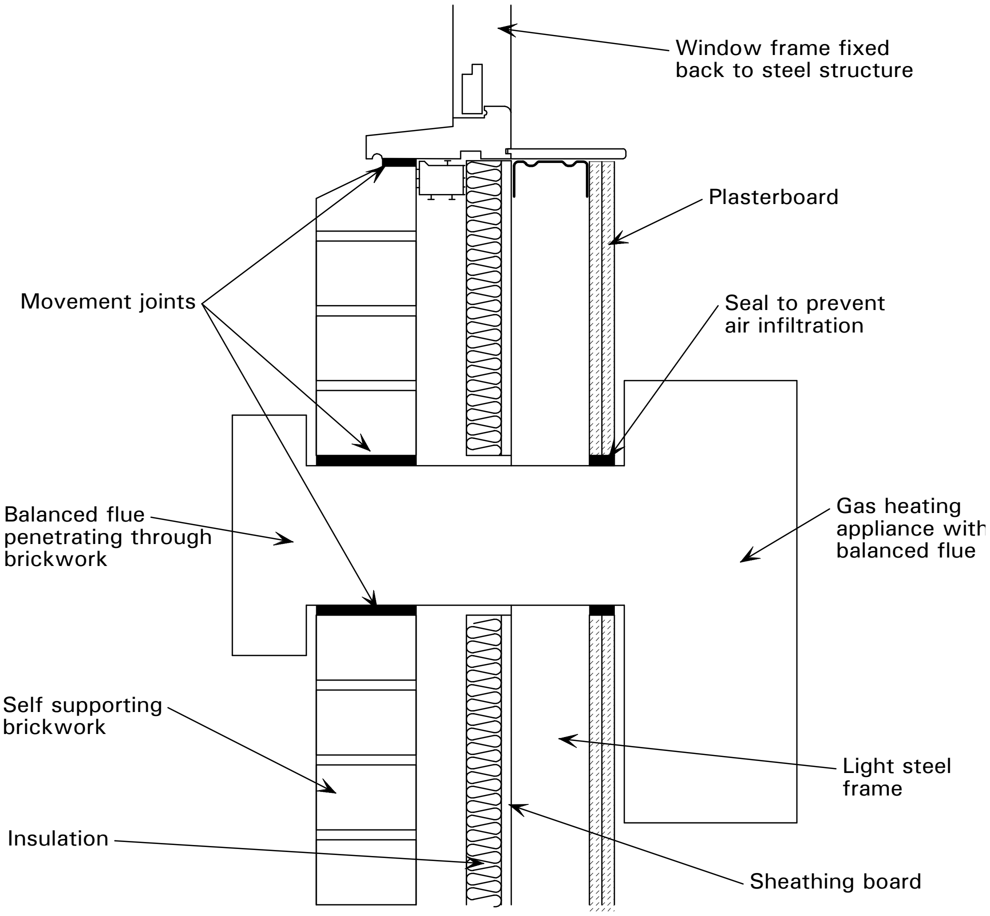


Figure 4.15 *Allowances for movement around penetrations*

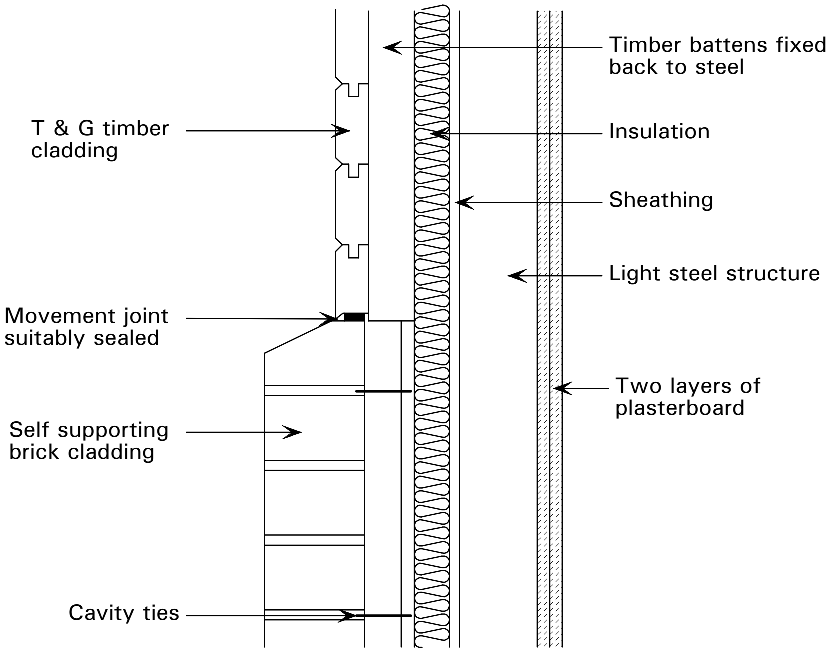


Figure 4.16 *Movement joints are required between masonry and lightweight cladding*

4.3 Roofing interfaces

Roofing materials for modular buildings generally comprise tiles supported on battens, or roof sheeting on purlins. Modern roofs may comprise tiles supported on roof sheeting or structural liner trays. Flat roofs can also be constructed with a variety of weatherproof finishes. Insulation in the line of the roof pitch is used where a 'warm roof' is created. However, in most cases, the roof space is 'cold', and insulation is placed directly on the upper surface of the modular units.

Roofs are generally designed as separate structures that are supported either continuously by the internal walls of the modular units, or as free spanning roofs between the outer walls. Roofs may also be designed as modular units for habitable space, and ease of installation, especially in taller buildings. However, conventional trussed rafter or purlin roofs are mostly used.

Figure 4.17 illustrates alternative pitched roof structures that may be used in modular buildings.

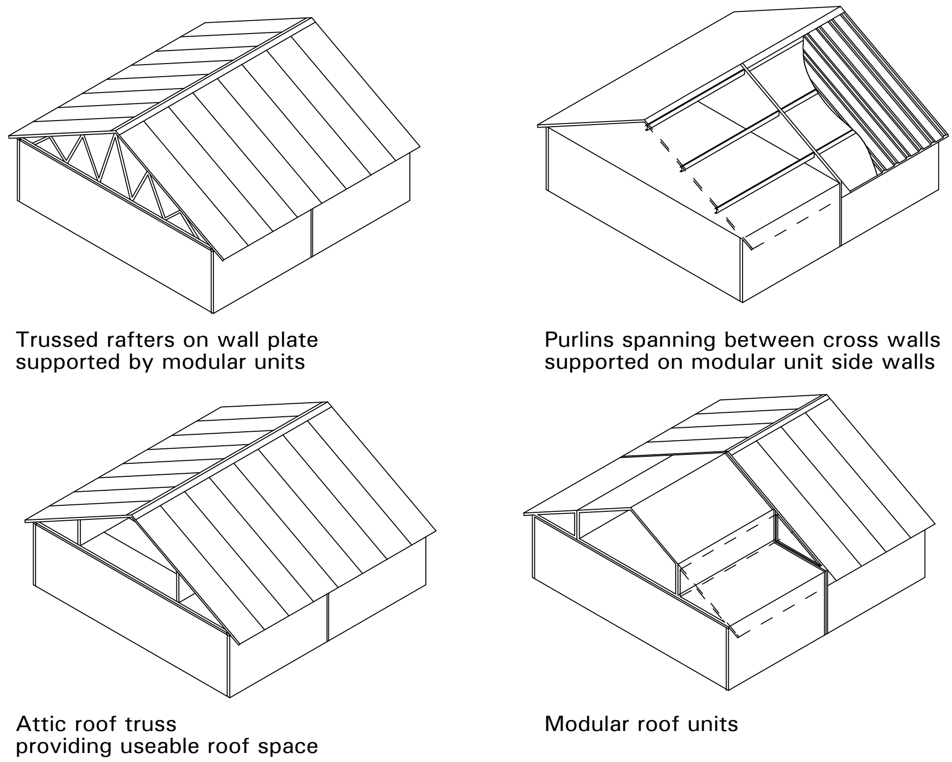


Figure 4.17 *Schematic of typical roof structures using modular units*

Roofs are designed to support the weight of the roof covering, snow loads, services and tanks stored on the roof space, and occupancy loads from habitable use. The interface between the roof and the modular units is designed to resist both compression and tension due to wind uplift. In some cases, the roof can be designed to be detachable so that the building can be extended later. Shallow pitch roofs can be designed to be supported directly by the modular units and are easily dismantled.

There are no Building Regulations requirements for fire resistance of roof structures, except when the roof space is habitable. However, any compartment walls that run through the roof space should provide the same period of fire resistance as that required beneath the roof space.

4.3.1 Pitched roofs

Pitched roofs are most commonly constructed using timber trusses manufactured to BS 5268-3 [35]. The trusses are located on timber wall plates located at the edge of each module, along the line of the external wall. Additional supports can be provided at internal walls of the modules, if necessary.

Roofs may be designed for either habitable or non-habitable use. Conventionally, roof trusses are manufactured in timber or light steel, with spans in the region of 7 to 10 m. A 'Fink' roof truss does not permit use of a habitable roof space but is a cheap and efficient solution. Trusses are generally spaced 600 mm apart and support the roofing battens directly. The roof space is 'cold' and insulation is placed on the ceiling of the modular unit below. An eaves detail for such a roof is illustrated in Figure 4.18.

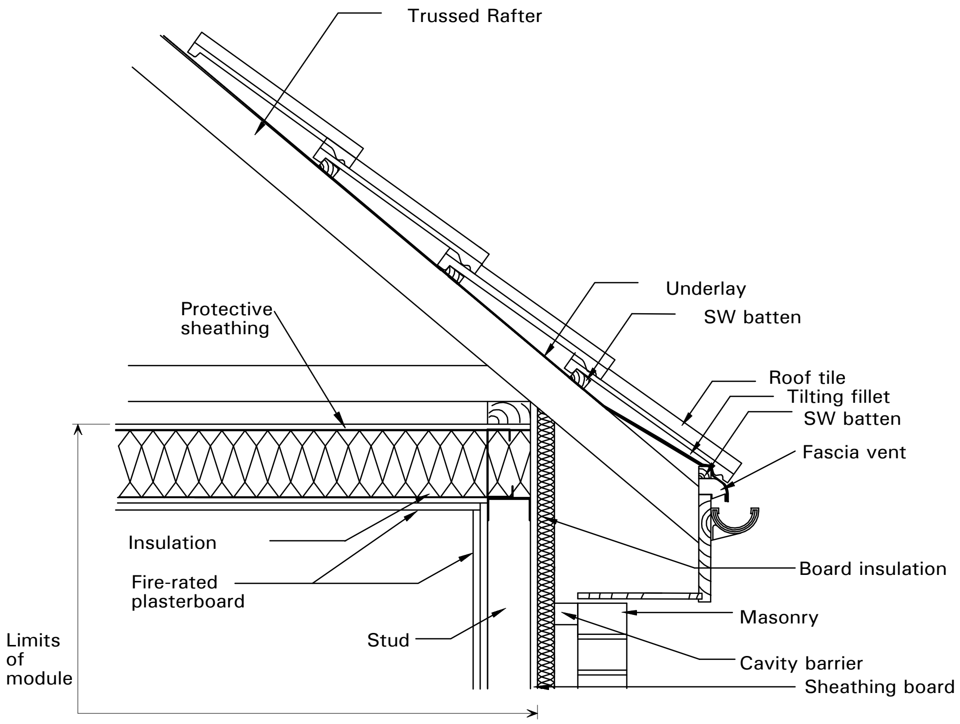


Figure 4.18 *Eaves detail for trussed rafter roof supported by a module*

Alternatively, an 'open roof' system can be created using either a steel 'attic' truss, or by purlins spanning between the flank walls or cross-walls. The first solution is more appropriate for large houses, whereas the second is very efficient for narrow terraced houses. An attic truss consists of C sections bolted together, so that the bottom chord and rafters provide mutual support. The purlins are usually in the form of discrete C or Z sections. An example of a prefabricated 'open roof' is shown in Figure 4.19.

