Investigation use of light prefabricated panels in buildings

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Abstract: The study focuses on the design, manufacturing, structural improvements and behavior of the floor systems during loading at the serviceability and ultimate limit states. This paper reviews recent developments in prefabricated construction systems using light steel and modular technologies, and describes the economic context in which the use of these systems has expanded. The composite construction concept offers flexibility in the assembly process, the ability to adapt to various load and boundary requirements, and efficient utilization of material properties that result in a light weight prefabricated structural element. The activities described in this paper are an extension of previous work where composite floor panels composed of light gauge steel joists were integrally cast with a thin-walled Engineered Cementations Composite slab.

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1. Introduction:

Many developed countries have invested in more research on 4 prefabricated constructions because their fast-growing economies have forced builders to build faster and more economically. Factory-constructed homes, manufactured homes, modular homes, prefabricated homes or prefab homes are common terms used to describe pre-made homes.

"The term prefabricated brings to mind a building system in which the essential pieces of structure are sent to the site on which the finished edifice will be constructed partially or completely assembled. Once there, it is necessary only to join and anchor the parts" (Bahamon, 2002). Prefabricated construction does not only reduce construction costs, but it also produces a more stable and fairly remunerated construction industry with improved safety and working conditions, greater investment in research, design creativity, and product development. It also reduces consumption of energy and material and generally increases the availability of better designed and high-quality built environments. (Anderson and Anderson 2007).

Modern OSM technologies achieve these targets, although industrialized 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 theme Dan House by Jean Prouve. 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. 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. So-called 'Modern Methods of Construction' are defined by their improvements interims of the targets set by the UK Government's Report 'Re-thinking Construction'. This leads to demand for building technologies that are fast to construct, lightweight and less site-intensive. 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 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 193000 completions per year (2005) is some 55000 short of that necessary to stabilize house price rises and to meet demographic and social demands. For two- or three-storey housing, relevant technologies are based on light steel framing, and the market share for steel is currently 3%.

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 programmed currently represents about 16% 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). The medium-rise residential sector, such as apartments, hotels and student residences uses similar steel and composite technologies, although at a more modest scale and steel construction has achieved a 20% market share in this important niche sector, which represents approximately 40% of housing output (2009).

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 optimize the 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.

However, the use of steel is much higher (33% estimated) in the student residence and military accommodation sectors, for which the current market is 30 000bed-units per year. To assist in understanding the various forms of prefabricated technologies, four levels of construction process are proposed in Figure 1.

