Application of Modular Construction in High-Rise Buildings

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Abstract: Modular construction is widely used in Europe for multi-story residential buildings. A review of modular technologies is presented, which shows how the basic cellular approach in modular construction may be applied to a wide range of building forms and heights. Case studies on 12-, 17-, and 25-story modular buildings give design and constructional information for these relatively tall buildings. The case studies also show how the structural action of modular systems affects the architectural design concept of the building. The combination of modules with steel or concrete frames increases the range of design opportunities, particularly for mixed-use commercial and residential buildings. An overview of the sustainability benefits and economics of modular construction is presented based on these case studies. **DOI: 10.1061/(ASCE)AE.1943-5568.0000057.** *© 2012 American Society of Civil Engineers.*

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Introduction

Modular construction comprises prefabricated room-sized volumetric units that are normally fully fitted out in manufacture and are installed on-site as load-bearing "building blocks." Their primary advantages are:

- Economy of scale in manufacturing of multiple repeated units,
- Speed of installation on-site, and
- Improved quality and accuracy in manufacture.

Potentially, modular buildings can also be dismantled and reused, thereby effectively maintaining their asset value. The current range of applications of modular construction is in cellular-type buildings such as hotels, student residences, military accommodations, and social housing, where the module size is compatible with manufacturing and transportation requirements. The current application of modular construction of all types is reviewed in a recent Steel Construction Institute publication (Lawson 2007). Lawson et al. (2005) describe the mixed use of modules, panels, and steel frames to create more adaptable building forms.

There are two generic forms of modular construction in steel, which affects their range of application and the building forms that can be designed:

- Load-bearing modules, in which loads are transferred through the side walls of the modules.
- Corner-supported modules, in which loads are transferred via edge beams to corner posts (see Fig. 1).

In the first case, the compression resistance of the walls (generally comprising light steel C-sections at 300 to 600 mm spacing) is the controlling factor. The double layer walls and floor/ceiling combination enhances the acoustic insulation and fire resistance of the construction system.

In the second case, the compression resistance of the corner posts is the controlling factor and for this reason, square hollow sections (SHS) are often used due to their high buckling resistance.

Resistance to horizontal forces, such as wind loads and robustness to accidental actions, become increasingly important with the scale of the building. The strategies employed to ensure adequate stability of modular assemblies, as a function of the building height, are:

- Diaphragm action of boards or bracing within the walls of the modules–suitable for 4- to 6-story buildings.
- Separate braced structure using hot-rolled steel members located in the lifts and stair area or in the end gables—suitable for 6- to 10-stories.
- Reinforced concrete or steel core–suitable for taller buildings.

Modules are tied at their corners so that structurally they act together to transfer wind loads and to provide for alternative load paths in the event of one module being severely damaged. For taller buildings, questions of compression resistance and overall stability require a deeper understanding of the behavior of the light steel C-sections in load-bearing walls and of the robust performance of the interconnection between the modules.

Modular Construction in High-Rise Residential Buildings

Spatial Arrangement of the Modules

Designing with modular construction is not a barrier to creativity. Modular rooms or pairs of rooms or room and corridor modules can be used to create varieties of apartment types. These types can be put together to make interesting and varied buildings of many forms. The nature of high-rise buildings is such that the modules are clustered around a core or stabilizing system. The particular features of the chosen modular system have to be well understood by the design team at an early stage so that the detailed design conforms to the limits of the particular system.

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Fig. 1. Light steel module with a perimeter framework (image by R. M. Lawson)

A typical module is 3.3 m (11 ft) to 3.6 m (14 ft) wide (internal dimensions) and 6 m (20 ft) to 9 m (30 ft) long. A module is 25 to 35 m^2 (270 to 375 ft^2) in floor area and is often used for single-person accommodation. Two modules are generally suitable for a 2-person apartment (with one bedroom) and three or four modules are suitable for family-sized apartments (Lifetime Homes 2010). In all cases, the kitchens and bathrooms are arranged next to the corridor or other accessible space so that service connections and maintenance can be carried out relatively easily.