With such roofs, a variety of finish can be used. For example, prefabricated panels which include the structure, insulation, felt and battens can be lifted onto the purlins by crane, with tiling fitted on-site. Alternatively, steel liner trays or decking can be used to span across the purlins and to support the tiling battens. A more conventional structure can also be used in which the purlins support timber or light steel rafters or sheeting, which in turn support battens and tiles.

Figure 4.19 *Pre-assembled roof structure craned onto a light steel framed house*

Special mansard roof shapes may be created to offer more efficient use of habitable space and may be manufactured as modular units. Various alternative roof forms are presented in *Over-roofing of existing buildings using light steel*[36].

For roof spaces that are to be used for habitable space, the insulation is placed on the outside of the roof members to create a 'warm roof'. The roof covering and battens are screwed through the insulation to the members. Supplementary insulation may also be placed between the rafters. Special details are required to prevent heat loss at the eaves. Further guidance is given in the SCI publication; *Building design using cold formed steel sections: Construction detailing and practice*(3).

4.3.2 Roof cladding and detailing

All the currently used roofing systems are applicable to modular buildings. Clay and concrete tiles, natural slates, cement slates and shingles can all be used with conventional detailing, using battens and roofing felt as necessary. Profiled steel and aluminum sheeting can also be used. Insulation in the plane of the roof is used where a 'warm roof' is created. However, in most cases, the roof space is 'cold' and insulation is placed directly on the upper surface of the modular units.

Building Regulations control the fire exposure of roofs depending on the building's proximity to the site boundary and its use. Most pitched roof cladding materials in common use have a fire rating of AA, which means they are permitted within 6 m of the site boundary.

4.3.3 Ventilation requirements

Approved Document F2 defines the requirements for control of condensation in the roof of buildings. These requirements can be satisfied by providing sufficient cross-ventilation into the roof space. For a pitched roof with a ventilated cold attic space, this would be the equivalent to a 10 mm continuous open strip along each of the eaves to provide cross ventilation (Figure 4.20a). Where insulation follows the pitch of the rafters and is between or below the rafters, a 50 mm air gap must be left between the top of the insulation and the underside of the roof covering, with a 25 mm ventilation grill at the eaves and a 10 mm strip at the ridge (Figure 4.20b).

Alternatively, a 'warm roof' solution can be designed in which the insulation is located on the outside of the structure, as recommended in BS 5250:1989 [37]. In this case, no ventilation is required (Figure 4.20c).

4.3.4 Flat roofs

The principles of using a flat roof are generally the same for modular buildings as for traditional construction. It is necessary to ensure that the structure of the modular units is designed to accommodate local loads. It may be possible to design the ceiling structure of the upper modular units to support the roof directly or, alternatively, a separate roof structure spanning between the walls of the modular units may be used.

A range of flat roofing finishes can be used. These include single layer or built up felt roofs on boarding laid on furrings, or a variety of panel type roofs which may be able to span greater distances and reduce the need for secondary components below.

Eaves details can be overhanging eaves with an external gutter and rainwater pipes on the face of the building or hidden gutters. Alternatively, parapet wall details, as shown in Figure 4.21, are possible, with internal rainwater pipes using standard flat roof outlets. In this case, the pipes are incorporated into the vertical service ducts that also accommodate the soil and vent pipes and other vertical services.

Care is required at abutments where differential movement may occur, particularly if masonry cladding is used. Roofs should be laid to falls of not less than 1:40. Cold deck, warm deck and inverted roofs can all be designed successfully.

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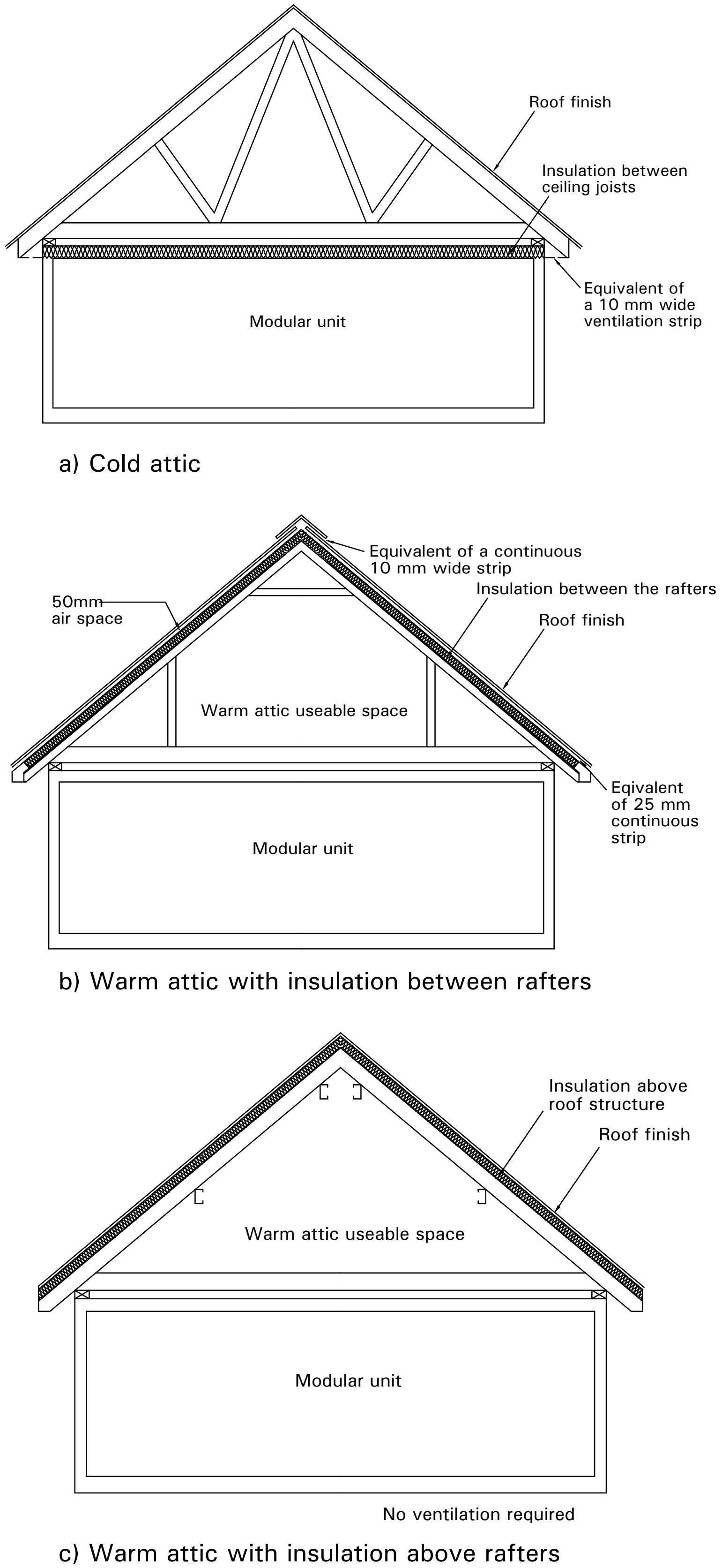


Note: Wall insulation should be continued up to the roof insulation, and is omitted for clarity.

Figure 4.20 *Ventilation requirements for roofs*

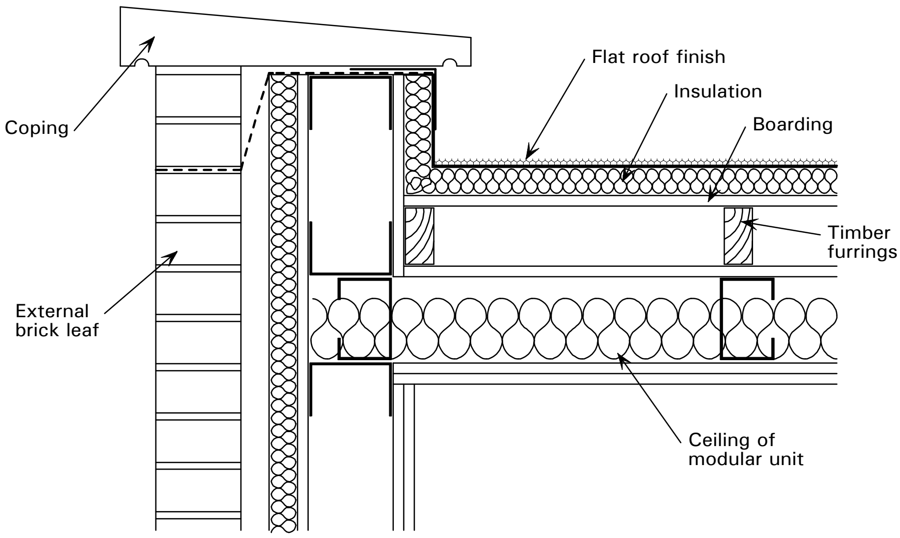


Figure 4.21 *Flat roof detail with parapet*

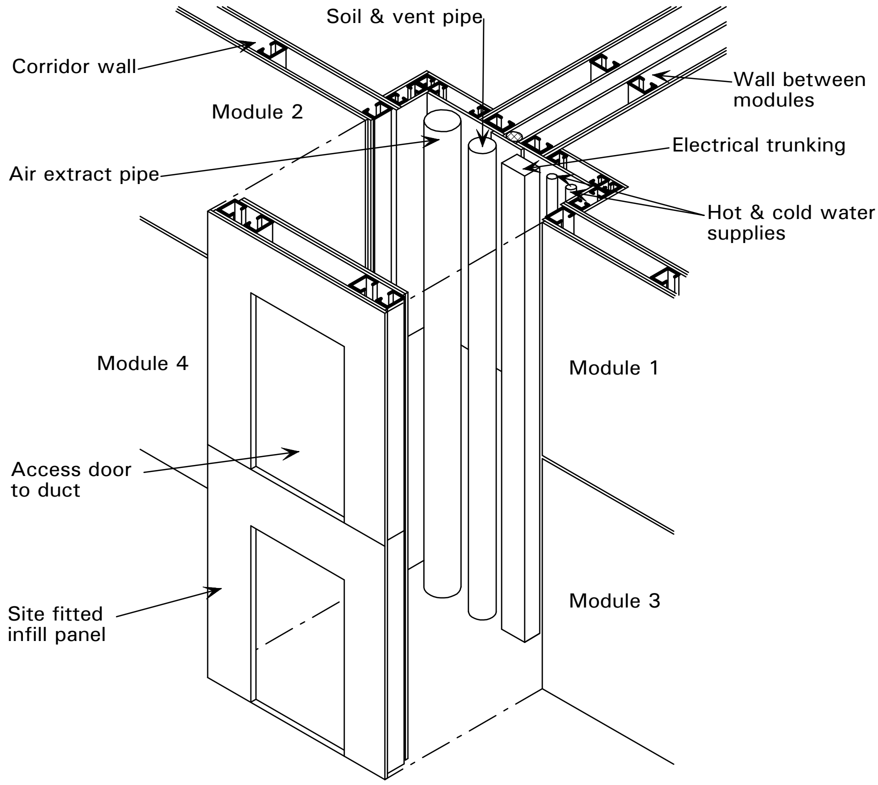
4.4 Service interfaces

The installation of electrical, plumbing and heating services in modular buildings can be largely achieved in the factory, and final connections are made on-site. Internal drainage can also be installed prior to the modular units being delivered to site. In traditional construction, such activities are labour intensive and time consuming on-site and are often on the critical path, so that any difficulties can cause delays. The removal of these site activities has significant benefits in terms of quality and speed of construction.