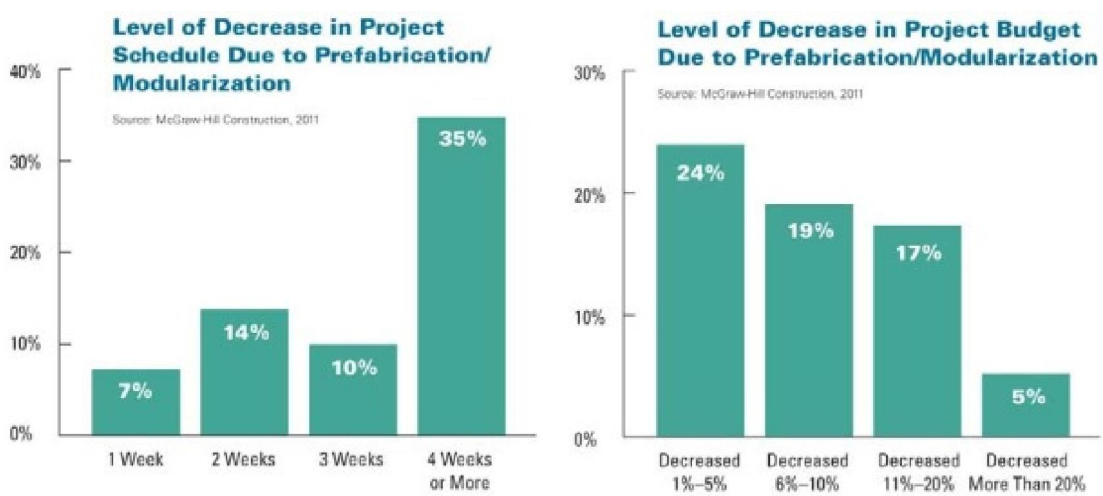

Figure 1: Level of Decrease in Project Schedule and in Project Budget

Recent projects have demonstrated the benefits of pre-fabricated construction technologies, such as the award-winning Murray Grove project in Hackney completed in 2009, which used volumetric construction based on the system. More recently, the Lillie Road project in building, completed in 2010 used light steel framing, modular bathrooms and a slim floor primary frame at first floor to optimize both the construction process and provision of space for this mixed-use building. In both projects, the client was The Peabody Trust, which took a strong interest in realizing the value-benefits of these relatively new technologies. The world's largest modular buildings are located in Manchester and use a similar technology based on the 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, and mixed communal-retail development for client OPAL consists of 1400 modules supported on a two-storey podium in composite construction. This second project required the setting up of a temporary production facility only 5 miles from it.

The estimated capacity of the supply side in MMC is 44000-56000 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 'systemized' building exceeded the technical understanding and collective experience existing at that 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. 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 breakthrough of OSM into the wider residential sector is still unit's infancy. Modern highly automated factories for modular production cost of the order of £14M to set up. Although much less than the £560 M required to set up a new automotive production line, these costs are distributed over a yearly output of 1200-2100 units in a changeable building market, in comparison to a typical annual production of 50 000 of a successful car model over a 7year cycle. Balanced against these fixed capital costs are savings due to more efficient production technologies, reduced site construction costs, higher quality levels, and time-related savings due to speed of construction.

The concept of “build it fast” in the most economical way has not changed since the beginning; however, new technologies have been developed to suit the modern world prefabricated construction. The underlying economics of off-site manufacturing (OSM), and modular construction in particular, is quite complex and requires significant production rate of repeatable components in order to be fully economic. Prefabricated construction has been a common construction method in the world for more than a century. Prefabricated construction is popular in many countries. 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. Although it is recognized that time savings of 35-65% in total construction time can braised by modern Smother economic value of this early completion depends on the business operation or early sales revenue. A typical factory assembly process is shown. 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.

The rationale behind the expansion of OSM depend noninvestment in numerically controlled machinery and integrated CAD/CAM software. 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. The additional costs of a permanent factory have to be balanced against savings in inefficient and wasteful site operations. Most OSM projects involve a proportion of site work (20 – 40% being typical), which are reflected in the broad costs. Although OSM leads to efficiencies in materials use and reduced wastage, many pre-finished components are bought in, this 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 14-17% in addition to time savings by reducing site infrastructure costs and increasing productivity and reliability.

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 describe din simple terms as follows:

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 are fixed rapidly, for example using ballistic nailing.

Light steel framing consists of galvanized steel C-sections of typically 65 to 200mm depth and in steel thicknesses of 1.2 to 2.4 mm. Walls are generally pre-fabricated as 2D- storey-high panels, 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 enwalls) 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 from 2D wall panels and floor cassettes in light steel framing, but are assembled into load-bearing ‘boxes’ which are fitted outland 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.

New technologies are not only helping contractors and owners get their buildings faster and more economically but they also help reduce construction waste and produce high energy efficiency buildings which results in a long term benefit to projects. On the other hand, prefabrication for residential construction has been used in Thailand for only less than two decades, but it has been growing very fast in the past five years. Recently, there have been many new developers, and contractors who have switched from traditional construction to prefabrication to keep up with this new trend.

Open-sided or point-supported modules where vertical loads are transmitted through corner and intermediate posts. Point-supported systems require deeper edge beams than continuously supported modules. In both systems, résistance to horizontal loads can be provided by bracing or diaphragm action in the walls, but for buildings more than six storey's high, 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 optimize 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 Corus, in which the central service core and stairs were manufactured as modules and the open plan space was provided by pre-fabricated 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 comprises X-braced wall panels, floor cassettes and stacked bathroom modules.