For modules with load-bearing walls, the side walls of the modules should align vertically through the building, although openings of up to 2.5 m width can be created, depending on the loading. For modules with corner posts, the walls are non-load-bearing, but the corner posts must align and be connected throughout the building height. Additional intermediate posts may be required in long modules, so that the edge beams are not excessively deep.

The design of high-rise modular buildings is strongly influenced by structural, fire, and services requirements. From a building layout viewpoint, two generic floor plans may be considered for the spatial relationship of the modules around a stablizing concrete core:

- A cluster of modules, which are accessed from the core or from lobbies next to the core, as illustrated in Fig. 2.
- A corridor arrangement of modules, in which the modules are accessed from corridors either side of the core, as illustrated in Fig. 3.

The addition of external balcony systems can be used to create a layer of external features that provide private space and architectural interest. Balconies can be attached at the corner posts of the modules or can be ground supported. Integral balconies within the modules may be provided by bringing the end wall in-board of the module.

The optimum use of modular construction can achieved by designing the highly serviced and hence more expensive parts of the building in modular form and the more open-plan space as part of a regular structural frame in steel or concrete. This requires careful consideration of the architecture and spatial planning of the building.

Structural Action of Tall Modular Buildings

The structural behavior of an assembly of modules is complex because of the influence of the tolerances in the installation procedure, the multiple inter connections between the modules, and the way in which forces are transferred to the stabilizing elements, such as vertical bracing or core walls. The key factors to be taken into account in the design of high-rise modular buildings are:

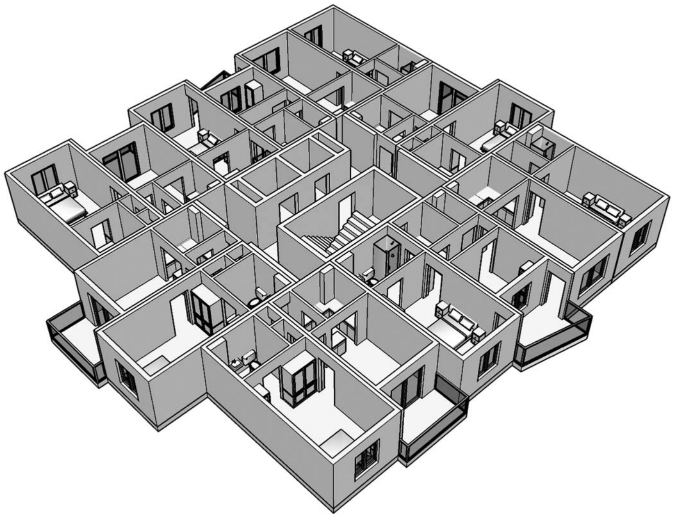

Fig. 2. Typical layout of rooms clustered around a core

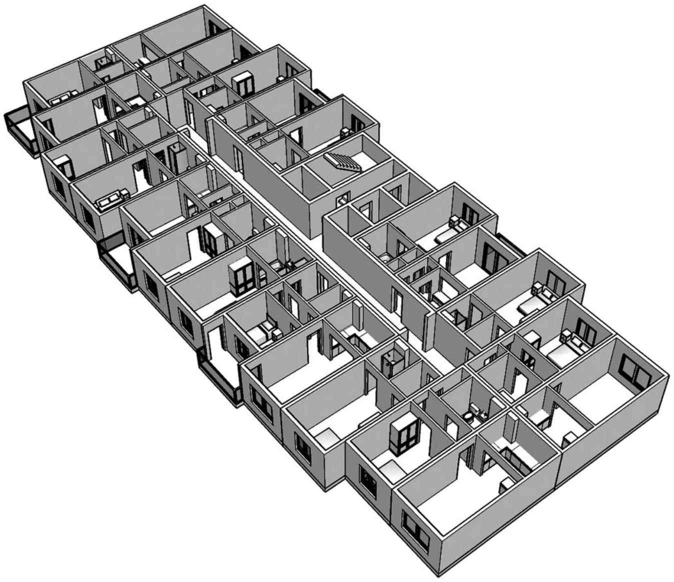

Fig. 3. Typical corridor arrangement of modules

- The influence of installation eccentricities and manufacturing tolerances on the additional forces and moments in the walls of the modules (Lawson and Richards 2010).
- Second-order effects due to sway stability of the group of modules, especially in the design of the corner columns of the modules.
- Mechanism of force transfer of horizontal loads to the stabilizing system, which is generally a concrete core.
- Robustness to accidental actions (also known as structural integrity) for modular systems.