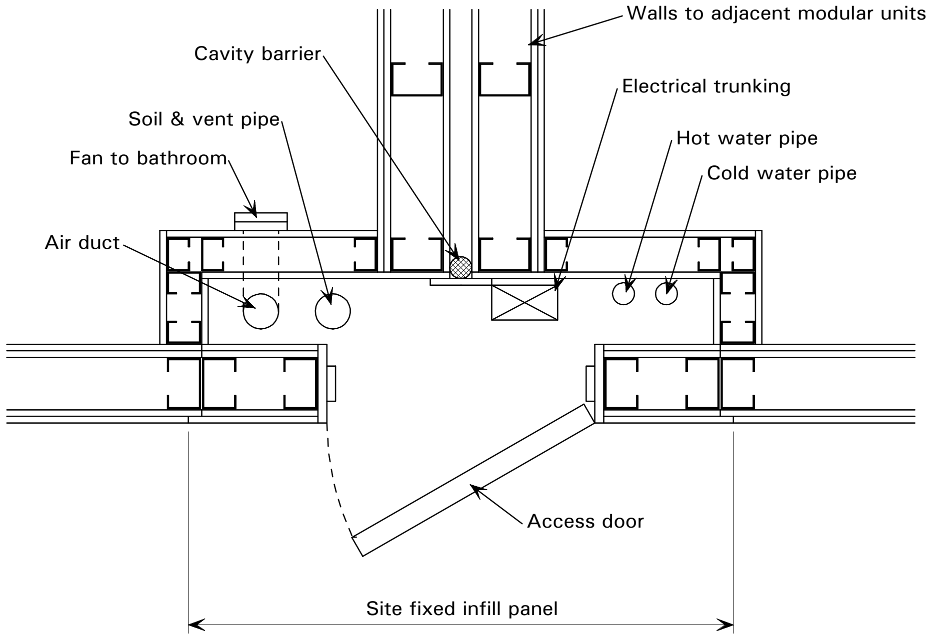
In hotel buildings, a vertical service duct is usually incorporated in the corner of each unit to accommodate the vertical drainage and pipework (see Figure 4.22). The services in each module are installed in the factory and terminate in the vertical duct. Testing of the services within the unit is carried out in the factory. Access to the service duct is generally only possible from circulation areas outside the modular unit. This allows the services to be connected on-site within the duct without the need to enter the modular unit. Thus, damage to the internal finishes from follow-on trades on-site is avoided.

The horizontal distribution of services between modules varies, depending on the building type. For hotel buildings, the corridor ceiling and floor voids act as service zones. Alternatively, services can be distributed within the roof space and drop down in each vertical duct. In apartment blocks, the ceiling voids of communal corridors can be used for service routes that are connected to the individual modules which form the apartments. For other house types, the modular units should be designed with consideration of the distribution of services and maximising the work that can be done in the factory.

In houses and apartments, the water, heating and electrics systems are installed and tested in the factory, and brought together at one point, such as in the airing cupboard or store. Within this space, the connections are made on-site and no further work is required. Vertical drainage stacks are also installed in the factory and a removable floor.



a) Isometric



b) Horizontal section

Figure 4.22 *Typical service duct in a modular hotel building*

panel is provided to allow the final connection to the drains installed in the ground on-site. This requires a high degree of accuracy in setting out service inlets on-site, and the modular manufacturers have developed procedures to ensure that the required accuracy is achieved on-site.

Service strategies that have been used in modular buildings include:

- Use of communal spaces for distribution of services.
- Use of the floor or ceiling zone within each module for service distribution.
- Installation of services within each module in the factory with site work involving only connection of modules.
- Drainage connections of modules connected to vertical risers in the corner of the modules.
- Wet areas are connected back to back to concentrate service zones.

In a modular building, it can be difficult to find the location of a leaking pipe as water may move down the building in spaces between modules before it becomes apparent. One way of mitigating this problem is to 'tank' the service areas (e.g. with a polyethylene membrane with a 100 mm upstand) and to provide an outlet into corridor drainage. This can help to identify leaks.

Where possible, services should be designed parallel with the primary framing members. However, to provide routes through the light steel structure, it is standard practice to provide punched holes at regular intervals in the steel members, as illustrated in Figure 4.23.

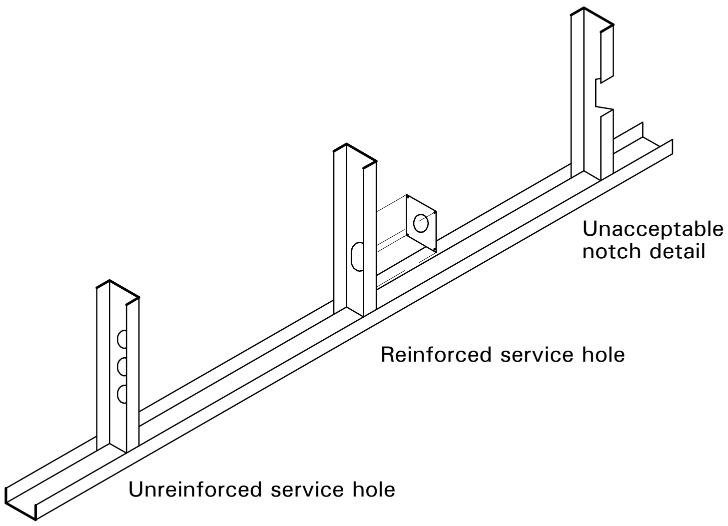


Figure 4.23 *Holes provided in joists and studs for electrics and pipes*

These holes allow small diameter pipes and electrical cables to be threaded through the structure. Rubber or polyethylene grommets around the openings are used to prevent damage to cables and contact between the steel and other metals used in the pipework. Electrical services can be installed in ducts to facilitate future upgrade and alteration. Larger pipes are usually located in the spaces between or below the joists. *Under no circumstances should the flange of a steel section be notched or cut away.*

Where holes are required in the web of the studs or joists, the maximum depth of unstiffened rectangular hole or slot should not exceed 40% of the overall depth of member, and its length should be less than three times the depth of the hole. The diameter of circular holes should be less than 50% of the depth of the member. Unstiffened holes should be spaced at least the depth of the member apart from edge to edge, and should be at least 1.5 times the section depth from the end of the member. Provided that the above limits are observed, the holes have negligible influence on the structural properties of the member. Larger openings in the steel joists and studs may require some reinforcement by an additional steel plate.

Pipe and plumbing services should generally not be threaded within separating or compartment walls, as any future access may damage the integrity of the walls.

When services pass through compartment floors, it may be necessary to take additional precautions to avoid compromising the fire integrity of the compartment. Fire stopping is needed around service ducts that pass through compartment floors. Manufacturers of modules have their own details to deal with this situation.

4.4.1 Electrical installation

The electrical design should take into account the fact that electrical cables, surrounded by thermal insulation, have an increased risk of overheating, and should be derated to compensate. Electrical services should be installed in accordance with BS 7671 [38].

The positioning of electrical fittings in separating walls should avoid back to back fittings, as acoustic separation can be compromised. Any electrical fittings in separating walls should be protected at their rear with two layers of plasterboard and a mineral wool quilt. Figure 4.24 shows typical electrical fittings located in a stud wall.

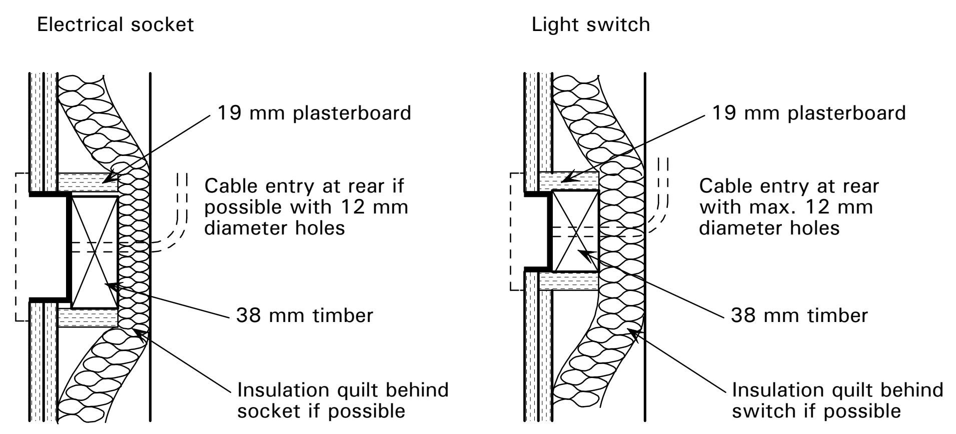


Figure 4.24 *Detail around a typical electrical fitting*

4.4.2 Gas installations

Domestic gas installations should be in accordance with BS 6400 [39]. The Institute of Gas Engineers publishes guidance on the installation of gas services in framed residential buildings. Generally, domestic gas installations follow a conventional pattern but much work is carried out off-site, including installation and initial testing of appliances. Wall-hung boilers with balanced flues can be used, and fixed to the structure, but must be placed so that the flue avoids the structural elements. The outlet must accommodate differential movement if masonry claddings are used (see Section 4.2).

4.4.3 Wall fixings

When heavy fixings are required in a particular area of wall, such as in kitchen units, additional light steel plates or noggins can be included in the design of the modules. Furthermore, self-drilling self-tapping screws can be used for fixing directly into the steel studs and joists. Lightly loaded fixings can be made to plasterboard walls with proprietary fixing devices, many of which are readily available. In some cases, modular manufacturers use gypsum fibreboard for wall linings, as these enable greater loads to be supported by direct fixings to the wall lining, and provide more flexibility in positioning.

