HIGH-TURNAROUND AND FLEXIBILITY IN DESIGN AND CONSTRUCTION OF MASS HOUSING

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ABSTRACT

There is a tremendous housing shortage in the world that can only be overcome by innovative designs and enlightened production management. This paper presents a method for fast erection of apartment housing units that have architectural flexibility, manufacturing flexibility, and erection flexibility. The paper describes innovative jointing methods for large panel erection and presents characteristics of an appropriate structural system to correspond to the mechanical jointing and quick erection needs. Erection speeds using this method are about ten times as fast as conventional methods. Details of erection requirements and equipment are given.

KEY WORDS

Flexibility, architecture, production, joint, precast, industrial housing, mass housing, prefabrication, structure, throughput, erection, manufacture, FMS, construction.

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INTRODUCTION

Quality housing is in short supply in the world. It is estimated that the world is short of 200 million dwelling units. To overcome this shortage within a reasonable time is not easy. Even considering that 100 years might be a reasonable enough time frame for this mammoth task, each dwelling unit will have to be delivered at the rate of 3.74 seconds during a normal 40-hour workweek. The non-delivery of adequate quality housing at a stage and time of the world's evolution when human population is expected to double within the next twenty years does not bode well for social and political well being. To address this challenge requires unconventional and innovative methods of housing construction. Only modern methods of housing manufacture and erection, utilizing principles such as computer integrated manufacturing (CIM), flexible manufacturing systems (FMS), and lean manufacturing coupled with innovative ideas can hope to erect houses at fast speed and high throughput.

The cam-nut and cam-screw method of joining large panels was explored for further development (Singh 1998, Singh and Yousefpour 1998). Tests revealed that this jointing method is adequate to carry all design loads. Structural testing indicated that structural adequacy could be assured if structural homogeneity could be assured. Finally, analysis was undertaken to determine how best to optimize construction speed within the technological constraints posed by large panel manufacture and erection for mass housing.

The prescribed cam-nut and cam-screw method furthers the principles and objectives of flexible and lean construction.

OBJECTIVES

The objectives are simply to design manufacturing and erection methods that are fast and cost-effective for mass housing. This further entails reduced waste, product innovation, and agile production.

RESEARCH METHODOLOGY

The following research methodology was followed:

1. Literature survey
2. Idea brainstorming
3. Selection of viable construction systems and technologies
4. Mechanical joint analysis and design
5. Structural analysis and design
6. Equipment and cost estimate
7. Erection and construction analysis

SCOPE

The scope of work is limited to establishing conceptual framework and conducting basic calculations for analysis, design, and cost for the erection of prefabricated large panels. The focus is primarily on obtaining high erection speeds on the job site, assuming that high large panel production will be available from the factory. Another limiting scope of this project is the use solely of concrete for housing units. The reason for using concrete is that concrete ingredients are less limited in their world supply than are steel ingredients. For mass housing, then, it is rationale to use a world resource that is more abundant.

The focus is also on the structural elements – the building shell. Items such as plumbing, electricity are excluded from this paper. The use of finishes in construction is minimized or eliminated through adequate finishing provided at the manufacturing shop. Emphasis is laid on explaining the application and furtherance of lean principles to the product.

FLEXIBILITY IN HOUSING

Whereas mass production is known to have economies of scale, there are certain bottlenecks when it comes to prefabricated housing. For mass housing to be an attractive option, it is essential to provide architectural flexibility wherein each new dwelling complex can be of different design, thereby avoiding architectural monotony. This is equivalent to having product variety (Bessant 1991, Barlow 1998). Under flexible manufacturing systems, we learn that production systems should have the following flexibilities in our stated project among other general manufacturing flexibilities (Browne 1984, Singh and Talavage 1991).

- process flexibility,
- mix flexibility,
- volume flexibility,
- routing flexibility, and
- machine flexibility

For our project, mix flexibility is related to architectural flexibility (e.g., a production plant is capable of manufacturing panels of different sizes and shapes on demand). Process flexibility is related to having multiple stations in a production plant that can perform identical and multiple operations for the purpose of quick turnaround. Volume flexibility relates to the capability of increasing and lowering production volume at short notice. Routing flexibility relates to the (automatic) ability to route a part (panel) to another station in case one or the other is busy. Finally, machine flexibility is related to machine reliability (Singh 1995).

Volume flexibility for mass housing is equally important on the job-site as it is in the factory for mass production. Job-site volume flexibility can be enhanced by innovative design that assists in quick erection. Thus, innovative design becomes very important to us in achieving our ends of high-speed mass housing. In addition, flexibility is closely related to lean and agile production, since many of their guiding principles and philosophies are identical. Importantly, the idea of flexibility to reduce setup time through repetitiveness is of particular application in this study.

