International Journal of Architecture, Engineering and Construction
Vol 4, No 2, June 2015, 64-79

Comparative Study of Various Wall Systems' Performance Attributes in Different Environmental Conditions

Ali M. Memari[1,*], Ryan L. Solnosky[1] and Mahua Mukherjee[2]

[1]Department of Architectural Engineering and Department of Civil and Environmental Engineering, Penn State University, 104 Engineering Unit A, University Park, PA 16802, USA

[2]Department of Architecture and Planning, Indian Institute of Technology, Roorkee, India

Abstract: Within the last 10 years there have been several efforts to support and provide a better environment for occupants. One area under heavy investigation is better performing building wall systems as the selection of a particular system over another may pose a challenge when one needs to consider the numerous implications associated with one decision. Although there have been many metrics studied under isolated criteria, there have been limited studies documented in multi-disciplinary metric comparisons of wall systems. This study expands upon other works through manufacturer specifications and literature reviews, to develop a broader comparison among different common residential wall systems. The discussion of the material is broken down into two categories: 1) multi-hazard and 2) design and serviceability. Wall systems examined were: insulated concrete forms, wood-frame, steel stud, structural insulated panels, concrete masonry unit, autoclaved aerated concrete, straw bales, and precast concrete panels. The attributes identified were tabulated in performance matrices tables that provide a quick reference for side by side comparison of these wall systems.

Keywords: Wall systems, residential design and construction, multi-hazard resistance

DOI: 10.7492/IJAEC.2015.007

1 INTRODUCTION

Nearly 25% of families in the United States spend more than 30% of their income on housing (National Association of Home Builders Research Center 2006). The value of new construction of residences in 2001 was 2.4% of the Gross Domestic Product (GDP) (U.S. Census Bureau 2001) and all residential homes (new and retrofit) accounted for about 5.3% of the GDP. These values indicate the importance of generating design solutions that will have impact on home performance. Wood-framed wall construction is the most prevalent type for single-family dwellings (Obiso 1997). With rising concerns or interest on natural hazards, sustainability, cost competitiveness, speed of construction, and energy efficiency, other alternative wall systems are becoming sought after. Alternative systems like light-gauge steel frame, insulating concrete forms, low-density concretes, structural insulated core panels, engineered wood wall framing, concrete block with insulated core, and a variety of hybrid wall systems have been studied at an experimental level over the last 20 years (Memari 2012; Memari et al. 2014). Comparative metrics among these systems with different attributes can provide some guidelines for designers in selection of the best wall systems under the desirable designer performance criteria.

During the NSF-Partnership for Advancing Technologies in Housing (PATH) Housing Research Agenda Workshop in 2004, an effort was undertaken between the industry and research organizations (U.S. Department of Housing and Urban Development (HUD) and the National Science Foundation (NSF)) to develop a national housing research agenda (Syal et al. 2004). This workshop identified the research needs in the following areas (Cramer 2004): home safety and security (including issues like terror and domestic crime, health and home environment, natural hazards, fire, etc.), affordability and constructability of housing, sustainability and durability in housing construction, and performance-based house design. These identified areas can directly relate back to wall systems, particularly exterior walls, as they are the primary barrier between the environment and the occupants.

*Corresponding author. Email: memari@engr.psu.edu

Current conditions that support this study are many that span from energy efficiency, cost, resiliency to hazards, etc. In fact, buildings account for 37% of the total primary energy use in the U.S., compared to 37% for industry and 26% for transportation (Diamond 2001). Ahrens (2007) records "NFPA estimates that U.S. fire departments responded to an average of 375,200 reported home structure fires per year during the five-year-period of 2000-2004". These fires caused an estimated average of 2,970 civilian deaths, 14,390 civilian injuries, and $5.6 billion in direct property damage per year. National Association of Home Builders (NAHB) recorded that Hurricane Katrina destroyed 310,353 single family houses (a whopping 87.9% of all residential type), 102,297 single family houses (73.4%) experienced major damages, whereas 135,879 houses (79.7%) were recorded for minor damages (FEMA 2006). The residential sector consumes 18 trillion Btu or 19,000 tera-joule of direct energy, representing about 19% of total U.S. energy consumption (Ochoa et al. 2002). Environmental impacts of residences on the consumption of nonrenewable resources and the emission of toxic and nontoxic substances to subsoil, land, water, and air can be significant depending on the materials used. Hendrickson and Horvath (2000) found that new construction of single-family dwelling units contributed 5% to the U.S. total Global Warming Potential emissions for their construction, and 6% to the U.S. total Equivalent Toxic Air Releases (Horvath et al. 1995). Adding to this, wall construction makes up a significant portion of the residential building, thus efforts in providing metrics to allow builders and designers to more accurately select the proper wall systems is necessary (Pierquet et al. 1998).

2 SELECTED STRUCTURAL WALL SYSTEMS AND EVALUATION METRICS

Although there exists many different viable load bearing wall systems that can be used for residential construction (Steven Winter Associates 2004), each can be classified according to their broad structural systems (Salvadori and Heller 1975; Obiso 1997). Furthermore, residential building trends vary depending on where the home is located. While most homes have similarities across regions, there are locations globally that have unique residential systems suitable for those regions, which were not included in this study; instead, only the U.S. market was considered though they may be utilized in other global markets. The classifications of wall systems considered in this study are as follows:

1. STUD SYSTEM (Closely spaced frame with sheathing)
   (a) Conventional wood-frame system
   (b) Light gage steel stud system
2. POST & BEAM (Frame and infill panel)
   (a) Structural Insulated Panel
   (b) Precast Concrete Panel
   (c) Masonry Panel
   (d) Agri-board Panel
3. STRUCTURAL MASONRY AND CONCRETE (Load-bearing structure)
   (a) Concrete Masonry Unit
   (b) Autoclaved Aerated Concrete, AAC
   (c) Insulated Concrete Forms
   (d) Straw Bale
   (e) Brick
   (f) Adobe

For this study, only the following eight wall types from the above list, that are more widely used, were investigated: Conventional wood-frame system (WF), Light gage steel stud system (SS), Structural insulated panels (SIP), Precast Concrete Products (PCP), Concrete masonry unit (CMU), Autoclaved aerated concrete (AAC), Insulated concrete form (ICF), and Straw bale (SB).

Different wall systems employ different materials and methods of construction, which leads to different metrics for consideration in their selection as part of design. In these wall systems, predominantly a single material type carries structural load, whereas for thermal protection, it is the combination of materials that can provide superior performance. Due to conflicting requirements in different performances, what is best for one behavior may not be best for another. This is where the study looked to document trends in designing and constructing such walls. Literature has identified there is a wide range of metrics with different classifications of wall system design that can be considered for selection (Memari 2012; Memari et al. 2014). This study considered performance under the following hazard types as well as design or serviceability considerations:

1. HAZARD PERFORMANCE
   (a) Fire resistance
   (b) Wind
   (c) Earthquake
   (d) Flood
   (e) Blast
2. DESIGN OR SERVICEABILITY ATTRIBUTES
   (a) Moisture control
   (b) Thermal
   (c) Design Flexibility
   (d) Constructability
   (e) Skilled Labor

All of these wall system types have the ability to act as structural load resisting elements within a home. Different kinds of natural or man-made hazards like fire, earthquake, tornado, hurricanes, flood, etc., are present globally which can affect life safety, and property loss. From 1994 to 2002, 85% of all fire fatalities were from firefighters being trapped by the collapsing building structure, of which 51% occurred in residential structures (Brassell and Evans 2003). Although blast hazard/threat situations are of great concern, the probability of such events occurring in residential buildings, particularly for one and two story homes is slim. Nonetheless, such a hazard was also added to this study for comparison purposes because of the existing interest (Naito et al. 2013).

Proper moisture control is critical to achieve in the design, poorly developed wall systems could lead to condensation that results in the growth of mold (Memari 2012; Memari et al. 2014). Selecting the system and how it is assembled in the proper sequence is necessary but also the material selection can help limit the growth of mold. The selection of materials for wall systems determines and influences their behavior under loads like difference in temperature, humidity, and wind flow rate. If the system performance ends up being less than recommended with the addition of structural and envelope building components, then other systems (mechanical and electrical systems) must compensate these deficient designs. To maintain a comfortable environment for the building occupants, the thermal insulation properties of the wall system must be considered in the selection. The best system may change based on climatic zone due to the requirements for thermal performance.