4.4.4 Drainage and other external services

Services in the ground are generally distributed in the conventional manner. Drains are buried in the ground to the base of each vertical drainage stack and are connected to the internal drainage when the ground floor units are positioned. Electricity, water and gas supplies are connected to a meter and central distribution point as necessary and the internal distribution between modules is connected at this point. Drainage from the roof is generally provided conventionally from the outside of the building. However, drainage can also be provided internally, subject to maintenance requirements.

4.4.5 Stairs and lifts

A variety of modular systems are available for stairs and lifts. Pre-fabricated stair and lift modules dramatically improve the efficiency of construction of modern buildings. They can be levelled and positioned accurately and the stair flights can be concreted later. In some systems, the stairs are installed as precast concrete units.

5 CONSTRUCTION PROCESS AND RELOCATION

5.1 Construction programme

In modular building projects, construction periods are reduced by 50 to 60% because slower site processes are replaced by more efficient factory production that is not influenced by weather or availability of resources. Modules can be installed rapidly at a rate of 5 to 10 per day. They are generally lined and fitted out before delivery to site, thus subsequent finishing activities are minimized.

The discipline of modular construction requires the early involvement of the modular supplier to reduce 'lead-in' times in production and to improve interfaces with other elements of construction, including service connections.

5.1.1 'Lead-in' times

The lead-in time required from ordering to delivery of the modular units can be as short as 6 to 8 weeks, if the modular units have been 'prototyped' previously on similar projects and the production logistics are well established. Even in a typical regular hotel project, there can be 8 different modular units representing internal, end bay, roof top and left and right handed units. However, the floor configuration of all the units is essentially similar.

For buildings in which modular construction is being considered for the first time, sufficient time should be allowed for manufacture of pre-production prototypes, which help to resolve potential design and production problems. A period of 4 to 6 weeks should be allowed for this prototyping stage. The sensible 'lead-in' time for delivery of the modules might therefore increase to 10 to 14 weeks. At this point the design is frozen; changes will lead to delays and possible additional costs.

Often it is the ordering of the lifts and any complex plant that determines the effective completion of the project, rather than the production of the modular units. Loose furniture is often moved in later, whereas fixed furniture is installed in the factory.

5.1.2 Typical construction programme

The construction programme of a typical modular building is often less than 50% of a building construction using wholly site techniques. These benefits may be considered by example for an 80 bedroom hotel project, considering three alternative methods of construction (see Figure 5.1).

On-site construction periods can be reduced from 45 weeks for conventional construction, to 33 weeks for light steel framing with prefabricated bathroom pods, and to 22 weeks for entirely modular construction. The main time savings are in the primary structure, services and fit-out.

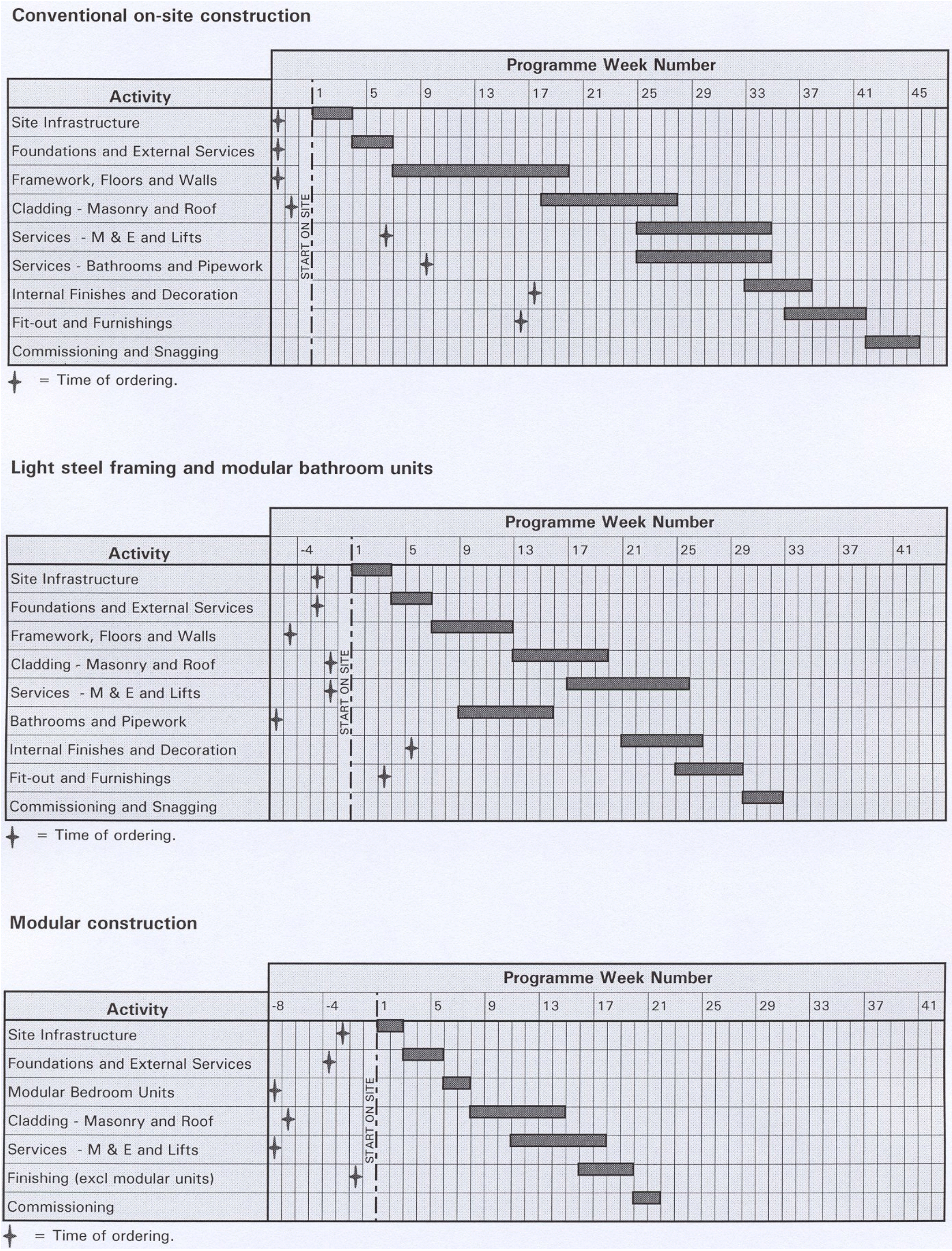


Figure 5.1 *Comparison of construction programmes for a typical medium-sized hotel*

The pre-site ordering period may increase for the various degrees of modularisation, which is entirely dependent on the ordering of the major services. Nevertheless, the **total** time from ordering to completion is much reduced, which effectively means that the variable site activities are replaced by more quality controlled and faster factory operations.

These approximate construction and lead-in times in Figure 5.1 are not intended to be definitive, but rather emphasize the importance of the decision-making and procurement process when using modular construction.

5.2 Transportation

The principal requirements for transportation concern the maximum width and height for loads carried on the highways. The maximum width normally allowed in the UK is 2.9 m for general applications, but this can be increased to 4.3 m with suitable police notice. The maximum height of the load is 4.5 m for motorways and most major roads but there may be local restrictions for clearance under older bridges, especially under railway bridges.

These transportation requirements are summarised in Figure 5.2. Modular units suitable for containerisation should be less than 2.3 m high and 12.2 m long.

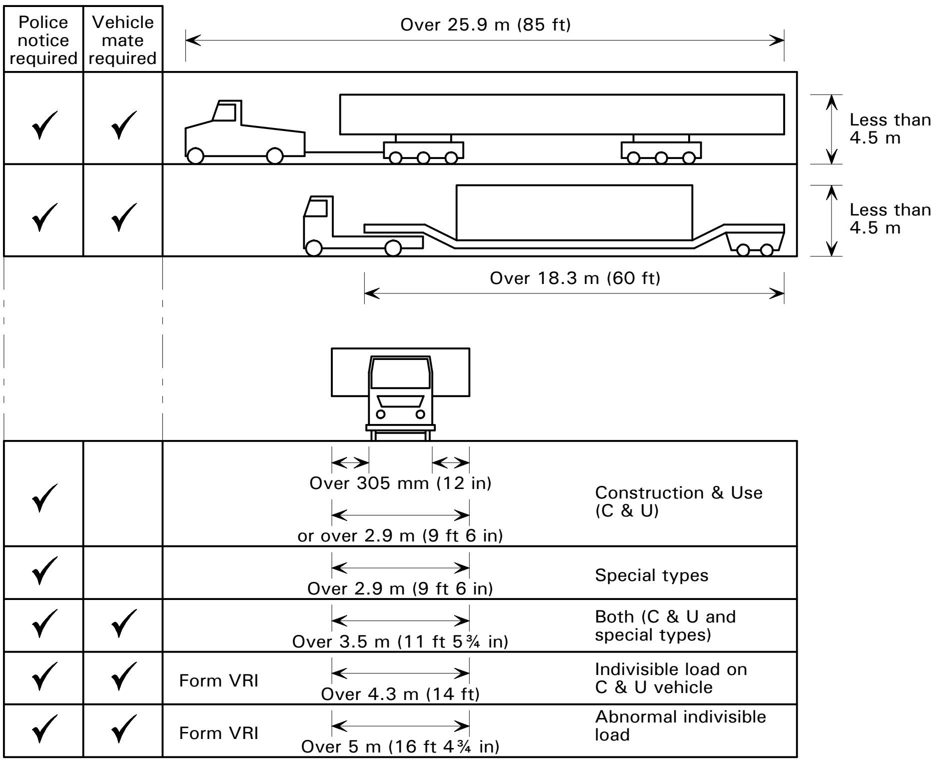


Figure 5.2 *Summary of transport requirements for modular units*

The modular units should be made weather-tight, particularly during the transportation phase, when damage due to wind buffeting can be a problem. The units are generally clad in heavy duty plastic, which remains in place during construction. However, care should be taken in the detailing of the joints between the units, corridors and spaces for services in order to prevent water ingress during construction.

Care must be taken to protect the modular units on-site from damage from the follow-on trades. It is important to take precautions to avoid damage during the commissioning process.

5.2.1 Installation procedures

Each manufacturer of modular units has developed procedures for ensuring a smooth construction process on-site. Some manufacturers have their procedures certified under ISO 9001 [40]. The manufacturer will give precise instructions to the groundwork contractor about the requirements for setting out the building. A grid is often used, with the locations of foundations, service connections, drainage points and any other important points all precisely specified. The groundwork contractor will be made aware of the tolerances that are acceptable as these are particularly critical to this form of construction.

Generally, the modular manufacturer will attend the site well before the units are due to be delivered, to ensure that all the requirements have been met. Any inaccuracies are highlighted at this point and need to be made good prior to the delivery of the units. The modular manufacturer may have a key representative responsible for liaising with the site, dealing with transporting the modules to site and ensuring they are erected correctly. The representative will make the groundwork contractor aware of any details that need addressing prior to erection.

5.2.2 Lifting and installation forces

Lifting and manoeuvring forces cause dramatically different internal stresses from those that exist during normal conditions. In particular, high forces exist at lifting positions and the adjacent members and their connections generally need to be strengthened to resist these forces. Often hot rolled sections are used at these positions, whereas light steel members are used elsewhere. There are various techniques for lifting, depending on the height of the crane jib, some of which are illustrated in Figure 5.3 and Figure 5.4.