LEAN PRODUCTION APPLIED TO CONSTRUCTION

It is notable that Slack (1997) has not defined the term “lean manufacturing” or “lean production” in his Encyclopedia of Manufacturing. This sends the signal – probably erroneous -- that “lean” is not a popular term among the industrial engineers and that other terms, such as group technology, flexible manufacturing, and computer integration are preferred. However, this is not to minimize the application of “lean”, since it is well known that the Toyota miracle owes much to the lean principles of Ohno, where he reduced waste and inventory at every opportunity in a scientific and organized manner (Delbridge 1998).

Essential production principles applied to lean construction include production parameters such as the following (Andery et al. 1998, Brandon 1995, Gowda, et al. 1998, Howell and Ballard 1998, Isatto and Formosa 1998, Singh and Ebeling 1995, Smook 1996, Warnecke and Steinhilper 1985):

- avoiding waste,
- standardization of repetitive work,
- creating a uniquely custom product,
- reduction of resource idleness,
- reduction of average waiting time,
- reduction of time between delivery of finished products,
- reduction of variability,
- decrease in time for processing parts to traverse the system,
- decrease in costs,
- reducing inventory, and
- increase in production rate.

It is frequently observed that above parameters are interrelated. Thus, it is important to tackle production at a holistic level where all above parameters are sought to be optimized (Warnecke and Steinhilper 1985, Singh and Skibniewski 1991).

The reduction of waiting time and resource idleness can be overcome by assuring that crews move in parallel for erection and grouting activities. Decrease in time for processing parts is assured by using the innovative methods developed herein and by assuring that crews are occupied through low resource idleness. Collectively, the above assure high production rate, and cost reduction occurs due to economies in mass construction.

INNOVATION FOR LEAN PRODUCTION

Continuous improvement is a hallmark to the way in which lean principles can be applied to any production process (see Andery et al. 1998). With improvement, waste in time, material, and money can be reduced, thereby contributing to efficient lean production. In addition, innovation contributes the same way as improvement. Indeed, innovation is essential for lean production (Martin and Formoso 1998, Malhedo 1998), since innovation has the characteristic of streamlining work flow—either through innovative design or through innovative task planning—it assists in the enhancement of lean principles.

Mass manufacture is known to assist with lean production. However, mass prefabrication has hitherto had the drawback of reduced product variety and reduced agility (Bessant 1991, Baker 1996, Burgess 1994). With architectural flexibility, the innovative production method developed in this paper is enhanced, thereby contributing to agile production.

INDUSTRIALIZED PRODUCTION AS CENTRAL THEME

Whereas the successes of industrialized housing is well known in Scandinavia, Finland in particular, and also in East Asia where Singapore is a prime example, it is desired to simplify site erection by reducing the number of parts that are required to fulfill a whole building.

Though buildings can be erected with columns, beams, slabs, and walls, the erection is simplified in our proposal through only the use of large panels.

LEAN CHARACTERISTICS OF PROPOSED PREFAB SYSTEM

The developed system using fully embedded cam-nut/cam-screw for joining concrete components allows immense repetition of work tasks for shell erection that can be undertaken using a single crew. Consequently, set-up time between activities is minimized and there is continuity to the process. In addition, after optimal speeds through learning are reached, those speeds can be sustained since there is no change of activity for construction of the mass housing. Again, management coordination is easier, since fewer subcontractors must be coordinated; there are fewer workers on site; and fewer number of different activities. Since the number of type of products required for shell erection is brought down to unity, there are fewer inventory categories.

In addition, the proposed system is a unique custom product. The design, too, is conducive to simplified workflow. Finally, the time to erect and cost to construct are significantly lower, which are the ultimate objectives in many a production system.

ARCHITECTURAL CHARACTERISTICS

The basic general architectural plan proposed consists of a 2,815 square foot floor plan, Figure 1. Various other basic general plans can also be proposed. The proposed unit has one three, one two, and two one-bedroom units, or modules. This basic layout can be configured to develop larger building units; thus, there is in-built architectural flexibility. The modules can be placed in different locations to meet various needs. These modules are standardized to allow for efficient manufacture, but still have flexibility in their layout, providing many possible floor plans. An axonometric for the basic configuration is given in Figure 2. Other configurations based on different combinations of the modules of Figures 1 and 2 are provided in Singh (1998).

A maximum story height of seven stories has been set, motivated primarily by the following factors:

- Building design and fire codes are less constrictive for buildings of seven stories or less.
- Site erection is simplified since tower cranes are not required.
- Construction costs rise significantly for buildings more than seven stories.

MECHANICAL CHARACTERISTICS OF CAM-NUT AND CAM-SCREW

Erection of the multi-story building using conventional methods is a time consuming task. Having the mechanical joint such as cam-nut/cam-screw for the assembly of walls, floors and columns can increase the speed and quality of construction compared to that of the conventional methods. The cost of erection of multi-story building using the cam-nut/cam-screw mechanical joint is much less than those using conventional methods. This is made possible due to ease of assembly of the components and correspondingly less use of labor.