Some wall systems provide a wider variety of design flexibility in comparison to others. Most of the time it becomes an issue while selecting a material as it will play a role not just from a performance standpoint but also in how it is built and its ability to meet architectural demands. The constructability of a wall system is critical as it can mitigate waste while maximizing time and effort. To tie in with constructability (Construction Industry Institute 1986), skilled labor plays a role. Different wall systems have different requirements and skills needed to construct them. The more complex and less likely used, the harder it will be to find the skilled labor to build the system, which could impact the quality that will directly then impact the performance.

Before comparing multi-hazard resistance performances and design attribute characteristics in further detail, a brief introduction will detail the system composition for the selected structural wall systems to provide reference in how they perform.

3 WALL SYSTEM DESCRIPTIONS

3.1 Wood Frame (WF)

WF stud walls (Figure 1) consists of normally 51 mm × 102 mm (2 in. x 4 in.) framing members and in some cases 51 mm × 152 mm (2 in. × 6 in.) for exterior walls spaced at 406 mm (16 in.) or 610 mm (24 in.) o.c. that carry the gravity load, and exterior structural panel sheathing (plywood or oriented strand board (OSB)) that stabilizes the studs and resists most of the lateral loading, thus providing in-plane shear resistance (Canadian Wood Council 2002). On the interior side, usually gypsum wall board (GWB) is used, while for insulation, normally fiberglass (batt) is placed between studs with a thickness equal to the framing members.

Figure 1. Wood framed construction

3.2 Steel Stud (SS)

The SS wall system (Figure 2) is built to the same dimensional configurations as the WF system and uses the same sheathing for lateral load resistance. SS walls are more widely used in commercial buildings as partition walls as well as backup system for brick veneer type of envelope system (Steel Framing Alliance 2003). The use of SS in load-bearing residential wall construction is relatively new and has yet to be widely recognized by builders, but its use in home building is met with more interest recently because of demand for green buildings (Hart 2012). The strength of SS does not have variation for a given gauge because of the manufacturing process (Piuter and Sherman 2006) unlike WF systems.

Figure 2. Stud construction(http://drywallamerica .com/drywall-services/steel-framing/)

3.3 Structural Insulated Panel (SIP)

SIPs are sandwich/layered panels (Figure 3) consisting of two structural boards with a center rigid insulation (APA 2007). The insulation can be of a variety of materials available such as expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PU), etc. The structural boards can also be made of variety of materials such as plywood, OSB, metal, or concrete. Concrete based SIPs are discussed within the PCP section of this study. SIP panels can be used as wall, floor or roof panels. Prefabricated panels are attached to one another at the job site using a variety of splice and fastener types. The most common application in residential construction is plywood or OSB sheathed SIPS.

Figure 3. SIP construction (image courtesy of Thermocore Panel Systems)

3.4 Precast Concrete Panel (PCP)

Precast concrete panels (PCP) are constructed by concrete molds specific to the wall location needed and most are solid or are sandwich wall panels with inner rigid foam insulation, while some can have hollow cores (Figure 4). These concrete panels can either be precast at a factory, where transportation is needed to deliver to the site, or cast-in place, where the panels are formed directly on the site (Portland Cement Association 2012). Precast concrete panels are recyclable and embody considerably less energy with respect to other concrete-based systems (Foam Control 2012). Sandwich based PCPs can be lateral bearing and gravity bearing systems made up of an interior section, or wythe, of insulating foam and exterior wythes of concrete to maximize structural efficiency while maintaining constructability (Naito et al. 2013). The interior and exterior layers are connected with shear ties. Varying the number and type of shear ties allows the interior and exterior wythes to act as a single composite unit.

Figure 4. PCP construction (image courtesy of Dukane Precast)

3.5 Concrete Masonry Unit (CMU)

CMU is widely used for basement wall construction (Figure 5), but it can also be considered for the load-bearing above grade walls of residential buildings as is commonly used in construction of low-rise department stores and other low-rise multi-story residential complexes (Ching 1975). The conventional size of CMU block is 203 mm × 203 mm × 406 mm (8 in. × 8 in. × 16 in.) although other sizes are available but not commonly used in residential applications. Load-bearing CMU wall can be designed as unreinforced masonry or reinforced masonry depending on the externally applied loading. Geographical zones with high seismicity do require reinforcing in CMU wall no matter the applied load, due to ductility requirements. CMU is known to have high fire-resistance, low maintenance, and high durability (Kim and Rigdon 1998).

Figure 5. CMU construction (http://www.concretoplus.com/gallery-foundation-work.html)

3.6 Autoclaved Aerated Concrete (AAC)

AAC is a highly lightweight concrete with significant air volume or pores ratio that gives it its lightness (Chusid 1999). The conventional method for residential building construction uses block and masonry as shown in Figure 6. Other AAC attributes include high fire-resistance, thermal and sound insulation, and relative softness that allows it to be cut with a hand saw just like wood. In addition to cement, lime and sand that are also present in CMU, AAC mix has aluminum powder that causes the slurry to increase in volume like a cake and create a cellular structure (Schnitzler 2012).

Figure 6. AAC construction (image courtesy of Portland Cement Association)

3.7 Insulated Concrete Forms (ICF)

ICF is a cast-in-place concrete wall system that is constructed by first placing two layers of rigid foam as forms for the concrete wall (Portland Cement Association 2008). The foam can be extruded polystyrene (XPS), expanded polystyrene (EPS), polyurethane (PU), or a cement-foam composite. The forms can be interlocking modular units (Figure 7) and dry-stacked to desirable height. Once the reinforcement is placed within the form, concrete is poured.

Figure 7. ICF construction (courtsey of LaBarge Cape Cod Engineering)

3.8 Straw Bale

Straw bale construction uses the waste product of baled straw from wheat, oats, barley, rice and others in walls covered by stucco (Wheeler et al. 2004). Most standard straw bales have nominal dimensions of 406mm × 610mm × 1219mm (16"× 24"× 48") (height, depth, width) and with a varying weight between 68 pounds to 105 pounds depending on the type of straw and how dry it was when manufactured (Ash et al. 2004). This technique for constructing walls has been recently revived as a low cost alternative for building highly insulating walls. These wall systems can function both structurally and non-structurally. The non-structural bale is useful for the construction of post-and-beam building systems or as infill walls. Post-and-beam is when the skeleton of the building is made up of vertical post and horizontal beams to support the roof (Department of Energy 1995). Once in place, the bales are given a reinforced skin made of heavy wire mesh attached to a wood frame (Wheeler et al. 2004). The walls are then plastered with lime, cement or an earthen plaster, depending on the site's environment (King 2006). The finished structure has walls that are two feet deep, this depth gives the building's designers the opportunity to create tailored built-in features. Two-string bales to large three-string bales and huge cubical bales or round bales are different types of shapes and sizes that straw bales come in most desirable straw bales for construction are medium sized rectangular three-string bales.

Figure 8. Straw bale construction (http://www.buildingwithawareness.com)

4 HAZARD PERFORMANCE OF WALL SYSTEMS

4.1 Wood Frame Performance

WF systems have highly desirable strength-to-weight ratio, which is a good attribute for earthquake resistance yet is quite vulnerable to extensive damage in hurricanes and tornados (Canadian Wood Council 2002). Besides direct wind pressures in these situations, flying debris during storms are another source of damage to WF residential buildings (Sherwood and Moody 1989). According to a literature review by Sherwood and Moody, WF houses are expected to handle lateral loads equivalent to wind speeds up to 193 km/hr (120 mph) (Yazdani et al. 2006). With respect to fire resistance, WF walls that include GWB can be designed to provide acceptable fire resistance in most residential situations as it is expected to have a 45 minute fire rating. In general, the thicker the wood member, the better its performance in fire situations due to a char layer forming that protects the inner parts of the wood. According to Sherwood and Moody (1989), wood systems with the best fire resistance are post and beam construction.