Normally, lifting involves attachment to the top of the units but it is possible to lift smaller units and pods from their bases. The angle of the lifting cables should be such that the horizontal component of their force is not excessive. To maintain optimum stability during lifting, the lifting points are generally located symmetrically between the corners and 25% of the length of the unit. Alternatively, units may be lifted from their corners. A pair of cross-beams or a lifting frame, of a size equal to the plan dimensions of the units, together with vertical chains, is preferred as they do not cause horizontal or shear forces in the units.

The manufacturer's recommendations for lifting, permissible loads and installation must be observed at all times, and failure to do so may cause damage to the finishes of the modules. Contractual responsibility for lifting is generally best placed with the manufacturer who knows how best to lift the modules and their robustness in handling.

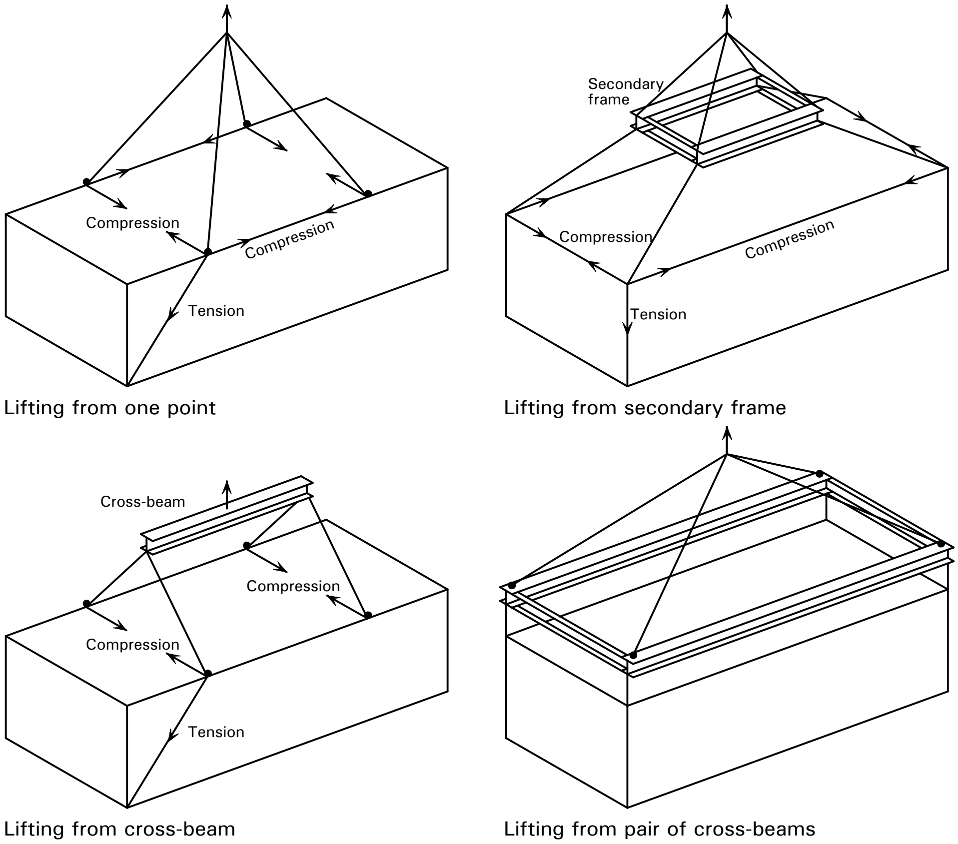


Figure 5.3 *Various methods of lifting modular units*

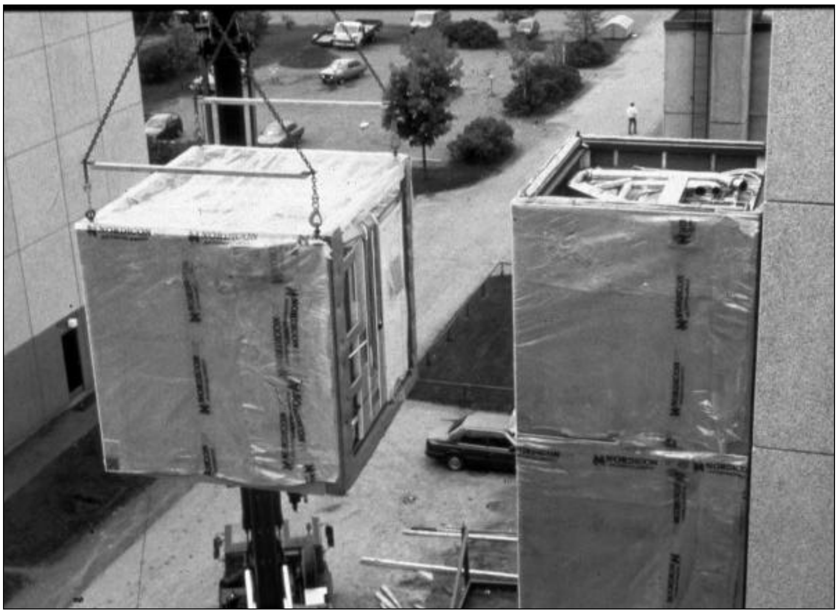


Figure 5.4 *Lifting and installation of modular bathroom units*

5.3 Replacement and relocation

Buildings constructed using light steel framed modular units can be disassembled and the modular units removed from site. The units can be reused in their original form on a new site or taken back to the factory for alteration or dismantling and recycling of components.

If it is known at the design stage that a building may be relocated, it will help the deconstruction process to consider how the modular units interact with other components such as wall cladding, roofing and service connections between the modular units. For example, masonry cladding is difficult to detach from the face of the units without damage to the units and cladding. Conversely, other lightweight claddings can be easily unscrewed or unbolted, and both the modular unit and cladding can be easily reused. Similarly, roof structures made from larger prefabricated components are more likely to be economically removed and reused.

There are examples of hotel buildings constructed using modular units that have been relocated to new sites. For example, in Germany, a local authority built a semi-permanent office building (Figure 5.5), which is to the quality of a permanent building but is designed to be relocatable, as demand for office space changes. The units are fully serviced.

The case for dismantling depends on the form of cladding, roofing, access and service connections. An independent roof and access structure does not load the modules and can be dismantled or modified independently.

Figure 5.5 *Relocatable office building for a local authority in Munich*

5.4 Modular construction in renovation

The same generic techniques of modular construction as presented earlier may be used in major renovation projects. A particular application is in the attachment of external modular units to concrete or masonry buildings. The modular units form part of the remodelling of the building facade and reduce the weathering or deterioration of the existing structure. The technical issues that are appropriate to the use of modular units in this sector are as follows:

- The buildings are often tall (10-20 storeys) and the modular units are stacked on top of each other. The lower units should therefore need to be strengthened relative to the modular units used at higher levels. (Avoid strengthening all units because the upper units would be 'over-engineered')
- Overall stability is provided by attachment to the original structure. Therefore, 'strong points' should be identified on the existing floors or columns to avoid instability of the stack of modular units.
- The cladding to the modular units should be compatible with the cladding to the rest of the building.
- Lightweight facade materials may need to be attached by sub-frames to the modular units and also to the existing building.
- Modular units used in roof-top extensions should be supported on load-bearing walls. The lightweight modules minimise the additional load on the existing structure. Figure 5.6 shows a module being lifted onto an existing roof.
- The foundations to the external modular units should be sufficient to avoid differential settlement relative to the existing structure.

The rationale for the use of modular construction in renovation is often determined by avoidance of disruption to the occupants, who are usually not moved out during the renovation process. The economics of modular construction improve considerably if a number of similar blocks are renovated in the same fashion.

Figure 5.6 *Modular over-roofing project in Copenhagen*

6 VALUE-BENEFIT ASSESSMENT OF MODULAR CONSTRUCTION IN RESIDENTIAL BUILDINGS

The motivation to use modular construction arises from various well defined client benefits. The value attached to many of these benefits is dependent on the particular client and on the building use and location.

Various common themes emerge showing factors that are normally not included in a conventional Bill of Quantities but which can be taken into account in a value engineering assessment. Adding value by standardisation and pre-assembly is discussed in a recent CIRIA report[41]. The value and assessment process is discussed in a recent SCI publication *Value and benefit assessment of light steel framing in housing*[42]. Included in the evaluation are the economic benefits of speed of construction.

The cost savings due to speed of construction on-site may be quantified as:

- Reduced site preliminaries for hire of site huts and other facilities, etc. Typically, site preliminaries are 8 to 15% of the total construction cost. Therefore, a 50% reduction in time on-site can lead to a commensurate saving in preliminaries. Although site preliminaries are identified in the Bill of Quantities, the benefit of these savings to the client is not necessarily apparent.
- Earlier return on investment to the client. This benefit depends on the business operation but the *minimum* level of this benefit is the savings in interest charges over the reduced construction period. The *maximum* level of this benefit is the earning potential of the building, when in early operation.
- Avoidance of loss of the earning potential of the existing facility. This is a real cost to the client that occurs particularly where existing buildings, such as hotels, are extended or modified. A reduced construction period will lead to commensurate savings to the client.
- Avoidance of cost over-runs. The duration of the construction programme, is more predictable and less weather dependent than in on-site processess.

The total benefit of speed of the construction operation can be in the range of 5-10% of the total building cost (calculated from the time saving on-site), in comparison to more traditional site-intensive construction systems.

6.1 Benefits in the construction operation

Normal construction operations are often constrained by the particular features or locality of the site. Modular construction can lead to considerable benefits in the construction operation and can reduce or alleviate many common problems that may be encountered, such as:

- Limitations on delivery of materials to site in terms of time of day and impact on traffic in the locality.

- Working time and other restrictions in sensitive sites (often inner city locations).
- Noise limitations on the construction operations, particularly adjacent to existing buildings.
- A short 'weather window' for construction, for example in an exposed or inhospitable location.
- Lack of suitable site trades, or the cost of transporting workers to a remote location.
- Lack of working space around the building for site storage, site huts, etc.

These constraints are often site specific but can be important, in themselves, in determining the method of construction. The opportunities for use of modular construction should be investigated early in the decision-making process in order that these factors can be quantified.

Other economies in the construction operation using modular construction may be quantified in a holistic cost study as follows:

- Less wastage and lower costs of disposal of waste materials.
- Less daily use of craneage, as the installation of the modular units can be carried out by a heavier crane that is hired for a short period.
- Fewer site operatives, potentially requiring fewer site facilities, etc.

These economies are independent of the site constraints but may be amplified considerably when combined with difficult site conditions, or in avoidance of disruption to neighbouring properties, particularly in inner city sites. These may be classified also as environmental benefits.

6.2 Economy of scale

Regular bedroom and bathroom units can be produced to standard dimensions and specifications and of a size that is readily transportable. In this case, there are economies of scale and speed and quality benefits through factory production and pre-testing.

The economy of scale in production leads to the following benefits:

- Greater investment in the production line operation, leading to greater speed of assembly and cost saving from production efficiency.
- More emphasis on improvement in design by testing and by rationalisation of details based on ease of manufacture.
- Establishment of strict QA procedures and avoidance of reworking.
- Better design, including the possibility of variants at modest additional cost or difficulty.
- More involvement of specialist suppliers, such as service suppliers.
- Reduction of waste by efficient ordering and use of materials.