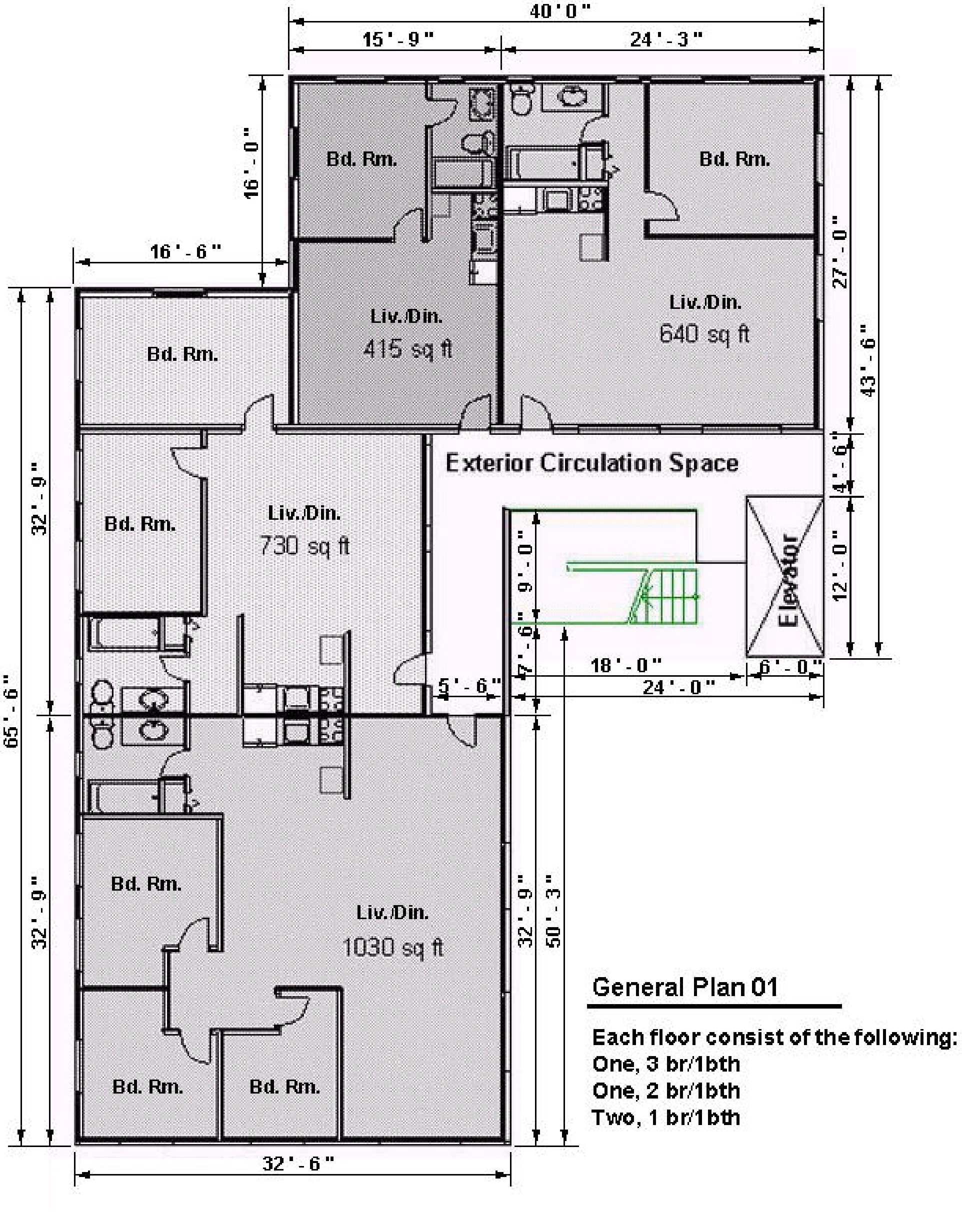

Figure 1: General Plan Layout

Before selecting the cam-nut/cam screw, several mechanical joint types such as bolt and nut, and welded joint were studied. The cam-nut/cam-screw was chosen due to better mechanical performance and faster assembly opportunities than other methods (Singh 1998).

Figures 3 and 4 show the schematic of cam-nut/cam-screw at loose and tightened positions. The cam-nut is embedded in the panel and the cam-screw is attached to the side of the adjoining panel. The joint was designed in such a way that as the two panels assemble, the cam-screw is inserted in the cavity inside the cam-nut; the cam-nut is then tightened

