Whole House Design
Through the Application of Multi-functional Precast Panels

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Abstract

Multi-functional precast panels (MPP's) incorporate structure, interior and exterior finishes, insulation, and energy systems into a single manufactured building panel. Application of MPP systems can improve the disaster resistance, durability, energy efficiency, and life cycle affordability of housing. Introduction of this technology requires a research and education program that addresses the development of MPP manufacturing systems that exhibit both careful coordination of design details and high quality fabrication; development of structural and utility connections and assembly processes that control cost without comprising performance; development of integrated energy system concepts; and more comprehensive models of both first cost and cost of ownership.

Keywords: Whole house, precast, concrete, insulation, energy

Introduction

Multi-functional precast panels (MPP's) consist of precast concrete sandwich panels with embedded insulation and energy systems. The MPP concept offers improvements in several of the target areas identified by the Partnership for Advancing Technology in Housing (PATH) including [PATH, 2002]:

?? Disaster resistance and safety
?? Durability
?? Energy efficiency and environmental impact
?? Affordability

With MPP technology, homebuilding can be accomplished with a *whole house* concept in which structure, finishes, insulation, and energy systems are integrated into pre-manufactured building panels. In contrast, traditional wood frame construction techniques rely on the field assembly of discrete elements by individual trades that may not share a common purpose. Traditional practices often result in a complex on-site management task, ample opportunities for failure, and less than optimal performance of the overall system.

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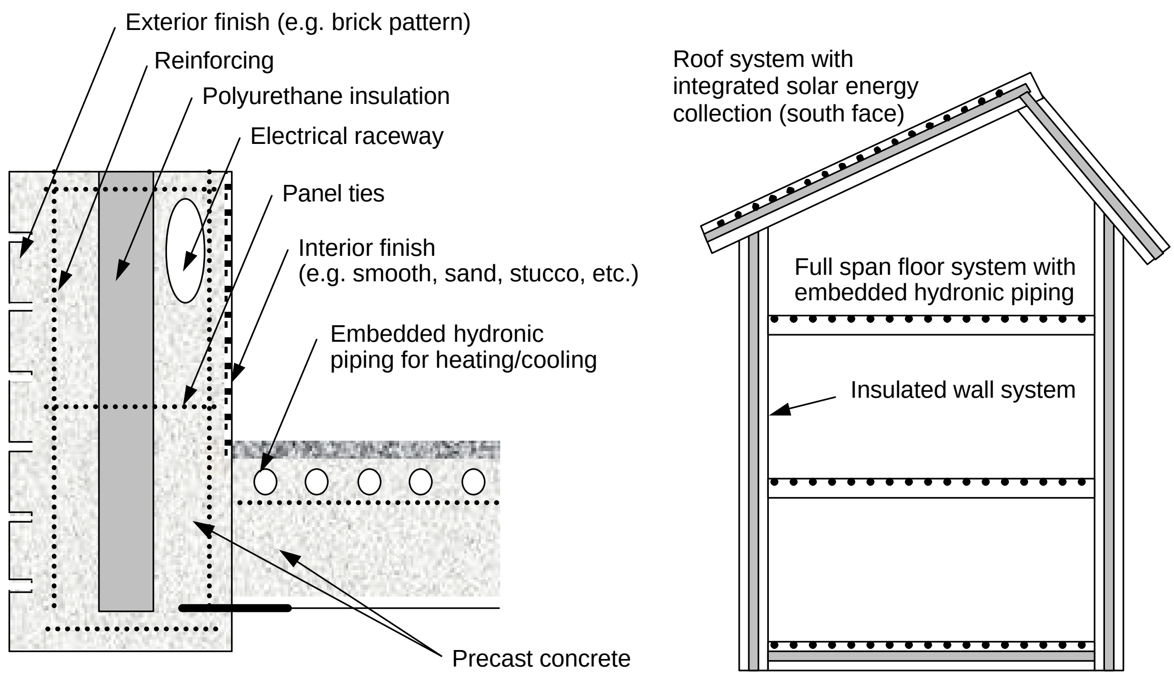
The multi-functional precast panel system is illustrated in Figure 1. Precast panels with reinforcing enclose high performance polyurethane insulation. Hydronic distribution systems or high velocity air distribution systems are cast into the panels to provide efficient heating and cooling. The piping and support frames for energy collection systems, such as solar thermal or solar PV, can also be cast into the panels. Both the interior and exterior finishes for the house are formed during the casting process. The variety of finishes that homeowners have come to expect are provided through careful control of mixture composition and curing and through the use of negative molds, dyes, and additives. Panels are designed to facilitate quick assembly in the field, thus reducing construction time and labor costs. These characteristics together with the inherent properties of concrete yield a building system with an extremely long life that is resistant to natural disasters, virtually maintenance-free, extremely comfortable, highly energy efficient, and that has an initial cost that is comparable to conventional homes.



