Comparative Study on Multi-hazard Resistance and Embodied Energy of Different Residential Building Wall Systems

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Abstract: Better performing building wall systems across building types are being requested by building owners. With the largest domain of buildings being the residential sector, there is strong support to provide a better environment. Sustainability and hazard resistance are considered to be trending and home owners or builders should be better informed. To select the proper wall and enclosure systems, there is a need for better understanding of these behaviors that will aid in selecting the final built systems. To date, there have been limited studies and very narrow viewpoints documented. Although there are many such multi-hazard and sustainability criteria, only the structural performance aspects relevant to life-safety and serviceability under natural hazards and embodied energy were looked at. This study expands upon other works to develop a broader comparison among different common residential wall systems. The presented material comes from a combination of detailed manufacturer specifications and literature reviews followed by comparative analytical study using ATHENA® Impact Estimator program for sustainability resistance. The discussion of the material is broken down into the two categories: Multi-hazard and embodied energy for insulated concrete forms, wood-frame system, Steed stud system, adobe, structural insulated panels, concrete masonry unit, autoclaved aerated concrete, and precast concrete wall systems. The results for all wall systems were compared against one another in a performance matrix table that professionals can adopt. This matrix has indicated that no one wall system is best for all situations and the primary factors are hazard type and geographic location.

Key words: Sustainability, life-cycle assessment, embodied energy, multi-hazard resistance, wall systems, residential design and construction.

1. Introduction

In new design and construction across the building industry from residential to commercial, the two areas that are becoming necessary to consider in design are sustainability and multi-hazard resistance. Each of these can have a multitude of facets to what they encompass. Sustainability can look at energy efficiency, embodied carbon and energy, recycling of materials, scoring metrics like LEED, high performance design, to name a few desirable attributes [1]. Multi-hazard resistance is equally varied and studied looking into the vulnerability of systems due to high winds (hurricane and tornados), debris impact, earthquakes, flood water effects, fire, and man-made hazards and events [2]. It is to the responsibility of the design professional to ensure that the solutions are in accordance with applicable codes and regulations regardless of the conditions incurred [3]. However, building codes do not address specific criteria related
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to the full array of different building systems and component types, nor do they prescribe guidelines for all environmental conditions [4]. This leads to the need for more studies into how wall systems behave, so that we can make better informed design decisions. Given that in recent decades there has been a significant increase in the number and severity of natural hazards [5], understanding more rigorous design metrics can provide better solutions that directly impact the economy and the environment.

Better designs lead to better resiliency which plays a crucial role in responding to and reducing devastating impacts [6]. Considering the enormous economic loss resulting from natural hazards, e.g., $12.5 billion in 2008 as a result of Hurricane Ike [7], it becomes essential to design and construct buildings and infrastructure systems to have desirable resiliency. Accordingly, 75% of the affected residential buildings and 87% of the fatalities and injuries are related to one- and two-family dwellings that experience one or more of these events [8]. National Fire Protection Association (NFPA) estimates an average of about 375,000 reported residential building fires causing 2970 deaths, 14390 injuries, and $5.6 billion property damage [8]. FEMA 548 [9] has similarly documented that during Hurricane Katrina, over 310,000 single-family houses were destroyed, major damage to over 102,000, and minor damage to over 135,000.

From an environmental standpoint, designers should choose more energy efficient materials and systems in their designs to reduce energy consumption [1]. The concept of sustainability, whether defined as the total energy consumed during a product’s life-cycle or the resultant environmental impacts, remains up for interpretation [10]. The drive towards a carbon neutral society and utilizing renewable resources places constant stress on organizations around the globe to strive to achieve an effective transition [2]. Common knowledge proves societal influences regarding clean burning fuels, atmospheric awareness of manufactories, and renewable energy conversion systems. Despite these issues, there is one aspect within our economy that creeps past the view of the public, the amount of energy that is needed to make products, before consumers use them [11].

Among sustainable initiatives, embodied energy is now starting to be used as a primary measure of sustainability and high performance for many new construction projects [2]. Analyzing the embodied energy or the total energy needed for a product (human resources, materials, required power, etc.), as well as completing a life-cycle assessment (LCA), examining the environmental impacts during a product’s lifetime, are two areas of measure necessary to provide a standard to gauge the overall energy efficiency [12]. Studies have shown that a single-family residential home can contain as much as 1000 GJ of embodied energy, or the equivalent of 15 years of operational energy [13]. Therefore, much is to be gained in the way of sustainability if the embodied energy of buildings was given greater consideration. Embodied energy is built into each individual product that goes into the construction of the home and is independent of the number of residents. Unlike operational energy, embodied energy is incurred once (except for maintenance and renovations), and can be minimized by a consumers choice in building material [13].