On the debit side, it should be noted that:

- The structure may be 'over engineered' for its normal applications because of the requirements for lifting and transportation.
- The need for 'standardisation' means that some economy in use of materials is sacrificed for production efficiency.
- Costs increase with the number of non-standard units in a given project.

In all cases, economy of scale will increase with greater standardisation and production line efficiency.

Testing of standard modules can lead to system approval, which overcomes the need to repeat design calculations for a wide range of otherwise similar projects.

6.3 Quality issues

Quality is often the crucial issue to the client who is concerned about the subsequent operation of the building. The following aspects of modular construction have a strong influence on quality:

- Some clients demand a high degree of quality assurance for their business operations and, in their view, a single point procurement route is beneficial because it concentrates the responsibility on the manufacturer.
- In modular construction, off-site trials can be carried out to 'prove' the system before installation. This is particularly true of highly serviced units, such as plant rooms, lifts and kitchens.
- 'Snagging' and 'call backs' costs are considerably reduced when using modular construction, in comparison with site construction. In conventional buildings, many contractors allow 1 to 2% for these costs.
- Light steel framing is robust and does not suffer from deterioration in performance. Movements are minimal and the avoidance of wet trades and the use of factory processes avoids cracking and shrinkage which damages finishes.
- Modular buildings offer 'proven' solutions (in conventional construction, every new building is a 'one-off' prototype).
- The client can carry out inspections of the modular units in the factory during the manufacturing process to ensure the desired quality and finish is achieved.
- The modular systems can have certification by LANTAC, BBA, Wimlas or other type approval.

6.4 Benefits for renovation

The renovation sector represents over 40% of the construction market and has its own features in terms of construction operation. The particular benefits of modular construction in renovation are:

- Reduced disruption in difficult sites. Units can be lifted easily into place.

- It may not be necessary to move the occupants during the renovation work (as in roof-top extensions).
- Modular units are light in weight and do not require extensive strengthening of the existing structure.

6.5 Benefits to the general contractor

The general contractor would perceive the benefits of modular construction in terms of the speed and efficiency of the construction process, as compared to any increased 'lead-in' time and additional costs due to manufacturing and delivery. For a major residential building, or series of similar buildings, the benefits of modular construction may be presented in terms of the operational efficiency and other cost savings due to the speed of construction on-site.

Certification systems such as BBA or Wimlas can also significantly speed up the process of obtaining Building Regulations approval.

The speed of construction on-site leads to savings to the contractor in terms of:

- Reduced site costs,, which are broadly in proportion to:
  - the time on-site (in terms of personnel costs)
  - the number of personnel involved
  - storage facilities and space around the building
- Hire charges for:
  - site facilities
  - scaffolding
  - site equipment

In addition, there is less waste and, hence, landfill charges in the use of construction materials and in rework due to poor quality. Evidence from real projects shows that waste is reduced by over 80%, which can lead to savings in handling and land-fill charges equivalent to 1 to 2% of the construction cost. Contractors often allow a small percentage for 'snagging' or correction of defects, which is much reduced when using modular construction.

Further operational gains may be difficult to quantify and depend on the location and size of the project, and on opportunities for repeatability in the manufacture of the units. The use of modular units is most efficient when:

- The same module size and design is used throughout the project.
- Prototyping is minimised by repeating the module design from other projects.
- The modules can be erected rapidly with suitable timing of road usage, and craneage from the roadside.
- Foundation design can be simplified.

Table 6.1 summarises the major construction benefits, as perceived by the general contractor. The total saving in construction operation-site preliminaries, storage and equipment can be 10 to 15% of the total construction cost.

Table 6.1 *Benefits and additional costs in the construction operation arising from the use of modular construction*

Benefit	Possible Additional Cost
C No adverse weather delays or 'down time' on-site.	C Hire of increased capacity crane for installation of modular units.
C Reduced allowance in tender price for snagging/call-backs.	C Transport cost to be added to ex-works price of units.
C Less equipment needed e.g. forklifts, wet trades, handling.	C Interfacing details between units require careful control and workmanship.
C Less risk through site control problems and re-work.	C Contractors profit is now concentrated on the bought-in components.
C Less storage required on-site for materials, scaffolding etc. (site dependant).	C Procurement may be much earlier than in other forms of construction, which may lead to additional costs or delays if the modular units are not designed/ordered promptly.
C Less dependent on craft resources	C Over-design of structure for temporary conditions (involved in ex-works price).
C Reduced site preliminaries - fewer facilities for staff - reduced hire charges - less scaffolding etc. - less supervision cost - fewer site overheads.	C Contractors organisation may not be experienced in modular construction.
C Less potential damage to expensive equipment during construction.	
C Less wastage of materials and removal of waste and land fill charges.	
C Less design cost of structure (particularly for D & B contractor).	
C Savings in foundation cost (due to lightweight structures).	

6.6 Benefits to the building owner

The client or building owner would perceive the benefits of modular construction in terms of the financial or business-related benefits due to speed of construction, or improved reliability of operation. Some of these benefits are directly calculable depending on the building type, but others are notional and depend on the consequential losses due to potential 'down-time' of the facility in operation.

In a residential building or hotel, the increased revenue and reduced interest charges due to early completion of the building may be calculated knowing the number of weeks that may be saved in the construction programme, and the revenue per week that can be realistically obtained. A simple calculation of these cost time savings, based on a 20 week saving in a 45 week construction period, for a medium sized hotel, demonstrates that the total saving in this case could be equivalent to 22% of the construction cost.

A more general estimate of savings to the client or building operator is presented in Table 6.2. Clearly, one of the major benefits is in the repeatability of use of standard modules in the project, or in other buildings of similar specification. Potential savings may be 10 to 25% of the construction cost, depending on the scale and importance (i.e. revenue return) of the project.

Table 6.2 *List of potential cost savings and possible additional costs to the client or developer (which may be passed on to the end-user)*

Benefit	Possible Additional Cost
C Savings in site preliminaries passed back to the client. C No shrinkage or cracking repairs and disruption due to drying-out. C Economy of scale through repeatable production operation. (Depends on size of project). C More predictable design life and less longer term risk to investment. C Economy of design by testing if a large number of similar units are to be produced. C Cash flow in building cost is reduced C Potentially, the building is relocatable in the future. [Depends on use].	C Possible structural redundancy is built-in due to lifting and handling requirements during installation. C Non-standard units or components may be more expensive (dependent on building form). C Client decisions have to be made early, and are costly if changed later.
Business dependent factors:	
C Call-backs are reduced with consequently reduced risk of loss of operation or use of the facility. C Early completion leads to early revenue and return on capital investment. C Ability to pre-commission complex installations off-site with less risk of delay of damage on-site. C Greater accuracy improves fitting-in of other precision components. C Reduced client security costs during construction operation.	

7 ARCHITECTURAL OPPORTUNITIES USING MODULAR CONSTRUCTION

Buildings designed using modular units can be just as varied and architecturally interesting as other forms of construction. However, to optimise the benefits of the modular approach, the design concept must recognise the economic constraints of the repetitive nature of production, and the need to avoid extensive modifications to modules to suit non-standard applications. Within these constraints, there are simple ways in which the visual appeal of otherwise rectangular building shapes can be improved without affecting the structural or production efficiency.

Figures 7.1 to 7.4 illustrate some of the architectural opportunities of using modular units as major ‘building blocks’. The techniques include off-setting the modules on plan or elevation, and the attachment of balcony or roof elements to modify the overall visual effect. Separate steel frames can be introduced to provide local support, particularly to balconies, or over gaps between the modules, e.g. to provide access at ground floor level.

The examples shown (Figures 7.1 to 7.4) are not comprehensive, but illustrate how modular technology can be made more flexible to respond to differing architectural and planning demands. It is necessary to liaise closely with the modular supplier at the detailed design stage, but all of these options are technically feasible within sensible economic constraints.

The use of external pre-fabricated balconies, stairs and lifts can add to the range of architectural opportunities. Internal pods for toilet and highly serviced units are already common in otherwise conventional framed buildings.

Figure 7.1 shows various ways in which modules may be stacked without greatly affecting their structural design. Figure 7.2 shows cantilever and atrium arrangements of modules. The atrium principle can be extended to include variants of the other arrangements. A separate roof canopy encloses the atrium space.

Figure 7.3 shows various roof forms. Mansards may be created by modifying the front face of the module, or by stepping back the roof-top modules. However, step backs should be carefully designed so as not to affect the load path on the modules below. Figure 7.4 shows how balconies and deck access modules can enhance the appearance of the building. Balconies can be cantilevered from the modules or, more commonly, are supported on a separate frame work. Fully glazed facades may be achieved by local strengthening of the corners of the module to resist wind forces.

Other techniques that not illustrated are: radially orientated modules, and open-sided modules, which are feasible with modest cost premium. It is usually not feasible to offset the load-bearing walls of the modules at different levels.

Discuss me ...

