Use of Innovative Connectors and New Combinations of Materials To Address Weaknesses in Light-Frame Construction

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Abstract

As building codes continue to mature, several ideas that are currently being discussed will become "codified" in the future. Some of the more important issues are the effects of finish materials, reliability of the structure, and "toughness" of the structure will affect the design objectives and methods in the near future. This manuscript outlines why several of these issues should be placed in the front of the research efforts to allow effective and accurate adoption of new methods of design and construction. The different approaches of the more typical prescriptive type building codes versus the performance code implementations are briefly discussed with the ramifications on research requirements highlighted. The improved performance goal is linked to both the connectivity and materials used in the building.

Keywords: Dissimilar Materials, Structural Systems, Non-Structural Elements, Connectivity, Design Objectives, Connectivity, Durability

Introduction

Historically, building codes, and therefore design specifications, have focused on a level of performance designated as "life-safety". While many people believe that this level of performance is provided if the building does not collapse, it is a bit higher than that. Life-safety implies that a means of egress is maintained and that secondary issues such as fire are prevented. Residential construction that typically consists of light-frame wood construction (95+%) has historically met this level of performance without a problem. Problems began to arise as the size of the buildings increased, the size of individual rooms increased, and the general building envelope was opened up to provide views and garages. While light-frame construction in the United States has developed from a concept of resisting gravity loads (snow and occupancy loads), historic construction also performed reasonable well when subjected to lateral loads (wind and seismic) due to the high redundancy inherent in the traditional forms. However, as the building architectural features have changed, the concept of lateral loading was all but ignored and the requirement of a functional load path was neglected. The result has been tremendous losses in high wind and seismic events.

When the failures are investigated, there are two issues that come to the forefront that cause the failures. In high wind events (hurricanes and tornadoes) the issue of connectivity and load path

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raises its head. Residential construction has not typically been highly engineered, and has been developed and codified following rules of thumb and experience. Many of the current practices can not be rationalized using design methods based on physics and engineering mechanics, and the political will to develop a fully rationalized set of prescriptive requirements currently does not exist.

Currently, there are four possible building codes that can regulate new residential construction in the United States: 1) the *International Residential Code* (ICC 2003), 2) the *International Building Code* (ICC 2003), 3) the *International Performance Based Code* (ICC 2003), and 4) the *NFPA 5000 Building Code* (NFPA 2002). All of these building codes address residential construction, but not in the same way. If new developments and technologies are to be introduced into the residential building construction process, they must consider how these different regulatory codes are developed and used.

The *International Residential Code* (IRC) is by far the most used code in residential construction. It was developed to replace the *CABO One- and Two-Family Dwelling Code* (ICBO, 1997) as is a prescriptive method to build a house. Not all of the requirements are based on engineering principals and this has led to some controversy. However, new structural performance provisions that are added to the code are being required to meet the load requirements and be based on resistances founded in engineering principals. Therefore, new technologies introduced into this code will be required to show a rational design process behind the prescriptive requirements provided.

The *International Building Code* (IBC) and *NFPA 5000 Building Code* are both more or less prescriptive codes, in that they provide a set of prescriptive performance requirements that must be met using a design process that is based in engineering principals. Any technologies introduced into these two codes will have to show how it will meet the performance requirements of the code using engineering principals.

Finally, the *International Performance Based Code* is rarely used for residential construction, but has a potential for wider acceptance and use in the future. This code lays out a process where the owner, designers, building official, and contractors develop a list of performance criteria for the building, and then the designers and contractors can use a wide scope of methods to meet the agreed upon performance. In many cases this code will rely much more heavily on reliability methods for setting the performance standards, and many of the deterministic methods used to develop design values will not be adequate.

Recently, insurance companies and owner associations have been proposing requirements that will move the minimum performance requirement of the building codes to higher levels of performance. Losses associated with events such as the Loma Prieta and North Ridge Earthquakes, and Hurricanes Andrew and Iniki have causes significant economic setbacks. In addition, since buying a house is the largest investment that the average American makes in their lifetime, and has served as one of the most effective mechanisms for building wealth in the United States, there is some pressure for the building codes to begin to regulate performance to provide damage control. These levels of performance have been termed Operational, Repairable, and Habitable. All of these terms imply levels of performance well above life-safety, and all three pertain to the performance of the structural system while accounting for the effect and performance of finish materials.