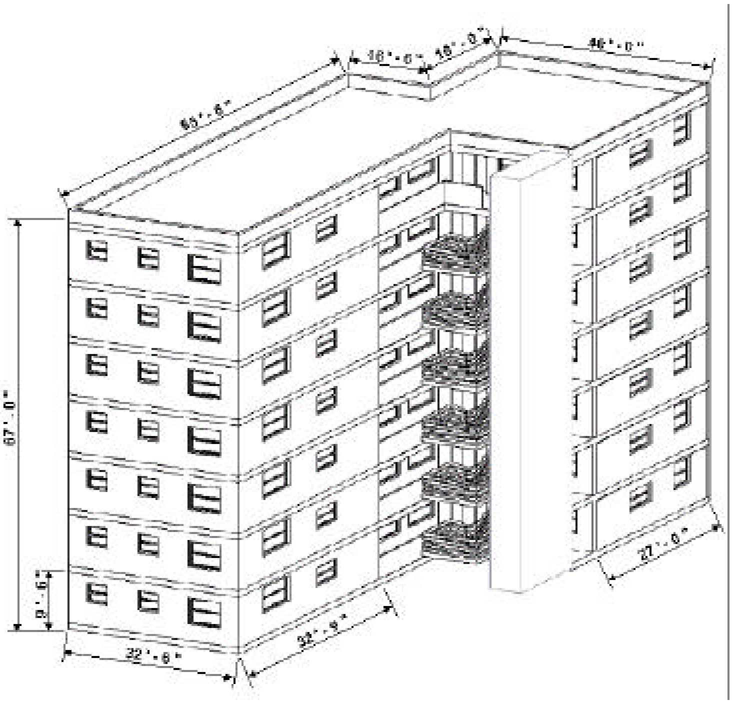

Figure 2: Axonometric View

using pneumatic or electrical power tools. The cavity inside the cam-nut is designed in a way that as the cam-nut is tightened, it *pulls* the cam-screw inside.

Since the panels have protruding screws, there are limitations to how the panels may be connected to each other. In addition, as it is expected that the architect will exercise his privilege of design flexibility, different types of panels, having varied loading conditions will be produced. Some of these panels may be having protruding screws on all sides, others on some sides only, and so on.

To accommodate this difficulty in joining panels when their protruding screws may come in the way, there are two essential erection scenarios (see Figures 5 and 6). The fundamental need to remedy this difficulty is to design “pockets” in the concrete that can receive the screws before the screws are slipped into nuts.

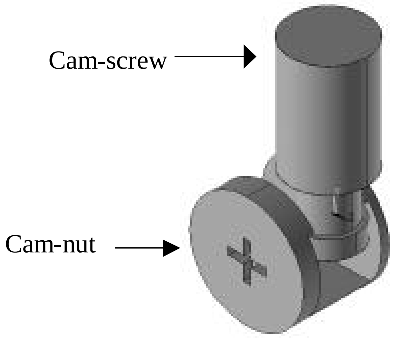

Figure 3: Joint at Loose Position

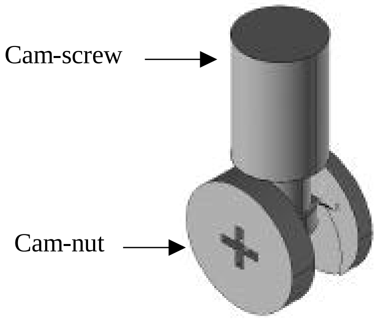

Figure 4: Joint at Tightened Position

STRUCTURAL CHARACTERISTICS

The building system is an all panel system. Buildings are made up of wall panels and floor panels, or slabs. The use of one structural element eliminates beams and columns. This greatly simplifies the design and manufacture process.

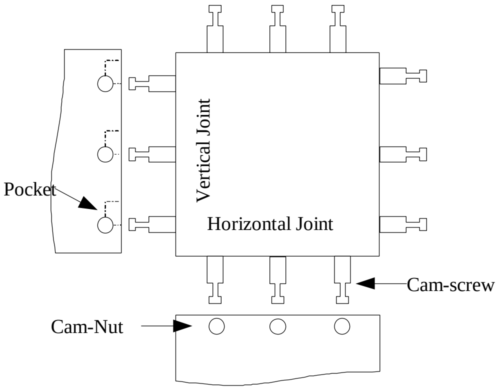

Figure 5: Panels with Protruding Cam-Screws at all Sides

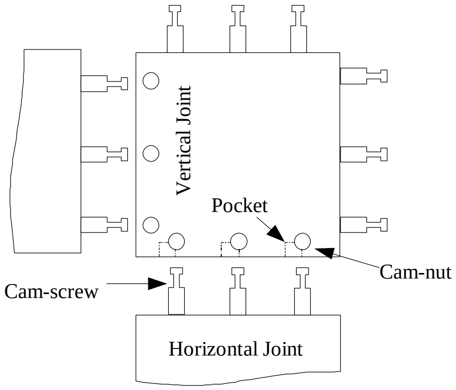

Figure 6: Panels with Cam-Nuts and Protruding Cam-Screws

The panels consist of a 6’ thick structural section, a 1.5” thick insulation section and a 2.5” thick facade section. The panels are joined with mechanical joints along the panel’s vertical and horizontal edges. The mechanical joints clamp the panels together with sufficient force to allow them to work together as a monolithic element. A gasket is placed between each panel and between the panels and the floor slabs to ensure a weather tight seal.