4.2 Steel Stud Performance

SS systems have attractive properties including a high strength-to-weight ratio, dimensional stability, and lack of warp, split or twist due to moisture conditions not affecting materials. The high strength-to-weight ratio and inherent ductility potentially make SS system appropriate for seismic regions (Tool Base 2012) subject to adequate design and detailing. Regarding performance under hurricanes and tornado winds, the same issues that exist for WF system would be true for SS system as well due to resistance being provided by the sheathing. According to Yazdani et al. (2006), missile impact tests have shown that the same type of projectile can penetrate a SS wall. However, according to Hubbs (2003), SS wall construction was perforated by a wood stud at 82 km/hr (50.9 mph) speed, almost

25% lower than that perforating WF. Though steel is non-combustible, it can lose its strength at high temperatures.

4.3 Structural Insulted Panel Performance

SIPs are known for their strength because of the composite sandwich structure. According to Morley (2000), SIP systems have shown to be able to maintain their integrity under both tornados and earthquakes. The reason for good performance of SIP system in tornado can be explained by considering that the exterior sheathing of the SIP cannot be torn away or dislodged from the rest of the panel, thus there is no pressurization of the attic. This resistance inhibits subsequent damage to structural system often observed in conventional WF. Filiatrault and Foschi (2001) and Terentiuk and Memari (2014) have identified that under lateral loadings the connections between panels is often a controlling limit state on the system level performance of SIPs. It is reported that their performance during the 1995 Kobe, Japan earthquake was favorable and remained relatively undamaged (Star Craft Custom Builders 2012). SIP panels on the other hand are made of wood and foam components that are flammable. Therefore, the interior side should be protected using GWB. In general, 13 mm (in.) thick GWB layer provides 15 minutes of fire rating, while two layers provide one hour (National Association of Home Builders Research Center 2006).

4.4 Precast Concrete Panel Performance

PCP walls have been found to increase the overall strength of structural system between 10-20%, depending on the panel composition and connection to the structure (Baird et al. 2011). From the perspective of fire resistance, these panels perform quite well based on the inherent resistance concrete has to fire, as long as the reinforcing bars are properly detailed and constructed with sufficient clear concrete cover. Large and small missile impact resulting during severe wind events are largely resisted by the concrete panels based on their robustness as compared to weaker materials such as WF and SIPS (Figueroa-Vallines 2013). The PCP itself in areas of flooding is not the issue if certain admixtures are provided in the mix to prevent water penetration (PCI 2011). The more significant issue with flooding is the joints and sealants used between the panels, as poor waterproofing details will allow water to penetrate in-between PCP layers or through the PCP resulting in damage to non-structural components. Naito et al. (2013) tested non-load-bearing, insulated, reinforced concrete sandwich wall panels under far-field blast loads and found that their performance was positive, yet the composite action quickly diminished based on the connection of the layers. The use of concrete provides a higher inertial mass than other cladding options such as wood or steel framed construction. This increased inertial mass provides a greater blast resistance for the facility against external detonations (Naito et al. 2012).

4.5 Concrete Masonry Unit

Yazdani et al. (2006) showed that 152 mm (6 in.) thick CMU walls may sustain some cracking of the shell through missile impact tests. However, the wall passed the test without projectile penetration. Based on the performance of masonry walls in 1995 Hurricane Opal in Florida, Samblanet (1996) states that load-bearing masonry walls and masonry veneer performed well. However, inadequate wall-to-floor connection in load-bearing walls and inadequate ties for veneer-to-backup connection were the cause of some failures. Johnson et al. (2004) describe how tests have been developed to protect walls from blasts. The CMU walls are essentially "retrofitted" with elastomeric systems for blast loads to avoid debris hazards from blast (Baylott et al. 2005).

4.6 Autoclaved Aerated Concrete

AAC has a much smaller compressive strength compared to normal concrete (Memari and Chusid 2003). Depending on the density of the material (3 to 10 kn/m^3 or 19 to 62 pcf), the compressive strength can be up to 35% that of concrete. According to (Hebel 2012), the performance of AAC building during Kobe Earthquake has been very good in terms of damage propagation and structural resiliency. Furthermore, because the material is non-combustible, it provides an inherent fire-resistant structural system. According to Aecrete (2012), a 102 mm or 152 mm (4 in. or a 6 in.) thick load-bearing AAC wall provides a 4-hour fire rating, which gives much higher protection than WF and SIP systems. Yazdani et al. (2006) also tested AAC walls for missile impact resulting from hurricanes and found that there was no penetration but there was minor cracking.

4.7 Insulated Concrete Form Performance

ICF is a form of monolithic concrete construction that gives desirable structural integrity to these defined hazards. Portland Cement Association (2012) reports that projectiles with a velocity of 167 km/hr (104 mph) have not been able to penetrate ICF walls and that they survive pressures resulting from wind speeds as high as 402 km/hr (250 mph). Although reports of actual performance of ICF in earthquakes may be hard to find, FEMA (2006) provides design guidelines for seismic design of ICF houses. The basis of these walls could be associated to that of reinforced concrete walls detailed by ACI 318. GAHC (2005) discussed the advantages of ICF with regard to seismic and high wind resistance and life safety are rated its performance very favorably. Although the concrete core of the ICF can have fire-resistance rating of up to 4 hours (Hubbs 2003), the foam forms are flammable, and therefore, GWB is needed on the interior side to achieve proper fire rating (Canadian Wood Council 2002).

4.8 Straw Bale Performance

A straw bale wall system can be thought of as a composite assembly of elements that work together to resist lateral and gravity forces. The outer layers on each side are called render with the straw bale center. Both Jones (2002) and King (2006) identified that reinforcement mesh can be used within the rendered surface in order to increase its strength. Ash et al. (2003) found that load-bearing straw bale walls with unreinforced render failed at lower loads than those that were reinforced. Generally the thicker the render, the higher the load that can be carried and the greater the protection offered from lateral load inducing hazards (Ash et al. 2004). Faine and Zhang (2002) compared the load-bearing capacity of earth-plastered and cement-plastered straw bale walls. It shows that earth-plaster and stucco facings are much stiffer than the straw bales themselves, and so if the compression struts in the bales are to be fully mobilized, the facings would have to first degrade significantly under load reversals as in earthquake conditions. Though limited studies are available to identify fire and flooding hazards, however, it is reasonable to project that due to the material composition the straw bale wall system does not fare well in these conditions.

A summary of the discussions presented on the performance of different wall systems under multi-hazard conditions is generated in Table 1, which provides a better understanding of attributes of such wall systems and key benefits and challenges designers need to consider before selecting a system. Key aspects of the walls are listed for ease of review, which permits the builders to assess systems before design takes place. Table 2 was also generated that proposes a relative rating system that can be used in conjunction with the first matrix for qualitative and quantitative comparison of the wall systems. The values assigned in the rating matrix are subjective and reflect current authors understanding based on available literature and other resources; an in-depth research study is needed to develop a more objective ranking system.

Based on the literature review presented on resistance of these wall system types, it is evident that compared to the vast amount of information available regarding the performance of WF systems in past hazards, there is less information about the behavior of other wall systems. One simple explanation is that these wall systems combined, constitute less than 10% of the existing stock of single-family dwellings for the entire exterior. The lack of data on actual performance of the alternative systems in natural hazard conditions is partly compensated with various side-by-side testing carried out for different purposes (wind pressure, missile impact, racking tests, and fire testing).

5 DESIGN AND SERVICEABILITY PERFORMANCE ATTRIBUTES

5.1 Wood Frame Attributes

Wood frame systems are constructed of elements that allow flexibility when generating design solutions. These framing systems are flexible in that they allow virtually any traditional building material to be incorporated into its system. Some municipal building codes do not require a registered architect or engineer to design or approve the structure given that basic and time proven methods of construction are followed. Framing system types, such as these, tend to have the ability to span moderate distances in dimensional lumber, but are often limited by commonly available types and grades. WF is very common and specialized skills are either readily available or are not needed. Traditional WF has a relatively low lead time, and there is no need to let the construction set or cure thus homes can be constructed at the longest around 4-6 months.

