Modular Construction using Light Steel Framing: An Architect's Guide

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Why use modular construction?

Modular construction uses pre-engineered volumetric units that are installed on site as fitted-out and serviced 'building blocks'. The use of modular construction is directly influenced by the client's requirements for speed of construction, high quality, added economy of scale, and opportunity for single point procurement. These benefits may be quantified in a holistic assessment of the cost and value of modular construction in relation to more traditional alternatives.

Light steel framing is an integral part of modular construction, as it is strong, light in weight, durable, accurate, free from long-term movement, and is well proven in a wide range of applications. It is part of an established infrastructure of supply and manufacture, and is supported by British Standards and various design guides.

Modular construction is also widely used in Japan and the USA, where light steel framing is the primary structural medium, and leads to flexibility in internal planning, robust structural behaviour (even in seismic zones), and the possibility of exciting architectural solutions. There are also important opportunities for modular construction in extensions to existing buildings either by attaching units to the sides of buildings or by roof-top modules.

This publication addresses the information that is required by clients, specifiers and architects when designing with modular units in residential buildings, in general building construction, and in renovation applications.

The Egan Report - Rethinking construction

The Egan Report 'Rethinking Construction' has identified five key drivers of change: *committed leadership, a focus on the customer, integrated processes and teams, a quality driven agenda and commitment to people.* Modular construction has all of the attributes that are promoted in this report in terms of quality, integrated manufacture, fewer defects, speed on site, and opportunities for innovation in design and in the manufacturing process. It also has broad environmental benefits by reducing waste, minimising environmental pollution and disruption, and ultimately, in being relocatable and re-usable.

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FOREWORD

This publication has been prepared by Dr R M Lawson and Mr P J Grubb of The Steel Construction Institute, assisted by Mr J Prewer and Mr P J Trebilcock as consultants to SCI. Dr M Gorgolewski of SCI prepared the section on acoustic and thermal insulation of modular construction.

The Modular Framing Group (MFG) has provided detailed assistance, particularly in preparing the case studies. The members of the MFG are:

Mr S Anderson	MACE Limited
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Mr J A Robinson	British Steel (Strip Products)
Mr A L Rogan	University of the West of England
Mr A Trinick	Representing DETR
Mr N Whitehouse	Terrapin International Group

This publication is the first in a series on modular construction using light steel framing and gives information suitable for use by all parties at the concept stage of the design process. It is supplemented by:

- Case Studies in Modular Steel Framing (SCI-P-271)
- Performance Specification and Design of Modular Steel Framing (forthcoming publication).

The work was funded by the Department of the Environment, Transport and the Regions as part of the Partners in Technology initiative, and by British Steel (Strip Products).

A list of acknowledgements for illustrations is given on page 95.

CONTENTS

SUMMARY

This publication addresses the design of modular or volumetric construction, in which modular units are pre-engineered in the factory and installed on site to form rooms or parts of complete buildings. The primary structure of these modular units uses light steel components, which are designed for normal structural actions and additional forces due to lifting and other construction operations. The publication provides information suitable for use by architects and specifiers at the early stages in the design process. Details illustrate the range of structural solutions, cladding attachments, and the high degree of thermal and acoustic insulation that can be achieved.

A broad value assessment of the benefits of modular construction is included which may form part of a more comprehensive cost-benefit analysis. Examples of recent projects in the UK and other countries demonstrate the current applications of modular construction, which include hotels, residential buildings, renovation by attachments and roof-top extensions, and highly serviced units, such as bathrooms, kitchens and lifts. Construction and environmental benefits are also assessed. Manufacturers' information and a comprehensive reference list are also given.

Constructions modulaires utilisant des structures légères en acier – Un guide de l'Architecte

Résumé

Cette publication est consacrée à la conception de constructions modulaires ou volumétriques, utilisant des modules préparés en usines et installés sur le chantier pour former des immeubles complets. La structure primaire de ces modules utilise des composants légers en acier qui sont calculés pour supporter les actions structurales normales et les forces additionnelles dues à la manutention ou à d'autres opérations sur chantier. La publication fournit des informations utiles, pour les architectes et les spécificateurs, dès le début du projet. Des détails illustrent les diverses solutions structurales, les modes de fixation des revêtements et le très haut niveau d'isolation acoustique et thermique qui peut être atteint.

La publication contient une large revue des bénéfices que l'on peut escompter avec ce type de construction, permettant ainsi de procéder à une analyse coût-bénéfice précise. Des exemples de projets récents, réalisés en Grande-Bretagne et dans d'autres pays illustrent la brochure. Ces exemples portent sur des hôtels, des immeubles résidentiels, des rénovations d'immeubles et des unités de services tels des salles de bains, cuisines et ascenseurs. Les bénéfices pour l'environnement sont également mentionnés. Une liste de références et d'informations sur des producteurs complète la brochure.

Modulares Bauen mit Stahlleichtbau: Ein Leitfaden für Architekten

Zusammenfassung

Diese Publikation widmet sich dem Entwurf des modularen oder volumetrischen Bauens, bei dem modulare Bauteile in der Werkstatt vorgefertigt und auf der Baustelle zu Räumen oder Teilen kompletter Gebäude montiert werden. Die Primärstruktur dieser modularen Bauteile besteht aus leichten Stahlbauteilen, die für normale Gebrauchszustände und Montagelastfälle bemessen sind. Die Publikation stellt Architekten passende Informationen im frühen Entwurfsstadium zur Verfügung. Details illustrieren die Bandbreite konstruktiver Lösungen, Fassadenbefestigungen und den hohen Grad thermischer und akustischer Isolation, der erreicht werden kann.

Eine breite Wertschätzung der Vorteile der Modulbauweise ist enthalten, die Teil einer ausführlicheren Kosten-Nutzen-Analyse sein kann. Neueste Beispiele von Projekten im Vereinigten Königreich und anderen Ländern verdeutlichen die aktuelle Anwendung der Modulbauweise in den Bereichen Hotels, Wohnungsbau, Renovierung, Anbauten, Aufstockungen und Einheiten mit hohem Installationsgrad wie Bädern, Küchen und Aufzügen. Vorteile beim Bau und im Umweltverhalten werden ebenso beurteilt. Hersteller-Informationen und eine ausführliche Referenzliste sind ebenso enthalten.

Guida architettonica alle costruzioni modulari realizzate mediante sistemi intelaiati in acciaio

Sommario

Questa pubblicazione tratta la progettazione di strutture modulari o volumetriche, nelle quali il sistema base viene assemblato in stabilimento e installato in loco per realizzare locali o parti di sistemi strutturali completi. La struttura portante di queste unità modulari è realizzata mediante componenti leggere in acciaio, progettate con riferimento sia alle usuali azioni sia a forze addizionali legate al sollevamento e alle altre operazioni associate all'assemblaggio in opera. Questa pubblicazione fornisce agli architetti e agli operatori del settore utili informazioni relative a ogni fase del processo progettuale. I dettagli illustrano il campo applicativo delle soluzioni strutturali proposte, i sistemi di attacco dei tamponamenti e l'elevato livello di isolamento termico o acustico che può essere raggiunto.

Un'esaustiva valutazione dei benefici associati alle costruzioni modulari, eventuale parte di un'analisi costi - benefici di più ampia portata, è inclusa nella pubblicazione. Gli esempi riportati, relativi a realizzazioni nel Regno Unito e in altre Nazioni mostrano le attuali applicazioni di questi sistemi modulari, relative principalmente a alberghi, edifici residenziali, adeguamenti strutturali mediante inclusione di nuovi locali o estensioni dell'uso del sottotetto, e unità di servizio complete come servizi, cucine e ascensori. Sono infine fornite informazioni relative ai produttori unitamente ad un'esaustivo elenco di specifici riferimenti.

Construcción modular mediante estructuras ligeras de acero: Guia para arquitectos

Resumen

Esta publicación se refiere al proyecto de construcción modular o volumétrica, en la que se preparan unidades modulares prefabricadas en taller que luego se instalan in-situ para formar habitaciones o partes de edificios completos. La estructura primaria de estas unidades modulares utiliza componentes ligeros de acero que se proyectan para las acciones habituales así como para elevación y otras operaciones debidas al proceso constructivo. La obra suministra información adecuada para uso de arquitectos y planificadores en las primeras etapas del proceso proyectual. Hay detalles que ilustran la banda de soluciones estructurales y revestimientos aplicables así como el alto grado de aislamiento térmico y acústico que puede conseguirse.

Se incluye una primera estimación de los beneficios de la construcción modular que puede tomarse como punto de arranque de un estudio coste-beneficio más preciso. El estado actual en UK y otros lugares, que incluyen hoteles, edificios de habitación, renovaciones y ampliaciones, así como unidades de servicio con baños, cocinas y ascensores. También se indican los beneficios constructivos y medioambientales. Finalmente se incluye información sobre fabricantes y una muy completa lista de referencias.

Modulbyggnader i Lättbyggnad med stål: Guide för arkitekter

Sammanfattning

Denna publikation handlar om utformning av byggnader med volymsmoduler. Modulerna förtillverkas i fabrik och monteras på byggarbetsplatsen samman till rum, delar av en byggnad eller till hela byggnader. Primärstommen i modulerna består av tunnplåtsprofiler som är utformade för att klara såväl normal belastning som belastning pga av lyft och hantering. Publikationen riktar sig mot arkitekter och konstruktörer i ett tidigt skede i projekteringen. Publikationen innehåller detaljer som illustrerar olika konstruktionstekniska lösningar t ex infästningsdetaljer för fasadmaterial samt lämpliga detaljlösningar för att uppnå god värmeisolering och ljudisolering.

Publikationen tar upp övergripande fördelar med modulbyggnad som kan utgöra en mer omfattande cost-benefit analys. Exempel på aktuella byggprojekt i Storbritannien och andra länder visar nuvarande applikationsområden av modulbyggnader, t ex hotell, bostadshus, renovering genom tillbyggnad och påbyggnad av befintliga byggnader, men också installationstäta modulenheter som badrum, kök och hissar. Byggtekniska fördelar och miljöfördelar värderas också. Information om tillverkare och en utförlig referenslista inkluderas.

1 INTRODUCTION

'Modular construction' is a term that is used for the factory production of pre-engineered building units that are delivered to site and assembled as large volumetric components or as substantial elements of a building. The modular units may form complete rooms, parts of rooms, or separate highly serviced units such as toilets or lifts. The collection of discrete modular units usually forms a self supporting structure in its own right or, for tall buildings, may rely on an independent structural framework.

Modular units may be used for a wide range of building types, from residential buildings to complete fitted-out buildings such as fast-food restaurants. Modular construction should be differentiated from temporary or relocatable buildings, which, although similar in volumetric concept, differ greatly in terms of their quality, structural design, use of cladding materials, and general performance criteria.

An example of the application of modular construction in a residential building is shown in Figure 1.1. This building has a traditional brick facade and pitched tiled roof although the internal structure consists of modular light steel units.

Figure 1.1 *Modular construction used in a residential building*

The motivation for using modular construction lies in the business-related benefits that make this form of construction more attractive to the client than alternative forms of conventional site-built construction. In such cases, the design decisions are mostly strongly influenced by:

- Speed of construction on site. Rapid construction leads to business-related benefits to the client, due to early completion and early return on capital investment.

- Avoidance of disruption and loss of operation of adjacent buildings. This is often important in extensions to existing buildings, such as hotels, and in sensitive sites.
- Buildings or components with a high degree of servicing. These require careful site installation, and pre-compliance trials, which are better carried out off site and off the critical construction path.
- A large number of regular or repetitive units. Factory production can facilitate transportation and can achieve economy of scale in production.
- Planning constraints, such as on delivery times, time of working, noise control on site.
- A short 'weather-window', or other site constraints to the construction operation.
- Lack of suitable skills at site. This might be the case at a remote site.
- Client requirements for an exceptionally high degree of quality control. This can best be achieved by off-site manufacture and pre-installation checks.
- A requirement for a single point procurement route. This can be achieved through a design, manufacture and build service, which the modular industry provides.
- Security or other related issues on site. Construction operations can be controlled more precisely when modular units are used.

It is often thought that modular construction is by definition more expensive than traditional construction. While this may be true for 'one-off' buildings, there are considerable economies of scale that can be obtained from greater refinement of the design (often by testing) and by investment in mechanised and possibly automated production.

The Japanese house building market is dominated by modular construction, and over 150,000 houses are produced annually in modular form. The high degree of sophistication at the design stage permits considerable input by the purchaser into the choice of finishes and even into the internal layout. A typical large Japanese house is shown in Figure 1.2. The extremely high cost of land in Japan creates an economic imperative to build quickly and to achieve rapid pay-back, which could not be achieved by a conventional construction programme.

In the UK, many major companies choose to go the 'modular route' because of the greater control they can exert over quality, speed and reliability, which are all business-related benefits. Good examples of the move from conventional to modular construction have been in hotels and fast-food restaurants, where on-site construction times can be reduced by over 60%. An example is illustrated in Figure 1.3.

Modular construction may be combined with other constructional systems, including:

- Framed construction. Modular units can be inserted on the floors or roofs of framed structures constructed of beams and columns.

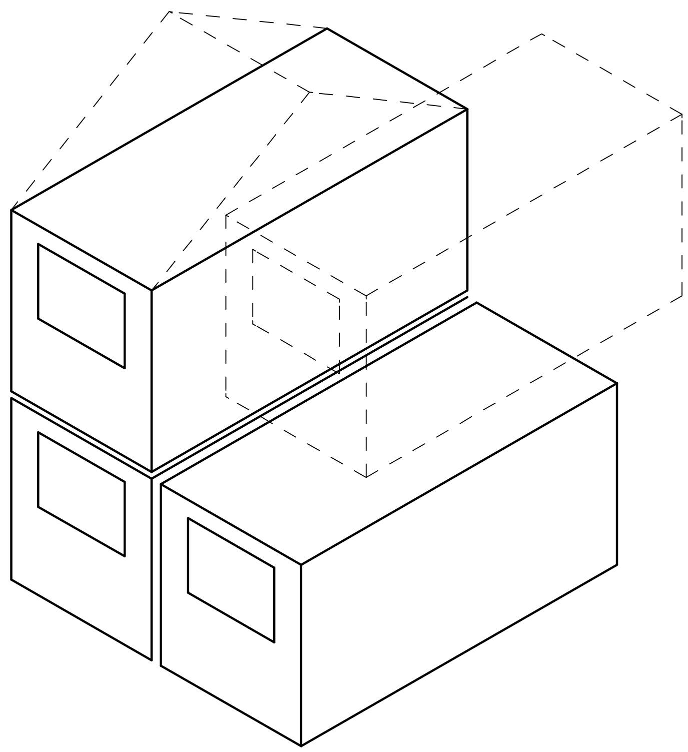
- Panel construction. Modular units can be used for the more highly serviced elements, while the remaining structure is built from two-dimensional wall and floor panels.

Figure 1.2 *Modular construction of large family houses in Japan*

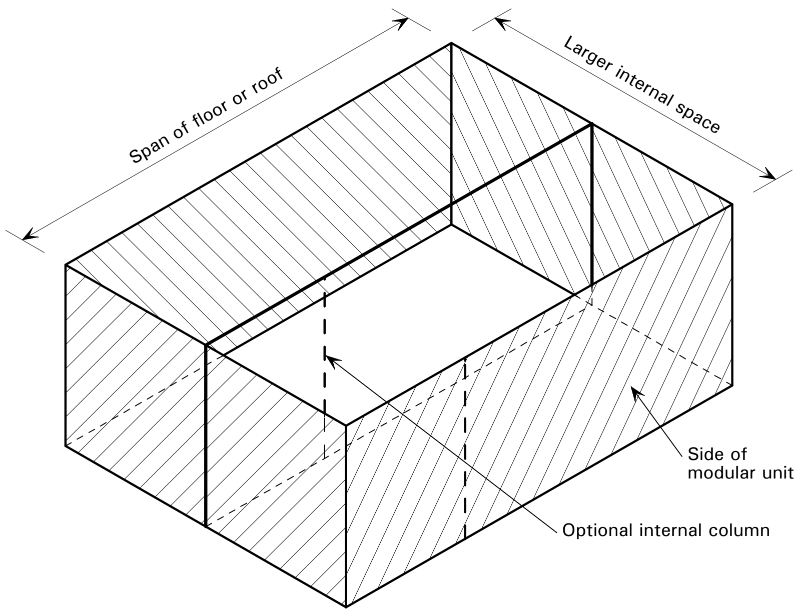
Figure 1.3 *Fast-food restaurant, which is fitted out before delivery to site*

Modular units may also be combined together to form larger rooms. In this case, the length of the modular unit is equal to the span of the floor or roof members forming the completed space. The 'open' face of the unit is braced or stiffened during lifting and transportation to provide stability.

Alternative forms of modular construction using single room-sized units or multiple units used to form larger rooms are shown in Figure 1.4.



(a) Modular units stacked to form cellular rooms



(b) Modular units combined to form larger spaces

Figure 1.4 *Various forms of modular construction*

1.1 Use of light steel framing in modular construction

Light steel framing comprises cold formed steel sections in C or Z form, or their variants, which are roll formed from galvanised steel strip of 1.0 to 3.2 mm thickness. The members are cut to length and assembled by various connection methods to form the structural framework of the modular units. The various section types are illustrated in Figure 1.5.

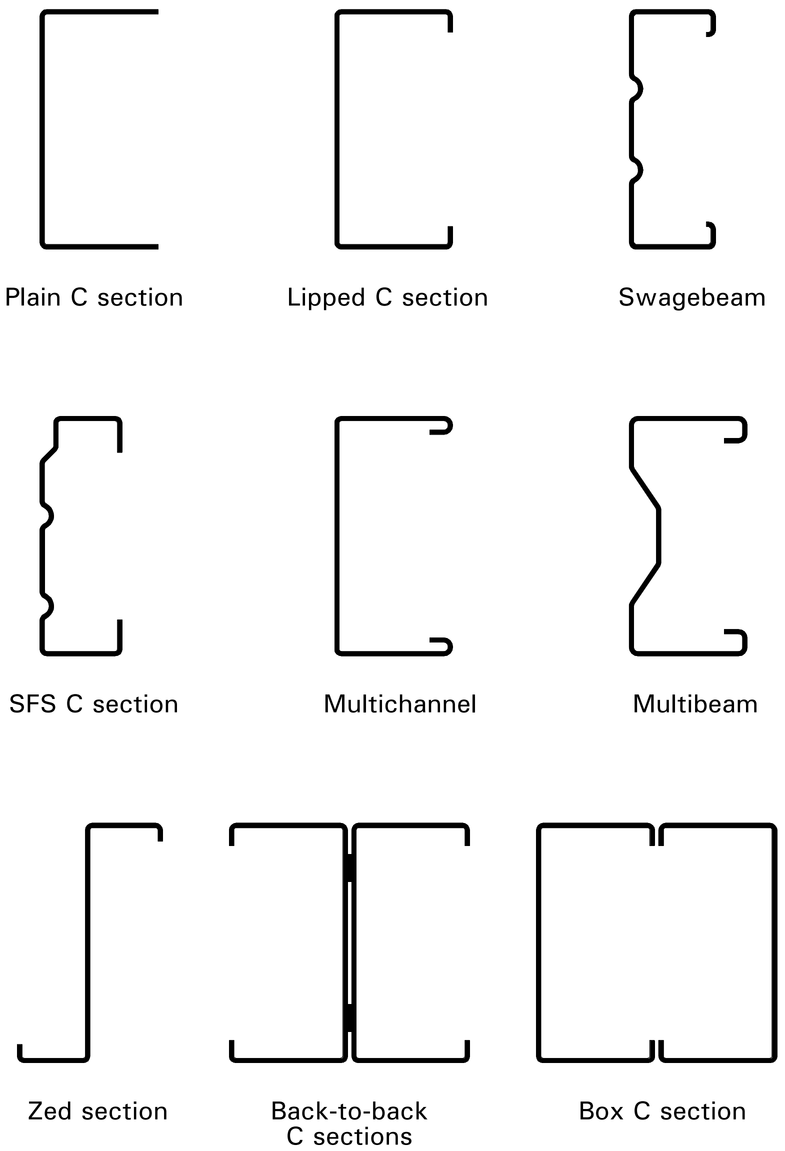


Figure 1.5 *Cold formed steel sections used in modular construction*

The general benefits of light steel framing in the context of modular construction are:

- robustness during lifting and transportation
- ease and speed of manufacture (including forming the connections)
- lightness (for lifting and transportation, and leading to smaller and cheaper foundations)

- good resistance to vertical and imposed loads
- suitability for long floor spans
- high levels of acoustic and thermal insulation can be provided on the framing
- ease of attachment of a variety of finishes and cladding materials
- robust connections made on site (by bolting for example)
- dimensional accuracy and reliable material properties
- freedom from long-term movement
- durability and long life
- fire resistance (steel does not contribute to the fire load).

Light steel framing is the ideal framing material for modular construction because of its efficient use of materials and its ability to be integrated into a sophisticated manufacturing process. It is also possible to mix the use of various section types including hot rolled steel members, such as I sections and hollow sections for heavily loaded applications, including at local lifting points.

An example of light steel framing used in modular construction is shown in Figure 1.6. In general, the structure may be 'over-engineered' for its normal applications, as sizing is more dictated by stability and rigidity in the lifting and transportation operations. Because of this, the in-service performance of modular buildings is often better than in more traditional buildings.

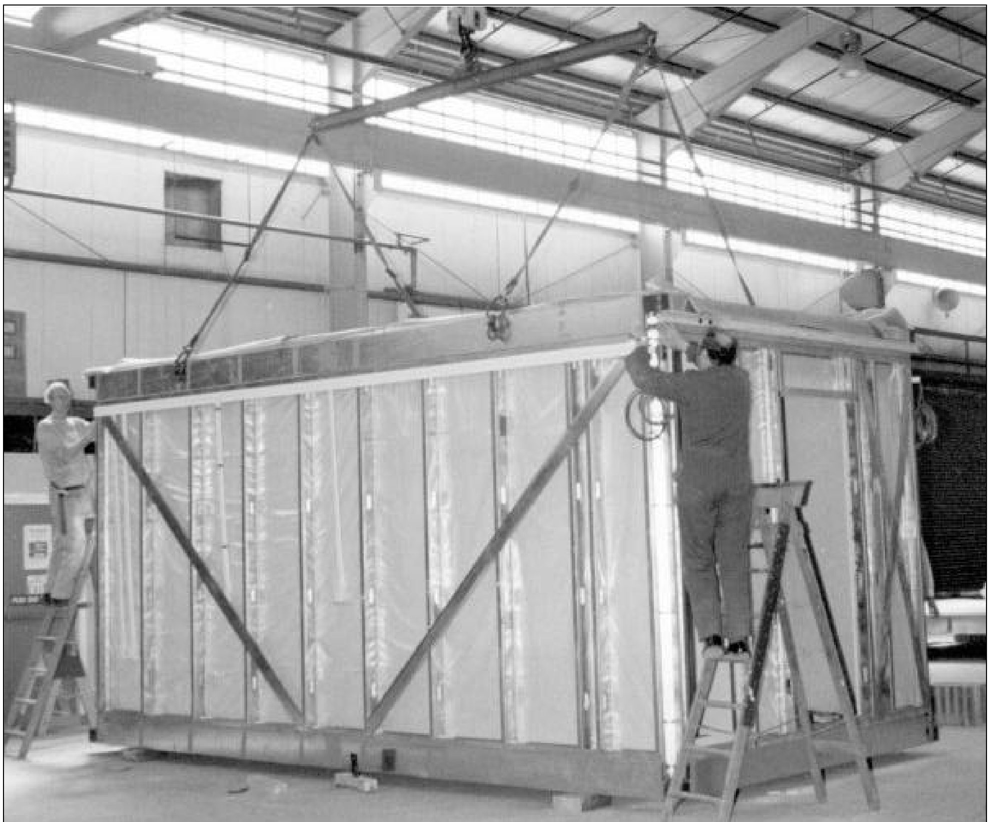


Figure 1.6 *Light steel frame used in modular construction*

1.2 Applications of modular construction in buildings

Modular construction comprising light steel framing has various applications in general building construction, and particularly in residential buildings such as hotels and apartments. Modular construction has not yet penetrated the low-rise housing market significantly in the UK, unlike its success in Japan. The following building types are most appropriate for modular construction:

- hotels and hotel extensions
- 'cellular' apartment units
- student residences
- educational buildings
- sheltered accommodation, such as old people's homes
- toilet units for commercial buildings
- plant rooms for commercial buildings, hospitals etc.
- highly serviced units, such as lift shafts and industrial 'clean' rooms
- roof top extensions to existing buildings
- external modular units in renovation of 'panel type' buildings
- pre-manufactured buildings, such as 'fast food' restaurants and petrol stations.