Therefore, to improve the performance of housing through technological improvements requires different levels of research, depending upon the level and rate of acceptance desired. However, in general, either the number of replications or the amount of analysis and simulation will increase as the higher levels of performance are targeted. In addition, the future research will have to account for more than the designated structural system and include the performance of finish materials.

The Problem

The principle problems currently hindering the performance of light-frame construction with respect to the extreme loadings associated with natural hazards (wind and seismic) are 1) lack of effective connectivity within the structure, 2) incompatibility of materials used, and 3) lack of durability (in view of the reduced effectiveness for detailing for moisture control.) The lack of effective connectivity within the structure causes the structure to be weak when lateral loads from wind and seismic events are imposed upon the building. Platform construction methods have improved the construction process to make it easier to frame the building and results in a more uniform shrinkage process for the building. However, this process of construction also results in inherent weak connections between the walls and the floors. Typically, this connection is made with smooth shank nails that have either zero capacity in withdrawal (end grain nails in the between the studs and the plates) or minimal resistance to withdrawal (plates to floor framing.) There are commercial connectors available to improve this connection, but they are significantly more expensive than the nails, which is a hindrance to their use. New connectivity technologies, if developed from a system standpoint, would significantly increase the strength and stiffness of residential buildings, reducing damage and providing wider opportunities for architectural innovation to the building form.

The incompatibility of the materials used in construction is a problem that is becoming more and more prevalent. Various technologies are developed in a vacuum. The performance of the product is tested only on the product and not on the system during development and experimental work to gain acceptance from evaluation services. However, this process often results in products that are well suited to accomplish the task envisioned, but the law of unintentional consequences produces a product that adversely affects the performance of the building system as a whole. Examples include some building wraps, External Insulation Finish Systems, adhesives, and others.) Another incompatibility that results from many of the current materials is that the performance parameters (stiffness, strength, etc.) are not compatible with the structural system or the finish system, which results in one material adversely affecting the others. Gypsum, stucco, and brick veneer attached to flexible structural systems are prime examples that cause the products to sustain substantial damage from a renovation and repair standpoint when the structural system has received little or no damage that requires repair. Development of material technologies that provide structural compatibility to the building system would reduce damage experienced during natural hazard events as well as simplifying the design process by making the real response of the structure follow the designer's conceptualization more closely.

The one most important variable affecting the durability of residential construction is the control of moisture. Architectural forces have eliminated many of the details historically used to control moisture and direct water away from the structure (elimination of overhangs, minimization of roof complexity, raised first floor platforms, etc.). To aggravate the problem, water sprinklers and other uses of water close to the building have resulted in the lower portions of the first floor wall system experiencing decay at rates not precedented in modern times. To compensate for these changes, new durable materials need to be developed. These materials need to be decay resistant in the presence of moisture, provide structural resistances that are at least as good as wood, and possibly integrate several of the elements currently used into a single product. This is one technological area that could incorporate several functions into a single product, reduce the skills required to install, improve the quality of construction and reduce the time of construction.

New Connectors

Connectivity and rational load paths for lateral loading are the two weak links in light-frame construction. While rational load paths are dependent on the architectural form of the structure and is only able to be controlled by the designer, the connectivity of the building is one area where research could have significant impact on the housing industry. New connectors that are effective at tying the structure together would significantly increase the strength and toughness of the building. These new connectors can provide strength plus ductility if conceived as an integral component of the larger building system. Damage will be reduced, while the reliability of the building would be significantly increased if the connectivity of the building in key locations is improved. Some of these types of connections have been developed and investigated recently. Adhesives that are applied either before or after the framing and sheathing have been attached with other fasteners (such as nails), have shown significant potential by increasing the strength of the building by more than 100% while also stiffening the building to reduce damage to drywall and other brittle finishes (Jacobs 2003). While this avenue of performance provides significant gains for resisting wind loading, it does proved a challenge for use in seismically active regions since the stiffness increase also increases the loads the structure experiences. Another hindrance to adoption of some adhesives has been the restrictions currently in the building code for the use of plastic foams in construction due to fire spread concerns.