Due to unique cellular structure, wood provides certain degree of insulation in the overall assembly. Adding insulation to the wood-frame structure is easier than other type of systems even in extreme cold climates (Canadian Wood Council 2002). A typical wall containing 2×4 studs spaced 406 mm (16 in.) on center with R-11 fiberglass insulation has a total wall R-value of 9.6 making it suitable for most climates. Wood can naturally absorb large amounts of moisture before reaching a moisture content level at which it starts to decay; nonetheless, mold growth could start before decay sets in. To ensure acceptable durability of wood-frame systems, it is crucial to recognize the wood's performance at various moisture levels. This will help understand the shrinking and expansion of wood members and the highest level of moisture content that can lead into decay (Canadian Wood Council 2000).

Unfortunately, the insulation that is typically used in combination with WF is susceptible to retaining moisture, which can cause mold growth. Applications of vapor barriers and considerations to wall constructions can both reduce / eliminate moisture problems within the system. Timusk et al. (1991) concluded that mold and mildew on inside wall of exterior corners due to moisture or humidity posed a common problem due to inadequate ventilation in wood-framed homes. Accordingly, defected sheathing caused additional cooling of the wall surfaces, particularly in corners where a quick alteration in wind pressure happened. According to Timusk et al. (1991) this problem can be avoided by having airtight sheathing at building corners by moving the air barrier (located on the room side of the wall insulation) to the weather side to perform two functions,

Table 1. Hazard performance comparison matrix

Wall Type	Hazard Performance			
	Fire	Wind	Earthquake	Flood
WF	Dimensional Lumber has an average resistance to fire for 0.75 - 1.5 hr	Dimensional stability; Standardized details for most wind loading conditions	Light weight, high strength-to-weight ratio, redundancy, and nailed connections that generate significant energy dissipation	Susceptible to moisture and decay if no drainage system is provided; Treated lumber can resolve issues but not common in wall systems
SS	Are susceptible to fires and requires other non-combustible sheathing materials for fire rating lasting 1 hr	Dimensional stability, and lack of warp, split or twist; Performs well under loading conditions	High strength-to-weight ratio, inherent ductility; Need proper connections that permit cyclic loading	Since used as a galvanized metal, issues of rusting and corrosion are minimal; Attached materials (sheathing) can be damaged
SIP	Because of the flammable core material, a half inch thick gypsum board on each side is required for a 1 *hr*. rating	Exterior sheathing of the SIP cannot be torn from the rest of the panel, and thus no pressurization	Performs well under earthquakes; Connections between panels are often the failure point	Wood portions are susceptible to decay
PCP	Light-weight and low densities concrete provides longer fire resistančż Inherent fire-resistant structural system	High resistance to impact tests	Increase the overall strength of structural system between 10-20%	Admixtures are provided in the mix to prevent water penetration; Issue is the joints and sealants used between the panels
CMU	Inherent fire-resistant structural system	High resistance to impact tests	Reinforced CMU is required and performs well under conditions when detailed properly	Acceptable to flood for longer periods; Reinforcing may corrode after time
AAC	Inherent fire-resistant structural system	High resistance to impact tests	Performs well but does have lower ductility and can become brittle under lateral loading	Acceptable to flood for shorter periods
ICF	Concrete portion is inherent fire-resistant structural system	High resistance to impact tests	When properly detailed they perform well under lateral loading	Acceptable to flood for longer periods; Reinforcing may corrode after time
Straw bale	Are capable of resisting fires if the bales are plastered Un-plastered bales can only withstand 30 minutes	Performs well under loading conditions	Bale ductile and energy absorption behavior; Connections and performance in strong EQ have been limitedly studied	Very susceptible to rot and decay; Not recommended for prolonged water submersion

Table 2. Multi-hazard rating matrix

Wall Type	Hazard Performance				
	Fire	Wind	Earthquake	Flood	Blast
Wood-frame	1	1	3	1	1
Light gage steel stud	1	1	3	1	1-2
Structural insulated panels	1	1-3	2-3	1-2	1
Precast Concrete Products	3	3	2-3	2-3	3
Concrete masonry unit	3	2-3	1-2	3	2
Autoclaved aerated concrete	3	1-3	2-3	1	1-2
Insulated concrete form	3	3	2-3	3	3
Straw bale	1	2	2	1	1

Note: 3-level multi-hazard rating where: 1=poor, 2=average, and 3=good

namely, to act as a rain screen and to prevent air from entering the wall cavity. Hendron (2005) suggests using exterior foam insulating sheathing as the primary sheathing and drainage plane WF.

5.2 Steel Stud Attributes

Steel stud (SS) systems remain relatively easy to work with, while the modular concept will be an economic one, especially when number of units being constructed is sizeable (Jellen and Memari 2013; Ramaji and Memari 2013). Since steel is stronger than wood, larger spaces between members and longer spans can be achieved thus permitting larger open flexible spaces on the interior of a home (CSSBI 1994). In addition, there can be two framing types: the traditional stick style of framing and as panelized systems, which decrease erection time during construction. The steel members contain pre-punched holes for electrical and plumbing utilities and readily accept most construction materials currently in use. Depending on the geographic region, finding experienced builders can lead to increased cost and time as trained laborers are necessary. Because steel framed structures are engineered and the screw connections are typically seen as more durable in cyclical loading applications than nails, these structures have greater resilience over time (CSSBI 1994). Since the main cost of a building repairs lies in structural elements, this greatly reduces costs if a home were to have an infestation (Najarian and Aliaari 2013).

Since steel is a very poor insulator and can cause highly conductive thermal bridge in exterior framing, some regional codes require that rigid insulation be applied to the exterior of walls to minimize the thermal bridge (Hart 2012). With new galvanized coatings, moisture issues such as corrosion are kept to a minimum. However, if this coating becomes damaged or scratched, the wall would be susceptible to corrosion. In this wall system, the air/vapor barrier is often a polyethylene sheet which is placed on the inside face of the stud (the warm side). To have an effective rain screen, air/vapor barrier must be selected and detailed to prevent leaks and contamination of the air space. This leads to advantages in design and serviceability, including less fatigue on connections and less warping of the structure over time (Najarian and Aliaari 2013).

5.3 Structural Insulated Panel Attributes

SIPs' main determinant in their durability is the degree of diligence exercised in the consideration of properties and environmental conditions (SipBuild 2008). Tests have shown that SIPs are two and a half times stronger (under out of plane bending conditions) than conventional WF as the skins take the load and distribute it evenly throughout the foam core (Blocker 1993). As a result, these panels are known to have the ability to span longer distances and minimized wall thicknesses (Adio-Moses et al. 2011). Because SIPs are panelized, curved walls and undulating shapes are relatively hard, and sometimes even impossible to obtain. Furthermore, significant forethought must be put into the placement of pipes and electrical prior to construction.

With respect to thermal performance, SIPs outperform standard wood frame construction due to the airtight qualities of the construction resulting in HVAC systems being down-sized nearly 50% (Blocker 1993; SipBuild 2008). Greater thermal insulation is achieved by SIP systems in two ways. The first is by using foams that have higher than typical R-values for residential construction, and the second is by having a continuous construction throughout the wall system (APA 2007). For practical values, a SIP system has been proven to provide typical energy savings of 40-60% over traditional construction (Kim and Rigdon 1998). The typical foams used in SIPs (expanded polystyrene, extruded polystyrene, urethane, and polyisocyanurate) all have closed cell structures which prevents excessive moisture absorption (APA 2007). The additional engineered wood panels, like all wood materials have moisture content, and a natural ability to resist some level of moisture.

5.4 Precast Concrete Panel Attributes

When designing the PCP, a proper level of durability should be planned to avoid any deterioration. Gaudette (2009) indicates that it can be improved by specifying minimum compressive strengths, maximum water-cement ratios, and an applicable range of air-entrainment. PCP panels are engineered products, this provides high flexibility for it can be made to accommodate a wide variety of owner features (PCI 2011). PCI (2011) provides the many requirements that drive the design as well as set recommendations for the limits. Included in PCI (2011) are conventional demands including shipping, handling, wind, and thermal requirements. ACI (ACI 533.1R-02) and PCI (MNL 120) specifications are used to design precast concrete elements. Involving the manufacturer during the design phase is recommended to ensure all of the material's inherent advantages are considered before decisions are completed (Portland Cement Association 2008). Their ability to create the most efficient panel and component sizes and to design connections in appropriate and effective locations can reduce the budget and speed construction (Gaudette 2009). The prefabrication of the panels allows for rapid erection of the building and short construction schedules. Typically, construction time can be reduced up to 30% with this method. The panels can be erected in any weather, so interior work will not be delayed according to Portland Cement Association (2009a).