Modular construction has so only been used for medium-rise cellular buildings. Greater flexibility in building height and internal planning can be achieved by the mixed use with primary steel structure. Various generic forms of construction may be employed by creating; A 'podium' structure of typically one or two storey's height in which the column spacing's 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. Composite construction may be used in which the podium level is designed to support the load from the modules above (typically six storey's). 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 minimize wall widths. 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. 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.

Open-building systems 'Open-building' technology is a general term used to describe systems, which provide flexibility in space planning and in inter-change of components. Many of the hybrid systems described above achieve some of the principles of 'open technology', but tube 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-Partner 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. Internal planning dimensions based on 600mm on plan(therefore 3 or 3.6 m are preferred internal modular widths)•floor-ceiling heights based on 2.4 m 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 optimized 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. Openings of unto 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. Open House AB is a Swedish system in which recessed modules are supported on a grid of 3.9 m by SHS columns. 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 reloadable.

Prefabrication plays an important role in the modern world construction of every building today; it refers to the making of parts in an offsite workshop or factory prior to the installation at the site. "The primary purpose of prefabrication is to produce building components in an efficient work environment with accesses to specialized skills and equipment in order to reduce cost and time expenditures on the site while enhancing quality and consistency" (Anderson and Anderson 2007). It is clear that most new construction will have to use more and more prefabrication. From primary structures to small architectural ornaments, prefabrication has become a major part of building construction.

The structural design of cold formed steel members is covered by BS5950-5 and in the future by Euro code 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 BS5268:Section6.1:1988, 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 3.1 4m square frames using Sections of 75mmdepth H 1.6mm thickness. Four self-piercing rivets were used attach connection. Plasterboard and sheathing boards were fixed with screws at 300mm centers, 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. The system was used in which the walls are not braced but rely on multiple inter-connections' between vertical Sections and 'top hat' horizontal members. The modules were later lined with plasterboard, but no other sheathing board was used. The module dimensions were 3.6mwide×7.5m long. A lateral load is applied to the head of the frame until a horizontal deflection of 4.8mm was measured corresponding to 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 were increased until failure occurred at large displacements. When compared to the results for the plasterboard-clad panel, the increase in design load is 95% for plywood, 57% for steel sheeting and 143% for cement particleboard. When the number of fixings was doubled, the test loads for serviceability increased by 11% to 30% for the three board mate-rails. Removal of support to an edger corner module causes the modules above to act as cantilevers. In this case, the tying forces can be estimated as follows for atypical 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/m, the horizontal tie forces at each corner are 16kN, and the vertical tie force is 25kN.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/m.

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 belong screws through the external insulation, which affects the stiffness of the wall tie system. The wall ties are bonded into the brick work, 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 Table3 and in all cases; serviceability is the controlling design condition. The attachment of brickwork with a single layer of 44 mm 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.

The basic stability of a pair of light steel modules was investigated in order to understand their in-plane and tensional behavior under unusual actions.. The thickness of the C-section is 1.6mm and the top hat section is 1.90 mm. Uniform load was applied using water containers. Vibration tests gave a natural frequency of over 12Hz for an imposed floor load of 0.5 kN/m and the damping ratio was 4 to 6.1%.The serviceability load tests on the floor gave a deflection of 8.8mm for apiary 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 23mm.The deflections for the second case when subject to a floor load of 2.3kN/m are presented. Removal of one corner support led to deflection of 19mm, which demonstrates the tensional 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 problematical, 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.

Conclusion:

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 behavior of light frames demonstrates considerable reserve in stability and structural integrity. Background tests have shown that a brick clad light steel frame can resist unfiltered shear forces of 4kN/mwall length, or 2.5kN/m for typical sheathing materials without considering the stiffening effect of brickwork. 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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