Developments in pre-fabricated systems in light steel and modular construction

Synopsis
This paper reviews recent developments in pre-fabricated construction systems using light steel and modular technologies, and describes the economic context in which the use of these systems has expanded. Examples of recent important projects using these technologies are illustrated. Hybrid or mixed construction systems have been developed which optimise on manufacturing costs and space provision. Background research and testing is also presented.

Introduction
Pre-fabrication by off-site manufacture leads to faster construction, improved quality and reduced resources and waste. Although pre-fabrication in not in itself new, off-site manufacture (OSM) describes a supply and construction process in which the major parts of a building are mass-produced in factory conditions rather than on site. ‘Modern Methods of Construction’ (MMC) are defined by their improvements in terms of the targets set by the UK Government’s Report ‘Re-thinking Construction’. Modern OSM technologies achieve these targets, although industrialised building technologies in all materials had a mixed record in the post-War period mainly because the supporting research and in-service experience was not in place. However, early examples of the use of cold formed steel in housing are performing well after 50 years, such as the Meudon House by Jean Prouvé.

Steel construction is, by its nature, pre-fabricated to some degree, but the innovative use of this technology has arisen in response to market demand for higher levels of pre-fabrication. In the context of this paper, the uses of highly pre-fabricated construction systems will be reviewed, showing how steel technology has developed over the last 5 years and how basic research information has been established to support these new developments.

The sector for which MMC is being promoted is in housing and residential buildings, which also includes single person accommodation and affordable housing, particularly in inner cities. According to the influential Barker report, current UK house building at 180 000 completions per year (2003) is some 70 000 short of that necessary to stabilise house price rises and to meet demographic and social demands. The MMC industry in all materials has been set the challenge of raising its supply and quality capabilities, as envisaged in ‘Re-thinking Construction’. The Housing Corporation encourages use of MMC technologies by Registered Social Landlords, whose new build programme currently represents about 11% of total housing output. Furthermore, the Government’s planning guidance PPG3 promotes mixed-use developments in urban locations and re-use of former sites (brownfield sites). This leads to a demand for building technologies that are fast to construct, lightweight and less site-intensive. Modern spatial design follows guidance such as Rowntree’s ‘Lifetime Homes Standards’.

Steel construction has established a ‘track record’ in the commercial building sector, where the benefits of speed of construction and long spans with service integration are well understood. The medium-rise residential sector, such as apartments, hotels and student residences uses similar steel and composite technologies, although at a more modest scale. Steel construction has achieved a 20% market share in the important apartment sector, which represents approximately 40% of housing output (2003). For two- or three-storey housing, relevant technologies are based on light steel framing, and the market share for steel is currently 3%. However, the use of steel is much higher (30% estimated) in the student residence and military accommodation sectors, for which the current market is 30 000 bed-units per year.

To assist in understanding the various forms of pre-fabricated technologies, four levels of construction process are proposed in Table 1 (based on an illustration by Gibb in the DTI’s pROSpA programme). MMC may be assumed to concentrate on Levels 3 and 4, which involve relatively high levels of prefabrication. Modular construction is an example of a high level off-site manufacture, but there are also opportunities for ‘hybrid’ planar and volumetric technologies, which optimise the

Fig 1. Installation of modular units at Murray Grove, Hackney

Fig 2. Completed mixed panel and modular project at Lillie Road, Fulham
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value-cost balance in housing. ‘Open building’ systems are relatively advanced as they allow for interchange of components to create more flexible building forms than is achievable in fully modular construction. This is the area in which the greatest advances are possible, and a CIB Working Group is currently exploring open building systems at an international level.

Case examples of MMC

Recent projects have demonstrated the benefits of pre-fabricated construction technologies, such as the award-winning Murray Grove project in Hackney completed in 1999, which used volumetric construction based on the Yorkon system. More recently, the Lillie Road project in Fulham and Lingham Court in Stockwell used light steel framing, modular bathrooms and a slim floor primary frame at first floor to optimise both the construction process and provision of space for these mixed-use buildings. For the first projects, the client was The Peabody Trust, which took a strong interest in realising the value-benefits of these relatively new technologies. The projects are illustrated in Figs 1 and 2.