In modular systems with load-bearing walls, axial load is transferred via direct wall-to-wall bearing, taking into account eccentricities in manufacture and installation of the modules, which causes additional buildup of moments and accentuates the local bearing stresses at the base of the wall.

Two layers of plasterboard or similar boards are attached to the internal face of the wall by screws at not more than

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300 mm spacing. Cement particle board (CPB) or oriented strand board (OSB) are often attached to the exterior of the walls of the modules. In production, boards may be fixed by air-driven pins enhanced by glued joints. These boards restrain the C-sections against buckling in the in-plane direction of the wall.

The ability of an assembly of modules to resist applied loads in the event of serious damage to a module at a lower level is dependent on the development of tie forces at the corners of the modules. The loading at this so-called accidental limit state is generally taken as the self-weight plus one-third of the imposed load, reflecting the average loading on all floors in this rare event. To satisfy "robustness" in the event of accidental damage to one of the modules, the tie forces between the adjacent modules may be established on the basis of a simplified model in which the module is suspended from its neighbors. For design purposes, it is recommended (Lawson et al. 2008) that the minimum horizontal force in any tie between the modules is taken as not less than 30% of the total load acting on the module and not less than 30 kN (3 tons).

Fire Resistance and Acoustic Insulation

In most European countries, 120-min fire resistance is required for residential buildings of more than 28 stories in height (10 stories typically), and in some countries sprinklers are also required. The fire resistance of modular construction derives from four important aspects of performance:

- The stability of the light steel walls is a function of the load applied to the wall and the fire protection of the internal face of the wall of the module.
- The load capacity of the module floor is influenced by the thermal-shielding effect of the ceiling of the module beneath.
- The elimination of fire spread by fire barriers placed between the modules (to prevent the spread of smoke or fire in the cavity between the modules).
- The limiting of heat transfer through the double-leaf wall and floor-ceiling construction of the modules.

Generally, the internal face of the walls and ceiling of the module are provided with two 15 mm (0.6 in.) plasterboard layers (at least one layer being fire-resistant plasterboard using vermiculite and glass fiber). Mineral wool is placed between the C-sections (also required for acoustic purposes). The floor and ceiling in combination and the load-bearing light steel walls generally achieve 120-min fire resistance, depending on the sheathing board used on the outside of the modules.

The double-layer walls and floor-ceiling of the modules also provides excellent resistance to airborne and impact sound, particularly when supplemented by external sheathing board. Additional sound reduction and floor stiffness to minimize vibrations can be achieved by a thin concrete floor screed either placed on the light steel floor or as a composite slab spanning between the walls or edge beams.

Case Study of Modules Stabilized by a Concrete Core—Paragon, West London

For high-rise buildings, the modules are generally designed to resist only vertical loads, including the cladding and corridor loads, and horizontal loads are transferred to the concrete core. In the cluster arrangement, the modules are connected directly to the core, generally by attaching ties to cast-in plates in the core. In the corridor arrangement, horizontal loads are transferred via in-plane bracing in the corridors and are again connected to the core. It follows that the distance of the outer module from the core is limited by the shear force that can be transferred via the corridor or by the travel distance for fire evacuation purposes.

Fig. 4. 17-story modular building stabilized by a concrete core (image by R. M. Lawson)

This concept has been used on one major project called Paragon in west London, shown in Fig. 4 (Cartz and Crosby 2007). A series of buildings from 11 to 17 stories were constructed using modules with loadbearing corner posts. The plan form of the L-shaped building is shown in Fig. 5. The modules were also manufactured with integral corridors, in which half of the corridor was included in each module. The corner columns were therefore in-board of the ends of the modules and the projection of the floor into the corridor was achieved by the stiff edge beams of the modules.