There have also been several new developments in nailing technology, but these developments have found only minor acceptance in the marketplace due to the perception of small gains in performance with associated increased cost.

Connectivity is one area where significant improvements in performance could be obtained with the minimum increase in cost (there is even a potential for a reduction in cost if the technology were to replace some of the more expensive connectors currently used to connect the major components together. If the connector technology can be developed that will incorporate the actual framing or sheathing elements that currently are used, and the weak failure mechanisms currently experienced could be eliminated or at least strengthened, the change would improve the performance of housing tremendously. For instance, if the connectivity at the base of the walls to the floors or foundation could be improved through a mixing of the connector and the actual framing, the single weakest link in this structural system could be eliminated for resisting the lateral loads associated with high wind and seismic loads, and the uplift loads associated with high winds. This one research area could easily improve the building performance for resisting lateral loads by a factor of 10.

Connectivity, as an area of technological development, will also provide the required strengthening of the structural system to allow light-frame construction to resist higher loads associated with seismic loading when heavy finish materials are used. Currently, conventional construction (as built under the IRC regulations) is too weak to hold the weight of brick veneer and other heavy veneer products for more than one story in height due to the lack of connectivity between the walls and the floors or foundation. Currently, if brick veneer is used for more than one story in higher seismic region, the IRC requires significant additional structural sheathing and hold-down connectors be placed in interior walls. If fastening technology between the structural components were developed that would address this problem, while either using the traditional interior sheathing materials (i.e., gypsum wall board) or reduce the cost associated with sheathing interior walls with structural sheathing. The associated improved performance of the building under high wind loads (missiles) would be further augmented by the use of the heavier finish materials.

Combinations of Materials

The second area of technological development needed is to develop design methods for incorporating dissimilar materials (and possibly more durable materials) into the structural system of the building. Currently, residential (and non-residential) construction consists of the "designated" structural system and the nonstructural components (the rest of the structure). While in reality all of the components of the building resist the loads, only the designated "structural" portions of the building are considered by the designer to resist the loads imposed. This creates at least three problems. The first is that the building may be significantly over-designed, in that the non-structural components are provided additional resistance that is currently not being accounted for by the designer. While the concept of over-design might be accurate from a technical point of view, the added margin of resistance is probably what has provided the level of performance expected by the owners as far as serviceability and safety are concerned. However, as architectural pressure continue to reduce the redundancy of residential building systems, the extra margin of safety will disappear.

The second problem is that the non-structural elements are often significantly stiffer than the designated structural elements, which means that the non-structural elements are actually the component that resist the loading until they fail. The designated structural elements must then have sufficient strength to resist the loading and prevent failure of the building. A problem with this concept is that the stiff non-structural elements also concentrate where the loads are applied to the structural elements (at the points where the non-structural elements fail first) and therefore dictate the locations where the designated structural system will fail.

The CUREE WoodFrame Project illustrated the significant impact that finish materials had on the system level performance of light-frame construction (Cobeen, et. al. 2003). Finish materials such as stucco caused a significant reduction in drift during both component and full-building shake table tests, but it also changed the failure mechanism from a relatively ductile bending of the sheathing nails in walls to a brittle fracture of studs with an associated reduction in both real and perceived performance. Monolithic finish materials disrupt the repetitive deformation pattern traditionally conceived by designers of light-frame construction and concentrate the displacement demand at the bottom of the structure. The result is that the lower third of the first floor framing experiences load and displacement demands significantly in excess of those envisioned by the designer. Fracture of the studs in localized bending and fracture of the bottom plate of the wall were observed mechanisms of failure.

As new materials are developed, the interaction with the rest of the structural system needs to be included as one of the development parameters. There are numerous products that have been introduced into residential construction that were conceived and tested as independent systems. However, when they were applied to the building, they adversely affected the rest of the system. Examples include some house wraps, external insulation finish systems, and other siding and roofing products. Some of these had drastic adverse effects on the structural as well as the insulation systems. (Some Building wraps, EIFS, etc.) Had the technologies been developed with consideration for the performance of the building as a whole, the final technologies would have probably enhanced the building performance rather than detracted from the performance, including durability.