An internal view of a modular bedroom unit is shown in Figure 1.7.

Figure 1.7 *Fitted-out modular bedroom unit*

Other applications may be advantageous, particularly where the benefits of speed of construction and a high level of quality control can be realised. The modern use of modular construction for permanent buildings should be differentiated from the wide range of temporary buildings that are designed to lower standards commensurate with their cost and use.

1.3 Scope of the publication

This publication offers guidance to architects, specifiers and clients on the type of buildings that may be appropriate for modular construction using light steel framing. It provides broad information on the design and application of modular or volumetric construction in general building construction. It is intended that designs involving modular construction will be developed further in consultation with appropriate manufacturers.

This guide is a sister publication to *Building design using cold formed steel sections: An architects' guide*[1], and it addresses:

- the history and main applications of modular construction in general building construction, including overseas uses
- the current use of light steel framing in modular construction
- the manufacturers of modular units in the UK, their products and recent projects
- the broad cost-benefit assessment of the benefits of modular construction
- general technical information that is appropriate at the scheme design stage
- guidance on planning and execution of projects involving modular units
- opportunities for modular construction in renovation.

It does not address:

- temporary buildings or transportable units such as site huts and kiosks
- detailed technical aspects of the design of modular units
- other forms of modular construction in timber or concrete.

The SCI publication *Design of structures using cold formed steel sections*[2] describes the structural aspects of the use of light steel framing, and it is not the purpose of this guide to repeat this information. However, the main technical aspects of the use of light steel framing relevant to modular construction are covered here. A wide range of projects using modular construction is illustrated in a series of Case Studies[3] published separately by the SCI.

Contact details of manufacturers of modular units for permanent buildings are given in Section 13. More detailed design and cost information can be obtained from the manufacturers.

An architect's check-list of questions to be asked in discussion with the modular supplier at various stages of the project is presented on pages 92 to 94 at the rear of the publication.

1.4 Client check-list

The client has an important role to play in the decision-making process in relation to the use of modular construction in part or as whole 'building blocks'. The following 'check-list' identified those aspects that should be considered first at the client briefing stage and later at the concept stage of the building design:

- Modular construction is the fastest construction technique on site, leading to business-related benefits to the client.
- Cellular buildings lend themselves to modular construction.
- Transport restrictions limit sensible module widths to 4.3 m.
- Economies can be lost if there are a large number of non-standard units.
- Modularisation of highly serviced components should be considered, even if the whole building is constructed more traditionally (see Section 8.3). Examples are toilet/bathrooms, and plant rooms.
- A close working relationship between the manufacturer and designer is important in the concept design, and later with the general contractor in the final design.
- The logistics of transportation, just-in-time delivery, and site installation should be considered in the briefing and planning stages.
- Local site and planning constraints encourage consideration of modular construction.
- Key design decisions as to the use of modular construction should be made early in the design process.
- The use of pre-production prototypes can help to resolve any design and production issues.
- The 'lead-in' time to manufacture of the modular units can be 8 to 12 weeks depending on the repetition of use of the modular units (see Section 8.2).
- Buildings of modular form can be extended and relocated as client demand changes.

These and other benefits of modular construction are reviewed in more detail in Sections 2.5 and 8.

2 INTRODUCTION TO MODULAR CONSTRUCTION

2.1 History of modular construction

In contrast to the startling growth and technical advances witnessed this century in many industries, progress in the building industry, particularly the improvements in productivity and technology, has generally been relatively slow. An exception has been the emergence and growth of modular building methods.

Ideas of factory-made housing developed in the late 1920s and 1930s; in Germany through architects such as Peter Behrens and Walter Gropius and in the USA through Richard Neutra and Buckminster Fuller. Mass production of motor cars led to similar concepts for housing, starting firstly with panel or component-based systems and later extending to modular or volumetric units.

In the USA, the modular industry originated with the travel trailer (caravan) industry and increased in the Second World War as trailers became homes for thousands of defence workers. After the War, severe housing shortages created a demand for trailers as permanent housing. The industry responded by developing what are now called mobile homes, with designs that tried to strike a balance between the functions of house and vehicle.

The relatively low cost of starting a factory in the early 1950s, when demand was strong, encouraged the formation of many new companies in the USA. In 1959, there were 268 manufacturers with 327 plants. By 1963, the companies producing manufactured housing had split into two distinct groups - mobile home producers and modular home producers. In 1955, plants could be started for as little as $15,000. By 1966, the average start-up costs had risen to $150,000. However, they were very low compared to the start-up costs of other manufacturing industries, and remain so to this day. Many companies have folded as a result of economic recession, and there are now 34 companies in the USA producing modular units from 173 plants.

In general building applications, the use of various module types owes its origins to progressive architects and designers who developed prefabricated components, such as 'pod' bathrooms. The idea of the bathroom pod has been around since at least 1937, when the American engineer/inventor Buckminster Fuller developed the steel prefabricated Dymaxion bathroom. Thirty years later, Nicholas Grimshaw produced a spiralling cluster of bathroom pods in a circular tower attached to a student hostel in London. In 1978 he used similar stainless steel toilet modules - suitable for mass production - and installed prototypes in his Advance factory units in Warrington, UK. Several years later, perhaps influenced by Grimshaw's toilet modules, Sir Norman Foster used steel toilet modules in his Hong Kong Shanghai Bank headquarters in Hong Kong (see Figure 2.1). The wide publicity this building attracted played a major part in helping architects to understand the advantages of using service modules in office buildings; modular building techniques lead to improved speed and quality.

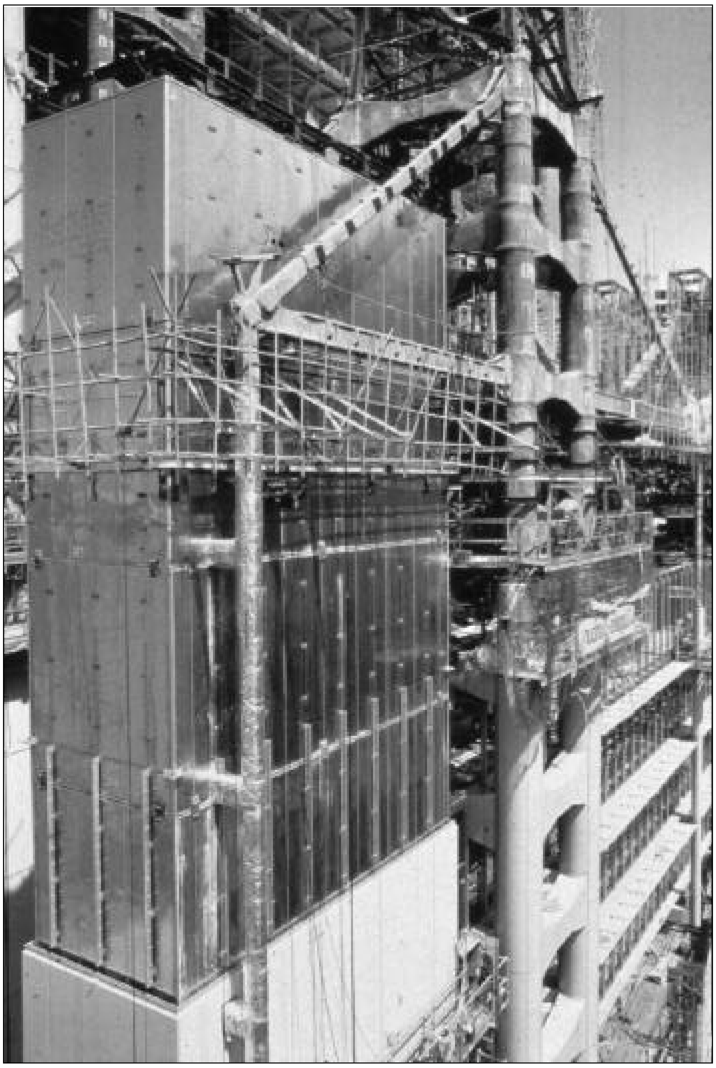


Figure 2.1 *Modular units used in the Hong Kong Shanghai Bank, Hong Kong*

During the office building boom of the 1980s in central London, where labour and logistical problems made life particularly difficult for contractors, many major office developments (e.g. Broadgate) made extensive use of toilet and plant room modules (see Figure 2.2). Proposals were made for completely modulising the core areas (a concept known at the time as *total core* 'TC') of major new office buildings. However, before those ideas could be implemented, the building boom was over, and they were shelved temporarily. A building that came closest to achieving total core was No. 22 Old Bailey in the City of London, where steel toilet modules, modular plant rooms, and modular lift shafts were used together for the first time. (These innovative applications are reviewed in Section 12.)

There has been a consistent growth in the use of bathroom pods for hotels, hostels, halls of residence etc. The larger hotel chains in Britain often specify bathroom pods for new hotel bedrooms, and for hotel extensions. It is worth mentioning that in most modern cruise ships, all classes of cabins either include toilet pods or are made as cabin pods with integral bathrooms, and that several manufacturers who make marine pods have built on that success and moved into the manufacture of modular products for the building industry.

Figure 2.2 *Toilet pods for use in commercial buildings*

A common characteristic of the various types of pod mentioned above is that they are all inserted into other load-bearing structures and therefore only need to be self-supporting. The highest loads are encountered when they are being handled or transported. Another characteristic of those module types is that the envelopes of the modules are generally designed to be as strong, lightweight, and economical as possible i.e. ideal candidates for the use of light steel framing.

The use of modular construction in housing has been relatively slow in all countries except Japan (see Section 4.2). Modular construction has attracted considerable attention from architects who were inspired by the opportunities of the construction technique and were not over-awed by the dimensional discipline that it imposed. Modular construction also introduced the benefits of 'mass production' to the construction sector, but self-evidently required a large market to lead to economies of scale.

In the UK, one of the first examples of modular housing construction using steel framing was in local authority (former GLC) housing in Hackney, London, which was reviewed in the magazine *Building with Steel* in 1974[(4)] (see Figure 2.3). At the time of writing, the housing association, Peabody Trust was constructing a major housing development also in Hackney, which was based on an extension of the now well established use of modular units in hotels.

Figure 2.3 *Early use of modular units in housing in the UK*

The type of material used for the structures of modules was frequently determined by the type of product that a company produced before becoming involved in manufacturing modular buildings. Module manufacturers that were originally involved in the production of timber frame houses, not surprisingly, prefer to make their modules from timber, while companies with a background in the production of heavier structures prefer steel as their medium. The companies that have switched to light steel framing have been motivated to do so because of the need to use a material that is consistent in quality and is well suited to efficient manufacturing processes and assembly operations.

In other European countries, the development in the use of modular construction has been relatively slow, and is often more associated with discrete architectural opportunities provided by the construction medium rather than a production-oriented market demand. However, a niche market in Scandinavia is in the renovation sector where modular units are used to renovate and extend existing tall concrete panel or masonry residential buildings of the 1960s (see Sections 3.4 and 11).

2.2 Types of module

There are three basic types of module using light steel framing or sheeting, namely:

Structural modules, which function as a load-bearing steel frame, a stressed skin box or combinations of the two functions. The modules can be stacked to produce multi-storey buildings or may be combined with primary structural frames, particularly in heavily loaded applications.

Non-structural modules, which are supported by a structural frame or on a concrete floor. These modules can be located between the primary structural members. Various examples are reviewed in Section 2.3.

Shutter modules, in which the steel modules act as permanent formwork for in-situ concrete (Figure 2.4). The applied loads are carried by the concrete cross-walls and floor slabs in the same way that they would be in a conventionally constructed concrete building. The light steel structure supports the loads during construction.

The detailed design of structural and non-structural modules is presented in Section 7. The shutter module system is site intensive and is not widely used currently.

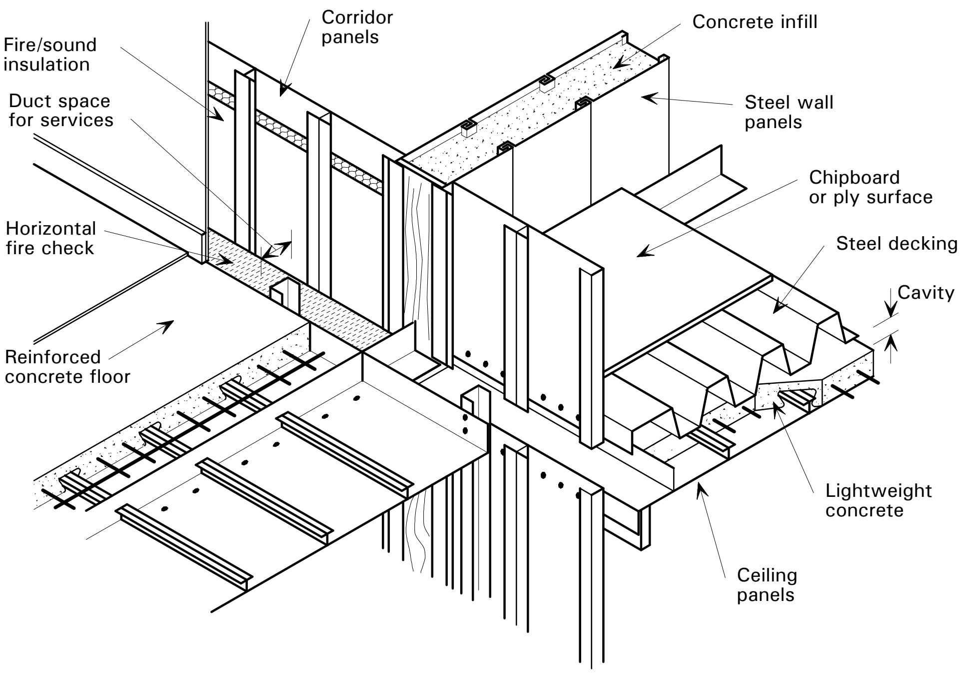


Figure 2.4 *Shutter-type modular construction, as used in the Domain system*

2.3 Other modular components

Various forms of other modular components have been used in major building projects. These modular units exploit the benefits of speed of construction by taking more complex parts of the construction programme off the 'critical path'.

Lifts: The time it takes to install conventional lifts will usually determine when a building is handed over to the client. Modular lift installation methods (e.g. Schindler's MLSC system, shown in Figure 2.5) have been in use for over 10 years, and allow lifts to be installed and commissioned quickly. Modular lift shafts can be fully integrated with the structure and can be designed to provide wind bracing, or they can be free standing elements.

Stairs: Prefabricated stairs are quick and easy to install, and are immediately available for use by the erection team and other building workers. Prefabricated steel stairs are usually erected as storey-high units and have been used for over 15 years in traditional steel framed construction (see Figure 2.6). They are installed with protection to finished surfaces, or in a partially finished state that can be finished later.

Figure 2.5 *Modular lift units by Schindler*

Figure 2.6 *Prefabricated steel stairs used in a commercial building*

Corridors: In some systems single hotel modules consist of two bedrooms each side of a corridor. Alternatively, bedrooms may be produced as separate modules. In this case, corridor units are created from floor panels that bridge between the modules. With this arrangement, the corridor can accommodate construction tolerances.

Plant rooms: The advantages and the limitations of M & E plant modules are well known and appreciated by service engineers, particularly those specialising in the design of large commercial buildings. In these applications, air handling and cooling plant can be installed by lifting onto the roof of buildings in modular units.

Toilet modules: Toilet modules can be constructed as self-supporting units and lifted and slid into place on the floor of buildings (see Figure 2.2). Clearly, the floor of the toilet modules will be higher than that of the adjacent floor unless a raised access floor or other covering is provided.

2.4 Production and logistics

Production efficiency and logistics, such as transport and crane costs, play an important role in determining the economic viability of modular building projects. The following points are relevant to these issues:

Ease of manufacture: Modules may not be as efficient structurally as they could be because of the need for an integrated assembly-line production and the requirements of the transportation and erection process. The way in which modules are assembled and fitted out in the factory, and lifted and assembled on site, frequently requires special components. However, there is also a need to minimise the number of components for production efficiency and to avoid unnecessary stocking.

Value per unit volume: The higher the value of the modular units per unit volume, the greater the distances over which modules can be transported and used competitively. It follows that the design of modules should be such that their value/size ratio is optimised to keep transport and installation costs at acceptable levels. Often the most highly serviced elements of the building are constructed from modular units and the remainder of the structure is constructed conventionally.

Finishing: Modules can be finished internally using 'dry-lining' techniques. Other methods may be more economic if they reduce assembly line costs.

Transportation: Delivery costs depend on travel distance from the factory to the site. To avoid problems arising from road transport width restrictions, modules should not exceed 4.2 m in width or 18 m in length. Whenever possible, modules, or parts of modules, should be sized so that they fit onto standard 20 ft (6.1 m) or 40 ft (12.2 m) long lorry trailers (see Section 7.1).

Erection: The larger and heavier the modules, the larger the crane needed to handle them. Also, the crane will require more space in which to operate. However, large rooms can be constructed from small modular units although additional bracing is required on the open faces of the modules to provide stability during lifting (see Figure 1.6).

Site logistics: The modular units are generally lifted straight from the lorry into their final position. It is self-evident that they should arrive on site at the right time and in the right sequence. In inner cities, road restrictions are often such that delivery and erection has to be done outside normal working hours. However, the operation is relatively quiet and does not involve significant waste on site (i.e. lower waste removal costs and less disruption). See Section 9: Environmental benefits.

2.5 Advantages of modular construction using light steel

The following general advantages may be attributed to modular construction using light steel framing:

Short build times: Typically 50-60% less than for the equivalent conventionally constructed buildings. However, longer procurement times may be required before construction starts on site.

Superior quality: Achieved by factory-based quality control methods and standards. Steel is a reliable quality assured material.

Economy: Efficient manufacturing processes, fixed prices and earlier completions (leading to early return on capital).

Low weight: Modular construction is about 30% of the weight of conventional masonry construction, leading to reduced foundation costs. Modular construction is ideally suited to roof-top extensions to avoid overloading the existing building.

Dimensional accuracy: Small tolerances can be achieved and maintained within the module interior and in the sizing and positioning of openings. This leads to ease and accuracy of fit-out in a production environment.

Environmentally less sensitive: Efficient factory production techniques are much less wasteful and disruptive on site than traditional construction operations.

Seismic properties: Steel modules have excellent robustness, which usually means that they can meet international seismic standards (with relatively minor modifications).

Relocatability: Buildings made from steel modules can easily be disassembled and modules can be relocated to create new buildings quickly and economically.

Innovative funding potential: The ability to recover and recycle modules quickly and easily provides scope for modules to be made available to users on terms that are not possible for conventional buildings (e.g. product lease or hire purchase).

Use on infill sites: Modules are useful in small urban infill sites, particularly where it is uneconomical to build because of problems of disturbance and site location.

Reduced site labour requirement: The erector and finishing teams who install and complete modular buildings involve fewer workers on site than traditional buildings.

Improved manufacturing skills: The way modules are made means that work in the factory and on site is reduced and greatly simplified, by advanced manufacturing techniques.

Safer construction: Modular construction sites have proved to be significantly safer than traditional sites because of the more controlled operations.

Component interchangeability: Standardised components, jointing details and the use of assembly jigs means that module components using light steel framing are readily interchangeable.

Adaptability or extendability: Adding modules to, or removing modules from, modular buildings is typically a very rapid and straightforward process that involves the minimum of disruption to the operations of adjacent buildings.

Mobility: Modules are designed to be transported easily and can be exported (subject to sensible transportation costs).

Reduced professional fees: Standardised design details for modular buildings simplify and reduce the need for specialist design input. Accurate costs can be obtained from the manufacturer.

Design flexibility: Steel modules can be grouped vertically and horizontally with good load resistance.

The above list is not exhaustive and new advantages of using modular construction are constantly emerging.

2.6 Relevance to 'Rethinking Construction'

The 1998 DETR *Egan* Report 'Rethinking construction'[5] called for a culture of cooperation and greater innovation in procurement, design and construction, leading to demonstrable savings and benefits to clients and to society at large.

Earlier, Sir Michael Latham said 'In a rapidly changing environment, both clients and the supply side are increasingly looking to improve performance and reduce and hopefully, eliminate conflict and disputes through a teamwork approach'.

The attributes of modular construction that are compatible with these objectives are:

- reduced construction costs, especially when combined with economy of scale of production (10%+)
- much reduced construction time on site (50% to 60%)
- increased profitability of the industry due to economy of manufacturing scale
- increased site productivity (up to 50%)
- greater certainty of completion on time and in budget
- reduced wastage in manufacture and on site.

These attributes are explored further in Sections 8 and 9.2.

3 USE OF MODULAR CONSTRUCTION IN THE UK

Modular construction has been used in the UK since the late 1970s but its rapid increase in recent years has occurred due to client demands in various well defined sectors. There are four major manufacturers of modular units in the UK, and many more who manufacture temporary buildings. Therefore, a strong infrastructure of design, manufacture and supply exists, which has expanded to meet the increasing demand of the late 1990s.

The motivation for using modular construction generally arises because of over-riding client requirements for speed of construction and for early return on investment. However, there is a noticeable trend to use modular construction in social housing, where speed of construction is allied to economy of scale and to reduced disruption in congested inner city sites.

The optimum size and span of the modular units is dictated by transportation limits. Generally, buildings of up to 5 storeys can be designed without being over-engineered (i.e. the same modular unit is used at all levels without need for strengthening). For taller buildings, additional strengthening elements can be introduced.

Recent examples of the sectors that have used modular construction are presented below. A number of case examples of recent projects is presented in *Case studies on modular construction*[3].

3.1 Hotels and extensions to existing hotels

Most major hotel chains in the UK have trialed modular construction for their out-of- town hotels, and most of these use light steel framing as their primary structural components. It is estimated that, up to the end of 1998, at least 30 hotels have been built in this way, and 100 or so are planned in the near future. The optimum use of modular construction is in the bedroom units, but it is also possible to use individual toilet/bathroom units in otherwise conventional steel framed structures.

Many projects have involved extensions to existing hotels, where avoidance of disruption and loss of earnings of the hotels are important client concerns. A 5-storey hotel project for the Granada Group is illustrated in Figure 3.1. By using modular construction, the client is able to design and order a large number of similar bedroom and bathroom units to a pre-determined and controlled quality and cost. The final service installations can be carried out on site.

The rationale for use of modular construction in this sector is largely speed of construction, as the construction period for a 60-bedroom hotel can be reduced from typically 35 weeks to as short as 15 weeks. The increased revenue due to the shorter construction period is easily calculated and compared with any slight increase in costs for the construction system. The business-related benefits to the client are explored further in Sections 8 and 9.