The durability of concrete and resistance to deterioration is dependent on durability of base materials used in the mix and reinforcement, proper design, and good workmanship. The key issue to be addressed in design of a cast-in-place façade element is durability related to environmental exposure such as moisture, carbonation of concrete, corrosion of embedded reinforcing steel, weathering, freeze and thaw, and alkali-aggregate reactions. These are the factors that can contribute to distress and deterioration of concrete (Duntemann 2007). Moisture protection with this type of wall system often is comprised of a barricaded system incorporating a sufficient joint seal. To have additional moisture protection, concrete coating or application of a sealer can be used. Even though film-forming coatings give an unattractive look to the precast concrete, it has a higher level of performance (Gaudette 2009). Ellis and Beliveau (2003) analyzed alternative PCP configurations and interconnections to reduce thermal bridging and thus maximize benefits that is given by thermal mass. If the PCP wall can be linked to a mechanical system, additional benefits can be attained.

5.5 Concrete Masonry Unit Attributes

CMU masonry provides a strong and durable structure, withstanding both routine natural wear as well as extraordinary impacts of natural and human disasters. It can be used as a structural or non-structural material thus making it very design flexible as it comes in different thicknesses (Lotfi and Shing 1994). Many charts and guides exist that limit the need for engineering calculations for residential construction. In looking at construction and skilled labor aspects, CMU is very time consuming to construct and requires the trades to be proficient in laying masonry, though it is a commonly used material (Bowser et al. 1996). From a thermal efficiency standpoint, CMU has a relatively high thermal mass and insulation properties due to concrete and also based on the air within the open core acting as a thermal barrier. One way to significantly reduce energy transmission through the webs of the block is through in-block insulation (Omniblock 2014). Another way is to mix insulation right into concrete at the plant. Moisture can be a problem if it accumulates in the internal core or if water seeps into the interior surface through the porous material in the cells or through the webs. Often when coupled with brick veneers, a moisture barrier is provided over CMU and/or proper drainage mechanisms between the veneer and CMU would be in place to reduce moisture effect that can lead to mold and possible corrosion of the reinforcing (Triantafillou 1998).

5.6 Autoclaved Aerated Concrete Attributes

AAC wall systems have a unique design advantage in that they are flexible enough to allow for carving and forming of complex structures such as arches using nothing more than a saw (Matsushita et al. 2000). Slender strips of AAC or manufactured stone, which is used to build up quoins, cornices, and other ornaments, can be laminated with adhesive mortar (Safe-Crete 2014). It is much lighter and easier to cut than conventional CMU block, which can benefit the labor impact. AAC is highly adaptable to a variety of architectural designs and can easily be engineered to meet structural load requirements (Varela et al. 2006). Because of its ease of construction, window trim, chases for plumbing, wiring and outlets, and other decorative features can be easily constructed at the job site (Klingner et al. 2005). Masonry crews do have to adjust to using a special polymer-modified thin set mortar system, which creates less margin for error.

According to Oak Ridge National Laboratory, energy demands of a home with AAC walls are about 18 percent less than wood-frame walls, 36 percent less than two-core CMU, and 23 percent less than steel stud walls (Moslemi 1999). Protection of exterior surfaces of AAC is similarly important. Using an exterior impermeable moisture system helps avoid water intrusions. According to the Varela et al. (2006), AAC will not rot, warp, corrode, or otherwise decompose, providing a very durable material that will last for many years as it has been examined that harsh climates have minimal effects on wall performance.

5.7 Insulated Concrete Form Attributes

ICF wall systems are flexible from a design standpoint in that they can be manufactured with any interior/exterior finishes, can take any shape like wood frames, and it is also cost effective (Portland Cement Association 2009a). The ICF forms are simple to assemble and fill with concrete, which requires less time to construct in comparison, to WF and SS construction resulting in reduced construction schedule, saving time, and faster occupancy. According to Cramer (2004), comparing to WF design, a house built using a screen grid block ICF system took 12.49% less time to construct. Due to the ICF's light foam form properties and with the help of machinery to move the concrete, the labor cost can be kept low and helps fabricating homes easily (Portland Cement Association 2009d). Minor skilled labor is required in regards to residential carpentry crews, but more advanced knowledge of concrete will be required (Portland Cement Association 2009a). Experience has shown a crew will typically require a three home learning curve to become familiar and efficient with ICF systems (Portland Cement Association 2008). Also the cost turned out to be about \$0.22 to \$1.01 more per square foot of floor area. The increase in cost for homes from wood to ICF frame systems is approximately 3.5% of the sale price and 7.2% to 8.4% of the construction cost (Portland Cement Association 2009c).

ICFs give the home a beneficial "thermal mass", which does not tend to overheat the home or drop temperatures drastically as the temperature change outside or the furnace/AC is turned on or off (Portland Cement Association 2009b). Because the ICF's concrete mass is sandwiched between two layers of foam, it can provide an R-value up to 40. In an experiment carried out in Florida Solar Energy Center, Chaser et al. (2002) compared two buildings, one with walls made out of ICFs and the other with WF walls. The measured data revealed that ICF construction can reduce cooling load up to 17-19% in comparison to WF one (Gajda and VanGeem 2000). Simulated data has shown 13% annual energy saving in case of ICF over WF, including lights and appliances (Kosny et al. 2001; WSU 2011). Air infiltration in an ICF Home is minimal due to the continuous air barriers provided by the foam insulation and the concrete. Likewise, there are no convection currents within wall cavities (Steiner 2007). For moisture control in an ICF building, it is necessary to use a non-petroleum based product to prevent saturation and decay of the exterior insulation and mold from forming on the outer surface (PCI 2011).

5.8 Straw Bale Attributes

With straw bale construction, the design flexibility of the system is fairly open as its masonry like stacking. Issues can arise though when homes require small wall sections on the exterior and at interfaces between the bales and windows and doors. Care must be taken when planning the design to ensure that other products do integrate with this system. To achieve stability and alignment in stacking of the bales, they need to be braced. During testing of the straw bales, Zhang (2002) found that initially upon loading, the bales compressed by 3 to 4% of their original height. It is common practice to pre-compress straw bales walls prior to plastering to avoid this settlement the first time the wall is loaded (King 2006). In early straw-bale codes, internal or external pinning of bales with rebar dowels has been approved, but does not provide a great deal of structural significance (Jones 2002). In regards to skilled labor and construction ease, straw-bales follow masonry design, in that they are stacked in a running or stack bond. When the bales are stacked on top of each other during construction, they need to be "pounded" into place to reduce movement and settling (King 2006). A skilled labor workforce is not necessary when working with straw-bale wall designs and only minimal training is required (Marks 2005).

Unlike WF construction with many pieces, straw-bales have a monolithic layer of straw that is usually covered with plaster on the inside and stucco on the outside unless straw is placed between post and beams where sheathing is then applied. When designed and detailed properly, a monolithic bale wall will result in little air leakage. This is due to the cellulose form in the straw that has high-quality insulating qualities that makes the straw-bale wall thermally resistant. Based on ASTM Testing by the Department of Energy (1995), R-values for these bales come between R-2.4 and R-3.0 per inch. Between the bottom of the bale wall and the foundation, an adequate waterproof barrier is necessary to stop any unwanted moisture. Moisture control can be a concern in this systems and must be accounted for. To help stop water from leaking through at the foundations, the building should have a layer of pea gravel between wood plates along the inside and outside faces (Goodhew et al. 2004).