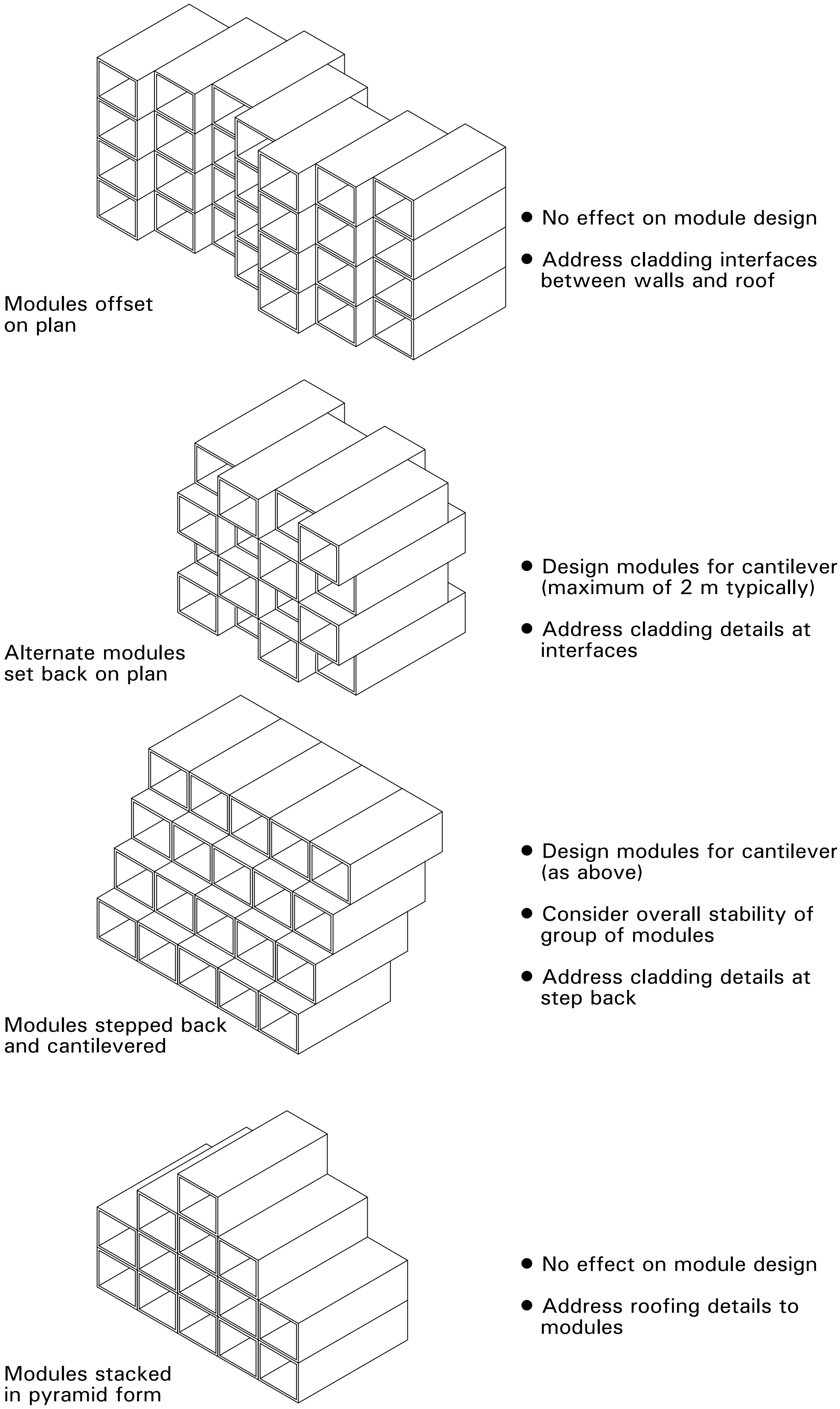


Figure 7.1 *Stacked arrangements of modules*

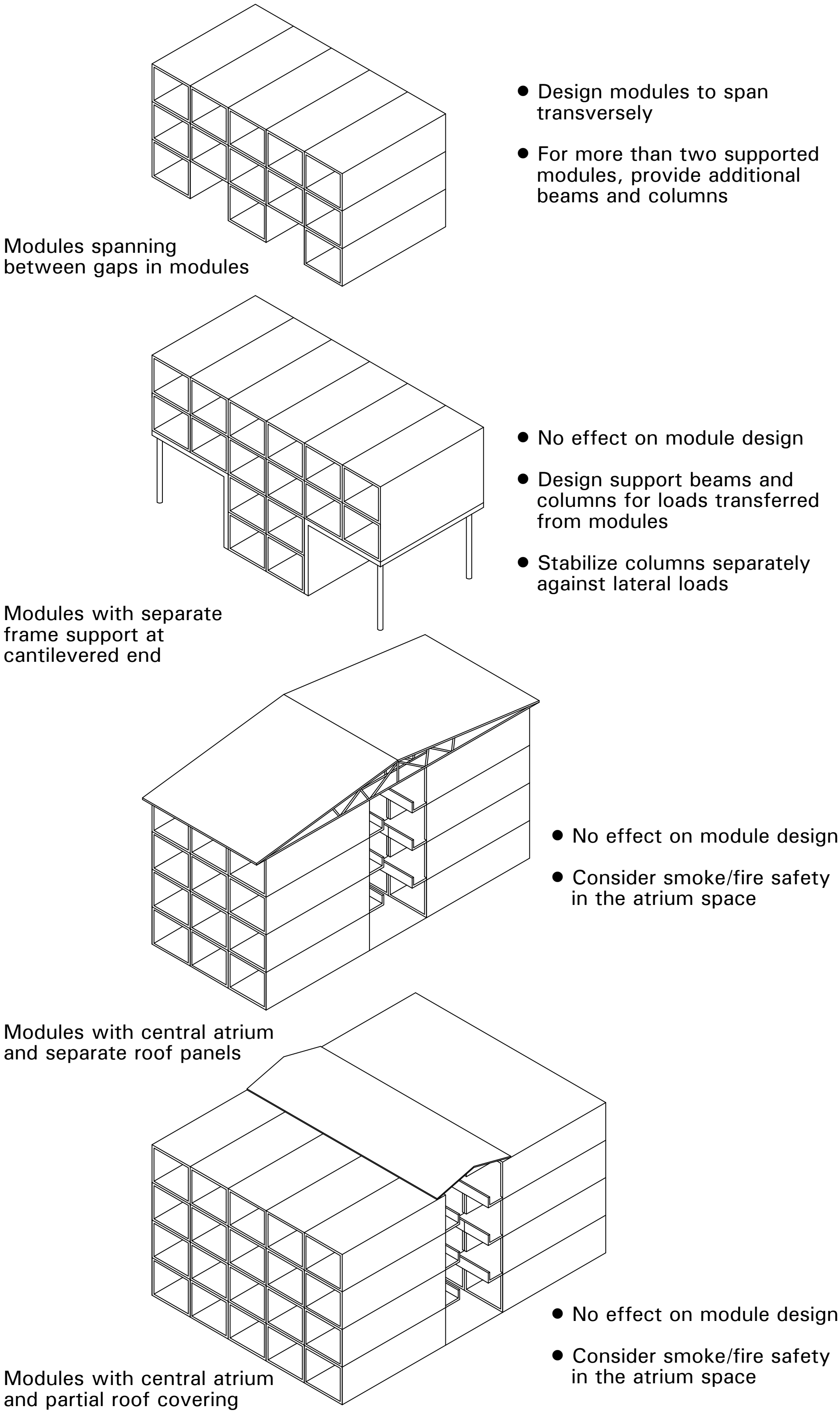


Figure 7.2 *Cantilever and atrium arrangements of modules*

Discuss me ...