Figure 3.1 *Multi-storey hotel using modular units*

The modular bedroom units can be up to 3.6 m wide, which is the limit for transportation without police escort. However, units of up to 4.2 m width have been manufactured for some hotel chains. Generally, the length of the units is the length of the bedroom. The central corridor area is completed on site as it often accommodates the main service runs. The corridor should be weather protected during construction.

The design of these modular units is now quite sophisticated. For example, the *Ayrframe* system uses a series of 'box' frames connected by longitudinal ribs that create a stiff unit to resist forces during lifting and transportation. The *Yorkon* system uses long modular units comprising two bedrooms and a central corridor in which the sheeted side walls act as a 'stressed skin' diaphragm to resist shear loads.

In all cases, the facade materials can be chosen to match the particular planning or design requirements. Brickwork is supported from a separate foundation and tied to the modular units using separate vertical 'tracks' to which the wall ties are fixed. Alternatively, lightweight panels can be attached to storey-high frames to offer a versatile and more rapid construction process.

One of the earliest examples of modular construction was the *Domain* system, which used the sides of the sheeted modular units as permanent formwork for in-situ concrete placed between them, as illustrated in Figure 2.4. This system was used for a major hotel construction for the oil industry in the Shetlands, where speed of construction in the short weather-window was the main requirement. The *Domain* system is no longer used but the general principles are attractive for taller buildings where the increased compression and shear resistance of the concrete walls can be utilised, while maintaining the speed of modular construction.

3.2 Residential buildings

One important example of the use modular construction in the residential sector was in the halls of residence for the University of Wales in Cardiff, which were completed in 1994 (it is illustrated in Figure 1.1). This 4-storey building was designed by Ove Arup and Partners and constructed by Trinity Modular Technology. The room-sized units 2.6 m wide by 3.5 m long were fully fitted-out before delivery to site. The external facade was in conventional masonry. Figure 3.2 shows the units being assembled on site. Construction was completed in 14 weeks.

Figure 3.2 *Modular units used in the student residence at the University of Wales, Cardiff (see completed building in Figure 1.1)*

A similar sized residential building was constructed in 1996 by Britspace at the Yorkill Hospital, Glasgow. It is used for overnight accommodation by patients' relatives (see Section 5.2).

A recent project that has attracted considerable interest is the Murray Grove housing project in Hackney, London. The client, the Peabody Trust, wished to procure a building that was architecturally interesting and met their requirements in terms of accommodation, low maintenance and speed of installation on-site. Architects Cartwright and Pickard designed the 5-storey building using 3.2 m wide room-sized modules which were manufactured by Yorkon. Two units make a one bedroom flat; three units make a two bedroom flat.

In the Murray Grove project, a cylindrical stair tower, external access balconies and a monopitch roof were all prefabricated. Stability was provided by external bracing although the modules are stable as a group. The external facades consist of clip-on terracotta tiles. This project is reviewed in Reference 3 and an architectural impression of the building is shown in Figure 3.3.

Figure 3.3 *Murray Grove project, Hackney (artist impression)*

There are a few examples of 2-storey houses produced in this way, and one example of sheltered accommodation for a housing association in Southwark, London, was constructed by Terrapin (see Figure 3.4).

Figure 3.4 *Social housing in Southwark, London*

In the low-rise housing sector, the use of light steel framing as prefabricated planar panels is well established in the UK. As yet, the motivation to use modular construction in this sector is not strong although there is a potential market in inner city housing projects where there are constraints on the construction operation, such as the need to avoid disruption to adjacent buildings.

3.3 Highly serviced units in commercial buildings

As described in Section 2.1, the boom in commercial building in the mid-1980s brought with it a demand for installation of highly serviced units such as toilet pods. The Broadgate development in London used these toilet pods in many of its buildings, which took this major aspect of servicing and fit-out off the 'critical path' of the construction operation.

Modular lift units have also been developed, as illustrated in Figure 2.5. These units comprise angle sections and sheeted walls with their guide rails and other lift components already installed. They are stacked precisely one on top of each other. The finishing of the outer surface of the lift shaft can be made later to meet acoustic insulation and fire resistance requirements.

Modular units are also used to house major items of plant such as chiller units that are installed on the roof or in on-floor service zones. Specialist modular units such as clean rooms for manufacturing and medical applications are used increasingly.

3.4 Renovation of existing buildings

The use of modular units in renovation is less well developed in the UK than in some other European countries. However, modular bathrooms are used in renovation in the same way as they are used in new-build construction. Modular units may be used externally to provide new facilities or to remodel the existing facade of old buildings. The modular units also improve the overall energy performance of the building and do not affect the loading on it. This form of renovation is potentially of wide application, provided sufficient room exists around the building for location of the modular units. The opportunities for modular construction in renovation applications are reviewed in Section 11.

Roof-top extensions can also be made in modular form, and they can be designed to span between the existing load-bearing walls. The main benefit of modular construction is in the creation of additional habitable space, and in the trade-off in construction efficiency between off-site manufacture, and the lifting and handling of a wide range of construction materials to the top of the building. Disruption to the occupants of the building is also minimised.

3.5 Pre-manufactured buildings

Fast-food restaurants using the Britspace and Yorkon systems have been installed on site in less than 24 hours using modular units that are fully fitted out in the factory. The units are constructed as part-rooms, kitchens and toilets, and the final connections are made on site (see Figure 1.3).

Other examples of pre-manufactured modular buildings include units for petrol filling stations and canopies, shops and kiosks. The portable petrol station illustrated in Figure 3.5 is sized for transportation in a standard shipping container. Architects Cottrell and Vermeulen have worked closely with Portakabin to develop modular primary schools and nurseries that are fully fitted out, as illustrated in Figures 3.6 and 3.7.

Figure 3.5 *Portable petrol station and canopy*

Figure 3.6 *Modular primary schools ('Akademy' Classroom by Portakabin)*

Figure 3.7 *Modular Nursery ('Lilliput' Nursery by Portakabin)*

4 INTERNATIONAL EXPERIENCE

Modular construction is well established in North America, in Japan, and in parts of Europe (particularly Scandanavia). International experience is described in the following Sections.

4.1 North American modules

Modular steel framing had its precursor with light steel prefabricated components. Since the Second World War, there have been persistent attempts to harness the technology and productivity of the steel industry to mass-produce cheap houses. *Arts and Architecture*, a Californian monthly magazine, devoted the July 1944 issue to prefabrication. Charles Eames demonstrated how the supply of cheap housing could be met through mass production. *Arts and Architecture* subsequently announced a Case Study House programme, which resulted in the now famous Eames house in California.

Modular building techniques are now widely used in the USA, especially in the affordable housing and budget hotel sectors. Nearly eight million single-storey manufactured units provide homes for almost thirteen million Americans. In the last two decades this has accounted for 25% of the annual single family housing production.

It is an industry rule of thumb in the USA that it is uneconomical to transport homes more than a day's drive from the plant where they are made - i.e. 200 to 300 miles - which is why there are so many plants in the USA. With such distance limitations, it is inevitable that some manufacturers will find themselves in areas where the market for their products has dried up because they are too remote from their new markets.

Road transport regulations in the USA mean that most modular homes are made from either one, two or three modules, each typically 14 feet (4.26 m) wide and up to 60 feet (18.3 m) long. The ex-works price of a modular home is typically 40% to 50% less than a traditionally built house of similar specification. By the time it is installed on its site and ready to move into, it will generally be about 20% to 30% cheaper. The modular home is usually installed on an individual plot and is indistinguishable from traditionally constructed houses.

Until recently, modular home producers concentrated on meeting local market requirements. They were too small to undertake long-term development work designed to improve product performance and cut production costs in the way that car manufacturers have. However, Fleetwood - the largest of the modular home builders in the USA, with an annual turnover exceeding $2 billion - has recently established a programme that is designed to strengthen their position in the national housing market by improving quality and cutting costs. Among Fleetwood's priorities is to develop multi-storey modular housing of the kind being proposed by the University of Wisconsin for the derelict inner city areas of Milwaukee.

New planning policies that mean housing will have to be built to much higher densities than before, and for the first time this is beginning to create a market in the USA for multi-storey modular housing. Until recently, there was no incentive for the modular manufacturers to develop designs for this market. As a consequence, although the USA has the world's largest modular housing industry, it is much less advanced technically than its Japanese or European counterparts.

For the foreseeable future, modular homes in the USA are likely to be confined to the lower end of the housing market. However, this situation will change as the American public becomes familiar with more up-market modular building types, and the advantages they offer.

4.2 Japanese modules

The most important difference between Japanese and American modular housing is that the market for the modular homes in Japan is among the upper and higher-middle income groups, whereas in the USA it is among the lower income groups. In Japan, there is almost no 'second hand' housing market and most sites are re-built every 20-30 years. Consequently the Japanese housing market is now 1.5 million dwellings per year (8 times that in the UK, although Japan's population is only double that of the UK).

The background to the development of the modern Japanese modular home industry is very different to that of its American counterpart, and is much more recent. In 1955, as a result of acute housing shortages, the Japanese government set up the Japan Housing Corporation (JHC). Initially JHC focused on the development of medium-rise concrete apartments, made from a limited range of heavy concrete panels. The resulting apartments were highly uniform in design and appearance.

The need to improve the flexibility of design, so that consumers could have detached houses that would fit onto small sites, led industrialised housing producers to develop prefabricated panel systems. In the mid 1950s, over-capacity in the steel industry forced large companies to find new markets for their steel production, and in 1955, the production of light steel sections for housing began. By 1970, the emphasis had shifted from quantity to quality and flexibility.

Industrialised building techniques of all types account for about 20% of housing production in Japan, or over 300,000 dwellings a year. The major builders in the industrialised production sector are Sekisui Chemicals, Daiwa, Misawa, and National. Their construction techniques are based largely on traditional framed construction using a combination of steel sections, which are designed in accordance with the strict Building Standard Law. The facade panels often use lightweight concrete (autoclaved concrete).

Sekisui Heim was established in 1972 as the modular building part of Sekisui Chemicals Ltd. Since then, Sekisui Heim has produced almost half a million modular homes (each house typically consisting of 12 to 15 modules) and is Japan's biggest modular home producer. In 1976, Toyota (the car company) followed suit by setting up a modular homes division. Although Toyota Homes' output of houses is only about a tenth that of Sekisui Heim's, its importance lies in its production methods, which owe much to sophisticated car manufacturing methods developed by the parent company. Though the two companies' production levels are very different, they produce modules that are technically similar. Sekisui Heim produces approximately 35,000 modular houses a year, and their largest factory produces approximately 7,000 houses a year.

Cramped sites and narrow roads mean that modules are constructed to shipping container width of 2.43 m and, generally a maximum 6.1 m length. High land values, crane handling and seismic design considerations require lightweight, very strong modules that can be grouped and stacked two or three storey high to create large (and expensive) single family houses.

Sekisui Heim and Toyota Homes use open framed steel modules that are customised to individual consumer specification to a significant extent. Customisation is possible because of the extensive use of computer aided design (CAD) and computer aided manufacture (CAM). The sophisticated software allows the architectural design and pricing processes to take place in the presence of the prospective home owner. When arrangements for the purchase of the house have been agreed, production drawings and specifications are produced - an operation that usually takes about an hour. The result is a unique house design made from a wide range of standard components. The Japanese refer to this approach as *mass customisation.* A typical Japanese house constructed using modular units is shown in Figure 1.2.

Each Sekisui Heim house is made from around 10,000 different components, but in order to provide consumer choice, the plant holds stocks of over 270,000 components. Without the use of CAM, the millions of possible component permutations would be unmanageable. The modules are manufactured on assembly lines like cars. Throughput is such that a module is completed every 3 minutes. Each module passes through 24 work stations, so that when it reaches the end of the assembly line after 3 hours, it is ready to transport to site. The production operation is illustrated in Figure 4.1. Preparation of the sites, construction of the foundations and the erection of modules are usually left to small building companies, subcontracted to the module manufacturers.

Figure 4.1 *Production of Japanese modular units*

The basic module in a Sekisui house comprises a 200 × 75 mm C section as a ring beam with a 125 mm square box section at the corners. The infill elements in the wall and floor joists use 125 × 50 mm C sections. Decking and chipboard is placed on the floors and quilt provides the necessary acoustic insulation. Each unit is finished internally before delivery, and is lifted from its four corners into position. As noted earlier, approximately 12 units form a typical large family house, which can be constructed in 40 days, including foundations and landscaping, compared to 120 days for traditional housing.

The products of the Japanese and American modular home companies are considerably different in terms of design, technology, quality and cost. Japanese companies also have large research and development budgets (for example, Sekisui Heim's Housing Research Centre is better equipped and funded than Britain's Building Research Establishment). The Japanese house construction industry was reviewed in a recent CIRIA report[6], which should be referred to for more background information.

4.3 European experience

The motivation to use modular construction is less obvious in the continent of Europe than in the USA or Japan. However, in Scandinavia the industrialised methods of the ship-building industry have led to extensions of this production technology into the building industry.

One well known architectural example of social housing in Tampere, Finland, uses tubular construction as the supporting framework for modular wall elements inserted between the horizontal members. The internal elements were designed to be adaptable. This building owes more to offshore construction than to traditional housing, as illustrated in Figure 4.2.

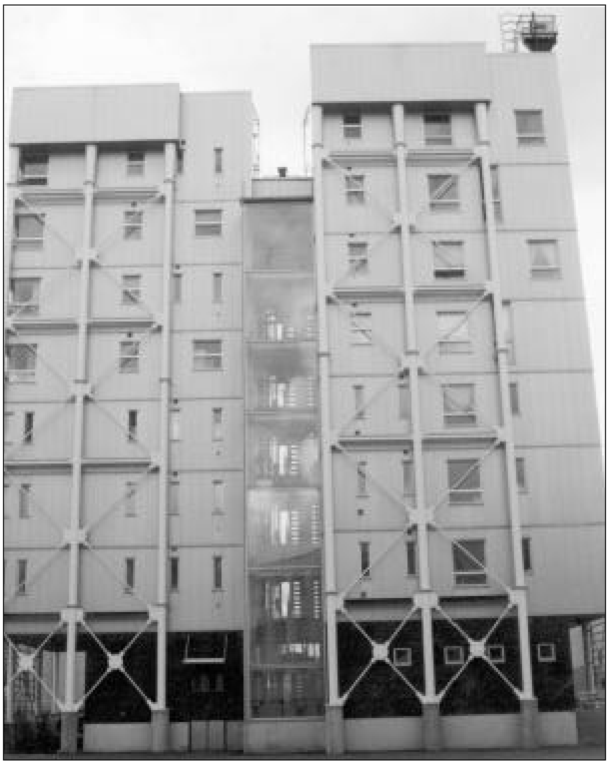


Figure 4.2 *Modular units used in tubular framework in Tampere, Finland*

The Finnish steel company Rautaruukki, through their division Rannela Metals, has developed a modular building system that is based on light steel units with cassette cladding panels to form the facades. Although equally appropriate for new-build construction, it has found its niche market in the renovation sector, where existing buildings can be extended horizontally and vertically to create new high quality space[7].

A wide range of building projects have used this system, mainly for new toilets and bathrooms, enclosed balconies and access stairs. Unlike conventional construction systems, modular units can be constructed and installed all year round, which makes modular construction more attractive in the Scandinavian climate. An example of this form of construction is shown in Figure 4.3. The modular bathroom units are fully serviced and fitted out before installation. They are used to form the new facade and often form part of a comprehensive over-cladding scheme (see Section 9).

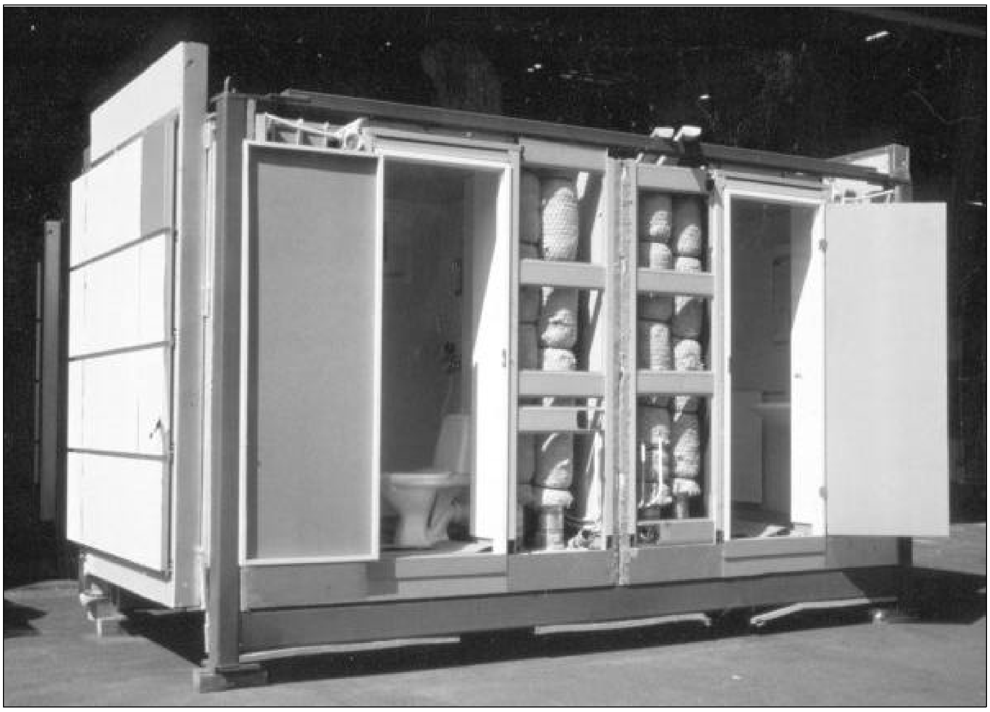


Figure 4.3 *Modular units used in new toilet and bathroom units in Finland*

In Denmark, modular units have been used in roof-top extensions in the renovation of apartment buildings, as in the example of Figure 4.4 in Copenhagen. In this project, the key to the use of modular construction was the speed of construction and light weight of the modular light steel frames, which could be lifted into place onto the roof.

Modular construction is well developed in Germany, where there are a number of manufacturers of modular units that are used primarily in housing. The largest manufacturer of modular houses is the company Alho, which has two manufacturing plants in Germany. They have also developed a system called a Generation house, which is based on a light steel frame substructure of up to 4.5 m width. The units can be extended as family sizes increase (see Figure 4.5).

Figure 4.4 *Renovation by over-cladding and modular roof-top extension in Denmark*

Figure 4.5 *Modular unit for housing manufactured by Alho in Germany*

Other modular systems have been used in office buildings of up to 4 storeys, banks, schools and hotels. Pitched roofs and balconies may also be produced as modular units. A recent issue of the magazine *Detail*[8] illustrates a 3-storey office building for a local authority in Munich, which consisted of 66 modular units. The building was designed for quick assembly and relocation to meet changing client demands (see Figure 4.6).

Figure 4.6 *Modular office building in Munich*

In this project, the modular units were of equal width of 2.5 m, and were 5.0 to 7.5 m long. The units were fitted out with roller blinds and cooler units in the facade. Some units had open sides to allow the creation of larger office space. The primary structure consisted of I beams and SHS columns. A separate external structure supports the sloping roof and steel escape stairways.

Other European experience (outside the UK) is limited, although the offshore industry has led to a demand for accommodation modules on production platforms.

The manufacturers of modular building units in the UK are reviewed in Section 5.

5 MANUFACTURERS OF MODULAR UNITS IN THE UK

This section reviews the output and main applications of the major modular unit manufacturers and suppliers in the UK (in alphabetical order).

5.1 Ayrshire Steel Framing

Ayrshire Metal Products plc produces a wide range of light steel components for use in the building industry. The company's two principal product ranges used in the building industry are the Ayrshire Steel Framing system and the Swagebeam system. The Ayrshire Steel Framing system comprises a range of special C sections of 70 to 340 mm depth, all with a shoulder joggle to enable box sections to be created. The Swagebeam is designed for use as a floor beam with cleated and bolted connections, or with moment resisting connections due to the embossment rolled into the section. These systems can be used separately or in combination to create dry envelopes, mezzanine floors, and residential and small office buildings up to 4 storeys high. Swagebeam is widely used in over-roofing and refurbishment applications.

In the context of modular construction, two forms of structure have been developed:

- conventional framing using load bearing wall panels, which are bolted or welded together and are supported at their corners.
- the *AyrFrame* system which is based on a series of transverse box frames with longitudinal members providing the necessary stiffness in this direction (see Figure 5.1).

Figure 5.1 *AyrFrame modules (unclad and unfinished at this stage)*

The *AyrFrame* design uses moment-resisting light steel frames that are connected longitudinally by top hat-shaped 'furring' runners and corner angles. No bracing members are required as the multiple connections of the furring member provide the necessary in-plane stiffness. The ends of the modules are closed with prefabricated panels. The walls are finished with two layers of plasterboard and can be as thin as 100 mm. The floor comprises 22 mm cement bonded particle board, which is moisture resistant, and improves the acoustic insulation of the floor. The roof of the unit comprises water-resistant chipboard.

The *AyrFrame* modular units have been used in recent hotel projects in their collaboration with the company Volumetric. The system has also been used for various residential buildings that are cellular in form. The *Ayrframe* units can be manufactured to suit particular applications as they can be fitted out in a separate off-site process or finished on site.

5.2 Britspace Modular Building Systems

The Britspace Modular Building System uses steel hollow section columns at the corners of the units and at 4 m intervals along the units. Floors, wall and roof members are galvanised steel C sections, and the wall members are bolted to the longitudinal floor and roof members. The flooring material is 28 mm moisture-resistant cement particle board. The walls and ceiling comprise two layers of fire resistant plasterboard to give 60 minutes fire resistance.

The system is offered with BBA certification for both residential and commercial buildings. Britspace has developed various forms of modular units for use in retail units, petrol filling stations, hotels and residential buildings.

Britspace and Yorkon have developed modular systems for use in fast-food restaurants for the McDonald's chain (see Figure 1.3). These modular units are fitted out before delivery to site and are connected together on site to form the complete building with minimal additional site work. The foundation details are specially designed to facilitate site connections to light steel piles that are suitable for all ground conditions. A project in Runcorn was completed in just 24 hours from the modules arriving on the prepared site to opening.

A 3-storey residential building was constructed by Britspace for the Yorkhill Hospital in Glasgow (reviewed in the Case Studies(3), and is illustrated in Figure 5.2). The modular units were manufactured as individual rooms and were stacked on site to form the completed building. Special features such as a curved facade and bay windows were introduced.

A sister company also produces relocatable buildings, which have all the attributes of permanent buildings.

Figure 5.2 *Residential home of Yorkhill Hospital constructed using Britspace modular units*

5.3 Metsec Framing

Metsec Framing is part of the Metsec Group, which produces a wide range of light steel sections and components. Metsec Framing has developed various light steel building systems, notably:

- *Gypframe* for housing
- *Metframe* for commercial buildings
- Steel Framing Systems (SFS) for general building construction.

Although not directly applicable to volumetric construction, the walls of the *Gypframe* and *Metframe* forms of construction are examples of pre-manufactured components that may be used in combination with smaller modular units. The *Metframe* system also uses the principles of composite construction in its flooring system.

For example, the Holiday Inn Express projects in Strathclyde and Cardiff included modular bathroom units as part of the *Metframe* concept (see Figure 5.3). Prefabricated steel stairs are also available in the *Metframe* system, which can be supported by the wall panels at the landings.

The SFS system is used principally in 'stick-build' construction on site, notably for infill walls to framed buildings and for roof trusses in long span or over-roofing projects (see Section 6.4).