Considering these issues, there is a significant need in residential construction to develop new materials and material combinations that will 1) enhance the overall toughness of the building (increased strength and displacement capacity), 2) combine the function of multiple elements in the building system to simplify construction and maintain load transfer capacity, 3) improve displacement compatibility between the different materials in the system, and 4) improve the durability of the building system. Improved toughness will provide the ability to experience shock, impact, and dynamic loads while maintaining the integrity of the structural and weather envelopes of the building. Preventing water infiltration would be a huge improvement in performance for resisting hurricanes.

New materials can simplify construction and improve quality while addressing the lack of skilled labor in the residential construction industry. The forms that are available using the technologies available and used in the production of composite materials can allow the new composite materials to have a form that reduces the measuring required and improves connectivity such as providing lap connections across the floor platforms, connecting the upper story walls to the lower story walls. This would address the issue of connectivity at the weakest position in the building system.

Materials and/or combinations of materials can be developed to equalize the stiffness and displacement capacity of lateral load resisting systems, thereby distributing the load and displacement demands throughout the structure. Current material combinations result in a concentration of demand in the location where the stiff brittle finish materials fail. New materials can be developed that would distribute the demand and improve the reliability of the structural system.

Finally, the new materials can be developed to resist decay in the presence of moisture. Some materials such as wood-plastic composites or other bio-based materials can be engineered to resist decay, while providing the necessary structural integrity to the system. New materials produced from recycled materials have shown themselves to be very functional in marine environments, adaptation of these types of materials to integrated structural elements is achievable in the short term, and can be expanded in application over the next decade.

Reliability

When research is considered, it has become apparent that the simple experimental investigation is not sufficient for achieving the jump to providing the ability to design for higher levels of performance than life-safety. Research projects should incorporate the concept of structural reliability into the scope of projects. In order to develop rational methods of design and construction that are sufficient for setting performance criteria for these higher levels of performance, a reliability basis is required. This involves developing the statistical data set required to define the resistance performance parameters at various levels of load and displacement demands. The traditional use of three replications in testing structural systems is insufficient when the variability of some of the performance parameters may be as high as 40% - 50%. In addition, the definition of the variables of interest needs to be carefully reviewed. During the CUREE Woodframe Project, some of the variables used to define the response of components or elements were dependent on one of the other variables being defined in the particular project. This resulted in coefficients of variation on the order of 200% for some parameters, especially stiffness (Fonseca, et al. 2002). This level of variability is not comprehensible for structural engineering. However, if one were to re-define the parameters of interest, while maintaining the ability to completely define the response, the variability can be reduced to a reasonable level of 10% - 30%. Even at the lower levels of variability, the number of specimens required to provide reasonable statistical information is relatively high.

One method of addressing the reliability of large-scale specimens is to use numerical simulation to develop the statistical information once the models are validated using a smaller number of large-scale experimental specimens. This requires that the specimen configurations used to validate the model provide a reasonable range of performance expected for the particular application.

Conclusions

There is a large performance benefit to be obtained if simple methods of improving the inter-component connectivity of the building were to be developed. The durability and reliability of the building would also be significantly increased should this avenue be pursued. Tying the building together has long been the biggest performance enhancement available to light-frame construction, and a low-cost, simple mechanism for accomplishing this would improve conventional construction by at least a factor of 10.

An introduction of new materials that improve the durability and compatibility of the elements forming the structural system would also provide a large improvement in global performance of the building. Reduction or elimination of decay in the lower portion of walls, elimination of some of the failure mechanisms currently in light-frame construction will also provide an increase in performance when subjected to natural hazard loading. New composite materials used in the framing can eliminate decay and strengthen the structure. In addition, these materials can provide the needed compatibility with finish materials.

Finally, if the two concepts can be combined to provide improved connectivity, durability, and compatibility of the system, the result will be a technology that will gain acceptance in the market place and improve the overall performance of housing. This can be accomplished with ingenuity of form, that will address the shortage of skilled labor to install the product and at the same time provide accurate installation and enhanced performance. With the new injection molded and extruded forms of composites, the new material technologies can address many of the connectivity and durability issues simultaneously

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