Dry rot fungus in a straw-bale wall system will cause significant damage when they sustain high levels of moisture, usually with humidity of 70-80 % or having 20 % of dry weight as compared to moisture that comes and goes at different intervals. From experience and tests, the best way to control the moisture content, is to make sure the bales can transpire the moisture back into the atmosphere. An air barrier (e.g. building paper) applied on the exterior wall sheathing (normally used in stud wall systems) can help transpire the moisture content outside and create a surface where the moisture can be inhibited. But this solution may not be applicable to straw bale (e.g. the plaster sheathed type), rather breathable sealers are usually the best because they do not allow the moisture to get in through the stucco and permits to transpire moisture out. A mistake that the building permit reviewers commonly make is on requiring barriers such as plastic or tar-impregnated paper cover the bales. This will not allow the straw bales to breathe, i.e. to release water vapor. Instead, it will be trapped against the straw-plaster interface, damaging it because the structure system depends on a thorough attachment of plaster and straw (King 2006).

To summarize the main outcomes of the discussions presented in this section in regards to design and serviceability attributes, a comparison matrix (Table 3) was formulated for these wall systems, where the corresponding attributes with the key characteristics are tabulated for designers to take into account before selecting a system. A rating matrix for design attributes was also generated and presented in Table 4. As many of the attributes can vary in degree in different geographic locations, the assigned values in the rating matrix should be considered more holistic of the system across the U.S.; needless to say this implies some degree of subjectivity in ranking and more quantitative research in several geographic locations should be considered to develop accurate values.

6 OVERALL WALL SYSTEM DISCUSSIONS

The two prior sections have detailed performance capabilities of different load bearing wall systems for multi-hazard resistance and many of the prominent design variables and serviceability performance characteristics necessary to provide a means to narrow down and select a system to further verify based on code provisions and engineering calculations. Based on the literature review results presented, there are clearly systems that provide 1) the best lifecycle performance in the environment and 2) the best measures that ease construction and will improve quality and durability. Based on the discussion presented on resistance of these wall system types, it is evident that the concrete-based wall systems are inherently more resistant to hazards; this comes as no surprise due to the volume of research conducted in this area as well as the material's inherent abilities to resist loads. With respect to thermal and moisture performance, concrete-based products also perform satisfactory if proper insulation and detailing is used. Stud-based walls (SS and WF) require the least amount of training while PCP and ICF requires the most skill sets.

Across the board, ICFs seem to score high in providing resistance to hazards across the hazard types. Furthermore, ICFs rate high in thermal and moisture control, yet in regards to building form, flexibility and

Table 3. Design and serviceability attribute comparison matrix

Wall Type	Design and Serviceability Attributes				
	Moisture Control	Thermal Resistance	Constructability	Design Flexibility	Skilled Labor
WF	Vapor barriers is necessary; High absorption could lead to decay; Wood changes dimension; Insulation is susceptible mold growth	Provides some insulation due to its cellular structure; Requires additional insulation	Simple to construct sizes; Standardized details	Wide variety of and can be customized	Common practice amongst enclosure system builders in residential settings
SS	Galvanized coating is needed to minimize corrosion; Need vapor barrier to prevent leakage through fasteners and openings	Require rigid insulation be applied to the exterior to minimize thermal bridging	Standardized layouts and details	Limited to standard sizes; Larger spaces between members; Longer spans	Trained laborers are necessary to put a steel framed structure together properly; Training time is minimal
SIP	High a high moisture absorption leads to decay of the wood; Insulation is not susceptible to mold growth; Vapor barrier is necessary	40-60% energy savings compared to WF; No extra insulation required	Can be modular to allow for increased speed (up to 34%); Standardized details	Longer spans; Minimized wall thicknesses	Recommend specialty labors for quick erection of homes (34% decrease in time)
PCP	Rebar susceptible to corrosion; Pigmented sealant or admixtures can protect the concrete absorbing water	Best performance when there is an insulation sandwich between two wythes of concrete	Construction time reduced up to 30%; Material waste reduction and replication can be easily achieved	Customizable forms; Can be solid, hollow, or sandwich	Specialty skills needed to fabrication and engineered designs are required
CMU	Moisture barrier, or proper drainage mechanisms between veneers and the CMU is needed	Can mix insulation into the concrete at the plant; Can place foam inserts into voids for better resistance	Easy to cut and modify; Standardized and custom units with details; Time consuming to construct	Standardized shapes; May or may not need reinforcing; Requires special joints	Common practice amongst enclosure system builders in residential settings; Does require experience in laying brick
AAC	Mold growth is very limited; Can absorb and store water in its air voids	Provides about 18% more insulation compared to WF and 36% less than CMU	Easy to cut and modify; Standardized and custom units	Can be carved to create graphics, signs, and etc.; Round edges can be created on the corners of AAC walls	Similar to CMU for constructing but will require training to know how to handle materials
ICF	Use a non-petroleum based product for moisture protection	13% saving over WW; No extra insulation required due to the foam		Standardized shapes	Crews can adapt easily to ICF construction
Straw bale	Barriers such as plastic or tar-impregnated paper will not allow the bales to breathe; provide alternative mechanism	Provides thermal insulation based on thickness; Requires plaster to stop air penetration	Standard details are less common; Often custom work and requires significantly more time to coordinate	Large/high walls require an additional a pole or post-and-beam support system	Minimal training is required; Specialized based on geographic regions

Table 4. Design and serviceability performance attribute rating matrix

Wall Type	Design and Serviceability Attributes				
	Moisture Control	Thermal Resistance	Constructability	Design Flexibility	Skilled Labor
WF	1	1	2	2	1
SS	1-2	1	1-2	2	1-2
SIP	1	2-3	1-2	2	2
PCP	3	2-3	2	3	3
CMU	2-3	2	2	2	2
AAC	2-3	2	2-3	2	2
ICF	3	3	1	2	1
SB	1	3	3	1	2

Note: 3-level Moisture, thermal, and flexibility rating are: 1=poor, 2=average, and 3=good
3-level Constructability rating where: 1=Difficult, 2=average, and 3=easy
3-level Skilled labor rating where: 1=minimal, 2=average, and 3=specialty training

being adaptable, receives a much lower score. Another example is wood frame walls, where with respect to hazards, they are only superior for earthquakes, while regarding other attributes they rate relatively low. Yet, wood walls require limited skilled labor and are very friendly in regards to constructability. Moisture and thermal design though require special care and attention to detail or opportunities will be lost. In the design attribute classification, based on the literature review, WF, SB, and SIP perform poorly to average under most hazards (except earthquakes) and also for moisture and thermal (except SIPs in thermal). Furthermore, with respect to moisture and flooding, the wood-based materials are very prone to mold and decay if not maintained and not detailed correctly for the application environment. These notions may not be ideal for the owners who want limited maintenance homes.

What is clear though is that owners and builders/ designers need to clearly discuss the wall system aspect of the home to ensure what will be built meets their goals and performance objectives and ability to maintain such systems over the lifecycle of the residential home.

7 CONCLUSIONS

This study has identified different metrics for various attributes under design and serviceability performance and multi-hazard situations. The work presented indicates that what is best for one wall system is not necessarily the best for all wall options due to multi-criteria metrics and the inner relationships to those metrics. It is also recommended to rank owner or builder goals for the walls in terms of performance when narrowing down and selection must be done. Several concluding remarks can be drawn from this study with regards to wall system metrics:

Multi-hazard Resistance Metrics:

- With respect to high winds, the main failures result from connection failure between elements, debris impact, and envelope breaching. WF, SS and SIPs perform the worse due to the lower resistance of the whole system towards impacts and excessive pressures that can damage connections.
- In seismic applications, nearly all wall systems function well except for CMU (in particular unreinforced). This is due to their more brittle nature and large weight.
- For fire situations, it is clear that concrete-based materials and systems as well as masonry systems provide a strong resistance, while the light-gauge steel and wood at typical member sizes are too small to provide long term resistance.