The world’s largest modular buildings are located in Manchester and use a similar technology based on the Ayrframe system, an innovative form of ‘stressed skin’ construction. The Royal Northern College of Music student residence consists of 900 modules in a six to nine-storey configuration (see Fig 3), and a mixed communal-retail development for client OPAL consists of 1400 modules supported on a two-storey podium in composite construction (see Fig 4). This second project required the setting up of a temporary production facility only 5 miles from the project site in order to achieve ‘just in time’ delivery.

Unite Modular Solutions, a major ‘design build finance operate’ provider in the student residence and key worker sector has completed eight major projects using fully modular construction, and has commissioned a new factory to produce bedroom modules at a target rate of up to 20 per day. A recent project in Plymouth is illustrated in Fig 5. Other new initiatives are underway involving a variety of modular and panel systems, notably by Advance Housing, involving collaboration of Terrapin and a major house builder, and by Kingspan Off-site.

Background studies

In his report for nCRISP on the Social and economic value of construction, Professor David Pearce identifies the problem that the construction industry has in adapting to rapid demand and technology change. To meet the environmental challenges of our age, the industry is encouraged to embrace sustainable developments and technologies which ‘ensure a better quality of life for everyone, now and for generations to come’. Although the construction industry has over 1.5M participants, it is very diverse and lacks ‘critical mass’ in many sectors. It uses 5% of UK total energy consumption and up to 25% of all materials are wasted in site-intensive construction. Recycling and re-use are increasingly important (90% of steel is recycled). Furthermore, the built environment uses 40% of the country’s total energy consumption, and both the UK Government through the Building Regulations and the European Commission through its directive on energy performance of buildings require significant operational energy reductions in new buildings in order to reduce CO2 emissions.

Pearce identifies various requirements of the construction industry to meet new challenges, which among others are:

- standardisation of building components
- lightweight and stronger materials
- wider user of information technology

<table>
<thead>
<tr>
<th>Level</th>
<th>Components</th>
<th>Description of technology</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>Materials</td>
<td>Basic materials for site intensive construction e.g. concrete, brickwork</td>
</tr>
<tr>
<td>1</td>
<td>Components</td>
<td>Components that are used as part of site-intensive building processes</td>
</tr>
<tr>
<td>2</td>
<td>Elemental systems</td>
<td>Linear or 2D components in the form of assemblies of structural frames and wall panels</td>
</tr>
<tr>
<td>3</td>
<td>Volumetric systems</td>
<td>3D components in the form of modules used to create major parts of buildings, which may be combined with elemental systems</td>
</tr>
<tr>
<td>4</td>
<td>Complete building systems</td>
<td>Complete building systems, which comprise modular components, and are essentially fully finished before delivery to site</td>
</tr>
</tbody>
</table>

Table 1: Illustration of various levels of building technologies in the context of MMC (adapted from Gibb in the ProSPA programme)
David Gann’s team at Imperial College has produced many influential reports, including those on overseas study tours to Japan, the Netherlands and Germany and a review of the supply side in MMC in this country. A UK Government briefing paper, *Modern methods of house building*, identifies the need for a ‘step change’ in the ability of the construction industry to meet demand for 3M new homes by 2016. The ‘triple bottom line’ of the economic/environmental/social cost-benefits is paramount in achieving this objective. The estimated capacity of the supply side in MMC is 30,000 – 40,000 housing units (in all materials), which represents 15 – 20% of current house building.

The question to be addressed is how to achieve this target and maintain high quality and user satisfaction, which was the problem in the 1960s and early 70s, when the rapid expansion in ‘systemised’ building exceeded the technical understanding and collective experience existing at the time. Fortunately, the industry has developed greater expertise, architectural skills, better quality materials, and design is supported by detailed guidance and stronger regulations. Nevertheless, it is still necessary to ensure that the quality keeps pace with new demands on the industry.

### Economics and production of OSM

The underlying economics of off-site manufacturing (OSM), and modular construction in particular, is quite complex and requires a significant production rate of repeatable components in order to be fully economic. OSM requires capital investment in the infrastructure of factory production, design development, product testing and certification, and overheads of a fixed facility and factory space. Cellular-type buildings, such as hotels and student residences have multiple similar units, and are the types of projects where OSM has proved to be successful. The breakthrough of OSM into the wider residential sector is still in its infancy.