The floor system consists of solid precast floor slabs, designed as one-way slabs (Figure 7). These slabs lie on top of the wall panels and are held in place by passing the cam-screw of the lower wall panel through the floor slab and into the upper wall panel. This clamps the floor slab in place. Solid slabs were used because they can tolerate the expansion and cracking problems, whereas precast hollow core slabs would not be able to. The wall panels provide bearing for the gravity loads and the cam-screw provides bearing for lateral loads.

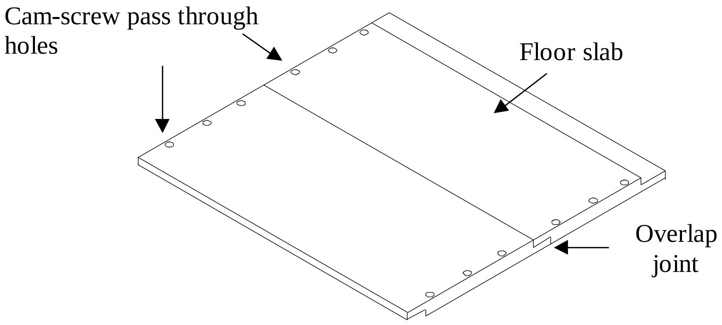

Figure 7: Floor Slab

Along the sides, the slabs overlap each other, allowing for a more continuous floor system. These joints are beveled to allow an epoxy grout to be placed between each slab to seal the joints and provide a flatter continuous floor.

ADEQUACY OF CAM-NUT/CAM-SCREW

The cam-nut/cam-screw was designed using finite element analysis (Singh and Yousefpour 1998). ANSYS finite element software was used. Design constraints for the mechanical joint were i) the size of the panel, ii) the amount of distribution of reinforcement, iii) the applied loads on the joint, and iv) the material of the joint.

The load was distributed on the three mechanical joints which are located at horizontal and vertical sides of the wall or floor-panels to connect one wall or floor-panel to adjacent wall-panels or columns. The loads applied on each joint located at the horizontal and vertical sides of panels at each level were taken from the ETABS output (Singh and Barnes 1999).

The joint can be made of AISI 1030 steel, a conventional material (Shigley and Mischke 1989). The results of finite element analysis (FEA) revealed that the maximum stress of the cam-nut and cam-screw for both vertical and horizontal joints was 12,341 psi and 8,865 psi, respectively. The stress factor of safety of 4.1 and 5.6, respectively, were achieved, for the yield strength of 50,000 psi. The cam-nut dimensions were 6”ϕ and 4.5” thk. The cam-screw dimensions were 4” at the end and 3” at the tip, by 9.4” in length. The same cam-nut as used in the horizontal and vertical joints can be used for a vertical joint between walls through a slab, since the loads are identical and cam-nut sizes are practically the same. The length of the cam-screw is 6” (thickness of the panel) longer than the cam-screw from the horizontal and vertical joints. The results of FEA revealed that the maximum stress of the cam-nut and cam-screw was 12,341 psi and 14,860 psi, respectively. The minimum stress factor of safety of 3.4 was achieved, for the yield strength of 50,000 psi. This high factor of safety is adequate for this critical mechanical structure.

STRUCTURAL ADEQUACY

In order for the panels and mechanical joints to be designed, the maximum loads that the panels and joints would be subjected to have to be determined. The building was analyzed for both earthquake and wind loads, with the larger of the two being used, following the Uniform Building Code, UBC. Computer structural analysis was performed using a special-purpose FEA program for building analysis, ETABS (Singh and Barnes 1999). Output from ETABS provided the necessary axial, shear, and moment loads on the panels. These loads were used to design the panels and the mechanical joints.

In order for the mechanical joints to work with the wall panels, they must be adequately anchored to the panels. To do this a system of steel plates and headed studs were designed. The cam-nuts and cam-screws are welded to a plate and long studs attached to the plate. These studs are embedded in the concrete during the casting of the wall panels.

JOINTING NEEDS

The cam-nut/cam-screw can be fastened using a pneumatic or electrical power tool. The amount of torque required to rotate the cam-screw about 190 degrees in order to sit into a tightened “click position” can be measured experimentally. However, commercially available power tools are available with large sized screw bits to execute the work. A crew of two workers is required to move in parallel alongside the panel erection to tighten the nuts.

ERECTION SEQUENCING

The erection sequence of the panels is crucial in the construction process. Although there is great flexibility in the erection process, there are still critical considerations to be followed. The biggest concern is the location of the pockets in the panels to accommodate protruding screws. The pockets along the horizontal sides (Figures 5 and 6), are on either side of the cam-nuts; thus, the panels can only slide in one direction. This is one of the controlling factors in the erection sequence. Great care must be made in ensuring the proper sequence of panel assembly is followed.

It is best to start construction assembly at one of the outside corners. This provides for the stiffest structure as the building is erected. No one outside corner is critical, so any outside corner may be picked. This allows for flexibility in the erection sequence. To accommodate the pocket system, work out from one corner in both directions, bringing the subsequent panels up against the installed one. As each panel is placed, the cam-nuts can be tightened.