The project consisted of a total of 827 modules in the form of 600 en-suite student rooms, 114 en-suite studio rooms, and 44 one-bedroom and 63 two-bedroom key worker apartments. The 17-story building consists of 413 modules. Modules are 2.8 m (9 ft) to 4.2 m (13.5 ft) wide, which is the maximum for motorway transport in the UK. The edge beams use 200 × 90 (8 × 3.5 in) parallel flange channels (PFC) at floor level and 140 × 70 (5.5 × 2.7 in) PFC at ceiling level to design partially open-sided modules of up to 6 m (20 ft) span. The one- or two-bedroom apartments were constructed using two or three modules, each with a 35 to 55 m^2 (375 to 590 ft^2) floor area. The plan form is presented in Fig. 6, which shows the many variations in room layouts that were possible using corner-supported modules.

Case Study of Modules on a Podium—Bond Street, Bristol

Modular construction may be combined with steel or concrete frames to extend the flexibility in space planning in applications where the dimensional constraints of modular systems would otherwise be too restrictive. An adaptation of modular technology is to design a "podium" or platform structure on which the modules are placed. In this way, open space can be provided for retail or commercial use or below-ground car parking. Support beams should align with the walls of the modules and columns are typically arranged on a 6 to 8 m grid (20 to 26 ft). A column grid of