Figure 5.3 *Modular toilet units used at the Holiday Inn Express, Cardiff*

5.4 Terrapin - Prospex

Terrapin specialises in light steel framing systems and volumetric buildings of various forms. The *Prospex* system uses C sections of 100 to 210 mm depth, which are assembled together with various hot rolled steel components to create the modules. The units are continuously edge supported but are lifted from their corners. The walls are braced by cross-flats (as illustrated in Figure 1.5).

The system is based on internal module widths of 2.7 and 3.5 m, with span increment of 600 mm up to a maximum of 9.6 m. A variety of cladding materials can be used. This modular system has been used for a wide range of building types, including sheltered accommodation and hotels, for the Travelodge chain, as shown in Figure 5.4. Bathroom and toilet modules are also produced for hotels and other highly serviced buildings.

Terrapin have also developed a cassette cladding system, which has a rigid backing so that panels up to 1.5 m wide can be manufactured. This system has been used in new buildings, and in over-cladding of existing buildings, notably the British Steel Management Training Centre at Ashorne Hill, Leamington Spa.

Terrapin also offers a main contractor role and markets a structural system called *Matrex*, which is built conventionally using long span hot rolled and light steel secondary beams. Recently, Terrapin has developed a system of composite construction that has patented shear connectors fixed to light steel sections.

Figure 5.4 *Terrapin Prospex system used for hotel construction*

5.5 Trinity Modular Technology

The TMT system is no longer available but the design rights are held by Ove Arup and Partners. One of the best examples of modular construction of this type was the 4-storey student residence at the University of Wales, Cardiff (illustrated in Figure 1.1).

The 2.4 m wide x 4 m long bedroom units were fully fitted out, stacked on site, and conventionally clad in brickwork to form a building of conventional appearance. The modules were constructed with walls of 'Durasteel' (a composite galvanised steel sheet and fibrous cement core), and a steel deck floor and roof. The floors were surfaced with OSB board, which is glued and screwed to the steel decking.

The modules are fully insulated and achieve 3 hours fire resistance and a high degree of acoustic insulation. They are supported one on top of each other at their corners, and connections are made by tie plates. Overall stability is achieved by the wall panels.

The completed installation of the modular units for the Cardiff project is shown in Figure 3.2. The masonry cladding and pitched tiled roof were constructed conventionally. A view inside a modular bedroom is shown in Figure 5.5 (as a light steel substructure), and in Figure 1.7 as a fitted-out room.

Figure 5.5 *View inside modular bedroom before lining and fitting out*

5.6 Volumetric

Volumetric is part of the Potton Group and has a long history of modular construction, firstly using timber framing, and now using light steel framing. In recent years, Volumetric has concentrated on the hotel market, particularly for the THF Post House Group.

The Potton Group offers a 'turn-key' design and build service. The modular units in recent projects were manufactured using the *Ayrframe* system, and were fitted out inhouse by Volumetric.

The recent Post House projects in Guildford and Cambridge demonstrated the speed of these operations in extensions to existing hotels. The construction period for the 3 storey project in Guildford was less than 10 weeks. Further projects include an 80 bedroom hotel completed in 26 weeks, and plans for a 8 storey inner city hotel.

5.7 Yorkon

Yorkon Ltd is a sister company to the larger Portakabin Ltd and provides permanent buildings by a single point procurement. Yorkon offer building systems based on two generic module types: the Yorkon building module and the Yorkon room module.

The Yorkon building module uses light steel framing and is suitable for structures up to 4 storeys high. It is based on a standard 2.94 m wide module with lengths up to 14.7 m. Modules of 3.8 m width can also be manufactured for use in low-rise buildings, but may require special transport (see Section 7.1). A wide variety of internal and external finishes may be applied. The system has a BBA certificate, which covers a 60 year design life. It has been used for offices, hospitals and educational buildings.

The system is based on 355 mm deep light steel floor beams and 150 mm floor joists. Four 100 mm square SHS members are used at the corners, and a variety of infill walls and cladding types may be used. Internal module heights are 2.5 m, 2.7 m and 3.0 m. The standard open sided modules may be assembled to form larger spaces of up to 12 m internal span (using a separate internal post).

Yorkon has also developed its own long span room module, which spans between facade walls and across the internal corridor. It utilises the principles of stressed skin design by using the shear resistance of flat steel sheets attached to the sides of the units to create a stiff 'box'. In hotel construction, the modules comprise two rooms and the corridor between them. In this system of monocoque construction, the module width may be in the range of 2.5 to 4.1 m, with internal lengths of 9.6 to 16.8 m in 1.2 m increments. The units may be stacked up to 6 storeys high. This modular system is illustrated in Figure 5.6.

Yorkon also works with independent architects and one of the best examples is in the recent Peabody Trust project in Hackney, London. The 5-storey block of 30 flats was constructed entirely from 3.2m wide × 8 m long fitted-out modular room units. The entrance area, stairs and roof were all supplied in modular form. The rain-screen cladding panels were also attached directly to the modules. A view of a module being installed is shown in Figure 5.7. An internal view of one module, which is combined with its neighbour to form a larger kitchen area, is shown in Figure 5.8.

Yorkon has also constructed a number of fast-food outlets, which are entirely fitted out in the factory. The new McDonald's outlet at the Millennium Dome project in Greenwich will be the largest in the UK.

5.8 Other systems

Bathroom and toilet units or 'pods' are produced by many companies, such as R B Farquhar, and have a long track record in the commercial building and hotel sectors (see Section 2.1). These units are designed to be robust to prevent damage (e.g. by loss of tiles) during transport and installation.

Schindler Ltd has developed a modular lift unit, which consists of storey-high lift units that are erected to a high degree of accuracy (see Section 2.3). The lift attachments are pre-installed so that the guide rails need only be located in them to form the final lift assembly.

The Unite Group has established a niche market in the student residence and Housing Association sectors where modular bedrooms and bathrooms are used in combination with traditional construction in both new-build and renovation.

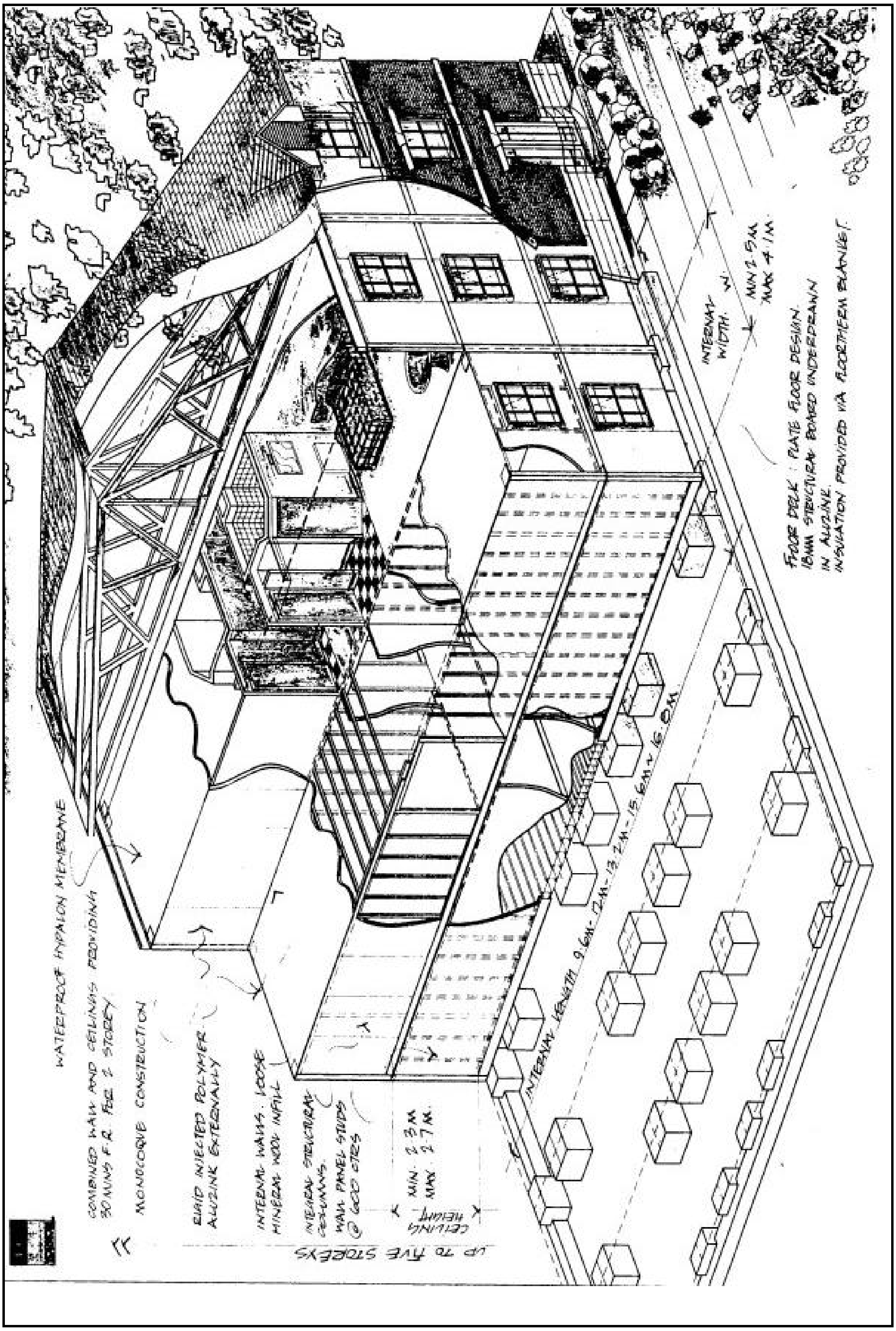


Figure 5.6 *Yorkon system of hotel construction using modules comprising two bedrooms and a corridor*

Figure 5.7 *Installation of Yorkon module at Murray Grove, Hackney (see artist's impression of completed building in Figure 3.3)*

Figure 5.8 *Internal view of kitchen module (temporary prop is removed after installation)*

6 USE OF LIGHT STEEL FRAMING IN MODULAR CONSTRUCTION

6.1 Steel grades and sections

Light steel frames are constructed from C, Z or similar cold formed steel sections using galvanised strip steel to BS EN 10147[9] (formerly to BS 2989). The steel grade is designated by its yield strength such as S280 or S350 (where the numerical value is the yield strength in N/mm^2). The standard thickness of zinc coating is 275 g/m^2 summed over both surfaces (typically 0.04 mm total thickness). This zinc coating gives sufficient corrosion protection for all internal and some external applications (see later).

The normal range of steel thicknesses used in structural applications is 1.2 to 3.2 mm. Section depths vary from 150 to 300 mm. The advantage of cold formed sections is that different section shapes can be manufactured easily for special applications. However, standard sections are recommended for floors and walls. There is a wide range of C and Z sections available in the UK (see Figure 1.5).

The design of cold formed steel sections is covered by BS 5950-5[10] and Eurocode 3-1-3[11]. Design tables of section properties and member load capacities are presented in *Design of structures using cold formed steel sections*[2]. Because of the lightness of these sections, they are well adapted to use as secondary members. In cases of very heavy point loading, it may be necessary to use hot rolled steel sections at these locations.

6.2 Floors and walls

The spacing of the structural elements in floors and walls is normally dictated by the spanning capabilities of the floorboards and plasterboard. It is for this reason that 400 and 600 mm are commonly used dimensions for layout of the structural elements to which the floorboards and plasterboard are directly attached (see Figure1.6). However, there has been a move to use wider member spacings of 1200 to 1500 mm, with secondary elements or steel decking in between, as in Figure 5.1. The economics clearly depend on the ease of manufacture and construction and the amount of material used in each case.

Wall elements are usually single C sections, except adjacent to windows and in braced panels, where double sections may be used to resist the higher forces in those areas. Floor elements are usually single C or sigma sections. Double sections may be used as stringers adjacent to openings. In modular construction, particular attention should be paid to the lifting points and the transfer of forces through the structure. This may require use of heavier edge beams.

A high level of acoustic insulation is achieved by a variety of measures including multiple layers of plasterboard supported on resilient bars and additional quilt materials placed between the sections. This is particularly important in separating wall and floors (see Section 7.5). Often the control of impact sound and flanking transmission is more problematical to resolve than airborne sound.

External walls are insulated to create a 'warm frame' by placing the insulation outside the frame. In some circumstances, insulation may also be placed between the wall elements but a vapour barrier should then be provided internally to avoid risk of condensation. A variety of cladding materials may be attached to the structure (see Section 7.4).

6.3 Connections

There are two basic types of connections between light steel framing components:

- factory-made connections, as part of a production operation
- site-made connections.

In conventional light steel framing, wall panels, roof units, and sometimes floor panels are prefabricated using the following connection techniques:

- self-drilling self-tapping screws
- welding
- clinching
- self piercing rivets.

Welded zones should be protected later with zinc rich paint. Other techniques do not damage the galvanised layer so no touch-up is required.

In modular construction, production issues dominate the choice of connection technique. The use of self piercing rivets has become the preferred method because of ease of handling of the connection tool using an overhead balancing arm (Figure 6.1), and the relatively high strength of the fixings. However, this technique cannot be used where access to the connection is difficult. For this reason, gusset plate details are often used for connection of smaller members.

Site connections between floor and wall panels are often made by bolts, for simplicity and ease of lifting and location. Discrete lifting points are also built into the construction, and these are often welded directly to the framework (commonly at the corners of the modular units).

Modular units are individually braced for stability during installation. Cross-flats are generally used as temporary bracing elements and are placed on the outside of the units. Floors are braced by the diaphragm action of the flooring material and do not require bracing.

Connections between modular units are usually bolted together on site. For example, vertical loads are transferred directly through columns or walls, which are aligned by bolts. Additional bracing elements or ties may be required later to provide overall stability or integrity of the modular units.

Figure 6.1 *Connections using self piercing rivets*

6.4 Roof construction

Roofs are generally designed as separate structures that are supported either continuously by the internal walls of the modular units or as free spanning between the outer walls. Roofs may also be designed as modular units for ease of assembly, especially in taller buildings, but normally they are constructed conventionally from individual trusses or purlins.

Roofs are 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 room below.

Alternatively, an 'open roof' system can be created using either a steel 'attic' truss or by purlins spanning between the flank 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 discrete C or Z sections with steel liner trays or decking spanning across them to support the tiling battens etc. In this case, the floor elements of the attic are supported by the walls beneath.

Special mansard roof shapes may be created to offer more efficient use of habitable space, and these mansards may be manufactured as modular units. Various alternative roof forms are presented in the SCI publication *Over-roofing of existing buildings using light steel*[12], and some typical examples are illustrated in Figure 6.2(a) and (b).

For habitable use, 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. Special details are required to prevent heat loss at the eaves. Further guidance is given in *Construction detailing and practice*(13).

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 is designed to be detachable so that the building can be extended later. Shallow pitch roofs, such as in the *Capella* system in Figure 6.2(c), can be designed to be supported by the modular units and are easily dismantled.

6.5 Opportunities for design by testing

Large-scale production of similar modular units or components leads itself to improvement of economy by testing, and by monitoring of performance in service. This is particularly important where design methods are not available or are too conservative, or the form of construction is not amenable to simple analysis.

Examples where design by testing will lead to considerable economy in the use of modular construction are:

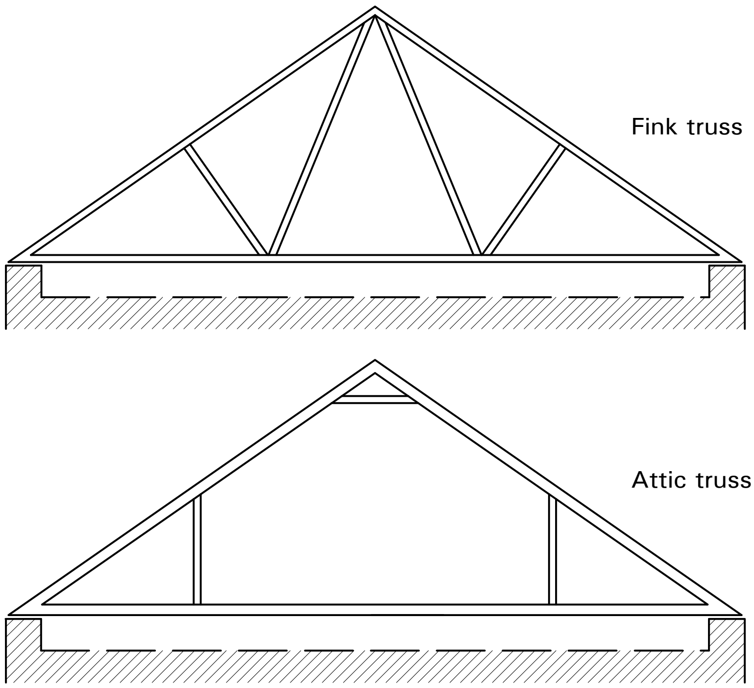
- connection design and lifting points
- 'stressed skin' design of wall and roof panels
- design for large openings in the walls
- acoustic insulation of floors and walls
- effective thermal insulation of external walls and roofs
- durability and weathering tests
- floor vibration tests (and perception of movement).

Testing may also be necessary to obtain type-approval or BBA certification where the structural design is outside the limits of the relevant standards.

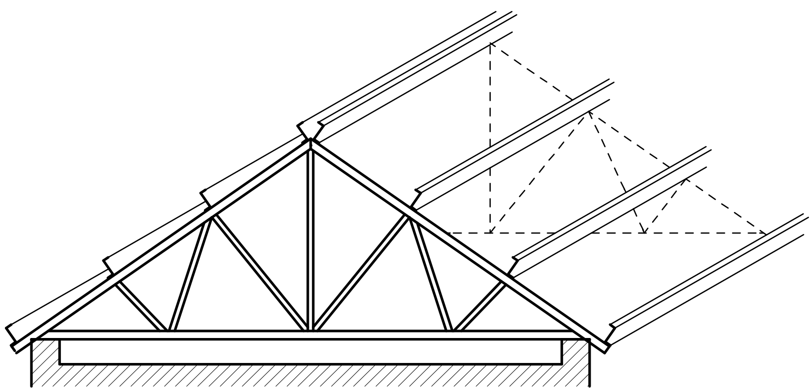
6.6 Structural design of walls

The load-bearing walls of modular units are generally constructed using lipped or plain C section studs at 400 or 600 mm centres and are primarily designed to resist axial loads due to gravity and wind loads. Walls that form the external skin of a building also resist bending moments due to wind loads.

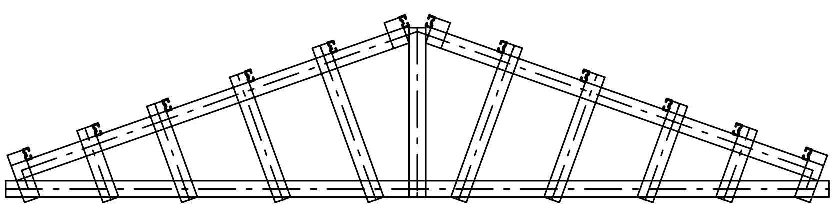
Light steel sections are relatively weak if unrestrained in their transverse direction. However, comparison resistance of single C sections can be increased by placing C sections back to back to form double C sections, or by laterally restraining the C sections at one or two points along their height.



(a) *Trusses for domestic applications*



(b) *Purlins on widely spaced trusses*



(c) *Capella system (by Ward Building Components)*

Figure 6.2 *Roof systems using light steel framing*

The tensile resistance of the studs is generally dependent on the form of the connections. This aspect is particularly important during lifting, and it is common practice to reinforce the members locally at lifting points. Often hot rolled hollow sections are used at the corner points.

6.6.1 Design aids for load-bearing walls

Load-bearing stud walls are subjected to axial loads from floors, and either wind moments or moments due to eccentric vertical load, or a combination of the two. Non-load-bearing stud walls are subject to wind loads only, which are resisted by bending of these members. External walls may be required to provide support to brittle finishes or cladding, and the deflection limits may be more strict.

The forces in the studs also depend on whether the wall is continuously or locally supported, and on any eccentricity of the support. Table 6.1 presents typical sizes of wall studs, which are designed either as non-load bearing (i.e. resisting wind loading only) or as load bearing (resisting vertical load from the modules above), depending on the number of storeys. These sections are assumed to be a lipped C shape (as in Figure 1.5) and are restrained in their weak direction at mid-height. If large openings are present, or there are unusual loading or support conditions, it may be necessary to increase these section sizes.

Table 6.1 *Typical section sizes (depth × steel thickness) for wall studs in modular construction*

Load condition on wall	Floor to floor height (m)		
	2.5	3.0	3.5
Non-load bearing wall*	75 × 1.2	75 × 1.6	100 × 1.6
Load bearing (up to 3 storeys)	100 × 1.6	100 × 2.4	120 × 2.4
Load bearing (4 to 5 storeys)	150 × 1.6	150 × 2.4	150 × 3.2

Studs at 400 mm centres.
* Wind loading # 0.75 kN/m^2.

The typical axial load for a continuously supported wall stud in a 3-storey building with a tiled roof is 20 to 30 kN, and the moment due to eccentricity and wind load is typically 1.0 to 1.5 kNm, making a 100 mm deep × 1.6 mm thick stud the probable choice for the facade members.

6.7 Structural design of floors

The floors of modular units are generally constructed using light steel C sections as joists, or 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 key members in providing a torsionally stiff box. Lifting / anchorage points are often at the corners of the module and thus at the end of the edge beams.

In general, light steel C sections may undergo the following modes of failure for loads applied along their length:

- Flexural failure involving local buckling of the section in compression. This mode of failure occurs when the floor joists or beams are fully restrained at intervals by frequent member connections, or continuously by floor boarding.
- Lateral torsional buckling between infrequent lateral restraints along the member.
- Actions during lifting that may lead to reversal of loads or to locally high loads.
- Web crushing under direct loads or reactions.
- Combined effects of bending and web crushing, and bending and shear.
- Serviceability criteria of excessive deflection, and control of vibration, as influenced by natural frequency.

For floor beams, these members are generally regarded as being fully restrained when a sufficient frequency of fixings between the beams and the floor is provided. Where restraints are not present, or are infrequent along the member, it is generally good practice to use double sections (i.e. back to back) because of their improved resistance to lateral torsional buckling.

6.7.1 Serviceability limits for floor joists

The design of floor joists is generally limited by serviceability criteria of deflection and control of vibrations. In the UK, the following design limits are generally adopted for lightweight floor construction:

- Imposed load deflection # span/450
- Total deflection (including self weight) # span/350 but # 15 mm
- Natural frequency # 8 Hz (calculated using the self weight of the floor and 0.3 kN/m^2, which represents the permanent loads applied to the floor).

Generally, it is the natural frequency limit that controls the design of longer span floors. An alternative criterion used in Sweden is to limit the deflection of the floor to 1.5 mm under a 1 kN local load. This requires a calculation of the number of joists that assist in resisting this load, and therefore the design procedure can be more complicated. The effective number of joists taken to resist a local point load is typically 2.5, increasing to 4 for heavier or stiffer flooring materials.

Experience has shown that limiting the total deflection of floor joists to 15 mm generally leads to acceptable natural frequency for control of vibrations. Therefore, the above deflection limits are sufficient for spans up to 4.5 m.

6.7.2 Design aids for floor joists

Table 6.2 presents the maximum spans for various C section floor joists, calculated according to the above criteria. Two applications are considered: domestic loading and office loading in both cases with joists at 400 mm centres. The self weight of the floor is assumed to be typical of 'dry' boarded systems providing appropriate acoustic insulation.