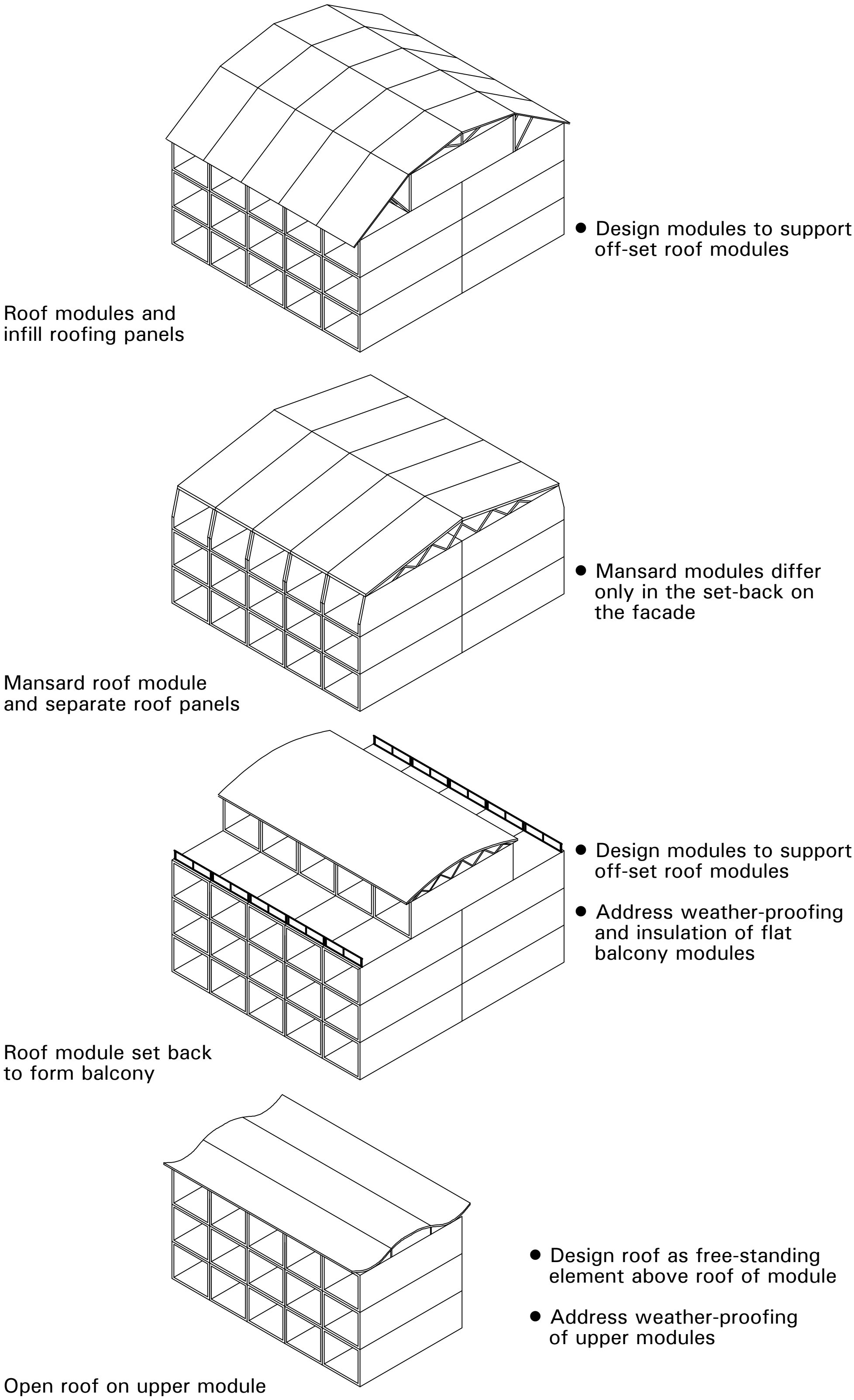


Figure 7.3 *Roof forms using modular construction*

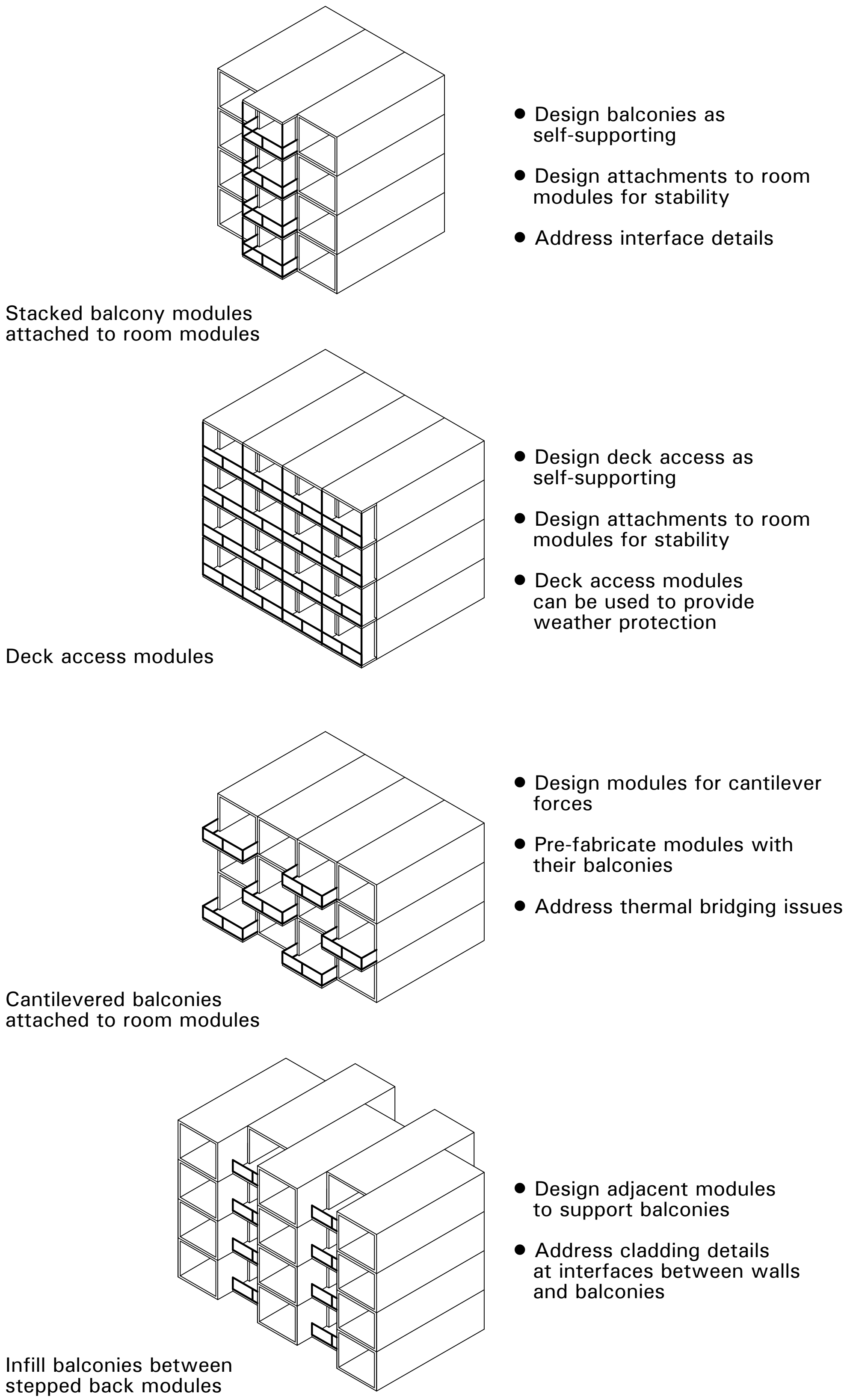


Figure 7.4 *Balcony and deck access modules*

8 SUSTAINABILITY INDICATORS FOR MODULAR CONSTRUCTION

The concept of using Sustainability Indicators is becoming accepted as part of the environmental assessment of building construction.

The Sustainability Indicators are derived from information produced by BRE, CIRIA and DETR, and in particular the ECO-Homes[43] [44] environmental assessment method. They are presented under the general ECO-Homes headings of:

- Energy Efficiency
- Minimising Transport
- Minimising Pollution and Waste
- Efficient Materials and Resource Use
- Water Conservation
- Ecology and Land Use
- Health and Well-Being

The Sustainability Indicators define the primary measures of sustainability and are a function of the materials used, the manufacturing or construction process, the in-service operation of the building, and the long-term recycling, re-use or other end of life criteria. Other factors may be relevant, depending on the specific location of the building, or the broader impact of the project on biodiversity, and these should be considered in addition to the Sustainability Indicators.

The Sustainability Indicators relevant to modular construction are listed, under the above ECO-Homes headings, in Table 8.1. Comments on how modular construction contributes to these indicators is given against each Indicator.

There is no consensus as to the relative importance (or weightings) of the Sustainability Indicators. However, the user may compare the competing construction products or systems against the relevant sustainability indicators in order to obtain a broad assessment of sustainability for each product or system.

For modular construction, it is appropriate to include whole life measures, such as potential re-use, or re-location which are not properly reflected in conventional measures of sustainability.

Some of the Indicators, such as the type of heating system, are neutral with respect to the form of construction. However, modular construction can be manufactured to conform to a wide variety of user requirements.

Table 8.1 *Sustainability Indicators*

Sustainability Indicator:	Comment on modular construction:
Energy Efficiency	
C Minimise Energy in Use	- good level of thermal insulation is provided - efficient heating and cooling system - minimum energy in deconstruction
C Energy Saving Measures	- control systems for energy saving can be provided
C Minimise CO_2 Production from Use of Fossil Fuels	- efficient manufacture - efficient operation and thermal insulation
C Minimise Embodied Energy in Materials	- efficient use of materials - factory controlled operation - ease of deconstruction and re-use
Minimising Transport	
C Suitable Site Location	- depends on public transport and adjacent public amenities (site specific)
C Minimise Transport Impact	- raw materials delivered in bulk to factory - modules delivered to site fitted out - reduced deliveries to site - fewer personnel on-site
Minimising Pollution	
C No Use of Ozone-depleting Substances	- insulation materials can be selected to suit client needs
C Minimise Waste Creation and Dumping	- efficient use of materials in factory - minimum waste in construction - recycling of scrap metal - re-use of modules or components
C Maximise Waste Recycling Ratio	- recycled steel used in manufacture - modules can be re-used
C Minimise NO_x Emissions	- efficient boiler design (low NO_x) dependent on heating system
C Minimise Nuisance in Construction	- noise/vibration/dust reduced - fast construction process - less waste disposal - fewer site deliveries.

Continued....

Sustainability Indicator:	Comment on modular construction:
Efficient Materials and Resource Use	
C Efficient Use of Materials	- steel has high strength to weight ratio - efficient design in materials use - long design life
C Proportion of Re-cycled to Primary Materials/Components	- recycled steel used in manufacture of framework of modules
C Ability to be Recycled or Re-used	- high proportion can be recycled - modules can be reused
C Low Maintenance	- few 'call backs' due to better quality of factory production - accessibility for maintenance is easier
C Provision for Future Adaptability	- ability to extend/modify building
Water Conservation	
C Minimise Water Use	- minimum water use in manufacture - 'dry' construction process on-site
C Water Saving/Recycling Measures	- water recycled in manufacturing process for steel - efficient services for water use can be provided in the modules
Ecology and Land Use	
C Suitability for Brownfield Sites	- protected against noxious gases from ground - light weight for use on poor ground
C Maximise Effective Land Use	- effective use of building footprint - modules can be re-located
C Protection of Biodiversity	- no noxious materials created - natural habitats can be reinstated
Health and Well-Being	
C Maximise Site Safety	- manufacturing process is safe - safer site operations
C Considerate Construction	- speed of construction on-site - minimised noise, disruption, etc.
C Good Acoustic Insulation	- good insulation between modules - facades insulated against external noise
C Adequate Day Lighting	- large windows can be provided in modules
C Worker Welfare	- safe and clean manufacture and construction - good operational conditions

9 CONTACTS

9.1 Companies involved in modular construction of residential buildings

Ayrshire Steel Framing
(A division of Ayrshire Metal Products plc)
Irvine, Ayrshire KA12 8PH

Tel: 01294 274171
Fax : 01294 275447

Britspace Modular Building Systems Ltd
Unicorn House, Broad Lane, Gilberdyke, Brough,
East Yorkshire HU15 2TS

Tel: 01430 440673
Fax : 01430 441968
www.horncastle-industries.co.uk

Corus Framing
Whitehead Works, Mendalgief Road, Newport,
Gwent NP20 2NF

Tel: 01633 244000
Fax: 01633 211231
www.corusgroup.com

Forge Llewellyn Ltd
13.3.1 The Leather Market, Weston Street, London SE1 3ER

Tel: 0207 357 7323
Fax: 0207 357 8157
www.forge-llewellyn.co.uk

R B Farquhar Manufacturing Ltd
Deveronside Works, Huntly, Aberdeenshire AB54 4PS

Tel: 01466 793231
Fax: 01466 793098

Terrapin Ltd
Bond Avenue, Bletchley, Milton Keynes MK1 1JJ

Tel: 01908 270900
Fax: 01908 270052
www.terrapin-ltd.co.uk

Thurlston Group plc
Quarry Hill Industrial Estate
Horbury, Wakefield, WF4 6AJ

Tel: 01924 265461
Fax: 01924 280246

Unite Integrated Solutions plc
103 Temple Street, Bristol, BS1 6EN

Tel: 0117 907 8100
Fax: 0117 907 8101

Volumetric Ltd
Rosedene House, 12 King Street, Potton, Near Sandy,
Bedfordshire SG19 2QT

Tel: 01767 261313
Fax: 01767 262131

Yorkon Ltd
New Lane, Huntington, York, YO32 9PT

Tel: 01904 610990
Fax: 01904 610880
www.yorkon.com

9.2 Information on light steel components

Corus Colors
Construction Advisory Service

Tel: 01633 464646
www.corusgroup.com

The Steel Construction Institute
Silwood Park, Ascot, Berkshire SL5 7QN

Tel: 01344 623345
Fax: 01344 622944
www.steel-sci.org/lightsteel

9.3 Other manufacturers of light steel and modular components

Metsec Framing Ltd
(incorporating Metframe and Gypframe),
Broadwell Road, Oldbury,
Warley, West Midlands B69 4HE

Tel: 0121 552 1541
Fax: 0121 544 0699
www.metsec.com

Portakabin Ltd
New Lane, Huntington, York, YO3 9PT

Tel: 01904 61155
Fax: 01904 61144
www.portakabin.co.uk

Structural Sections Ltd
PO Box 92, Downing Street, Smethwick, Warley,
West Midlands B66 2PA

Tel: 0121 555 5915
Fax: 0121 555 5659

The Elliot Group Ltd
Glebe Court, Peterborough, PE2 8EE

Tel: 01733 552151
Fax: 01733 313002

Ward Building Components Ltd
Sherburn, Malton, North Yorkshire YO17 8PQ

Tel: 01944 710591
Fax: 01944 710555

9.4 Other organisations

The Brick Development Association
Woodside House, Winkfield, Windsor, Berkshire, SL4 2DX

Tel: 01344 885651
Fax: 01344 890129

APPENDIX A - SITE INSPECTION CHECKLIST

Modular manufacturers have established their own procedures to ensure that their modular units leave the factory defect-free and some manufacturers also have ISO 9001 certification. The principal checks required on-site are on the works that are carried out on-site and in ensuring that no damage has occurred to the units during transport and erection.

The checks on-site principally concern connections to or between modules, such as interfaces between modules and foundations, external cladding, roof and services.

The CDM regulations require that a Health and Safety Plan is prepared and the installation of modular units would require a detailed method statement to be followed on-site.

A site checklist for modular construction is as follows:

Foundations/drainage (pre-module delivery)

- Check that foundations are within the tolerances specified by the module manufacturer.
- Ensure that locating and holding down details are correctly installed.
- Check that drainage and services are installed and tested prior to delivery of modules.
- Check that below-ground drainage is correctly located on-site, and is within tolerance, for connection to modules.

Module/module connections

- Check that the connections between the modules and holding down details are correctly installed.
- Check for continuity of waterproofing and thermal insulation between modules.
- Check that cavity barriers and fire seals between modules and around site service connections are correctly installed.

Cladding

- Check that the installation of the main roof structure and bracing is as specified.
- Check that additional roof insulation has been correctly installed on-site.
- Check that cavity trays and brick ties are properly installed.

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