(a) Panel details **(b) MPP house construction**

Figure 1: Multi-functional precast panels for residential construction

Current State of the Art

Despite the benefits and level of integration offered by the MPP concept, it is not currently employed for homebuilding because:

- ?? Conceptual plans do not exist for manufacturing systems that can achieve the level of finish and system integration necessary for complete panelized systems;

?? Techniques for on-site assembly, including interconnection of energy systems and maintenance of finish continuity do not exist;
?? Concepts do not exist for energy systems that take full advantage of the insulating properties, thermal capacitance, and opportunities for energy collection offered by the MPP system; and
?? Detailed knowledge of the effect of MPP construction on the cost of construction and ownership is not available.

Presently, the use of concrete in the US housing industry is relatively limited. Due to a variety of cultural and resource considerations, wood frame construction dominates residential building in this country. Various forms of concrete construction including tilt slab, cast-in-place, and precast construction are much more common in other US building sectors and in the residential sectors of other countries. For example, tilt slab construction is frequently used in warehouse and commercial construction throughout the US. Tilt slab is commonly implemented as a single layer concrete slab with an exterior finish and interior insulation applied after erection. Multi-layer composite construction with insulation in the middle is also in use on a growing number of tilt slab projects. Cast-in-place concrete construction is in widespread use for commercial buildings in the US but residential use is limited primarily to foundation wall construction. In contrast, residential cast-in-place construction is quite prevalent in Latin America, Europe, Asia, and Africa.

Precast construction is used in the US primarily for large and medium scale commercial buildings where it is often applied in architectural precast elements and in precast curtain walls. In residential construction, it is increasingly used for foundation walls (e.g. products by Superior Walls, Pulte Homes, and others). In Europe where precast concrete quality is at the highest level, commercial applications are much more common, however, residential applications are still rare.

Concrete construction is not widely used in residential applications because of a variety of potential problems including shrinkage cracking, scalling, spalling, popouts, blisters, and water dissipation causing steel corrosion [Adams, 1983]. Most of these problems relate to mix design, curing and finishing and can be controlled given the proper quality assurance program [NAHB, 1999]. However, residential site conditions and practices often do not allow for the needed quality assurance. The use of more complex finishing techniques, interstitial insulation and utility systems, and other features only magnifies the challenges of on-site casting.

Precasting of concrete building elements in a controlled manufacturing environment can eliminate the vast majority of problems associated with concrete production, casting, finishing and curing. This results in better quality concrete for precast elements when compared to cast in place concrete. Moreover, in a manufacturing environment, the precast assembly can be built to incorporate finished interior and exterior surfaces, insulation and energy collection and distribution systems. Thus, the development of precast systems for residential applications can help to bring the advantages of disaster resistance, durability, energy efficiency, and long-term affordability associated with concrete construction to the housing market.

Research at Virginia Tech funded by NSF and undertaken in collaboration with our industrial partners seeks to:

- Refine the MPP concept to address specific design and construction issues including methods of reinforcement, insulating systems, interconnections, etc.;
- Develop and test concepts for the manufacturing and assembly of MPPs;
- Develop and test concepts for energy use and collection;
- Assess the cost of ownership for houses constructed using MPP techniques.