Table 6.2 *Typical maximum spans of floor joists*

Joist size (depth × thickness, m)	Domestic loading (1.5 kN/m^2)	Office loading (2.5 kN/m^2)
150 × 1.2	3.6	3.2
150 × 1.6	3.8	3.5
175 × 1.2	3.9	3.6
175 × 1.6	4.2	3.9
200 × 1.2	4.1	3.8
200 × 1.6	4.5	4.2

Joists at 400 mm centres.

Self weight of floor is 0.32 kN/m^2.

The floor joists are generally supported by heavy longitudinal beams. Where these beams are not continuously supported, the combined deflection of the floor joists and longitudinal beams should be considered when comparing with the above design limits. In such cases, the sides of the modules are often braced to improve the stiffness of these beams.

7 DETAILED DESIGN OF MODULAR CONSTRUCTION

The detailed design of modular units should take into account their special requirements for lifting and transportation, installation on site, and attachments of roof and wall cladding and service connections. The design of the light steel framing components follows conventional practice, as covered in various SCI publications(2, 14, 15), and as reviewed in Section 6. Furthermore, the interface between the modular units and other components must be considered in the design process.

The aspects of design that are particularly relevant to modular construction, rather than to conventional site construction, are described below.

7.1 Requirements for transportation and weather-tightness

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 3.5 m for general applications but this can be increased to 4.3 m if access routes permit. The maximum height of the load is 4.5 m for service roads but there may be local restrictions for clearance under older bridges, especially railway bridges. A maximum height of 3.9 m should be used in these cases, which may require use of a low lorry trailer.

These transportation requirements are summarised in Figure 7.1, based on guidance by the Road Hauliers Association following the Road Vehicles (Construction and Use) Regulations 1986. Special types of vehicles and their loads may be up to 2.9 m wide without restriction. When the overall width of an abnormal load exceeds 5 m, prior approval must be obtained, and a copy of the movement order (form VR1) must be carried on the vehicle. A mate must travel on Special types vehicles when the load is more than 3.5 m wide or more than 18.3 long, or in all cases if the length of the vehicle and trailer exceeds 25.9 m. Modular units suitable for containerisation should be less than 2.43 m high and 12.2 m long.

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. This is normally the responsibility of the module supplier.

7.2 Lifting and installation forces

Lifting and manoeuvring forces cause different internal stresses from those that exist during normal conditions. In particular, locally 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.

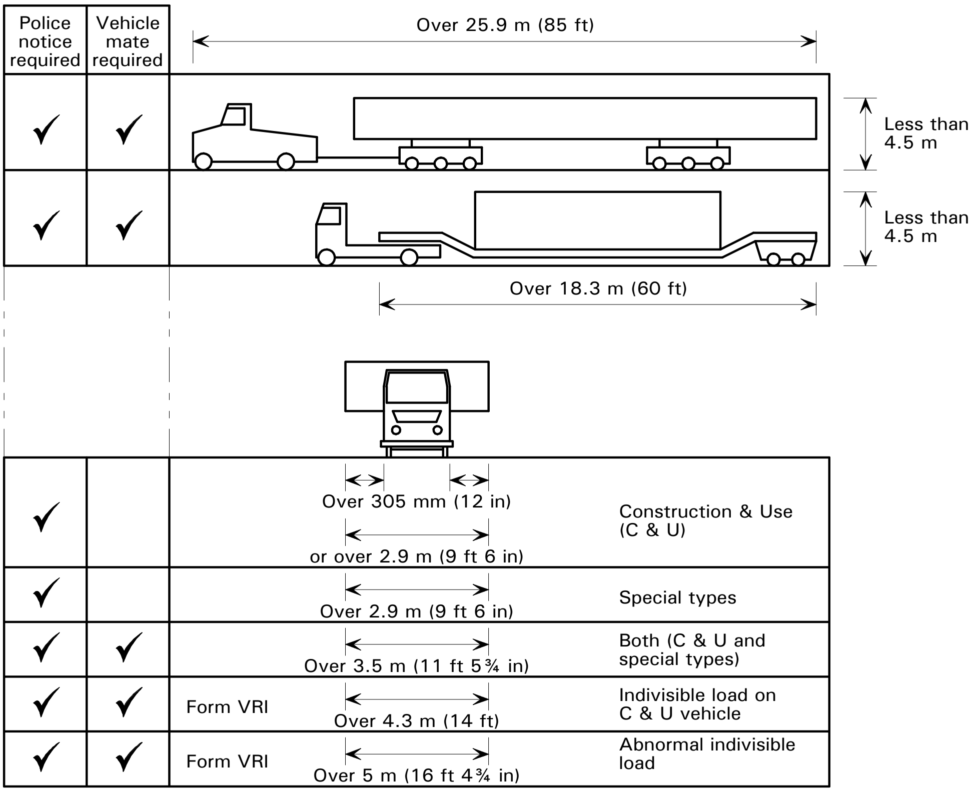


Figure 7.1 *Summary of transportation requirements for unusual sized loads*

There are various techniques for lifting, depending on the height of the crane jib, some of which are illustrated in Figure 7.2. Normally lifting is carried out from the top of the units, and the angle of the lifting cables should be such that the horizontal component of their forces is not excessive. The optimum lifting points are at 20% of the length of the unit in from both ends, so that the structure is most stable. However, units are often lifted from their corners, which generally necessitates the use of a separate lifting frame or pairs of cross-beams. A heavy lifting frame equal to the plan dimensions of the units is preferred as it does not cause horizontal or shear forces in the units.

It is also possible to lift small units from their base. However, in this case, the change of angle of the lifting cables over the top of the module may cause local damage to the upper corner of the units.

For design purposes, lifting forces should also include a dynamic component as a multiple of the self weight of the unit.

Forces are normally distributed equally among the four lifting points, but should also include the horizontal forces (due to the component of force acting in the sloping cables), as illustrated in Figure 7.2.

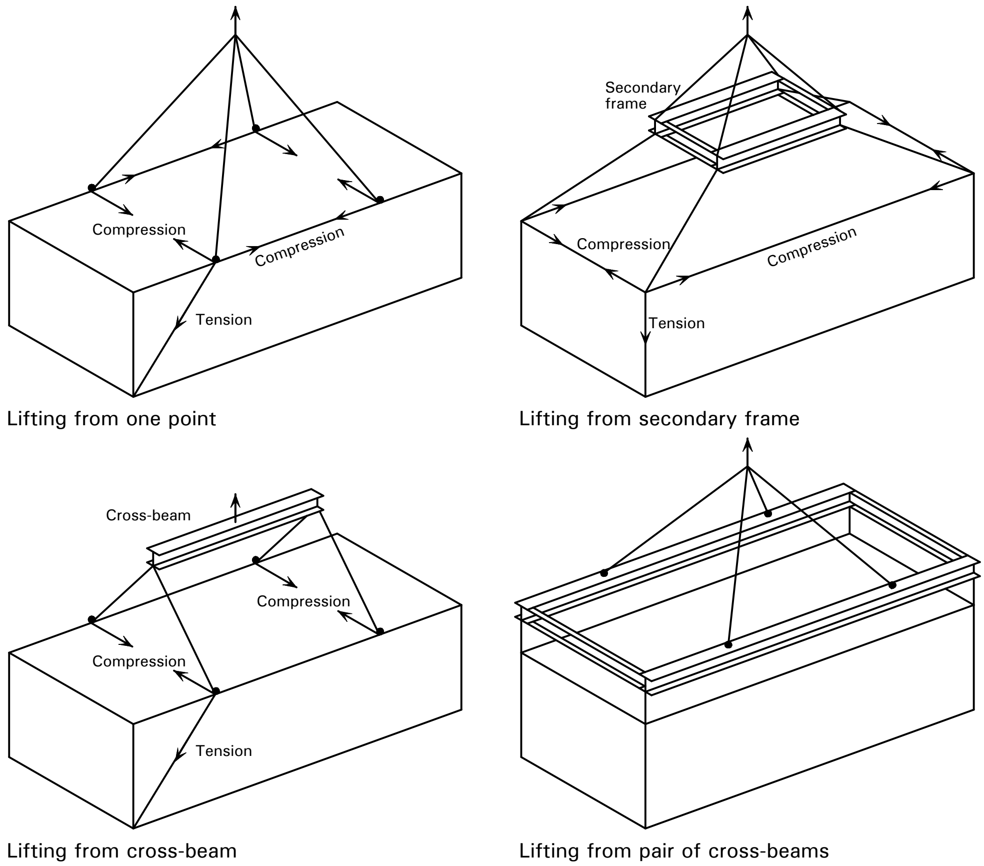


Figure 7.2 *Methods of lifting modular units*

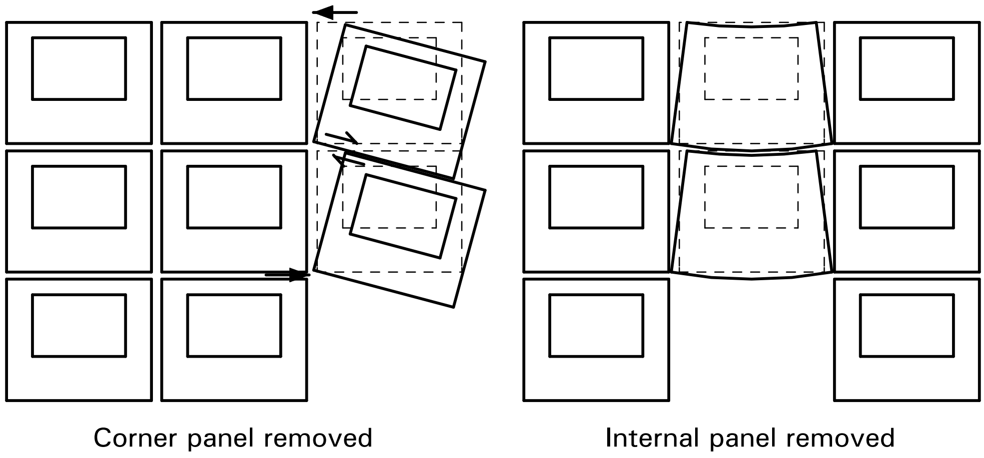
7.3 Requirements for overall stability and integrity

The requirements for overall integrity and stability are characterised by the term 'robustness'. In principle, in the event of failure of one element of the construction, the remaining structure should be sufficiently robust to support the loads acting on it without disproportionate damage.

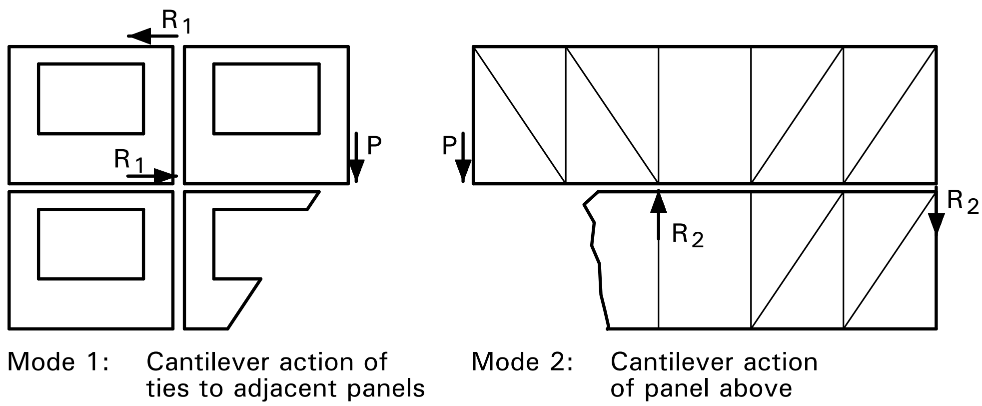
Modular units differ from normal construction in that the units, although robust in themselves, are placed together so that the load path is through the walls of the units below. The possibility of the removal of this load path means that the walls should be designed either to:

- span horizontally over the damaged area by acting as a deep beam or diaphragm, or
- be supported in tension by the adjacent units.

This latter aspect means that the units should be tied together horizontally in addition to being tied vertically. This action is illustrated in Figure 7.3. Manufacturers can supply details of these horizontal attachments to satisfy 'robustness' requirements. Typical support details providing this tying action are given in Figure 7.4. A suitable construction gap between the units should allow for tolerances and alignment.



(a) Removal of wall panels



(B) Cantilever action of modules

Figure 7.3 *Strategies to achieve 'robustness' of modular construction*

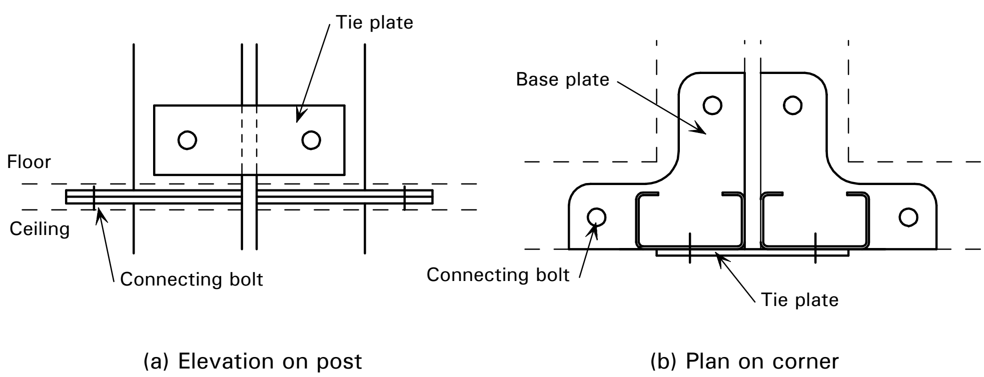


Figure 7.4 *Typical details of corner support to modular units*

7.4 Cladding materials

Cladding is used for the facades and roof and their associated interfaces.

7.4.1 Facades

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 at 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
- metal panels or sheeting attached to subframes or directly to the structure
- louvres or other features.

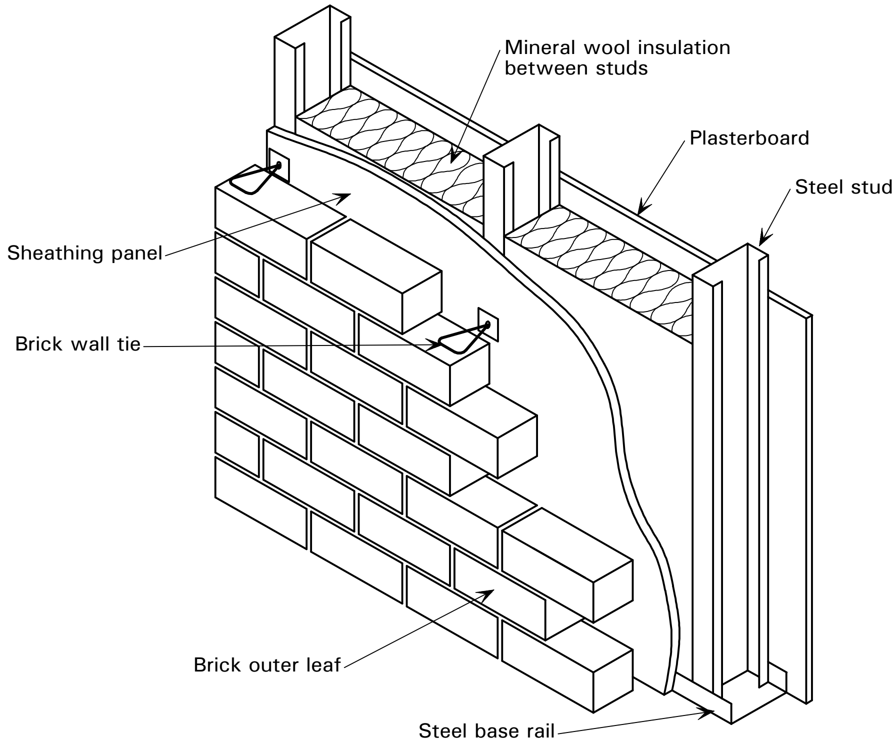
Examples of cladding that can be pre-attached to the modular units are:

- cassette panels with infill pieces that are placed over the joints between the units
- panels with brick slips, tiles or render, in which the joints between the units are either emphasised or concealed for architectural effect.

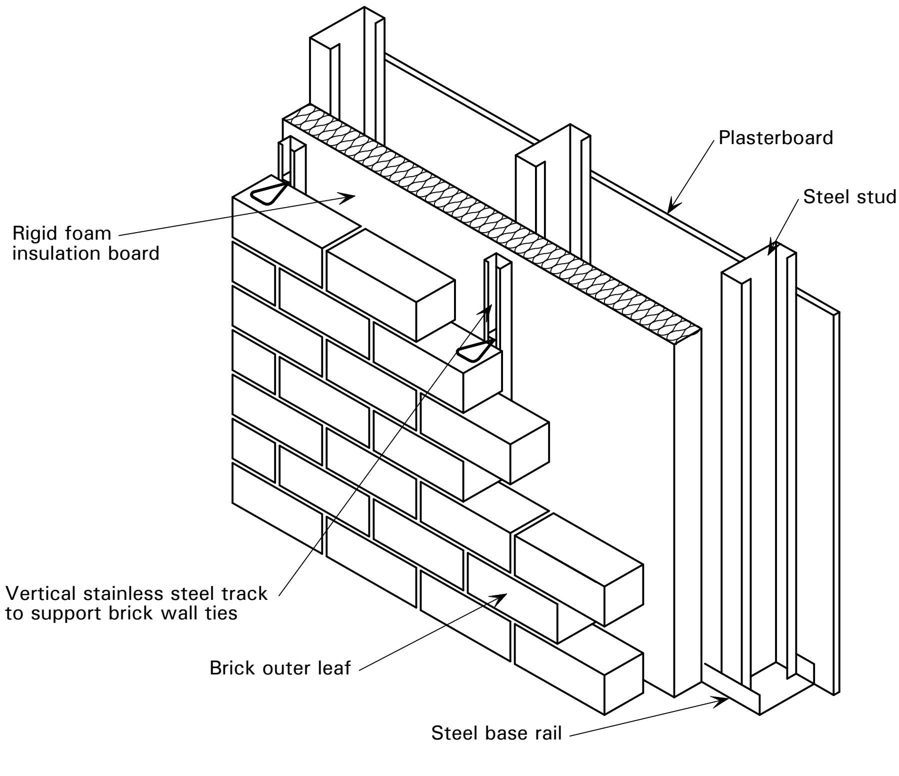
Placing of brickwork is a site activity that can be slow and requires its own foundation. Self-supporting brickwork walls can be designed up to 12 m high, although with use of high strength bricks, taller walls can be constructed. Lateral support is achieved by ties cast into the brickwork and attached to the light steel structure. The ties are placed at a minimum density of 2.5 ties/m^2 of the facade area. In light steel framing, this can be achieved by 'Chevron' shaped ties similar to those used in timber frame construction, or by attaching vertical tracks through the insulation to the steel studs. These vertical tracks are placed at 1.2 m spacing so ties should be attached every 5 or 6 brickwork courses.

For tall buildings (more than 4 storeys high), separate vertical supports at each or alternate floor levels may be required, and the modular units should be designed to resist these additional loads. Typical support details for brickwork are shown in Figure 7.5. Differential vertical movement is accommodated by the ties.

Light cladding may be in the form of profiled sheeting, liner trays, cassette panels, composite panels, tile hanging, or timber boarding. Profiled sheeting, liner trays and composite panels are linear elements, whereas cassette panels are discrete square or rectangular elements of typically 600 to 1200 mm dimension. Generally, a secondary framework is required to support these cladding elements. The secondary framework is isolated from the internal structure to avoid cold bridging. Typical support details for alternative cladding types are presented in Figure 7.6. Cementitious render onto rigid insulation boards may also be used. Specialist contractors can do this work on site.

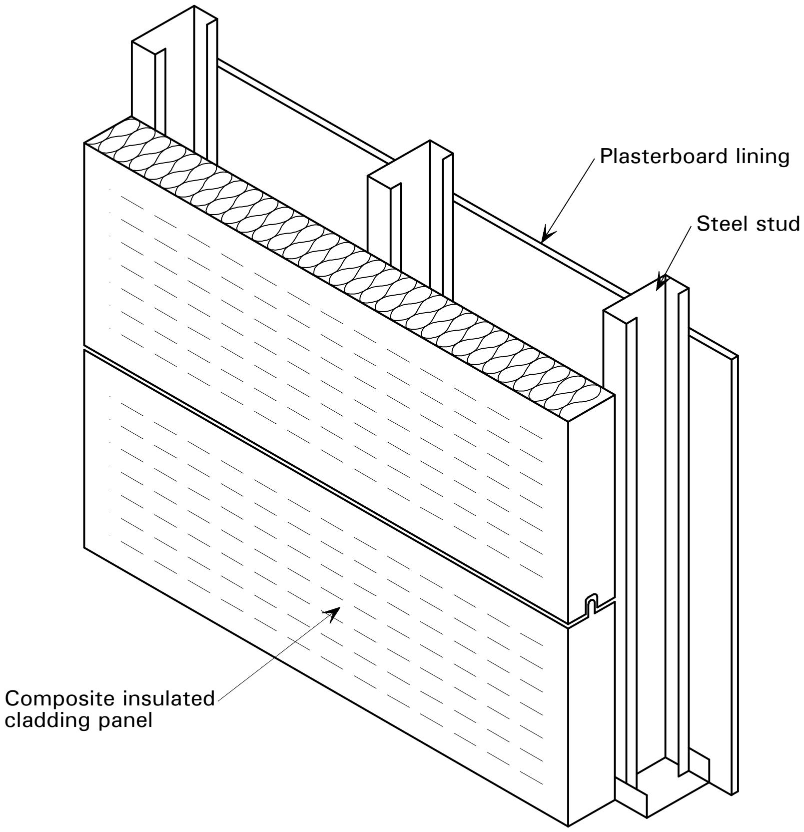


(a) Insulation between the studs and sheathing panel

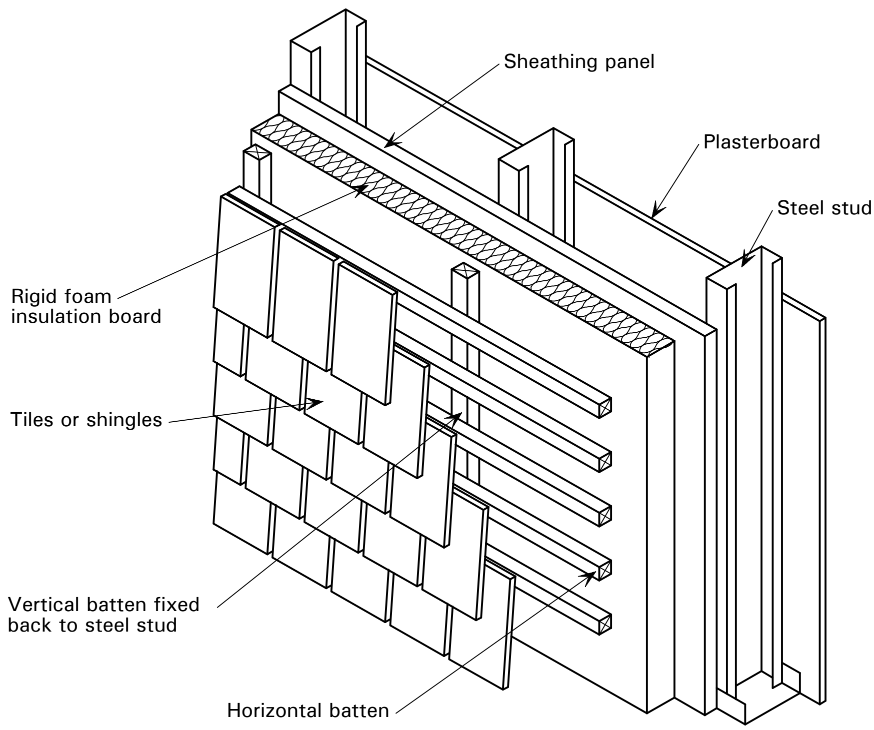


(b) External insulation and vertical track for wall ties

Figure 7.5 *Interface details for masonry cladding*



(a) Composite panels directly attached to studs



(b) Tile-hanging onto battens fixed to studs

Figure 7.6 *Interface details for other cladding systems*

7.4.2 Roofing materials

A variety of roofing types may be used in modular construction, and supported on different types of roof trusses, as presented in Section 6.4. Roofing types generally comprise two types:

- tiles supported on battens between trusses
- sheeting supported on purlins spanning between heavier trusses or gable walls.