Despite extensive developments in building materials suitable for structural systems and innovations in construction technology, the residential building sector has not been seriously impacted or studied on these two topics [1, 2, 14]. This means that the conventional wood-frame construction after many decades still enjoys over 85-90% of the market share [15, 16]. However, there are other factors besides the initial cost that may play a role in the choice of the structural system type and construction technology. Examples of the criteria that are becoming more important for selection of a system include: energy efficiency, sustainability, indoor air quality, durability, maintenance, fire resistance and performance under natural disasters such as earthquakes, hurricanes,
tornados, and flood [6, 9, 10]. Some of these performance criteria encompass various systems in buildings besides structural. For example, energy efficiency, sustainability, indoor air quality, durability, and maintenance deal more with HVAC, lighting, glazing, insulation, and envelope materials [14].

Although comparisons of wall systems can be based on many such multi-hazards and sustainability criteria, in this paper, only the structural performance aspects relevant to life-safety and serviceability under natural hazards and embodied energy as a metric for sustainability will be discussed. Sustainability is strictly defined by a life-cycle and material analysis of the product in question relative to embodied energy. As part of this preliminary investigation study, the results summarize the appropriateness of different wall systems for single-family dwellings in a simple rating form that can allow professionals and builders to make more informed decisions about these wall systems.

2. Selected Structural Wall Systems

Although there exists many different viable load bearing wall systems that can be used for residential construction [17], only the following eight load bearing types that are more widely used compared to others are reviewed here:

- Conventional wood-frame system
- Light-gauge steel stud system
- Structural insulated panels
- Concrete masonry unit
- Autoclaved aerated concrete
- Insulated concrete form
- Adobe
- Precast Concrete Products

All of these wall system types have the ability to act as structural load resisting elements within a home. Before comparing multi-hazard resistance performances and sustainability characteristics, a brief introduction in this section will detail the system composition for the selected structural wall systems.

2.1 Wood-frame System (WF)

The conventional WF construction system is known as “platform” system where for a two-story building with basement, the first floor, which is normally made up of wood sheathing over joists, is constructed over foundation walls. The stud walls for the first story are then erected on top of the first floor, followed by a second floor built over the first story walls. The walls in this system are not continuous over multiple stories as is the case in “balloon” construction system popular prior to 1930’s [18]. The walls of the second story are then erected over the second floor, and finally the roof trusses are erected and supported on top of the second story walls. The stud wall consists of wood studs, normally 51 mm × 102 mm (2 in. × 4 in.) (in some cases 51 mm × 152 mm (2 in. × 6 in.) for exterior walls) spaced at 406 mm (16 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 [19]. Fig. 1 shows the standard construction. On the interior side, usually gypsum wall board (GWB) is used. For insulation, normally fiberglass (batt) is placed between studs.

2.2 Steel Stud System (SS)

The SS wall system emulates WF wall system and uses the same kind of sheathing for lateral load resistance (Fig. 2). SS walls are widely used in commercial buildings as partition walls as well as backup system for brick veneer type of envelope system [20]. Besides stud wall application, SS can be used to construct floors and roof trusses as in conventional WF system [21].

Fig. 1  Wood stud system (by author).
2.3 Structural Insulated Panels (SIPs)

SIPs are sandwich panels consisting of two structural boards with a center rigid insulation [22]. 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. 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 (Fig. 3).

2.4 Concrete Masonry Unit (CMU)

CMU can be used to construct the walls of a house. Currently, CMU is widely used as the basement wall, but it can also be the load-bearing above grade walls of residential buildings as is commonly used in construction of low-rise department stores and other low-rise commercial buildings [23] (Fig. 4). The conventional size of CMU block is 203 mm × 203 mm × 406 mm (8 in. × 8 in. × 16 in.). Load-bearing CMU wall can be designed as unreinforced masonry or reinforced masonry. CMU is known to have high fire-resistance, low maintenance, and high durability [24].

2.5 Autoclaved Aerated Concrete (AAC)

AAC is a highly lightweight concrete with significant air volume or pores that gives it its lightness [25]. A block form is conventionally used for residential building construction (Fig. 5). Besides being lightweight, 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 as a cake and create a cellular structure [26].
2.6 Insulated Concrete Form (ICF)

ICF developed in Europe over three decades ago 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 [27] (Fig. 6). The foam can be expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PU), or a cement-foam composite. The forms can be interlocking modular units and dry-stacked to desirable height. Once the reinforcement is placed within the form, concrete is poured. This wall system brings significant insulation property to reinforced concrete walls and can be used as foundation as well as above grade walls (Fig. 6). Besides insulation and sound barrier, the form provides a backing for GWB on the interior side and stucco or veneer on the exterior.