Design and Serviceability Attribute Metrics:

- The residential buildings suffer moisture penetration that normally leads to rotting of WF, SIP, and SB members with mold growth but there is not significant structural damage in flood situations.
- Geographic location, in particular, related to skilled labor can significantly drive the manufacturing and the construction costs (particularly related to PCP).
- Relatively all wall systems have a strong ability to resist thermal loading in their minimal state. WF and SS need more additional components (barriers and insulations) to be able to compete with these other systems.
- Panelized units (SIPS and PCP) are often more easily constructible as they have higher quality control and can be made to fit accurately.
- Design flexibility is rather consistent amongst the projects. SB is the worse as it limits the architecture and ability to be modified easily whereas PCP is the most flexible as it a largely engineered system thus allowing for full customization.

The comparison matrices presented provide a good indication into how each wall system performs for the various metrics. Such metrics however, should not be used as the sole criteria for selecting a wall system in new construction situations though. Many other factors impact the particularly when the wall systems have openings and specialty features. Furthermore the attachments to foundations and roofing systems may change the course for alternative selection. Before definitive conclusions can be made on the building material and wall system types as the best package for a given location, further and more advanced and comprehensive studies need to be carried out. Follow up studies would ideally build upon the limitations such as better models for various materials, composite systems that utilize multiple of these systems, use of a robust simulation tool on large research databases or further experimental testing. To understand the implications for selecting a wall system that is best for where the project will be located, such studies at greater depth and scope need to be carried out for that area.

ACKNOWLEDGMENT

The paper presented is part of a study partially supported by the Pennsylvania Housing Research Center (PHRC). The support is gratefully acknowledged. The contributions of Jayesh Choksi in this study is acknowledged. The views expressed are those of the authors and do not necessarily represent those of the PHRC or of the companies who provided the images.

REFERENCES

Adio-Moses, D. A., Adebayo, A. K., and Obi, P. O. (2011). "The hybrid approach for lean construction of urban housing." *International Conference on Innovations in Engineering and Technology Faculty of Engineering*, 1–18.

Aecrete (2012). *AAC Benefits*. Available at <http://www.aecreteadvantagellc.com/aacbenefits. html>.

Ahrens, M. (2007). *Home Structure Fires*. Fire Analysis and Research Division, National Fire Protection Association.

APA (2007). *Product Guide: Structural Insulated Panels*. APA.

Ash, C., Aschheim, M., and Mar, D. (2003). "In-plane cyclic tests of plastered straw bale wall assemblies." *Report no.*, Ecological Building Network, Sausalito, California.

Ash, C., Aschheim, M., Mar, D., and King, B. (2004). "Reversed cyclic in-plane tests of load-bearing plastered straw bale walls." *13th World Conference on Earthquake Engineering*, 1–8.

Baird, A., Diaferia, R., Palermo, A., and Pampanin, S. (2011). "Parametric investigation of seismic interaction between precast concrete cladding systems and moment resisting frames." *Structures Congress*, 1286–1297.

Baylott, J. T., Bullock, B., Slawson, T. R., and Woodson, S. C. (2005). "Blast response of lightly attached concrete masonry unit walls." *Journal of Structural Engineering*, 131(8), 1186–1193.

Blocker, M. (1993). "Homes demonstrate foam core panels; producer says market is warming up." *Automated Builder*, November, 26–27.

Bowser, J. D., Krause, G. L., and Tadros, M. K. (1996). "Freeze-thaw durability of high-performance concrete masonry units." *ACI Materials Journal*, 93(4), 386–394.

Brassell, L. D. and Evans, D. D. (2003). "Trends in firefighter fatalities due to structural collapse, 1979-2002." *Report No. NISTIR 7069*.

Canadian Wood Council (2000). *Moisture and Woodframe Building*. Number Building Performance Series No.1. Canadian Wood Council, Canada.

Canadian Wood Council (2002). "Wood-frame housing - A north American marvel." *Report No. Building Performance Series No. 4*.

Chaser, D., Moyer, N., Rudd, A. F., Parker, D., and Chandra, S. (2002). "Measured and simulated colling performance comparison: Insulated concrete form versus framed construction." *Proceedings of ACEEE 2002 Summer Study*, 1–10.

Ching, F. D. K. (1975). *Building Construction Illustrated*. Van-Nostrand Reinhold Co., New York.

Chusid, M. (1999). "Building with autoclaved aerated concrete." *Masonry Construction*, January, 24–27.

Construction Industry Institute (1986). *Constructability: A primer*. Construction Industry Institute.

Cramer, S. M. (2004). "Structural design and materials - Research needed to reinvent housing in the United States, Focus area 2 report." *Report No. Vol. 1*, NSF-PATH Housing Research Agenda Workshop Report.

CSSBI (1994). *An Introduction to Residential Steel Framing*. Canadian Sheef Steel Building Institute.

Department of Energy (1995). "House of straw." *Report No. DOE/GOI0094-01*, Energy Efficiency and Renewable Energy, Department of Energy, United States.

Diamond, R. C. (2001). "An overview of the u.s. building stock." *Report No. LBNL-43640*, Lawrence Berkeley National Laboratory.

Duntemann, J. F. (2007). *Building Envelope Design Guide - Cast-in-place Concrete Wall Systems*. Available at <http://www.wbdg.org/>.

Ellis, M. and Beliveau, Y. J. (2003). *Whole House Design through the Application of Multifunctional Precast Panels*. Available at <http://www.pathnet.org/>.

Faine, M. and Zhang, J. (2002). "A pilot study examining and comparing the load-bearing capacity and behavior of an earth rendered straw ball wall to cement rendered straw bale wall." *International Straw Bale Building Conference*, 1–10.

FEMA (2006). "Summary report on building performance, Hurricane Katrina 2005." *Report No. FEMA 548*.

Figueroa-Vallines, J. (2013). "Structural hardening of critical facilities for FEMA and ICC compliance." *Structures Congress*, 970–979.

Filiatrault, A. and Foschi, R. O. (2001). "Static and dynamic tests of timber shear walls fastened with nailsand wood adhesive." *Canadian Journal of Civil Engineering*, 18, 749–755.

Foam Control (2012). *Foam control R-control SIPs*. Available at <http://www.foam-control.com/>.

GAHC (2005). "A green affordable housing coalition fact sheet, wall systems." *Green Affordable Housing Coalition*, 16, 1–5.

Gajda, J. and VanGeem, M. (2000). "Energy use in residential housing: A comparison of insulating concrete form and wood framed walls." *Report No. R&D Serial No. 2415*, Portland Cement Association.

Gaudette, P. E. (2009). *Building Envelope Design Guide - Precast Concrete Wall Systems*. Available at <http://www.wbdg.org/design/>.

Goodhew, S., Griffiths, R., and Woolley, T. (2004). "An investigation of the moisture content in the walls of a straw-bale building." *Building and Environment*, 39(12), 1443–1451.

Hart, K. (2012). *Light-gauge Steel*. Available at <http://www.greenhousebuilding.com>.

Hebel (2012). *Japanese Report - Hebel Buildings in Kobe Earthquake*. Available at <http://www.hebel.co.nz/>.

Hendrickson, C. and Horvath, A. (2000). "Resource use and environmental emissions of U.S. construction sectors." *Journal of Construction Engineering and Management*, 126(1), 38–44.

Hendron, R. (2005). "Installing windows with foam sheathing on a wood-frame wall." *Report No. NREL/SR-550-37583*, Building Science Corporation, Westford, MA.

Horvath, A., Hendrickson, C., Lave, L., McMichael, F., and Wu, T. (1995). "Toxic emissions indices for green design and inventory." *Environmental Science Technology*, 29(2), 86–90.

Hubbs, E. (2003). "If walls could talk." *Nursing Homes/Long Term Care Management*, 5(6), 1–3.

Jellen, A. C. and Memari, A. M. (2013). "Residential vertical expansion of existing commercial buildings using modular construction methods." *Proceedings of the 2nd Residential Building Design and Construction Conference*, 216–229.

Johnson, C., Slawson, T., Cummins, T., and Davis, J. (2004). "Concrete masonry unit walls retrofitted with elastomeric systems for blast loads." *24th Army Science Conference*, Orlando, United States, 1–9.

Jones, B. (2002). *Building with Straw Bales: A Practical Guide for UK and Ireland*. Green Books, Totnes.