Generally, roofs are constructed conventionally on site. Although not often done except for mansard roofs, it is also possible to prefabricate whole roofs including their outer skin.

The tile-hanging detail in Figure 7.6(b) is also typical of pitched roofs and mansards. This figure illustrates a 'warm frame' in which the roof space is insulated. However, in most cases, the roof space is 'cold' and insulation is placed directly on the top of the modular units. Roof sheeting attached to purlins is typical of normal steel construction and is often used in shallow pitch roofs, where hidden by the facade.

A detailed review of roofing systems is outside the scope of this publication.

7.5 Acoustic insulation of separating floors and walls

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 along the members. Modular units are often used in hotel buildings because hotels generally require a high standard of acoustic insulation between rooms.

The construction gap between the wall of one module and the adjacent module reduces the risk of sound penetrating across the construction. Similarly, there is a gap between a unit and the one below because the floor construction of one is independent of the ceiling construction of the other. The units are only connected at the corners or other discrete points, for structural purposes. At these points the direct transfer of sound is limited by the use of acoustic pads.

Table 7.1 shows the requirements of Part E of the current Building Regulations for acoustic performance of separating walls and floors. Also shown are more stringent targets suggested by the *Quiet Homes* project, a DETR sponsored initiative, which may form the basis for a future revision of Part E of the Building Regulations. These figures are compared with independently measured data in constructed modular buildings of light steel construction. The modular buildings provide a very high level of acoustic separation and the performance can be seen to be well in excess of both the Building Regulations and the Quiet Homes standard.

Table 7.1 *Comparison of acoustic performance of walls and floors*

	Separating wall airborne sound insulation (D_{nTw})	Separating floor airborne sound insulation (D_{nTw})	Separating floor impact sound transmission (L_{nTw})
Building Regulations	>53 dB	>52 dB	<61 dB
Quiet Homes	>56 dB	>55 dB	<58 dB
Tested modular buildings			
Hotel - Peterborough	60 dB	57 dB	48 dB
Prototype - Terrapin Prospex	72 dB	62 dB	49 dB

Some of the features that manufacturers of modular units use to improve sound reduction (attenuation) between units include:

- Ensuring that a clear gap is maintained between walls of adjacent units, and between the underside of the floor structure of one unit and the top of the ceiling structure of the unit below.
- Two overlapping layers of 15 mm plasterboard are attached to the inner face of the steel members of each module.
- Approximately 100 mm of quilt insulation is included between the steel members to reduce reverberation.
- A layer of plasterboard or OSB (oriented strand board) fixed to the outside of the steel members of each unit as an external sheathing.
- Resilient bars can be used to mount the plasterboard on the ceiling and the walls. This reduces the direct transfer of sound into the structure but is often not found to be necessary to achieve good acoustic performance.
- Acoustic pads separate the modules at structural joints and reduce the transmission of sound. Neoprene gaskets are often used.
- A built-up floor, consisting of several layers, including a resilient layer, can also be used to give enhanced acoustic performance. Such a floor may consist of a layer of chipboard with a 30 mm floating floor grade mineral wool and 19 mm plasterboard.
- Alternatively, an acoustic mat can be included on the upper surface to reduce impact transmission through the floor.

Details of separating floors and walls between modules that achieve excellent acoustic insulation are shown in Figure 7.7. Two options are shown for each case that are typical of modern modular construction. Resilient bars supporting the plasterboard are effective in source attenuation. Mineral wool is placed between the wall studs and either between the floor or ceiling joists as shown in Figure 7.5(a). General guidance on acoustic insulation in light steel construction is presented in *Acoustic insulation* [14].

Because sound attenuation can be particularly affected by air paths between spaces, special care is taken around openings for service pipes and other penetrations. Electrical sockets penetrate the plasterboard layer and should be carefully insulated by quilt at their rear, and back to back fittings should be avoided. 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.

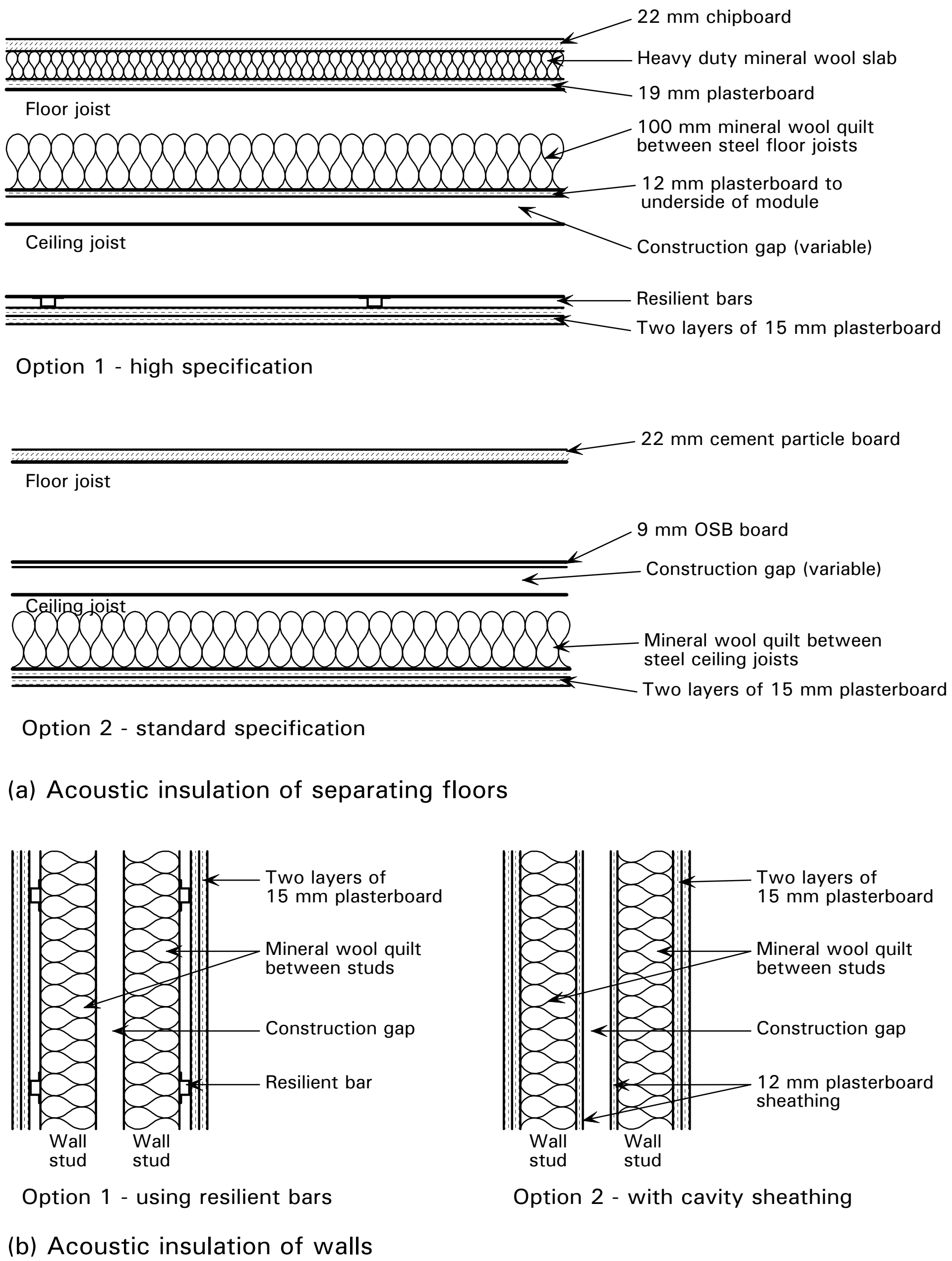


Figure 7.7 *Acoustic insulation between modular units to achieve good sound attenuation*

7.6 Thermal performance

Light steel construction can provide a high level of thermal insulation and airtightness economically and without leading to excessively thick walls. Construction with U-values of below 0.2 W/m^2K have been achieved in the UK (Table 7.2). This has both environmental benefits and cost benefits (from reduced fuel bills). Furthermore, occupant comfort can be improved.

Fabric insulation levels in buildings are slowly improving and there is an increased concern to reduce heat losses through air infiltration. Consequently, some traditional construction details may become inappropriate. Modular construction allows a greater degree of control of the construction process, which enables higher standards of thermal performance to be delivered without being compromised by site practices.

Table 7.2 illustrates the current requirements of Part L of the Building Regulations, which deals with thermal performance. Part L is currently under review and revised, requirements are expected to be introduced in 2000. These new requirements are expected to include a significant improvement in the U-value standards, requiring additional insulation, and it is possible that a maximum allowable air infiltration rate will be introduced.

Table 7.2 *Review of typical and best practice U-values currently achieved in the UK*

	U-values (W/m^2K)			
	Walls	**Floor**	**Roof**	**Windows**
	1995 Building Regulations			
For SAP energy rating of 60 or less	0.45	0.35	0.2	3
For SAP energy rating of over 60	0.45	0.45	0.25	3.3
	U-values achieved in the UK in practice			
Good practice	0.35	0.32	0.2	2.8
Ultralow energy	0.2	0.2	0.15	2
Light steel-framed - typical	0.35	0.35	0.25	3
Light steel-framed - best practice	0.2	0.35	0.2	1.8

When using light steel framing for modular units, it is important to ensure that the framing elements do not form a 'thermal bridge' through the external wall insulation layer. The 'warm frame' principle is used to prevent steel elements penetrating from the inside to the outside of the thermal insulation and to minimise the effect of cold bridging. Thus, a significant proportion of the insulation in the external envelope is placed on the outside of the steel framing elements. This means that the light steel elements remain essentially within the insulated envelope. Consequently, both cold bridging and the risk of condensation are reduced.

In addition to the insulation on the outside of the frame, some manufacturers include up to 100 mm of insulation between the light steel elements. Such a detail can provide very low U-values that are well below those required in the Building Regulations (see Table 7.2, 'best practice'). In such cases, care must be taken to ensure continuity of insulation at junctions between modules. The system adopted in Figure 7.5(a) has been used in hotels, where the lower level of occupancy reduces the risk of high humidity and condensation.

Air infiltration can be addressed by attention to detail and by ensuring that joints are well sealed. Vapour barriers, if well sealed, can act as very effective air barriers and prevent air movement. Care needs to be taken to avoid cool external air from infiltrating into the construction cavities between each module, as this air could eventually filter into the modules. Because the individual modules are constructed in the factory, greater attention can be given to achieving good seals between components to reduce air infiltration, and to ensuring that insulation is properly fitted, than is possible on site.

Typical details of 'warm frame' construction and associated cladding attachments are shown in Figures 7.5(b) and 7.6.

7.7 Foundations

Modular units are by their nature light in weight so foundations are not as large as in conventional construction. Strip footings are located under load-bearing walls and shear attachments are made by resin anchors into the concrete. The levelling of the foundations or ground beams is crucial to the subsequent installation and alignment of the modular units. Often it is necessary to provide for some adjustment in the foundation or in the legs of the modular units, and each manufacturer has its own system. Generally, a variation in level of about 20 mm in the top of the foundations can be accommodated. Brickwork cladding also requires suitable strip foundations, which can be the same as used for the modules.

In poor ground, piled foundations may be used, and the bottom chords of the modular units can be designed to span between pile caps. Alternatively, the walls of the modular units can be designed as storey-high braced panels to span between the foundations. Piled foundations were used in the McDonald's projects because they are suitable for all ground conditions (see Figure 1.3).

7.8 Services and drainage

Installation of services, particularly bathrooms, is labour and time-consuming in traditional construction. Therefore removal of these activities from site has significant benefits in quality and speed. In modular construction, the key plumbing and electrical services are installed in the factory.

Generally, a vertical service duct is incorporated into each unit, which provides for vertical drainage and pipework, and all service connections are made within this duct. In hotels, the longitudinal distribution of services between modules is made in the ceiling or floor of the corridor, which acts as a service duct. Access to these services is usually made outside the module.

Regular openings can be provided in the floor joists and wall studs for cables and small diameter pipes. Rubber grommets around the openings prevent damage to these cables. Larger pipes are usually located in the space between or below the joists.

Drainage from the roof is handled conventionally from outside the building. Clearly, routing of services within or below the structure requires careful planning.

7.9 Fire safety

Fire resistance of the steel components is achieved by suitable fire protection. Two layers of fire resistant plasterboard achieve 60 minutes fire resistance, which is normally sufficient for buildings up to 6 storeys high. General guidance on fire protection to light steel framing is given in *Building design using cold formed steel sections: Fire protection*[15].

A further requirement is to prevent passage of smoke or flame, particularly between the units, along corridors, and through service ducts. Special fire dampers and intumescent seals can be introduced at strategic locations to reduce the risk of fire spread.

8 DESIGN AND PROCUREMENT PROCESS

8.1 Decision-making process

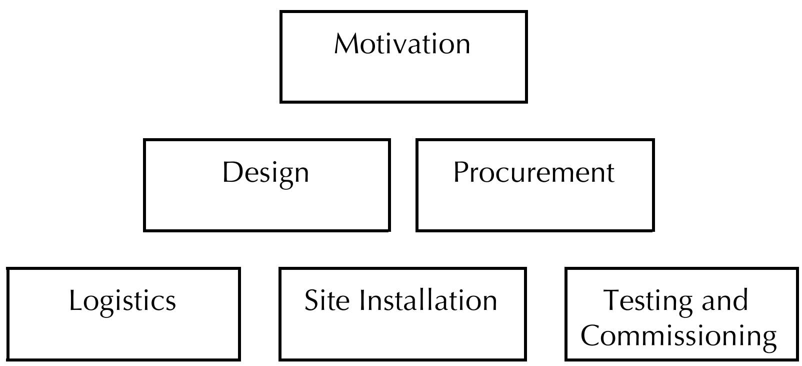
The decision-making process for modular construction differs from more traditional methods of construction because of:

- the close involvement of the client in assessing the business-related benefits of the choice of method of construction
- the direct involvement of the manufacturer in terms of the design, costings and logistics
- a close working relationship between the manufacturer and main contractor in terms of delivery and site installation
- the need to make key decisions early in the procurement process (as such decisions would be relatively expensive to modify later)
- 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 sizes and on the inter-relationships of modules.

Because the benefits of modularisation are realised through prefabrication, the initial space planning, subsequent detailed design, and service integration and co-ordination are critical. There is less capacity for significant spatial, material or structural alterations at a later stage. The design needs to be fully complete prior to the commencement of manufacturing.

The appropriate degree of modularisation is also an important part of the decision-making process because it is possible to identify those parts of the construction that could be pre-assembled and those parts that could be constructed more conventionally. In this context, pre-assembly means the factory production of large units or major self-standing components such as bathrooms or plant rooms. All elements of steel construction are effectively prefabricated (i.e. factory manufactured) whereas other competitor materials generally involve a greater level of site construction.

A recent BSRIA Report[16] defines six 'building-blocks' in the successful use of modular or pre-assembled construction, as follows:



Motivation requires that the client and design team must be strongly motivated to use modular construction at the early stages in the process.

Design means that modular construction must be considered early in the design process, and that the economy of scale must be achieved through design.

Procurement is the process by which the design is realised through a series of manufactured products before they are delivered to site, and assembled to create a functioning unit.

Logistics concern transportation and assembly (and possibly later disassembly), and also 'just-in-time' delivery to site.

Site Installation relates to the physical method of installation, and assembly on site, including formation of larger units and attachment of ancillary components such as cladding and service.

Testing and Commissioning are important for highly serviced units, which can be partially carried out off site.

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, the decision-making process is even more important. Direct involvement of the client, manufacturer and main contractor (if different) is important at the concept stage of the project.

For the full benefits of modular construction to be realised, the notion of volumetric/modular building must be considered at the conceptual stage of a scheme. The design development can then harness all the aspects of a modular approach, including requirements for production and interfaces with other components of the building.

8.2 Procurement process

Procurement defines the process from completion of 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, and is therefore time-related from the point where design decisions are made.

Procurement is also represented by 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 by 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. Indeed some companies offer the complete turn-key package, providing design, manufacture and erection services. However, in many projects, the client will appoint an architect who is responsible for the overall design and coordination of all the inputs from specialist manufacturers.

Two procurement methods are most commonly used:

1. The architect may specify the manufacturer who will undertake the work and this will enable the parties to work together from inception to completion. The architect may select the manufacturer by competitive interview, track record or reputation.
2. Alternatively, the architect may draft a performance specification for the works, which is usually done in consultation with one or more modular manufacturers. 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 its modules differently. They will be prepared to offer advice and provide detailed drawings but may not wish to divulge commercially sensitive technical details.

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.

The influence of modular construction on the lead-time to starting on site and on the time-savings in the construction programmes are shown in Table 8.1. For comparison, three alternative construction types are considered for a typical medium size hotel project:

- concrete frame with masonry cladding and entirely site-installed bathrooms and services
- light steel frame with masonry cladding and pre-assembled modular bathrooms
- building composed of entirely modular bedrooms with site-installed corridors, and with masonry cladding.

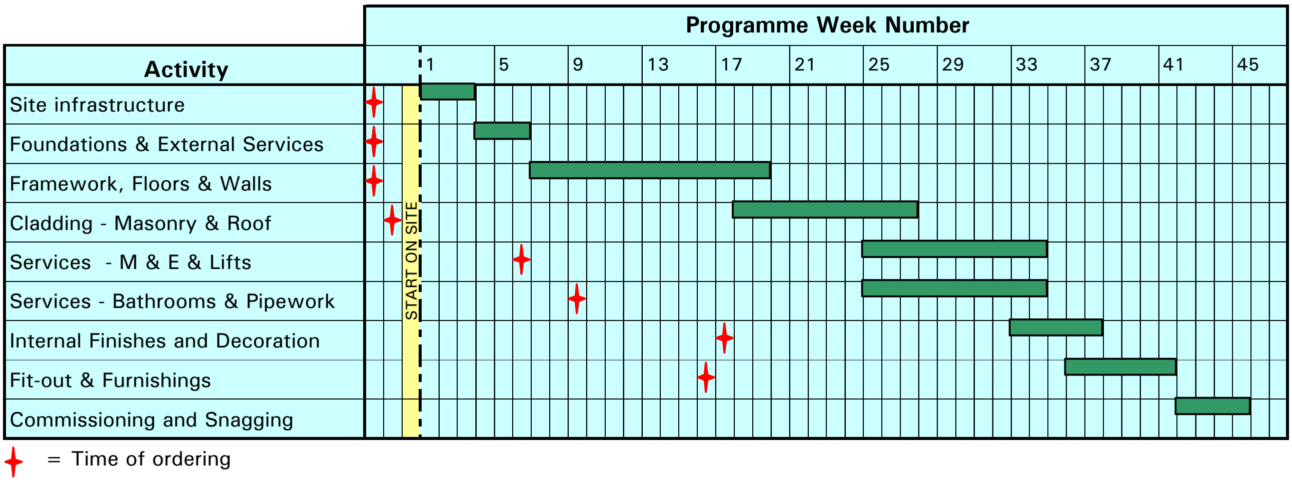
The hotel consists of 60 bedrooms in a 3-storey rectangular plan shape, constructed on a 'green-field' site so that the site infrastructure and servicing activities are not overly important.

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.

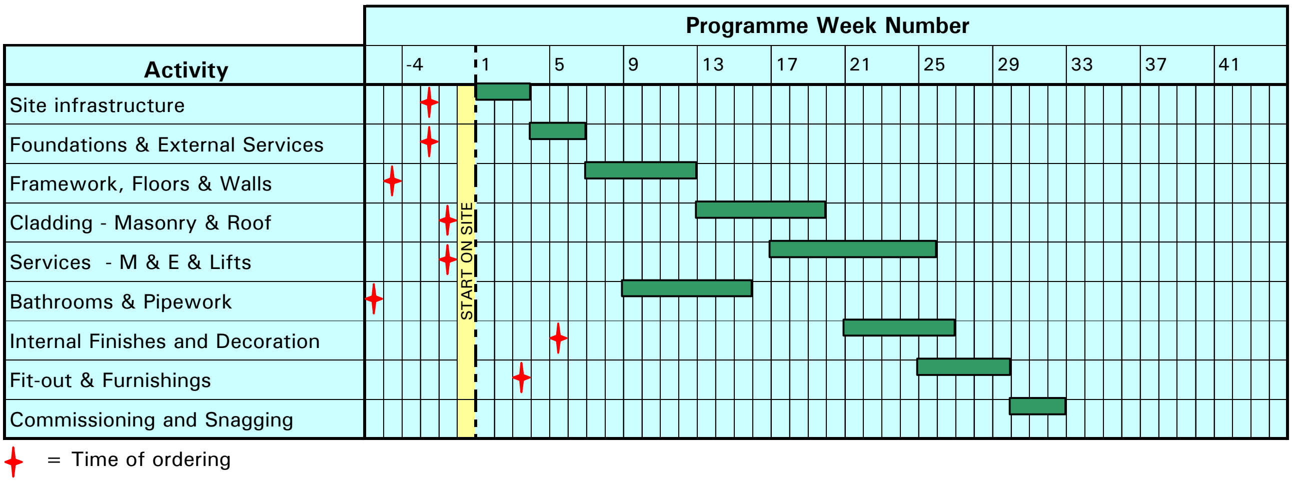
For buildings in which modular construction is being considered for the first time, sufficient time should be allowed for manufacture of pre-production prototypes, which help to resolve potential design and production problems. A period of 4 to 6 weeks should be allowed for this prototyping stage. The 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.

Table 8.1 *Comparison of procurement and construction processes for a typical medium-sized hotel*

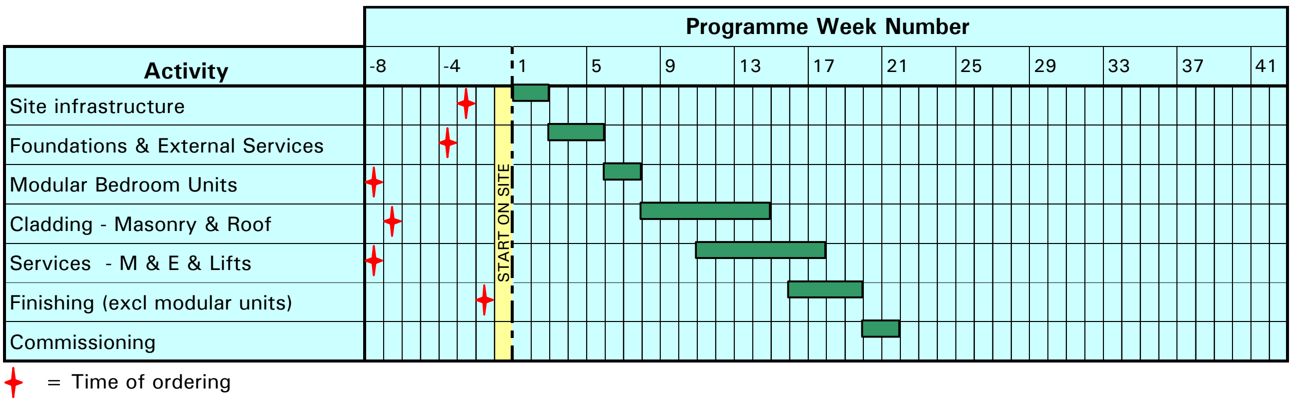
Conventional on-site construction



Light steel framing and modular bathroom units



Modular construction



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. A lead-in of 18 weeks is allowed for lifts but this can be reduced significantly if the modular manufacturer has arrangements with particular lift suppliers. Loose furniture is often moved in later whereas fixed furniture is installed in the factory.