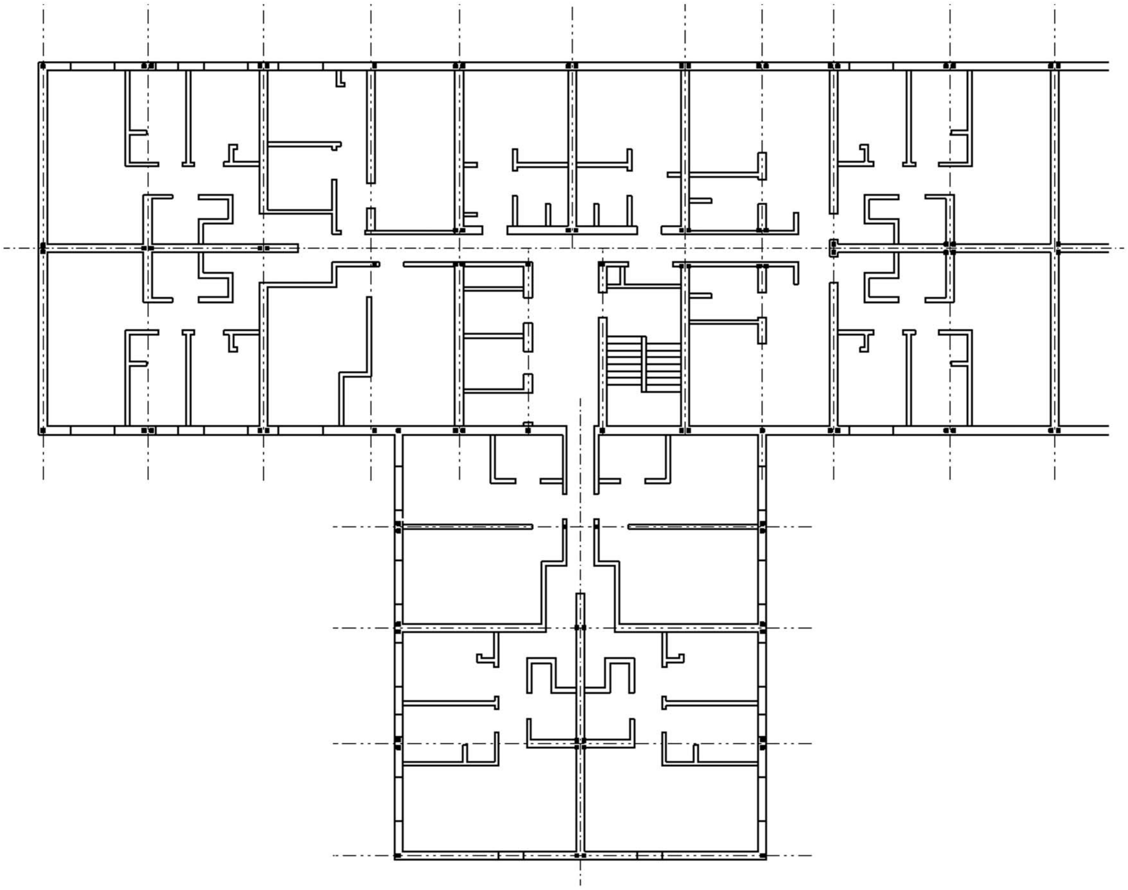

Fig. 5. Plan form of the building in Fig. 4 showing the location of the corner posts in the modules

7.2 m (24 ft) is optimum for car parking at ground floor or basement.

Fig. 6 shows a 12-story mixed student residence and commercial building in Bristol in the west of England, in which 6 to 10 stories of modules sit on a 2-story steel framed podium. The 400 bedroom modules are 2.7 m (9 ft) external width, but approximately 100 modules are combined in pairs to form "premium" studios consisting of two rooms. The kitchen modules are 3.6 m (12 ft) external width. Stability is provided by four braced steel cores, into which some modules are placed. The plan form is illustrated in Fig. 7. A double corridor is provided so that a cluster of five rooms forms one compartment. Stability is provided by braced steel cores and the maximum number of modules placed between the cores is seven.

Fig. 6. 12-story modular student residence at Bond Street, Bristol (image by R. M. Lawson)

The building used a lightweight cladding system consisting of a "rain screen" in which the self-weight of the cladding is supported by the modules. The air and weather-tight layers and the majority of insulation is contained within the module as delivered.

Case Study of High-rise Building in Wolverhampton

A 25-story modular construction project in Wolverhampton in the midlands of England was studied to obtain data on the construction process. It has three blocks of 8 to 25 stories and in total consists of 824 modules. The tallest building is Block A, which is shown in Fig. 8 during construction. The total floor area in these three buildings is 20,730 m^2 (223,000 ft^2), including a podium level. The floor area of the modules represents 79% of the total floor area. The average module size was 21 m^2 (226 ft^2) but the maximum size was as large as 37 m^2 (398 ft^2).

The project started on site in July 2008 and was handed over to the client in August 2009 (a total of 59 weeks). Installation of the modules started in October 2008 after completion of the podium slab, and construction of the concrete core to Block A was carried out in parallel with the module installation on Blocks C and B. Importantly, the use of offsite technologies meant that the site activities and storage of materials were much less than in traditional

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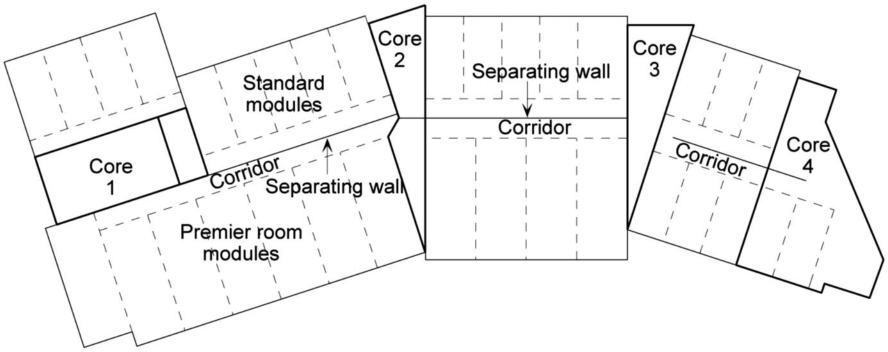

Fig. 7. Plan of modular building at Bond Street, Bristol, showing the irregular-shaped core positions

Fig. 8. 25-story modular building in Wolverhampton, England, during construction (image by R. M. Lawson)

construction, which was crucial to the planning of this project. The tallest building, Block A, has various set-back levels using cantilevered modules to reduce its apparent size. Lightweight cladding was used on all buildings and comprises a mixture of insulated render and composite panels, which are attached directly to the external face of the modules. The total area of cladding was 10,440 m^2 (112,300 ft^2) for the 3 blocks.