Modern highly automated factories for modular production cost the order of £10M to set up. Although much less than the £500M required to set up a new automotive production line, these costs are distributed over a yearly output of 1000 to 2000 units in a changeable building market, in comparison to a typical annual production of 50,000 of a successful car model. The additional costs are savings due to more efficient production technologies, reduced on-site construction costs, higher quality levels, and time-related savings due to speed of construction. Although it is recognized that time savings of 30 – 50% in total construction programme can be realised by modern OSM, the economic value of this early completion depends on the business operation or early sales revenue. This can be quantified for a hotel chain or a time-constrained operation, such as a university, but is less apparent for a house builder in a speculative market.

The broad economic comparison between on-site construction and OSM is illustrated in Fig 6. Essentially, the additional costs of a permanent factory have to be balanced against savings in inefficient and wasteful on-site operations. Most OSM projects involve a proportion of site work (20 – 40% being typical), which are reflected in the broad costs in Fig 3. Although OSM leads to efficiencies in materials use and reduced wastage, many pre-finished components are bought in, which increases their cost. Small OSM projects may not result in significant economies, unless the same form of construction is repeated in a number of similar projects. However, large OSM projects can lead to cost savings of 10 to 20% in addition to time savings by reducing site infrastructure costs and increasing productivity and reliability.

The rationale behind the expansion of OSM depends on investment in numerically controlled machinery and integrated CAD/CAM software. In Europe, parallel technology was first developed in the timber frame industry, whereas in Japan, companies such as Sekisui and Toyota Homes are advanced in implementation of steel–based technologies in modular construction. Light steel sections may now be produced by small-scale roll-forming machines, and panels are assembled accurately on tables and boards and cut rapidly, for example using ballistic nailing. A typical factory assembly process is shown in Fig 7. Turning tables permit panels to be worked on from both sides, and services can be pre-installed. Up to 30 stages are required in a continuous modular production facility, although fit-out is often carried out manually. Completed modules are weather-protected and then either sent directly to site or to holding locations for ‘just in time’ delivery.

### Generic forms of light steel and modular construction

Historically, steel has been used in housing for 70 years, and there are many good examples of its use worldwide. The modern forms of steel and mixed construction systems that are widely used in the housing and residential sector are described in simple terms as follows:

**Light steel framing; elemental and panel systems**

Light steel framing consists of galvanized steel C-sections of typically 65 to 200mm depth and in steel thicknesses of 1.2 to 2.4mm. Walls are generally pre-fabricated as 2D-storey-high panels, as in Fig 8, whereas floors can be installed in elemental form as joists or in 2D-cassette form. For two-storey buildings, platform construction may be used (i.e. floors sit directly on walls) but for general design, it is necessary to achieve continuity in load paths through the walls by supporting the floors, for example on a Z trimmer attached to the top of a wall panel.

**Modular construction**

Volumetric or modular construction systems are manufactured...
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from 2D wall panels and floor cassettes in light steel framing, but are assembled into load-bearing ‘boxes’ which are fitted out and transported to the construction site. The primary limitations are those of production and transport as factory manufacture requires multiple similar units, and transport without police escort necessitates a unit width of less than 4.1m.

Two generic forms of modular construction exist:

- Continuously supported or 4-sided modules where vertical loads are transmitted through the walls (see Fig 9).
- Open-sided or point-supported modules where vertical loads are transmitted through corner and intermediate posts (see Fig 10).

Point-supported systems require deeper edge beams than continuously supported modules. In both systems, resistance to horizontal loads can be provided by bracing or diaphragm action in the walls, but for buildings more than six storeys high, a separate bracing system is required, which is often provided around the access core. Forces are transferred by the module-module connections in the form of plates and bolts, assisted by horizontal bracing in the corridors.