It is apparent from Table 8.1 that the on-site construction period is reduced from 46 weeks for conventional construction to 33 weeks for light steel framing with prefabricated bathroom pods and to 22 weeks for entirely modular construction. Time savings can be even greater on real projects.

However, the pre-site ordering period can increase from 3 weeks to 6 and 8 weeks respectively for the various degrees of modularisation, which is also dependent on the ordering of the major services, cladding and fitments. However, it is evident that 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 are not intended to be definitive but rather emphasise the importance of the decision-making process when using modular construction.

8.3 Procurement of building services

The recent BSRIA report[16] reviews the opportunities for installation of mechanical and electrical building services either as pre-assembled units or as prefabricated components. The distinction between pre-assembly and prefabrication is important because most services involve some amount of prefabrication; the innovation in modular construction comes in the pre-assembly of components before delivery to site.

Pre-assembly is most well established in the area of boiler rooms and air handling and chiller units, which can be located on the roof of buildings or installed on intermediate service floors. The installation has to be carefully planned so that it is not affected by other operators or by external scaffolding. It is also possible to introduce a degree of prefabrication in complex pipework and duct work that would otherwise be difficult to achieve on site.

The BSRIA report also introduces a useful hierarchy in the decision-making process, which is reviewed in Section 8.1. The use of a high level of pre-assembly must be identified and agreed among the design team (also involving the M & E contractor) early in this process. Significant productivity and speed gains can be achieved on site, even though it is recognised that pre-assembled components may be more expensive in manufacturing terms.

The long lead-in time for major components of building services, such as plant rooms and lifts, often dictates the timeliness of the decision-making process. Furthermore, most building services are installed by specialist contractors who should be involved in the concept stage of the design process in order to maximise the benefits of modular construction.

Modular pipework and electrical services were recently used for the 420-bed Dartford and Gravesend Hospital. The 6 m long modules were located in the ceiling void. Similarly, the plant rooms comprised large modular units, some housing specialist facilities.

9 VALUE ENGINEERING ASSESSMENT OF MODULAR CONSTRUCTION

The motivation to use modular construction arises from various well-defined client benefits (as noted in the Introduction). 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 however,which can be taken into account in a value engineering assessment of factors that are normally not included in a conventional Bill of Quantities. Adding value by standardisation and pre-assembly is discussed in a recent CIRIA report(17). The value and assessment of light steel framing in housing is discussed in an SCI publication(18). Included in the discussion are the economic benefits of speed of construction.

9.1 Speed of construction on site

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 estimated at 8 to 15% of the total construction cost. Therefore, a 50% reduction in time on site can lead to a commensurate saving in preliminaries cost to the contractor. 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 on the cost of the land and the average construction cost over the reduced construction period. The *maximum* level of this benefit is the earning potential of the building when in early operation.
- 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.
- Predictability of construction programme (i.e. less risk of over-runs).

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

9.2 Benefits in the construction operation

Normal construction operations are often constrained by the 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 due to 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 in themselves can be important 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 (see Section 8.1).

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 cranage, 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 avoidance of disruption to neighbouring properties, particularly in inner city sites. These may be classified also as environmental benefits (see Section 10).

9.3 Economy of scale

Regular bedroom and bathroom units can be produced to standard dimensions and specifications that are readily transportable (see Section 7.1). 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 therefore leads to the following benefits:

- greater investment in the production-line operation, leading to greater speed of assembly
- 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 re-working
- better design, including the possibility of variants at modest additional cost or difficulty
- more involvement of specialist suppliers, e.g services
- reduction of waste by efficient ordering and use of materials.

On the debit side of this argument, it should be noted that:

- the structure may be 'over-engineered' for its normal applications due to 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.

9.4 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 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.
- In conventional buildings, many contractors also allow 1 to 2% cost for 'snagging' and 'call backs'. These costs are considerably reduced when using modular construction, in comparison with site construction.
- Light steel framing is robust and does not suffer from deterioration in performance. Movements are minimal, which avoids cracking of finishes.

9.5 Application to 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 (true of roof-top extensions).
- Modular units are light in weight and do not require extensive strengthening of the existing structure.

Applications in renovation are reviewed in Section 11.

10 ENVIRONMENTAL BENEFITS

Steel construction, and particularly light steel framing, has the following environmental benefits:

- Steel is very efficient as a structural material and a relatively small quantity of steel (expressed as kg/m^2 floor area) achieves long spans and high load-bearing capacity.
- Light steel framing is light in weight and can be handled easily on site without expensive equipment.
- Galvanised steel sections used in light steel framing have consistent properties and excellent durability and do not deteriorate or rot in an internal environment.
- Steel construction is adaptable to change of use by bolting on or welding attachments, cutting openings, strengthening, etc.
- All steel can be recycled, and indeed up to 50% of new steel production is currently from old scrap steel.
- Steel sections can be salvaged and re-used easily.

Modular construction has distinct environmental advantages over more traditional site-intensive construction from the points of view of:

- energy use in manufacture
- the construction operation, (see Section 10.1)
- energy use in-service operation (see Section 10.2)
- relocatability and re-use of the modular units (see Section 10.3).

The role of steel in environmentally responsible buildings(19) sets out the merits of steel in context of the building industry's impact on the environment and includes the benefits offered by light steel.

10.1 Environmental benefits during the construction operation

The main environmental benefits during the construction operation are derived from the shorter construction period, which lessens the impacts on the local environment. However, there are other, less obvious local environmental benefits of the construction operation, which are identified as follows:

- Site installation of the modular units is a rapid and quiet operation that can be done 'just in time', with no requirement for site storage or additional noisy equipment.
- The delivery and installation of the modular units can be timed to observe any site working or road traffic constraints.
- The delivery of a large number of relatively small amounts of site materials is much reduced.

- Less waste is created so dumping of material waste from site is much reduced. Foundation excavation is minimised and there are fewer potentially wasteful site activities.
- Materials are used more efficiently, with considerable economy of use in production than is achievable on site.
- The main construction operations are less disruptive to adjacent or connected properties in terms of pollution and associated nuisance, etc.

10.2 Environmental benefits in use

The environmental benefits in use concern the high level of performance that can be achieved economically, as follows:

- Good acoustic insulation is provided due to the separation between the modules.
- Good thermal insulation can be provided easily in light steel framing by creating a 'warm frame'. These buildings are very efficient thermally, leading to reductions in energy use and consequent CO_2 emissions.
- Modular units are very stiff and strong, due largely to requirements for lifting and transportation, and therefore have a solid 'feel'.
- All light steel framed structures require minimal maintenance and no call-backs for shrinkage, etc.

10.3 Environmental benefits in re-use

The benefits in terms of re-use are:

- Modular buildings can be extended easily (or reduced in size) as demand changes.
- Modular units are fully relocatable at modest cost, with consequent reduced energy cost in dismantling, and no wastage of materials.
- Long-term use of resources is reduced.

11 OPPORTUNITIES FOR MODULAR CONSTRUCTION IN RENOVATION

Many countries are faced with an increasing financial burden in maintaining and running inefficient concrete and masonry buildings of the 1950s, 60s and 70s. It is estimated that in the European Union there are over 10,000 concrete panel buildings of four or more storeys, and many of these buildings will require major renovation in the next 20 years.

There are considerable opportunities for use of modular construction as part of a comprehensive refurbishment of these buildings. The opportunities include:

- Extensions to the buildings to provide new toilet and bathroom units.
- Enclosing existing open balconies to provide better internal environments.
- New enclosed stairs and access walkways.
- New balconies and other features.
- New external lifts.
- Roof top extensions to create new apartments or communal space.
- Conversion of redundant office buildings into apartments.

Often, new modular units are used as part of an over-cladding or re-facading process in which the thermal insulation of the existing facade is improved greatly in order to reduce the overall energy use of the building. Light steel framing is ideally suited for over-cladding and over-roofing schemes, as explained in recent SCI publications[12, 18, 20].

The economics of these major renovation projects are such that they must pay-back over 30 years in terms of:

- Reduced heating bills.
- Increased rental charges (due to better quality environment and habitable space).
- New sales revenue, such as of roof-top apartments.

11.1 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 be strengthened in order to avoid over-engineering of the modular units at higher levels.

- 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 subframes to the modular units and also to the existing building.
- Modular units used in roof-top extensions should be supported on load-bearing walls. Care must be taken not to overload the existing structure.
- The foundations to the external modular units should be sufficient to avoid differential settlement problems with 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.

11.2 Modular toilet and bathroom units

Highly serviced toilet and bathroom units may be stacked externally to the building and accessed either through the existing facade or by the covered former walkways that are now part of the habitable space. Installation of a modular toilet unit at a project in Forssa, Finland[7] is shown in Figure 11.1. The units were clad with steel cassette panels, which were insulated behind with 100 mm thick mineral wool.

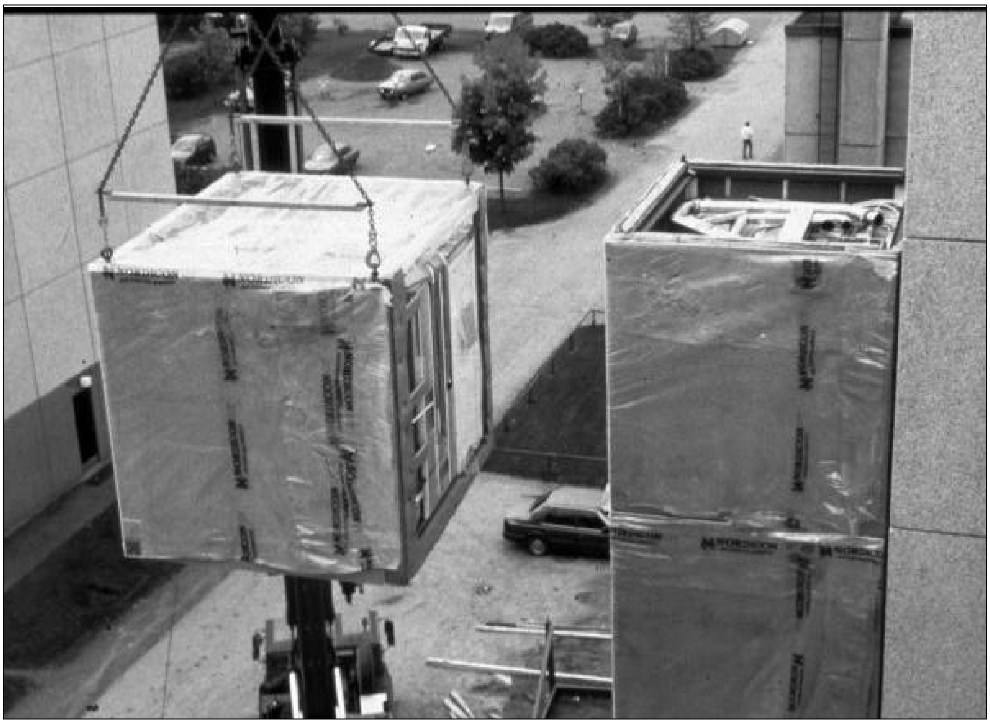


Figure 11.1 *Installation of modular toilet units*

The box-like appearance of the original concrete panel structure was transformed by these modular units with new galvanised steel balconies spanning between them. Service connections between the units were made on site. The horizontal junction between the modular units was made by site-installed cassette panels. The completed building is shown in Figure 11.2.

Figure 11.2 *Completed over-clad building in Forssa, Finland*

The same technique was also used in a project in Raahe in northern Finland. In this case, the whole facade was extended by modular toilet units and by enclosed balconies, which were supported by a separate vertical structure, as shown in Figure 11.3.

Figure 11.3 *Completed over-clad building in Raahe, Finland*

11.3 Modular roof units

Modular roof units may be prefabricated and lifted into place, provided the crane has sufficient height and capacity. It is apparent that this technique is most appropriate for low- and medium-rise buildings. Units are designed to span between load-bearing walls, usually internal cross-walls. The flooring elements and cross-beams need to be sufficiently rigid to allow them to span between the cross-walls.

In a project in Copenhagen[20], one 8-storey and two 4-storey apartment blocks were renovated using steel wall panels and modular units to create new communal space. One of the roof-top units being lifted into place is shown in Figure 11.4. The building's appearance was further enhanced by use of steel tubular members to support the cantilevered roof and to protect the walkway around the new roof units (see Figure 4.4).

The units were supported on three cross-beams that were supported on steel columns over the existing concrete walls. The roof construction used stainless steel sheets on plywood and insulation. A cross-section through the new roof construction is shown in Figure 11.5.

11.4 Modular stairs and lifts

In the projects noted in the previous Sections, new external stairs and lifts were provided by modular components. Disabled access can also be provided.

11.5 Conversion of redundant buildings into apartments

There is currently a social move to provide new accommodation in inner-city areas by converting redundant office buildings and other poor quality buildings into apartments. Modular construction is appropriate for the highly serviced components, lifts and stairs in such conversions. New internal walls and a new facade are often formed from conventional light steel panels to avoid overloading the existing structure and floor.

The modular units can be lifted externally and slid into place rather like in new prestige office buildings built using modular units. This technique has been used by *Unite* in conversions to student residences in the UK. In apartment buildings, it may be possible to group 2 or 4 toilet/bathrooms together to create a larger modular service unit with common pipework. Service pipes are usually installed below a false floor rather than by perforating the existing floor at frequent points. Other overhead services systems are also available.

Figure 11.4 *Erection of modular units in roof-top extension in Copenhagen (see completed building in Figure 4.4)*

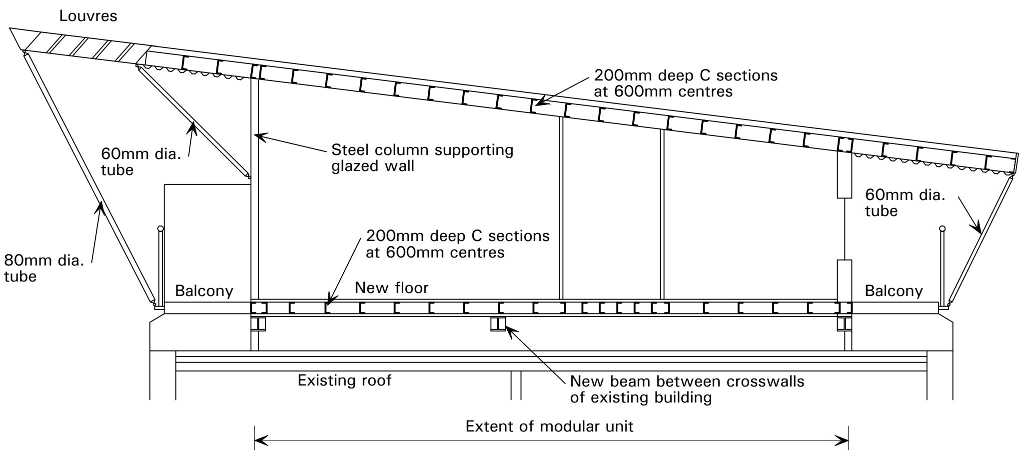


Figure 11.5 *Cross-section through over-roofing scheme in Copenhagen*

One exciting use of this technology was in the conversion of a disused water tower in Finland to create a new multi-storey apartment building. New balconies and external lifts were installed, as shown in Figure 11.6.

Figure 11.6 *Conversion of an apartment block in Finland showing new balconies and over-cladding*

12 FUTURE TRENDS

The future trends and innovation in modular construction are likely to be driven by:

- architectural interest
- manufacture and transportation requirements
- new applications and design innovations
- client requirements for speed and quality.

Module suppliers will be able to cut the cost of manufacture for their products and develop further innovations as the scale of the opportunity and benefits of economy of production are realised.

12.1 Architectural interest

Few projects in this emerging technology have inspired the architectural profession in recent years, as much as Cartwright Pickard's Murray Grove social housing project (see Figure 3.3). The realisation of the expressive use of modular construction can only come through greater architectural interest and involvement. These ideas are increasing and are often encouraged by architectural competitions promoting innovation in housing schemes.

The Shuffle House by architect Piercy Conner, illustrated in Figure 12.1, redefines the concept of the traditional home by using fully serviced and mobile pods within an adaptable space. Other modular buildings combine alternative roof and elevational profiles, such as in the example of Figure 12.2 by Tom Meikle.

High-rise living using modular units has been investigated in a number of schemes, such as in Figure 12.3 by Avery Associates, which also included pre-fabricated lifts and detachable facade elements. Modules slotted into skeletal steel frameworks were pioneered in Sir Norman Foster's Hong Kong Shanghai Bank (see Figure 2.1), and this concept is readily extendable to high-rise residential buildings.

Although the benefits of modular construction are realised through manufacture, certain techniques may be used to increase the architectural appeal, such as by off-sets of the modules on plan, extendable facade elements, balconies and walkways. Modular construction may also be combined with more traditional construction methods to maximise the value of the modules and give more scope for architectural input.

Architects must 'rethink construction' and work more closely with manufacturers and the supply chain in order to better integrate the process of design and construction, while still achieving good quality through design. Modular construction creates considerable opportunities to rethink construction and is ready to be exploited architecturally.

Figure 12.1 *Proposal for relocatable internal pods in an internally adaptable space*

Figure 12.2 *Alternative roof profiles in modular construction*

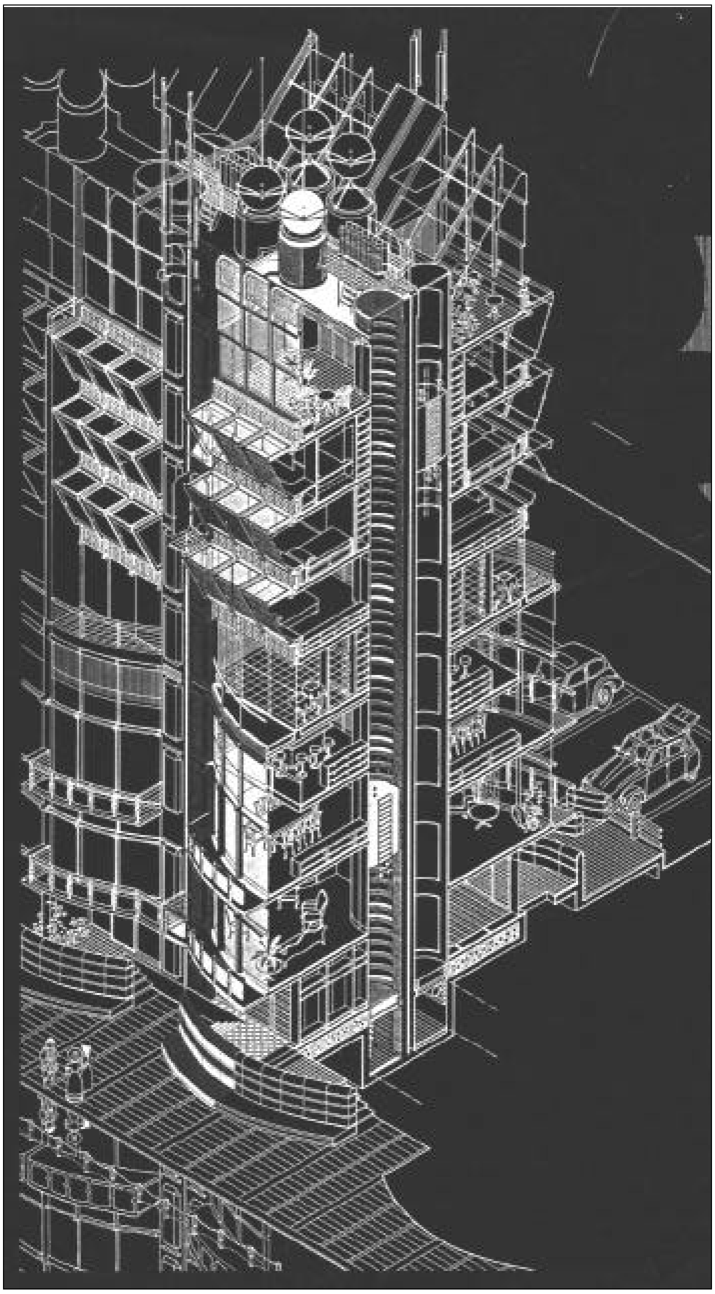


Figure 12.3 *Modular units in high-rise construction*

12.2 Standardisation and containerisation

In order to move products efficiently and cheaply over very long distances, modular units will have to be compatible with the international transport system based on the ISO container unit. It is estimated that by the end of 1996 there were over 15 million shipping containers in use around the world, representing an investment of over £50 billion.

By using ISO container lengths (6.1 m and 12.2 m) and widths (2.43 m), and the standard corner details, modules can be moved by the existing international freight container transport systems. The height of the units can be varied in accordance with national road clearance height standards and/or the type of vehicle used.

It should be noted that if a modular unit can be transported on its side, its maximum width is determined by the transport height (typically 3.9 m) and its maximum height by the transport width (2.43 m). The minimum floor to ceiling height in a standard module is 2.29 m, which means that the combined depth of the floor and ceiling structure cannot exceed 140 mm if the limiting 2.43 m width dimension for containerisation is not to be exceeded. Achieving the necessary structural strength and stiffness for a module with a floor and ceiling 3.6 m wide, and whose combined thickness is 140 mm, is technically challenging.

Modules may be transported fully assembled or as pack-flat panels grouped to form container-sized units. Bathroom pods can be designed to fit *inside* shipping containers.

12.3 Composite modules

To keep transport costs as low as possible and to increase design flexibility, manufacturers exploit use of *composite* modules (sometimes referred to as 'semi-modules'), which are easily transported high-value-per-unit-volume modules (e.g. bathrooms and kitchens). They are extended in an enclosed assembly facility at the building site by bolting highly finished panels onto them to create additional spaces. The resulting composite modules are finished internally, and are then handled and installed in the same way as standard modules.

Although these modules require skilled workers to assemble and finish them on site, the number required is usually small and the large savings in transport cost (typically well over 60% for the equivalent factory-assembled modules of similar size and specification) comfortably offset the additional site operations.

Composite materials - Modular construction uses relatively stiff materials such as cement particle board and sheet steel, which together achieve considerable increased stiffness and strength.

Structural connections and attachment points - A further important step towards standardisation includes the adoption of standard structural connections between modules and standard cladding attachment points.

12.4 Future growth

From the descriptions earlier in this publication of the modular industries in Europe, North America and Japan, it is apparent that modular products cover a broad range of building types. The range is from large luxurious single family houses and high grade hotel bedrooms at one end of the spectrum to small study bedrooms for universities and toilet pods for budget hotels at the other.

In the USA, Howard Johnson International (HJI) recently announced plans to build nearly 300 extended-stay inns by the year 2000 - most of them in Texas and California. HJI's expansion programme will involve almost 60,000 standard rooms, which means they are ideal candidates for modular manufacture. Extended-stay modular accommodation made and managed on this scale is highly competitive with traditionally built and operated hotels.