Construction Data

The module weights varied from 10,000 to 25,000 kg, depending on their size, and the module self-weight was approximately 5.7 kN/m^2 (120 $pounds/ft^2$) floor area. The modules in the first Block C were installed by mobile crane, whereas the modules in Blocks A and C were installed by the tower crane that was supported by the concrete core. The installation period for the 824 modules was 32 weeks and the installation team consisted of a total of eight people plus two site managers. The average installation rate was 7 modules per day, although the maximum achieved was as high as 15 per day. This corresponds to 14.5 man-hours per module.

The overall construction team for the nonmodular components varied from a further 40 to 110 with three to four site managers, increasing as the 59-week project progressed. It was estimated that the reduction in construction period relative to site-intensive concrete construction was over 50 weeks (or a saving of 45% in construction period).

It was estimated that the manufacture and in-house management effort was equivalent to a productivity of 7.5 man-hours per square meter module floor area (0.7 man-hours per square foot) for a 21 m^2 (225 ft^2) module floor size. This does not take into account the design input of the architect and external consultants, which would probably add about 20% to this total effort.

For modules at the higher levels, approximately 14% of the module weight was in the steel components and 56% in the concrete floor slab. At the lower levels of the highrise block, the steel weight increased to 19% of the module weight. The steel usage varied from 67 to 116 kg/m^2 (14 to 24 $pounds/ft^2$) floor area, which is higher than the 50 to 60 kg/m^2 (10 to 12 $pounds/ft^2$) for medium-rise modular systems.

The estimated breakdown of man-effort with respect to the completed building was 36% in manufacture, 9% in transport and installation, and 55% in construction of the rest of the building. The total effort in manufacturing and constructing the building was approximately 16 man-hours per square meter (1.5 man−hours per square foot) completed floor area, which represents an estimated productivity increase of about 80% relative to site-intensive construction.

Deliveries and Waste

Site deliveries were monitored over the construction period. During installation of the modules, approximately six major deliveries per day were made, plus the six to twelve modules delivered on average. During concreting of the cores, approximately 6×8 m^3 (280 ft^3) concrete wagons were scheduled to be pumped to construct the core at a rate of one story every three days.

Waste was removed from site at a rate of only two skips of 6 m^3 (210 ft^3) volume per week during the module installation period and six skips per week in the later stages of construction, equivalent to approximately, 3,000 kg of general waste, including off-cuts and packaging. This is equivalent to about 9 kg per m^2 (1.8 pounds per ft^2) floor area.

The manufacturing waste was equivalent to 25 kg/m^2 (5.1 pounds/ft^2) of the module area, of which 43% of this waste was recycled. For the proportion of module floor area to total area of 79%, this is equivalent to about 5% of the weight of the overall construction. This may be compared to an industry average of 10 to 13% wastage of materials, with little waste being recycled. It follows that modular construction reduces landfill by a factor of at least 70%.

Summary of Sustainability Benefits of Modular Construction

Modular construction systems provide several opportunities to improve the sustainability of the project in terms of the construction process and the performance of the completed building.

- Construction waste is substantially reduced from 10 to 15% in a traditional building site to less than 5% in a factory environment, which also has greater opportunities for recycling of waste.
- The number of visits to site by delivery vehicles is reduced by up to 70%. The bulk of the transport activity is moved to the factory, where each visit can be used to deliver more material than is usually delivered to a construction site.
- Noise and disruption are reduced on-site, assisted by the 30 to 50% reduction in the construction period, which means that neighboring buildings are not affected as much as in traditional building processes.
- The air-tightness and the thermal performance of the building fabric can be much higher than is usually achieved on-site due to the tighter tolerances of joints that can be achieved in a factory environment.
- The efficient use of lightweight materials and the reduced waste means that the embodied energy of the construction materials is also reduced.
- Acoustic insulation is greatly improved by the double-layer construction.
- Safety on-site and in the factory is greatly improved, and it is estimated that reportable accidents are reduced by over 80% relative to site-intensive construction. The modules can be installed with pre-attached protective barriers or, in some cases, a protective "cage" is provided as part of the lifting system.