The slabs are installed after the panels are in place. The slabs are placed on top of the panels and the cam-screws pass through the slab. Slabs may be placed before all the panels have been erected. The only factor controlling this is to ensure that all the panels that are below the slabs are in place.

The entire erection sequence will be fastest if following a predetermined sequence. This is not always possible though. Many circumstances may be unforeseen. If all the panels do not arrive at the site, or some become damaged during transit, erection does not have to stop. Although there are a few critical panels, erection can start at any outside corner with whatever panels arrive first. If during the construction the next needed panel is damaged or not available, erection may start at a different area. Since all the panels do not have to be erected for the slabs to be placed, the erection sequence is not entirely dependent on all the panels being erected first. This affords considerable erection flexibility.

Figure 8 shows the layout of the structural panels. There are 33 wall panels numbered one through 33 and 13 slabs labeled A through M. After panels 1 through 12 have been erected, for instance, slabs A, B, and C can be placed. This allows yet more flexibility in the erection sequence. Slabs can be erected on the finished panels while any missing panels are being replaced. This prevents any waiting time and resource idleness in the construction process.

Table 1 shows four options for erecting the panels; all options start from the corner of panels 2 and 3, Figure 8. Options 1 and 2 simply start from one corner and move counter-clockwise to complete the erection sequence, with slight differences between them.

Table 1: Erection Sequence Alternatives

OPTION	PANEL NUMBER																																
Option 1	3	2	1	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	23	22	24	25	26	27	28	29	30	31	32	33
Option 2	2	3	4	1	5	6	7	8	9	10	11	12	14	13	15	16	17	33	23	18	21	19	20	22	24	25	26	27	28	29	30	31	32
Option 3	3	2	4	1	5	6	7	31	32	30	29	28	27	26	25	24	22	8	9	10	11	12	13	14	15	16	17	18	19	20	21	23	33
Option 4	3	2	1	4	5	6	7	22	24	25	26	27	28	29	30	31	32	8	9	10	11	12	13	14	15	16	17	18	19	20	21	23	33

Options 3 and 4 start at the same corner but stop at panel 7. Option 3 starts up again with panel 31 proceeding through panel 22, then moving to panel 8 to finish the sequence. Option 4 switches to panel 22 proceeding through panel 32, then moving to panel 8 to finish the sequence. This shows how flexible the erection sequence can be.

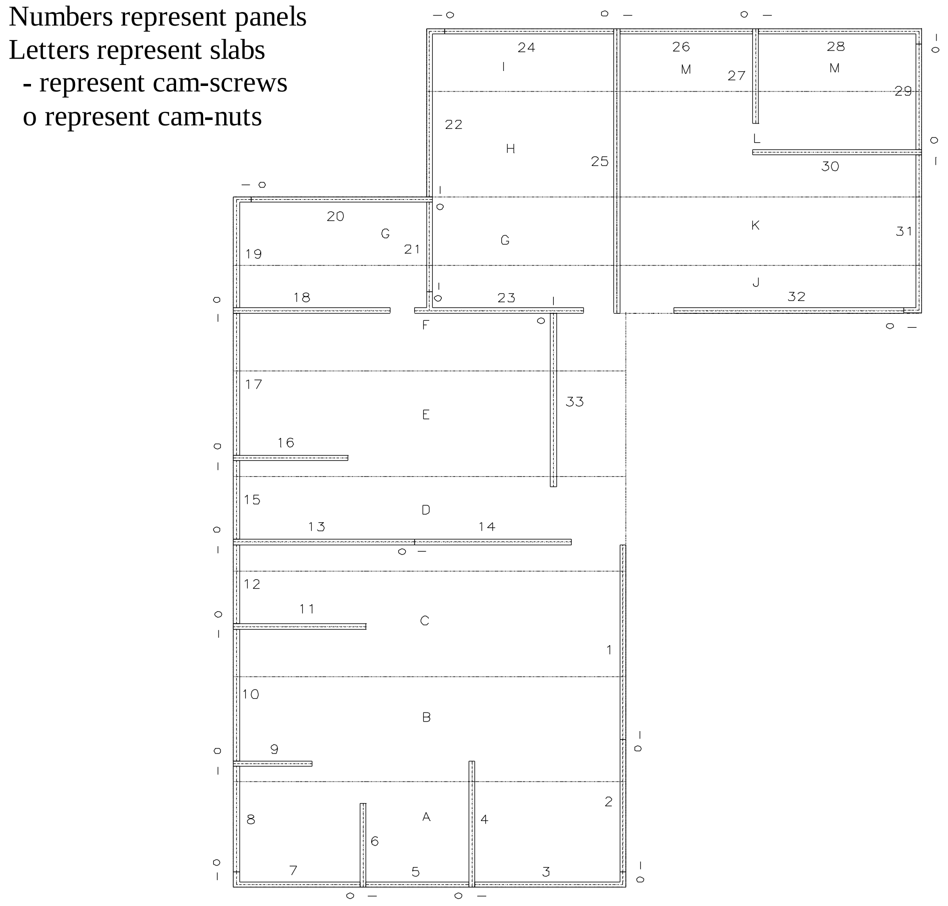

Figure 8: Panel and Slab Layout

TRANSPORTATION OF PANELS

The size of the panels and slabs are limited by the transportation used to deliver them. By limiting the lengths of the panels and slabs to under 40 feet and the widths to under 10 feet, standard trailers can be used. Larger size panels and slabs may be used but special permitting and routing to the construction site may be needed, adding to the cost of construction. Coordinating delivery so that the panels arrive as they are erected adds to efficiency, but because of the flexibility of this system this is not critical.