Kim, J. J. and Rigdon, B. (1998). "Sustainable architecture module: Qualities, use, and examples of sustainable building materials." *Report no.*, National Pollution Prevention Center for Higher Education, University of Michigan, Ann Arbor, MI.

King, B. (2006). *Design of Straw Bale Buildings: The State of the Art*. Green Building Press, San Rafael, California.

Klingner, R. E., Tanner, J. E., Varela, J. L., and Barnett, R. E. (2005). "Autoclaved aerated concrete: Innovative materials and civil infrastructure." *International Workshop on Innovations in Materials and Design of Civil Infrastructure*, 1–10.

Kosny, J., Petrie, T., Gawin, D., Childs, P., Desjarlais, A., and Christian, J. (2001). "Thermal mass - energy savings potential in residential buildings." *Report no.*, Buildings Technology Center, ORNL.

Lotfi, H. R. and Shing, P. B. (1994). "Interface model applied to fracture of masonry structures." *Journal of Structural Engineering*, 120(1), 63–80.

Marks, L. R. (2005). "Straw bale as a viable, cost effective, and sustainable building material for use in southeast Ohio." M.S. thesis, Ohio University, Ohio University.

Matsushita, F., Aono, Y., and Shibata, S. (2000). "Carbonation degree of autoclaved aerated concrete." *Cement and Concrete Research*, 30(11), 1741–1745.

Memari, A. M. (2012). "Comparative study of multi-hazard performance of different wall systems used in single-family dwelling construction." *6th Congress on Forensic Engineering*, 1–10.

Memari, A. M. and Chusid, M. T. (2003). "Introduction to architectural aspects and developments in research on structural performance of autoclaved aerated concrete (AAC) products." *Proceedings of 2003 Architectural Engineering Conference - Building Integration Solution*.

Memari, A. M., Solnosky, R. L., Tufano, J., and Dillen, M. (2014). "Comparative study on multi-hazard resistance and embodied energy of different residential building wall systems." *Journal of Civil Engineering and Architecture Research*, in press.

Morley, M. (2000). *Building with Structural Insulated Panels (SIPs: Strength and Energy Efficiency through Structural Panel Construction*. Taunton Press.

Moslemi, A. A. (1999). "Emerging technologies in mineral-bonded wood and fiber composites." *Advanced Performance Materials*, 6, 161–179.

Naito, C., Beacraft, M., Hoemann, J., Shull, J., Salim, H., and Bewick, B. (2013). "Blast performance of single-span precast concrete sandwich wall panels." *Journal of Structural Engineering*, 04014096(13).

Naito, C., Hoemann, J., Beacraft, M., and Bewick, B. (2012). "Performance and characterization of shear ties for use in insulated precast concrete sandwich wall panels." *Journal of Structural Engineering*, 52–61.

Najarian, E. and Aliaari, M. (2013). "Special delivery." *Modern steel construction*, November, 30–34.

National Association of Home Builders Research Center (2006). *Structural Insulated Panel (SIPs) - The Home Building Industry's 'Hybrid'*. Available at <http://www.toolbase.org/>.

Obiso, M. L. (1997). "Analysis of means and methods of construction improvement in single family housing in mid-atlantic rural university towns." M.S. thesis, Virginia Polytechnic Institute and State University, Virginia Polytechnic Institute and State University.

Ochoa, L., Hendrickson, C., and Matthews, H. S. (2002). "Economic input-output life-cycle assessment of U.S. residential buildings." *Journal of Infrastructure Systems*, 8(4), 132–138.

Omniblock (2014). *Insulated concrete block*. Available at <http://www.omniblock.com/>.

PCI (2011). "State of the art of precast/prestressed concrete sandwich wall panels, second edition." *PCI Journal*, 56(2), 131–176.

Pierquet, P., Bowyer, J. L., and Huelman, P. (1998). "Thermal performance and embodied energy of cold climate wall systems." *Forest Products Journal*, 48(6), 53–60.

Piuter, W. F. and Sherman, G. A. (2006). "Steel stud framed residences." *The Desert Contractor*, 4(27), 6–8.

Portland Cement Association (2008). *Insulated Concrete Form*. Available at <http://www.cement.org/>.

Portland Cement Association (2009a). *Building a Better House with Concrete*. Number Concrete Homes - Technology Brief No. 2.

Portland Cement Association (2009b). *Comfort and Quiet with Concrete Homes*. Number Concrete Homes - Technology Brief No. 6.

Portland Cement Association (2009c). *Concrete Homes Built-in Safety*. Number Concrete Homes - Technol-

ogy Brief No. 9.
Portland Cement Association (2009d). *Plastic Foams for Concrete Homes*. Number Concrete Homes - Technology Brief No. 5.
Portland Cement Association (2012). *Concrete Homes Built-in Safety*. Number Concrete Homes Technology, Brief No. 6.
Ramaji, I. J. and Memari, A. M. (2013). "Identification of structural issues in design and construction of multi-story modular buildings." *Proceedings of the 1st Residential Building Design and Construction Conference*, 294–303.
SafeCrete (2014). *Weather Resistant AAC Properties*. SafeCrete.
Salvadori, M. G. and Heller, R. A. (1975). *Structure in Architecture*. Prentice-Hall.
Samblanet, P. J. (1996). "Hurricane Opal's impact on masonry structures." *Masonry Today*, 6(1), 1–4.
Schnitzler, S. (2012). *Autoclaved Aerated Concrete as a Green Building Material*.
Sherwood, G. and Moody, R. C. (1989). "Light-frame wall and floor systems analysis and performance." *Report No. General Technical Report FPL-GTR-59*, U.S. Department of Agriculture, Forest Services, Forest Products Laboratory.
SipBuild (2008). *SIP Build UK: Sustainable Building Systems*. Available at <http://www.sipbuilduk.co.uk/>.
Star Craft Custom Builders (2012). *Structural insulated panels (SIP) construction*. Available at <http://starcraftcustombuilder.com/sip.htm>.
Steel Framing Alliance (2003). *Performance of Steel Framed House during the Earthquake*. Steel Framing Alliance. Available at <http://www.steelframingalliance.com>.
Steiner, B. (2007). "Making a good thing better : Foam plastics such as expanded polystyrene can greatly enhance the energy efficiency of traditional masonry." *Report no.*, Plastics Division of the American Chemistry Council.
Steven Winter Associates (2004). "Residential panels benchmark requirements." *Report no.*, U.S. Department of Housing and Urban Development, Office of Policy Development and Research, Washington, United States.
Syal, M., Hastak, M., and Mullens, M. (2004). "Housing research agenda: Summary report." *Report No. Vol. I*, NSF-PATH Housing Research Agenda Workshop Report.
Terentiuk, S. and Memari, A. M. (2014). "Seismic evaluation of structural insulated panels in comparison with wood-frame panels." *Buildings*, 4, 394–417.
Timusk, J., Seskus, A. L., and Ary, N. (1991). "The control of wind cooling of wood frame building enclosures." *Journal of Building Physics*, 15(1), 8–19.
Tool Base (2012). *Cold formed Steel Framing*. Available at <http://www.toolbase.org/>.
Triantafillou, T. C. (1998). "Composites: A new possibility for the shear strengthening of concrete, masonry and wood." *Composites Science and Technology*, 58(8), 1285–1295.
U.S. Census Bureau (2001). *Structural and Occupancy Characteristics of Housing: 2000*. Department of Commerce, Washington, United States.
Varela, J., Tanner, J., and Klinger, R. (2006). "Development of seismic force reduction and displacement amplification factors for autoclaved aerated concrete structures." *Earthquake Spectra*, 22(1), 267–286.
Wheeler, A., Ridley, D., and Boothby, T. (2004). *The Effects of Plastered Skin Confinement on the Performance of Straw Bale Wall Systems*. Available at <http://www.ccw.co.uk/>.
WSU (2011). *Building a More Efficient Future*. WSU.
Yazdani, N., Perry, S. G., and Haroon, S. A. (2006). "Large wind missile impact capacity of residential and light commercial buildings." *ASCE Practice Periodicals on Structural Design and Construction*, 11(4), 206–217.
Zhang, J. (2002). "Load carrying characteristics of a single straw bale under compression." *International Straw Bale Building Conference*, 1–8.