Hotel companies have considerable buying power and are able to standardise their product range, unlike many industrialised building manufacturers. Potentially the hotel industry could move into the housing business by providing one-bedroom apartments based on the same generic technology as in hotels, and with all the benefits of mass production.

The international need for affordable accommodation for one or two people is huge; for example, recent surveys show that of the projected 4.4 million new household formations in the UK between now and 2016, 80% (3.5 million) will consist of single people. Demographic studies show that the total projected growth of single person households in the EU countries over the next 15 years is expected to total about 14 million. No figures are available to show what proportion of those single person households requires new dwellings. However, even if only 25% (3.5 million) of the 14 million singles require new homes - assuming an average ex-works price of approximately £29,000 per modular unit, the market is worth over £100 billion.

Alternative forms of transportation are also possible. The recent construction of the Chek Lap Kok airport in Hong Kong provided an opportunity to transport 'super-modules' by sea. Siemens has recently announced the production of airships that could be used for long distance transport of modules, particularly between congested cities or sites.

12.5 'Total Core' concept

In the late 1980's, modular toilets were used almost routinely in the construction of large commercial buildings. Architects such as Norman Foster have demonstrated that modular toilets and plant rooms (for example, of the kind used in the Hong Kong Shanghai Bank building) offer a number of advantages over their traditionally constructed equivalents.

In 1989, Schindler Ltd initiated a programme to develop modular lift shafts, and the first company to incorporate the use of toilet modules and plant rooms with modular lifts was Bovis. Together they produced a concept for building all the core areas of large offices as modules. The concept became known as 'Total Core' and involved installing stairs, plant rooms, lift shafts, toilets, tea rooms etc. as modules.

By using the Total Core approach, it is possible to install and commission the core areas of a large office building with one installation team at the rate of one core every three days. Further advantages of Total Core are improved quality, smaller core sizes, and more accurate construction (e.g. tighter tolerances on modular lift shafts mean that they are about 5% smaller on plan than lifts installed in conventionally constructed shafts). An example of the Total Core concept comprising different modules types is illustrated in Figure 12.4. The core can also be extended or modified easily as client requirements change.

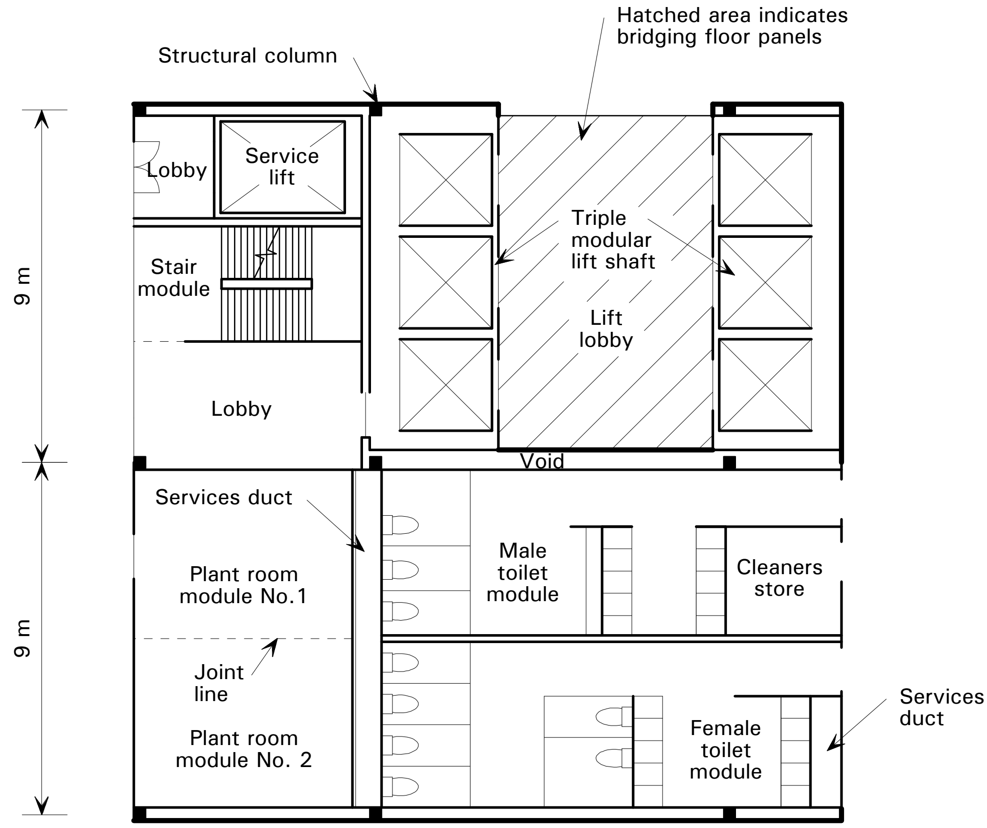


Figure 12.4 *'Total Core' concept for service cores of major buildings*

12.6 Modular plant rooms

Modular plant rooms are normally used where speed of construction and commissioning is important. Under controlled factory conditions, equipment can be installed onto module floors or platforms and the walls and floors positioned around them. The equipment can frequently be positioned close to the edge of the platform and 'bunched' more closely than would be possible in the confined spaces likely to be encountered in traditional plant rooms.

Plant installed in modules tends to be installed more carefully, which encourages higher quality workmanship and results in more reliable plant. These modules are generally placed on the roof or adjacent to buildings, although some units can be slid into place on internal floors. In the same way that plant room modules can be installed quickly, they can also be removed and replaced when major refurbishment or upgrading of plant becomes necessary.

An adaptation of this technique is the use of modular kitchen and toilet modules, which can be moved around the office floor and linked to essential services.

12.7 Stair modules

Prefabricated stair modules greatly improve the efficiency of construction of modern buildings. They can be levelled and positioned accurately and the stair flight can be concreted later or in some systems the stairs are installed as precast concrete units. An example of such a system developed by Bison Structures is shown in Figures 12.5 and 12.6.

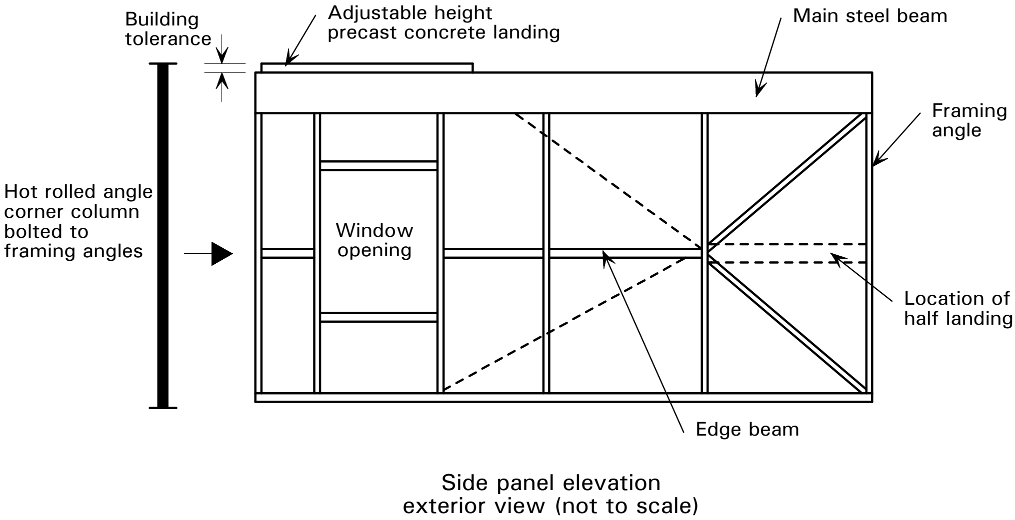


Figure 12.5 *Prefabricated stair modules*

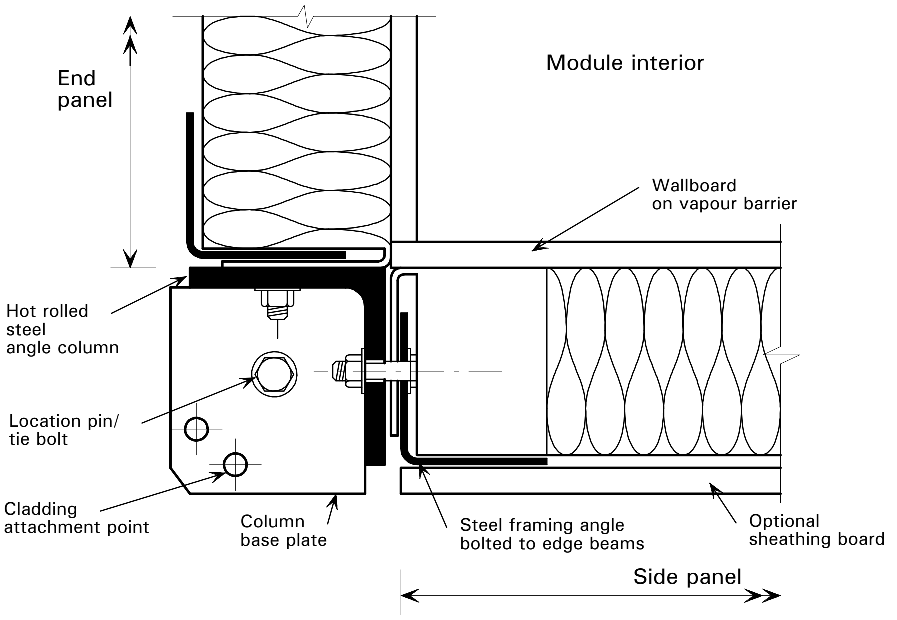


Figure 12.6 *Connection between modular stair units*

12.8 Bathroom modules

The transportation of complete bedroom units is relatively expensive and it follows that small modular toilet/bathrooms can be cost effective. In hotel construction, modular toilets may be constructed not only singly but also in pairs to facilitate transport and installation (see Figure 12.7). Service connections are made through a common vertical service duct. The remaining structure is constructed using light steel framing as a mixture of planar and modular construction.

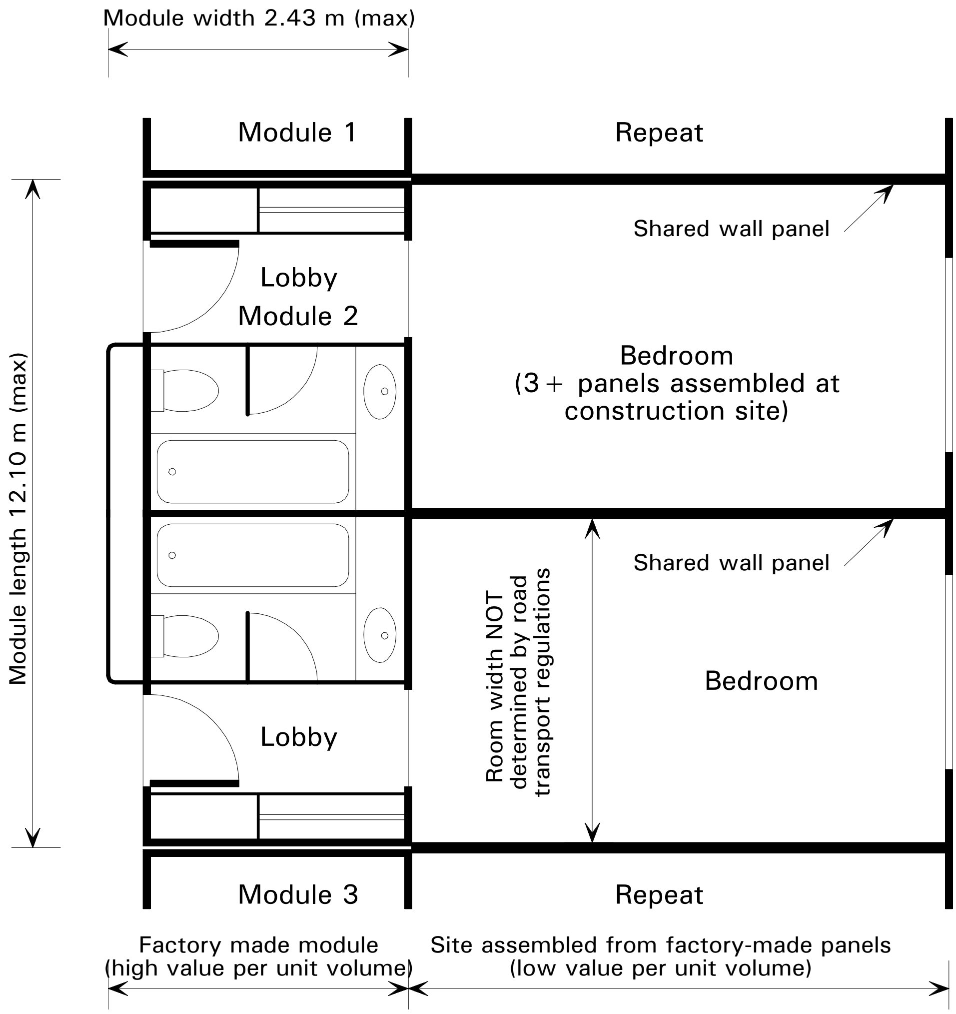


Figure 12.7 *Semi-modular construction using modular bathrooms and light steel panels*

12.9 Complex plan forms

In hotels or similar buildings, the corridor zone between bedroom units can be designed to act as an in-plane truss by careful tying together of the units, as illustrated in Figure 12.8. These tie beams also support the corridor floor.

In this way relatively complex plan forms can be created that do not necessitate the rectilinear approach of conventional modular construction. The in-plane truss is tied into shear walls or cores in order to provide overall stability.

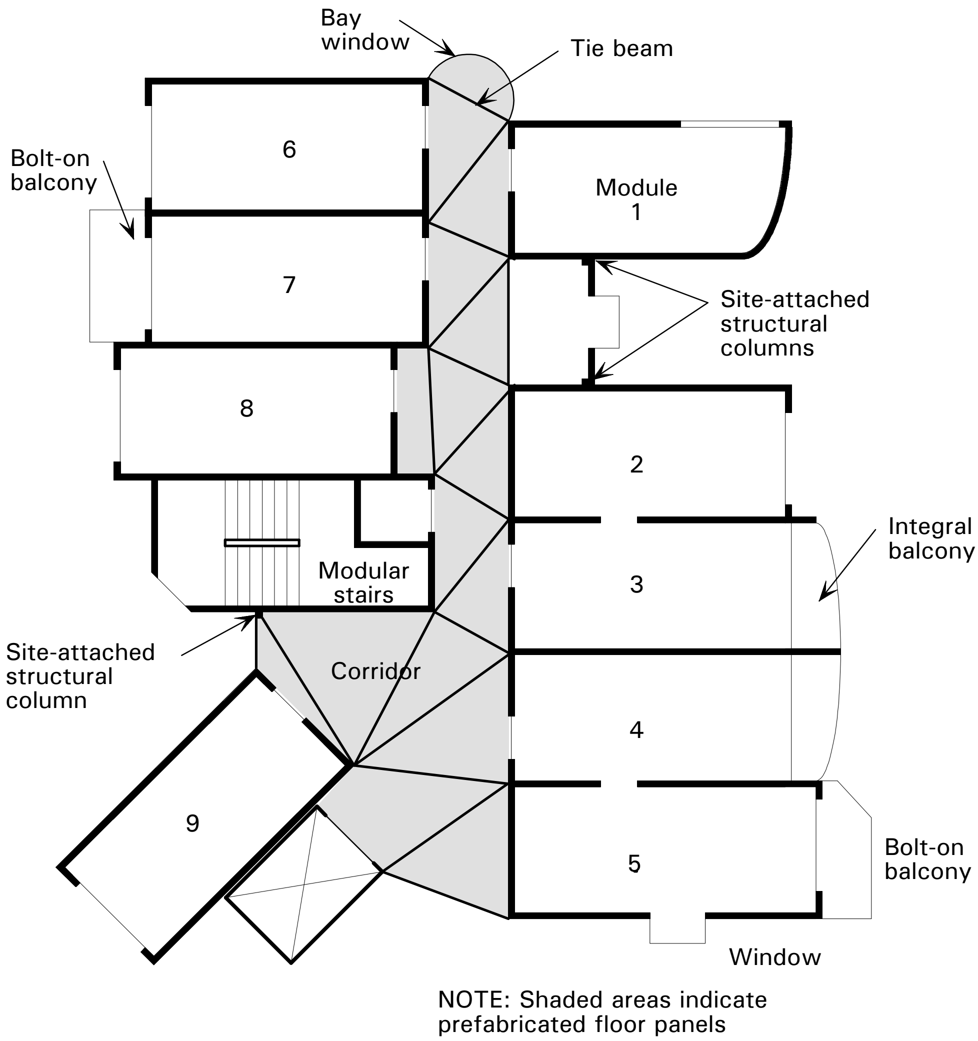


Figure 12.8 *Application of modules to complex plan forms*

13 SOURCES OF INFORMATION

13.1 Manufacturers and suppliers of modular units in permanent buildings

Ayrshire Steel Framing (a division of Ayrshire Metal Products Ltd)
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

Terrapin Ltd
Bond Avenue, Bletchley, Milton Keynes MK1 1JJ
Tel: 01908 270900 Fax: 01908 270052

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

13.2 Other companies involved in modular construction

R B Farquhar Manufacturing Ltd
Deveronside Works, Huntly, Aberdeenshire AB54 4PS
Tel: 01466 793231 Fax: 01466 793098

Unite Group plc
33 Zetland Road, Redland, Bristol BS6 7AH
Tel: 0117 907 8607 Fax: 0117 907 8632

13.3 Information on light steel components

The Steel Construction Institute
Silwood Park, Ascot, Berkshire SL5 7QN
Tel: 01344 623345 Fax: 01344 622944

British Steel Framing
PO Box 28, Mendalgief Road, Newport, Gwent NP9 2WX
Tel: 01633 244000 Fax: 01633 211231

British Steel Strip Products
Construction Advisory Service
Tel: 01633 464646

Metsec Framing Ltd
(incorporating Metframe and Gypframe), Broadwell Road, Oldbury,
Warley, West Midlands B69 4HE
Tel: 0121 552 1541   Fax: 0121 544 0699

Structural Sections Ltd
PO Box 92, Downing Street, Smethwick, Warley,
West Midlands B66 2PA
Tel: 0121 555 5915   Fax: 0121 555 5659

Ward Building Components Ltd
Sherburn, Malton, North Yorkshire YO17 8PQ
Tel: 01944 710591   Fax: 1944 710555

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ARCHITECTS' CHECK-LIST

The following check-list defines the range of questions that the architect may raise in discussion with the modular supplier. The list is not definitive but covers the broad issues. The architect should also address issues related to design responsibility, relationship between the modular supplier and main contractor, and architectural opportunities within the overall manufacturing and constructional technology.

Detailed discussions should be held with the chosen modular supplier. Contractual relationships and duties of the architect may influence the timing and responsibilities for resolving these issues.

Feasibility

- Is the overall building shape appropriate to the economic use of modular construction or alternatively to mixed use of modular construction and panel systems?
- How high can the modules be stacked, and at what point are other strengthening members or support frameworks required?
- When modules are used in combination with steel or concrete frameworks in new or existing construction, are any special measures required and what are the methods of installation?
- Can modular units be placed in a staggered arrangement with off-sets on the facade to create balconies and more interesting details?
- At what scale of repetition is the modular approach economical?
- Can the units be made with raked sides and non-rectangular on plan (e.g. curved facade)?
- How can modules be combined to create large open spaces or glazed facades?
- What are typical module sizes? Are there any transport or site restrictions on the size of modules for delivery?
- Are typical interface details with cladding, roofing, foundations, balconies, lifts available?
- Is the pre-manufacture of a prototype unit required in order to assess feasibility and ease of manufacture and transport before production begins.

Procurement and costs

- What are the different procurement routes that may be employed? How is a competitive element between modular manufacturers maintained?
- At what point does the final design become 'fixed' before committing to production?
- What are the performance requirements for modular construction?
- Who takes responsibility for the adequacy and performance of the modular units and the final design?

- What are typical module costs in £/m^2, depending on the level of fit-out required? Can these costs be provided at the scheme design stage?
- Does the manufacturer tender at scheme design stage or at final design, and how is the manufacturer's design input recognised?
- What are potential time savings in the modular route, and other benefits in terms of theconstruction programme?
- What guarantees and independent approvals are available (e.g. Agrément or Lantac)? What is the design life of the modules?
- What guidance on contractual responsibility is available? Does the architect 'nominate' the module supplier?
- What guarantees or warranties are available?

Detailed design

- What factors will determine the size and repetition of the modules, e.g.
  - local roads for transport
  - site constraints and cranage
  - room sizes to be created.
- Are the modules edge supported or corner supported and what are the implications for foundations, cladding, services etc? Are there special requirements for tall buildings?
- Is bracing required and, if so, where can bracing elements be located in open-sided modules? What is the length of the side of a module that can be left open?
- What interface details for the chosen cladding systems are appropriate?
- How are balconies or other features attached to the modular units, or can they be manufactured as projections to the modules.
- How can the building facade be modified to create the required architectural style?
- What are the typical wall, floor and ceiling thicknesses?
- What are the sensible acoustic insulation and thermal insulation characteristics that can be achieved?
- Where are major service routes located both horizontally and vertically? Can rainwater pipes be incorporated internally?
- How are service connections between units made, and how can they be accessed for maintenance?
- How is the spread of fire prevented between modules, and what fire resistance period can be achieved for the modules?
- What information is required for building control, and who provides structural details of the module design and the supporting design calculations?
- Who takes responsibility for dimensional coordination?
- How and when are lifts and stairs installed?
- What British Standards are appropriate to modular construction?

- What degree of differential foundation settlement can be resisted without distress. Are movement joints necessary? Is a separate foundation required for the masonry facade?

Working details

- Can cladding and windows be attached in the factory, and what features may be used to conceal the joint between the modules? How is the cladding protected during transportation?
- How is insulation attached? In what circumstances can it be fitted between the wall studs, or must it be placed externally?
- What are the attachments between the modules and to the foundation?
- Can brickwork coursing be arranged to suit window openings, taking account of module heights and construction tolerances?
- What dimensional tolerances are appropriate for manufacture and for site installation?
- What materials are appropriate to protect the modular units during transportation? Can they be left in place after construction?
- What details are used for the floor-floor junctions, including floor coverings?
- At what stage are the working details of the modules and their attachments provided?

Construction

- How does the designer deal with CDM issues (and safety plans)?
- What notice is required for police escort, if necessary?
- How can deliveries be timed to suit road restrictions?
- Who provides the cranage - the main contractor or the modular supplier? Is special cranage required for tall buildings?
- What is the typical weight of a module?
- What area is required for off-loading the units? Can the units be placed directly in their final location?
- Who makes the service connections and ensures satisfactory installation?
- If cladding is installed in the factory, who co-ordinates the later site infills?
- Can floors and tiles be bonded satisfactorily? What remedial work may be required on site?
- Can pre-compliance trials be done off site and who is responsible for them?
- What maintenance schedule is given or is necessary?
- How can any trapped water during construction or due to a burst pipe be dealt with?
- How can the modular units be adapted at a later date?

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1.1/1.2	John Prewer (*also on cover*)
1.3	Britspace Modular Building Systems Ltd
1.6	Terrapin Ltd
1.7	John Prewer
2.1	Sir Norman Foster and Partners
2.4	John Prewer
2.5	Schindler Ltd
3.1	Terrapin Ltd
3.2	John Prewer
3.3	Miller Hare for Cartwright and Pickard Architects (*also on cover*)
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12.1	Piercy Conner Architects
12.2	Tom Meikle Architects
12.3	Avery Associates
12.4	John Prewer
12.5	Bison Structures Ltd
12.6	Ove Arup and Partners
12.7/12.8	John Prewer