POCKET GROUTING

All pockets must be grouted after installation. For the general plan, there are 113 pockets per floor and 188 cam-nuts per floor. The pockets are grouted by pressure injecting grout through small access holes. The grout gun injects the grout through the hole and the hole is plugged with a plastic slug. The grouting can be done as the panels are installed. The grout would be non-shrinking and pumped or pressure injected. Using a pneumatic, shoulder carried grout pump, a crew of four can grout approximately five floors per day (Means 1997).

SLAB JOINT GROUTING

The slabs overlap one another along their long axis. This joint is beveled, has exposed reinforcing, and is filled with epoxy-grout. The exposed reinforcing along with the epoxy-grout ties the slabs together, providing a stiff diaphragm. The epoxy grouting also smoothes the transition between the slabs. This system eliminates the need for cast in place concrete over the entire slab area. Using a grout pump, a crew four can finish approximately five floors per day (Means 1997).

EVALUATION OF TECHNOLOGY

Various techniques for evaluating construction and building technologies using manufacturing principles have been provided in literature through mathematical precepts (Singh and Ebeling 1994, Martin and Formoso 1998). An evaluation of the proposed system can be made after a complete process simulation is executed (for instance, refer Singh and Talavage 1991, Gowda et al. 1998).

TIME AND COST ESTIMATES FOR LARGE PANEL ERECTION

Erection costs are dramatically reduced since construction durations are reduced by nearly ten times. Prefabrication is currently more economic than conventional construction for residential apartment complexes in many world locations, such as Finland and Singapore, for example. This means that with industrial conversion and mass consumption, the economies of industrialized building can be well exploited.

Four panels can be erected per hour with crane and four-man crew. Therefore, it would take 1.5 days to erect the 46 panels for the entire floor. (These results are based on estimates of prefab construction from site data, expanded application of learning curves, and Means Manual.) In contrast, conventional construction can take from 10 to 20 days to finish a floor on site, which is 670% to 1330% longer than in the proposed prefab construction.

A 7-story building will take approximately 11 days to finish; traditional construction would take 105 days. Extending this arithmetic further, the panel system can build nine full buildings in the amount of time it takes traditional construction to build one building. Working 250 days a year, one crew can erect 22 such buildings having 616 housing units; traditional construction would have constructed only 2 buildings or 56 housing units. With 100 crews, 61,600 housing units can be built in one year.

Therefore, the construction time is approximately ten times as fast as conventional construction. Conventional construction can take from10 to 20 days to cast a complete floor.

Correspondingly, erection costs are dramatically reduced since construction durations are reduced by an average of ten times.

With the flexibility of the system, costs can be further reduced. In traditional construction each sequence of construction, such as formwork or pouring concrete, stops or dramatically slows the work of others. Walls for each story must wait until the entire slab of that story is complete. With the panel system, walls of the next story can be erected before all the slabs of current story are complete. This means that there is less conflict in scheduling the work crew. With this system in particular, the pocket grouting crew does not have to wait for all the panels to be in place for one floor to start grouting. Once a few panels are in place, they can begin grouting.

Pocket grouting requires a shoulder carried grouting gun. The pockets to be filled are 7”x7”x4” or 0.111CF. There are 113 pockets per floor with this typical building, giving 12.45 CF of grouting per floor. Taking the assistance of Means (1997), we estimate that one grouting labor, one equipment operator and one helper can grout approximately 70 CF per day. Thus, they can do five floors per day. Floor grouting for the longitudinal construction joints of slabs can be done at similar speeds.

Both nut tightening and pocket grouting are faster work activities per panel in contrast to panel erection. Nut tightening involves only the mechanical tightening of the nut, which can be done by a two-man crew.

CONCLUSIONS

The following major conclusions are derived:

- The cam-nut/cam-screw mechanical jointing method is mechanically and structurally feasible.
- Architectural flexibility, i.e., product variety, is ensured.
- The cam-nut/cam-screw joint can increase the speed and quality of construction.
- Production agility is increased.
- The success of this system will depend on the production of large panels under factory conditions, produced at high speed using lean construction, flexible manufacturing, and improved production management principles.

REFERENCES

Andery, P., Carvalho, A. N., and Helman, H. (1998). “Looking for What Could be Wrong: An Approach to Lean Thinking.” *Proc. 6th Ann. Conf. Intl. Group Lean Constr.*, Guaruja, Brazil, 13-15 Aug.