Economic Benefits of Modular Construction

Modular construction takes most of the production away from the construction site, and essentially the slow, unproductive site activities are replaced by more efficient, faster factory processes. However, the infrastructure for factory production requires greater investment in fixed manufacturing facilities and repeatability of output to achieve economy of scale in production.

An economic model for modular construction must take into account the following factors:

- Investment costs in the production facility.
- Efficiency gains in manufacture and in materials use.
- Production volume (economy of scale).
- Proportion of on-site construction (in relation to the total build cost).
- Transport and installation costs.
- Benefits in speed of installation and reduced minor repair costs.
- Savings in site infrastructure and management (preliminaries).

Materials use and wastage are reduced and productivity is increased, but conversely, the fixed costs of the manufacturing facility can be as high a proportion as 20% of the total build cost.

Even in a highly modular project, a significant proportion of additional work is done on-site. Background data may be taken from a recent National Audit Office (NAO) report "Using Modern Methods of Construction to Build Homes More Quickly and Efficiently" (National Audit Office 2004). This report estimates that this proportion is approximately 30% in cost terms for a fully modular building, and may be broken down approximately into foundations (4%), services (7%), cladding (13%), and finishing (6%). However, in many modular projects, the proportion of on-site work can be as high as 55% (see case study). Modular construction also saves on commissioning and minor repair costs that can be as high as 2% in traditional construction.

The financial benefits of speed of installation may be considered to be:

- Reduced interest charges by the client.
- Early "start-up" of business or rental income.
- Reduced disruption to the locality or existing business.

These business-related benefits are clearly affected by the size and type of the business. The tangible benefits due to reduced interest charges can be 2 to 3% over the shorter building cycle. The NAO report estimates that the total financial savings are as high as 5.5%.

Lessons Learned

The case studies show that modular construction can be used for residential buildings up to 25 stories high, provided the stability under wind action is achieved by a concrete or steel framed core. Modules in tall buildings can be clustered around a core, or alternatively, they can be connected to a braced corridor, which transfers wind-loading to the core. The design of the load-bearing walls or corner posts should take into account the effects of eccentricities due to manufacturing and installation tolerances.

Three case studies of modular buildings showed the different plan forms that can be created depending on the type of modular system. Modules with corner posts provide more flexibility in room layouts but are more costly to manufacture than the wholly light steel load-bearing systems. For the 25-story modular building, the steel usage ranged from 67 to 117 kg/m^2 (14 to 24 pounds/ft^2) floor area because the modular system had a concrete floor slab. The modular components accounted for approximately 45% of the completed cost of the building. The construction period was reduced by over 50% relative to site-intensive building. Waste was reduced by 70% on-site and most manufacturing waste was recycled.

Conclusions

This paper shows that modular construction can be used for residential buildings up to 25 stories high, provided the stability is achieved by a concrete or steel framed core. The structural design of the modules is strongly influenced by installation and manufacturing tolerances and tying action between the modules. In terms of layout of the modules, three modules efficiently form a two-bedroom apartment. Modules in tall buildings can be clustered around a core, or alternatively, they can be connected to a braced corridor, which transfers wind-loading to the core,

Three case studies are presented of modular buildings of 12, 17, and 25 stories in height. In the tallest building, data was collected of the manufacturing and construction operation. For a high-rise modular building, the steel usage ranged from 67 to 117 kg/m^2 (14 to 24 pounds/ft^2) floor area depending on the floor level. The modular components accounted for approximately 45% of the completed cost of the building. The construction period was reduced by over 50%

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