‘Hybrid’ modular and panel systems

‘Hybrid’ or mixed modular and panel systems optimise the use of the 3D and 2D components in terms of space provision and manufacturing costs. Modular units are used for the higher value more highly serviced areas, such as bathrooms, and wall panels and floor cassettes for the more flexible open space. Two generic forms of ‘hybrid’ construction may be considered:

- load-bearing modules with floors supported by the modules
- non-load bearing modules (or pods) supported by floors.

The first system was used in a demonstration building for Corus17, shown in Fig 11 and 12, in which the central service core and stairs were manufactured as modules and the open plan space was provided by prefabricated panels and floor cassettes spanned up to 5.7m. In this way, the internal space could be partitioned to suit the user’s requirements. The construction of the Lillie Road project (in Fig 2) comprises X-braced wall panels, floor cassettes and stacked bathroom modules, as shown in Fig 13.

‘Hybrid’ modular, panel and primary steel frame

Modular construction has mainly been used for medium-rise cellular buildings. Greater flexibility in building height and internal planning can be achieved by the mixed use with a primary steel structure. Various generic forms of construction may be employed by creating:

- a ‘podium’ structure of typically one or two storeys height in which the column spacings are located at multiples (two or three times) the module width;
- a skeletal structure, which provides the open plan areas and the stacked modules provide the highly serviced areas or cores;
- a skeletal structure, in which non load-bearing modules and wall panels are supported on the floor.

A podium structure is often used where retail outlets or communal space are provided at ground floor and car parking in the basement, as in the project shown in Fig 14. Composite construction may be used in which the podium level is designed to support the load from the modules above (typically six storeys).

A skeletal structure may be designed in the form of slim floor beams using UC or RHS sections in which the modular and floor cassettes are supported on the extended bottom flange so that the beams occupy the same depth as the floor. A pair of modules would be located within the column grid and the corners of the modules are recessed in order that they fit around SHS or narrow columns in order to minimise wall widths, as shown in Fig 13.

A commonly used form of construction for multi-storey buildings is to design a primary steel frame in composite construction or Slimdek, and to use non-load bearing light steel infill walls for external and separating walls as in Fig 15. Bathroom ‘pods’ may be slid into place and, in order to obtain a consistent level, their floor depth is the same as the built-up acoustic layers on the slab.

Fig 9. Continuously supported module in light steel framing
Fig 10. Corner-supported module
Fig 11. (Left) Demonstration building using mixed panel and modular construction
Fig 12. (Right) Hybrid panel and modular construction (courtesy of Corus)
Fig 13. Load-bearing braced walls and stacked bathroom modules in the project shown in Fig 2
Open-building systems

‘Open-building’ technology is a general term used to describe systems, which provide flexibility in space planning and in interchange of components. Many of the hybrid systems described above achieve some of the principles of ‘open technology’, but to be more widely applicable and to achieve economy in manufacture, geometrical standards and common interface standards are required for the cladding, services, lift and stairs and other key components. A recent DTI Partners in Innovation project attempts to define geometric standards that may be used for concept design which are based broadly on the following dimensions:

- wall width of 300mm for internal separating walls and external walls;
- floor depth of 450mm for the combined floor and ceiling depth in modular and ‘hybrid’ construction systems;
- floor depth of 600mm when a supporting primary steel structure is used;
- internal planning dimensions based on 600mm on plan (therefore 3 or 3.6m are preferred internal modular widths);
- floor-ceiling heights based on 2.4m for residential buildings and 2.7m for commercial, health or educational buildings.

Modular construction achieves the benefits of OSM, but it requires a new discipline in construction technology based on building ‘blocks’ rather than skeletal or planar components with which designers are familiar. An optimised modular system must allow for greater flexibility in internal planning, but must retain the primary benefits of OSM in terms of speed of installation and improved quality. The inter-relationship between modules and efficient provision of space can be improved by strategically placed internal posts, which allow for both open-sided design and for re-orientation of modules. A typical plan of such a group of modules is illustrated in Fig 16.

Openings of up to 3m width can be created, and a cluster of posts form a column which can support loads of up to eight storeys.

The Open building approach has been applied in two building systems. OpenHouse AB is a Swedish system in which recessed modules are supported on a grid of 3.9m by SHS columns, as illustrated in Fig 17. In this way, modules can be re-orientated. Smart House is a system used in the Netherlands using a tubular steel frame. A central non load-bearing service core is provided, and all light steel walls and floors are relocatable. An internal view and a detail of the ‘hidden’ connections are shown in Fig 18.