Other organizations currently exploring MPP design and construction issues include the Precast/Prestressed Concrete Institute (PCI) which publishes cases studies and design guidelines for the application of precast concrete panel systems many of which specifically address residential construction [PCI, 2003]. The Portland Cement Association also supports the development of concrete construction [PCA, 2003a] and maintains a website dedicated specifically to the use of concrete in residential construction [PCA, 2003b]. The state-of-the-art for precast concrete sandwich panels has been reviewed by Einea et al. [1991] and by Seeber [1997]. While these reviews focus primarily on commercial and industrial scale projects and the possibility of embedded energy systems is not addressed, many of the other issues (wythe connections, panel connections, insulation, composite vs. non-composite panels, etc.) related to residential MPP construction are discussed. Seeber [1997] identifies the importance of evaluating thermal performance based on detailed wall descriptions and mentions the beneficial effects of the thermal mass. The author references simplified approaches to evaluate the overall thermal resistance [ASHRAE, 1985] and to optimize the benefit of the thermal mass [Eley Associates, 1994]. However, other research suggests that more powerful techniques are required to adequately model the influence of wall details including 3-dimensional thermal bridging effects and distribution of thermal mass. Kosny and Kossecka [2002] have shown that the thermal bridging effects can be much more significant with concrete construction than with wood frame construction and that simple 1-dimensional parallel path models due not adequately quantify these effects. In addition, Kossecka and Kosny [2002] have also shown that building mass is most beneficial when located within the building insulation system. The systems analyzed by Kosny and Kossecka [2002] included insulating concrete form walls (ICF) and various configurations of sandwich panels. As part of our work at Virginia Tech, we are using techniques developed by Kossecka [1998] to analyze alternate precast panel configurations and interconnection designs with the goal of minimizing the impact of thermal bridging and maximizing the benefits provided by thermal mass. Results from an on-line analysis tool maintained by the Oak Ridge National Laboratory, [ORNL, 2003] suggest that the annual energy savings achieved with properly designed concrete wall systems can exceed 17 % relative to conventional wood frame walls with comparable R-values. Integration of heating and cooling systems into the precast elements can further reduce energy use by locating the heating and cooling distribution system within the insulating envelope rather than in attics or crawl spaces where heat transfer and air leakage can increase energy use by 10-25%.

The savings from reduced energy use as well as reduced maintenance and insurance cost can offset marginally higher first costs associated with MPP construction. An economic evaluation of precast concrete for residential construction was included in a competitive assessment by the USDA Forest Service [Spelter, 1996], which found that a precast exterior wall system for a 2,000 ft^2 home cost roughly $1,200 more than comparable wood frame systems. The authors assumed an annual cost savings of $300 for concrete construction based on a location in a high wind zone (insurance savings of $150 plus $150 savings for heating/cooling costs) and found a payback period of roughly 5 years for the additional investment in a concrete wall system. Cost models that incorporate more detail and that are validated over a wider range of scenarios are needed to establish the economic merit of the MPP system.

Future Research Directions

The introduction of multi-functional precast panel construction in the US housing industry will require the development of new manufacturing approaches for precast panels, new field assembly techniques, and an entirely new approach to home energy systems. Future research that will support the introduction of this important new housing technology should address:

- Development and evaluation of structural connections that can be assembled rapidly and inexpensively in the field; that are robust and readily verifiable; that can withstand seismic loads; and that minimize the effects of thermal bridging.
- Development of inexpensive, durable surface treatments that yield precast roof assemblies that are impermeable to water without the need for additional roofing materials.
- Development of systems for utilities (electricity, hydronic heating, plumbing, etc.) that are economical; code compliant; amenable to pre-fabrication of panels; and capable of being field modified.
- Development of industrialization concepts for the precast industry that facilitate the translation of residential designs into precast assembly details – these concepts must address information management, process planning, and manufacturing processes.
- Development of wall system details that provide high effective R-values (after accounting for bridging); minimize infiltration; and maximize the amount of thermal mass located inside the building envelope.
- Development of energy systems that can be embedded within the precast assembly – these systems may include hydronic heating/cooling as well as high velocity air systems.
- Development of sufficient cost data and estimating models so that residential precast projects can be reliably estimated and builder financial risk reduced.
- Development and dissemination of economic models for the cost of ownership that reflect not only first cost but also energy, maintenance, and insurance costs for MPP construction relative to conventional construction.
- Development of techniques for accurately assessing the environmental life cycle cost of MPP construction and identification of approaches for minimizing the environmental impact.
- Development of construction standards, codes, and field inspection protocols for small scale precast projects that may lack the level of engineering supervision common to larger commercial projects.

These research efforts must be undertaken in conjunction with an education and industry outreach program so that architects, engineers, code officials, and builders are aware of the capabilities of the MPP system.

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