ANSYS User’s Manual (1994). Revision 5.2, ANSYS, Inc. Houston, PA.

Baker, J. (1998). “Less Lean but Considerably more Agile,” *Proc. 6th Ann. Conf. Intl. Group Lean Constr.*, Guaruja, Brazil, 13-15 Aug.

Barlow, J. (1998). “From Craft Production to Mass Customisation? Customer-Focused Approaches to Housebuilding,” *Proc. 6th Ann. Conf. Intl. Group Lean Constr.*, Guaruja, Brazil, 13-15 Aug.

Bessant, J. (1991). *Managing Advanced Manufacturing Technology.* NCC Blackwell Ltd., Manchester, Great Britain.

Brandon, J. (1995). *Managing Change in Manufacturing Systems*. Product. Pub., Olney, UK.

Browne, J. (1984). “Classification of Flexible Manufacturing Systems,” *FMS Magazine,* IFS Publications, April.

Burgess, T. (1994). "Making the Leap to Agility: Defining and Achieving Agile Manufacturing through Business Process Redesign and Business Network Redesign," *Intl. J. Oper. and Prod. Mgmt*, 14(11).

Delbridge, R. (1998). *Life on the Line in Contemporary Manufacturing*. Oxford Univ. Press.

Gowda, R., Singh, A., and Connolly M. (1998). "Holistic Enhancement of the Production Analysis of Bituminous Paving Operations," *Constr. Mgmt. and Econ.*, 16(4), 417-432.

Howell, G. and Ballard, G. (1998). "Implementing Lean Construction: Understanding and Action," *Proc. 6th Ann. Conf. Intl. Group Lean Constr.*, Guaruja, Brazil, 13-15 Aug.

Isatto, E. L. and Formoso, C. T. (1998). "Design and Production Interface in Lean Production: A Performance Improvement Criteria Proposition," *Proc. 6th Ann. Conf. Intl. Group Lean Constr.*, Guaruja, Brazil, 13-15 Aug.

Martin, A. P. S. and Formoso, C. T. (1998). "Evaluating Building Systems Based on Production Process Management and Lean Construction Concepts," *Proc. 6th Ann. Conf. Intl. Group Lean Constr.*, Guaruja, Brazil, 13-15 Aug.

"Means" (1997). *Building Construction Cost Data*, 55th Ed., R.S. Means Co., Kingston, MA.

Melhado, S. (1998). "Designing for Lean Construction," *Proc. 6th Ann. Conf. Intl. Group Lean Constr.*, Guaruja, Brazil, 13-15 Aug.

Shigley, J. E. and Mischke, C. R. (1989). *Mechanical Engineering Design*, McGraw-Hill, Inc., 758-761.

Singh, A. (1994). "An Overview of the Philosophy and Concepts of Flexible Construction Systems," *American Prof. Constructor*, Amer. Instit. of Constr., 18(3), 25-35, Sept.

Singh, A. (1998). "Architectural Flexibility, Building Configurations, and Energy Consumption in Modular Precast Buildings for Mass Housing using Concrete Panels," Tech. Report, *Oak Ridge Natl. Laboratory, U.S. Dept. of Energy*, Dec.

Singh, A. and Barnes R. (1999). "Structural Analysis and Design of Precast Concrete Panels Joined by Cam Nuts and Cam Screws," Tech. Report, *Oak Ridge Natl. Laboratory, U.S. Dept. of Energy*, Jan.

Singh, A. and Ebeling, K. (1994). "Construction Process Simulation Using Standardized Configuration and Model," *Proj. Mgmt. J.*, PMI, Vol. XXV(4), 45-54, Dec.

Singh, A. and Skibniewski, M.J. (1991). "Development of Flexible Production Systems for Strip Mining," *J. Mining Sci. and Tech.*, Elsevier, 13(1) 75-88, July.

Singh, A. and Talavage, J.J. (1991). "Methodology for Design of Efficient Flexible Construction Systems," *Engrg. Mgmt. J.*, American Society for Engineering Management, 3(3), 27-42, Sep.

Singh, A. and Yousefpour, A. (1998). "Finite Element Analysis of Cam Nut and Cam Screw for Precast Concrete Panels." Tech. Rept., *Oak Ridge Natl. Lab., U.S. Dept. of Energy*.

Slack, N. (ed.)(1997). *The Blackwell Encyclopedic Dictionary of Operations Management.* Blackwell Publishers, Cambridge, Mass.

Smook, R., Melles, B., and Welling, D. (1996). "Coordinating the Supply Chain – Diffusing Lean Production in Construction," *Proc. 4th Ann. Conf. Intl. Group Lean Constr.*, Birmingham, England.

Warnecke, H. J. and Steinhilper, R. "Flexible Manufacturing Systems and Cells," in Warnecke, H. and Steinhilper, R. (eds.), *Flexible Manufacturing Systems*, IFS Pubs., Springer-Verlag, UK.