Background testing

A considerable amount of research has been carried out by light steel and modular construction, and some of the recent structural testing by The Steel Construction Institute (SCI) and Corus is presented here.
Diaphragm action and influence of brickwork

The structural design of cold formed steel members is covered by BS 5950-519 and in the future by Eurocode 3 – 1.3. Light steel frames resist in-plane loads due to wind action by X-bracing or by integral K-bracing. However, effective in-plane resistance and stiffness can also be achieved by diaphragm action of board materials. For timber framing, the contribution of brickwork to resistance to wind loads is given in BS 5268: Section 6.1:1988, but this approach is not readily extended to light steel framing because of its different stiffness characteristics and wall tie systems.

Representative tests were carried out on light steel wall panels to investigate the performance of different sheathing materials for 2.4m square frames using C sections of 75mm depth and 1.6mm thickness. Four self-piercing rivets were used at each connection. Plasterboard and sheathing boards were fixed with screws at 300mm centres, but for the later tests, the spacing was reduced to 150mm. All holding down arrangements had standard bolted brackets at the base of the panel.

A lateral load is applied to the head of the frame until a horizontal deflection of 4.8 mm was measured corresponding to a serviceability limit of height/500. No vertical load was applied, as in light steel framing, the stiffening effects of vertical load are smaller than in timber framing where tensile action at the base of the wall studs dominates. After the stiffness tests, the horizontal load was increased until failure occurred at large displacements. Table 2 summarises the results of the tests for wall panels with and without windows, and presents the design loads that may be resisted. When compared to the results for the plasterboard-clad panel, the increase in design load is 95% for plywood, 57% for steel sheathing and 143% for cement particle board. When the number of fixings was doubled, the test load for serviceability increased by 11% to 30% for the three board materials.

Tests were also conducted on similar wall panels attached to brickwork to evaluate their enhanced shear stiffness. Wall ties fitted into vertical steel channels, which were attached to each stud giving a wall tie density of approximately 4.4/m². As light steel framing is designed as a ‘warm frame’ in which most of the insulation is external to the frame, the channels were fixed by long screws through the external insulation, which affects the stiffness of the wall tie system. The wall ties are bonded into the brickwork, and are relatively stiff in the horizontal direction, but are flexible in the vertical direction. The results of these brick-clad panel tests are presented in Table 3 and in all cases, serviceability is the controlling design condition. The attachment of brickwork with a single layer of 35mm thick insulation more than doubles the shear resistance compared to an unclad frame. The test results are relatively independent of the panel type, indicating that the stiffening effect of the brickwork is dominant. The stiffening effect was 10 to 30% less when two layers of insulation were used.

<table>
<thead>
<tr>
<th>Frame type</th>
<th>Without brickwork</th>
<th>With brickwork and plasterboard</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Frame with plasterboard</td>
<td>35mm thick insulation</td>
</tr>
<tr>
<td>1 Plain panel – no bracing</td>
<td>3.7</td>
<td>10.8</td>
</tr>
<tr>
<td>2 Plain panel – single bracing</td>
<td>5.1</td>
<td>9.4</td>
</tr>
<tr>
<td>3 Plain panel – double bracing</td>
<td>5.5</td>
<td>11.3</td>
</tr>
<tr>
<td>4 Window panel – double bracing</td>
<td>2.7</td>
<td>11.4</td>
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not specify minimum limits for the tying forces. Light steel frames consist of multiple inter-connections in the form of screws, rather than discrete bolted connections between members. Therefore tying forces are distributed over the connected elements.

In BS 5950-1, the simple requirement for tying forces equal to the factored shear force was established from catenary action of a concrete floor plate subject to an accidental load of its dead load plus one third of its imposed load. For a concrete structure, the ratio of the accidental load to factored load is in the range of 0.5 to 0.6, whereas for a light steel structure, the ratio can be 0.3 to 0.35. It may be calculated that the tensile forces are equivalent to 0.7 times factored shear force in normal conditions. The typical factored load for a lightweight floor is 3.3kN/m², and for a 4.5m span, this corresponds to a tying force of approximately 5kN/m length of wall. Had these forces been combined at a notional column for a 4.5m square grid, the tying forces would have been approximately 25kN.

For light steel walls, an analogy with masonry is used in which an approximate length of wall of 2.5 × height is considered to be affected by a blast pressure. The stability of the wall may be calculated using a 20% enhancement in the steel strength due to the effect of high strain rates and the statistical observation that the average material strength is significantly higher than the minimum design value in BS 5950-5. A Cowper-Symonds enhancement factor for high strain rates may be calculated using a 20% enhancement in the steel strength due to the effect of high strain rates and the statistical observation that the average material strength is significantly higher than the minimum design value in BS 5950-5. A Cowper-Symonds enhancement factor for high strain rates would be 7% for S280 steel and 15% for S350 steel. The robustness of the test house described earlier was demonstrated during its controlled demolition, in which walls were progressively removed, as illustrated in Fig 20. Guidance on structural integrity is given in SCI P-301.

Robustness of light steel framing

The Building Regulations Part A²² require that all structures are ‘robust’ and do not suffer disproportionate collapse in the event of an explosion or impact or other accidental action. These aspects of design are termed ‘structural integrity’ and recommendations for hot rolled steel structures are presented in BS 5950-1:2000²², which requires the provision of discrete ties with a maximum tensile resistance of 75kN at floor and roof levels. BS 5950-5²² cross-refers to these requirements, but does
Robustness of modular construction

The basic stability of a pair of light steel modules was investigated in order to understand their in-plane and torsional behaviour under unusual actions. The Ayreframe system was used in which the walls are not braced but rely on multiple internal connections between vertical C sections and ‘top hat’ horizontal members, as shown in Fig 21. The modules were later lined with plasterboard, but no other sheathing board was used. The module dimensions were 3.6m wide × 7.5m long. The thickness of the C section is 1.6mm and the top hat section is 1.34mm. Uniform load was applied using water containers. Vibration tests gave a natural frequency of over 12Hz for an imposed floor load of 0.5kN/m² and the damping ratio was 3 to 5.6%. The serviceability load tests on the floor gave a deflection of 8.8mm for a pair of modules and 6.1mm for a single module.

Two tests were carried out to assess the stability of a pair of modules; firstly, when support to one longitudinal side removed, and secondly when support to one end and half of one side was removed. The first test showed that the modules were able to span as a deep beam with one longitudinal support removed and the maximum deflection was 25mm. The deflections for the second case when subject to a floor load of 2.3kN/m² are presented in Fig 22. Removal of one corner support led to a deflection of 19mm, which demonstrates the torsional action of the box.

Modular units are stable 3-D structures, and are connected both horizontally and vertically at their corners, although the practical installation of connection plates and bolts can be problematic, given site tolerances and ease of location etc. ‘Robustness’ of a group of modules is established by a scenario-based approach in which, in the worst case, the support to the modules is selectively removed. Removal of support to an edge or corner module causes the modules above it to act as cantilevers. In this case, the tyres can be estimated as follows for a typical module of width of 3.6m and length of 7.5m. The self weight of the modules is typically 5t when fitted out. For an accidental load of 2.3kN/m², the horizontal tyre forces at each corner are 16kN, and the vertical tyre force is 25kN.

Conclusions

This paper reviews modern methods of light steel construction that are used in the residential sector, and identifies mixed forms of skeletal, planar and volumetric construction that are economic in the medium-rise sector. The structural behaviour of light frames demonstrates considerable reserve in stability and structural integrity. Background tests have shown that a brick-clad light steel frame can resist unfactored shear forces of 4kN/m² wall length, or 2.5kN/m for typical sheathing materials without consideration of stiffening elements. Robustness of light steel framing may be achieved by designing for minimum tying forces of 5kN/m, increasing to 25kN for connections between modules.

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REFERENCES

3. Delivering stability: Securing future housing needs; Barker Review of Housing supply for the Office of the Deputy Prime Minister, 2004
6. Promoting Off-site Production Applications www.prOSpa.org

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