2.7 Adobe

Adobe brick (Fig. 7) is made from a mix of clay, sand, aggregates, water and straw (for strength) and is molded and sun dried [28]. The mortar for adobe is also of a similar mixture as the bricks. In modern uses of adobe, some cement stabilizer may be used. Adobe is considered to be a highly sustainable material [24] and this is one reason for some renewed interest in this indigenous material [29]. Its use in the U.S. has been limited to southwest regions, but it is widely used in rural areas of most under-developed and some developing countries where bamboo or other materials may also be used as joint reinforcement [30].

2.8 Precast Concrete Panel (PCP)

Precast concrete panels (PCP) have been around for some time, mostly on larger scale projects (Fig. 8). PCPs are constructed by concrete molds specific to the wall location needed and most are solid, while some can have hollow cores. 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 required [31]. Precast concrete panels are recyclable and embody considerably less energy with respect to other concrete-based systems [32].


For any new wall system to be embraced by builders as an alternative to the conventional wood frame construction, certain attributes should provide advantage over what wood frame offers. This is especially true for attributes such as cost, speed of
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construction, energy efficiency, durability, aesthetics and more importantly, resistance under different man-made or natural hazards. This portion of the paper details different commonly available load-bearing wall systems made of different materials for residential homes that builders or building owners may choose from when building or remodeling.

3.1 Wood-Frame System Resistance

WF system has 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. With respect to fire resistance, WF walls that include GWB can be designed to provide acceptable fire resistance. WF with GWB is expected to have a 45 minute fire rating. In general, the thicker the wood member, the better its performance in fire because of the char layer that forms to protect the inner parts of the wood.

Major cause of wind storm damage to WF systems in the past has been inadequate roof-to-wall attachment and insufficient roof sheathing panels-to-framing connections. Besides direct wind pressures, flying debris during storms are another source of damage to WF residential buildings. According to a literature review by Sherwood and Moody [33], WF houses are expected to handle lateral loads equivalent to wind speeds up to 193 km/hr (120 mph). Tests per Florida Building Code have shown that a 4.08 kg (9 lb), 51 mm × 102 mm (2 in. × 4 in.) wood stud projectile with a velocity of about 55 km/hr (34 mph) will penetrate a WF system with plywood or OSB sheathing and stucco on the exterior [34].

According to Canadian Wood Council [19], WF construction is one of the safest building systems during earthquakes, because of a light weight, high strength-to-weight ratio, redundancy, and nailed connections that generate significant energy dissipation. This does not mean the building will not sustain damage. In fact, damage could be extensive but not life-threatening. According to EERI [35], the Northridge Earthquake caused extensive damage to WF construction but minimal structural damage. Examples of such damage include sliding of building off of foundation due to poor sill plate anchorage and cracking of building walls because of WF flexibility.

3.2 Steel Stud Framing Resistance

The use of SS in load-bearing walls is relatively new in residential construction and is yet to be widely recognized, but its use in home building is met with more interest recently because of demand for green buildings [36]. Some of the attractive properties of SS systems include its high strength-to-weight ratio, dimensional stability, and lack of warp, split or twist due to moisture conditions. The strength of SS does not have variation for a given gauge because of the manufacturing process. The high strength-to-weight ratio and inherent ductility potentially make SS system appropriate for seismic regions [37] subject to adequate design and detailing.

With respect to performance under hurricanes and tornado winds, the same issues that exist for WF system would be true for SS system as well. According to Yazdani, et al. [34], missile impact tests have shown that the same type of projectile can penetrate a SS wall. However, according to Hubbs [38], SS wall construction was perforated by a wood stud at 82 km/hr (50.9 mph) speed, almost 25% lower than that perforating WF. Even though steel is non-combustible, it can lose its strength at high temperatures.

3.3 SIP Resistance

SIPs are known for their strength because of the composite sandwich structure. According to Morley [39], 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 from the rest of the panel, and thus no pressurization of the attic
and subsequent damage to structural system can occur as in conventional WF. There are not many evidences of the performance of SIP houses in earthquakes, but it is reported [40] that their performance during the 1995 Kobe, Japan earthquake was favorable and survived the earthquake relatively undamaged. SIP panels on the other hand are made of wood and foam components that are flammable, and therefore, the interior side should be protected using GWB. In general, 13mm (½in.) thick GWB layer provides 15 minutes of fire rating, while two layers provide one hour [41].

3.4 Concrete Masonry Unit Resistance

Yazdani, et al. [34] 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 [42] 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.

3.5 Autoclaved Aerated Concrete Resistance

Although entered the U.S. market in 1995, AAC is still considered a relatively new material for builders. AAC has a much smaller compressive strength compared to normal concrete [43]. Depending on the density of the material (3 to 10 kn/m³ or 19 to 62 pcf), the compressive strength can be 15% to 35% that of concrete. According to Hebel [44], the performance of AAC building during Kobe Earthquake has been very good. Aecrete [45] and Sungarden [46] mention the satisfactory hurricane wind resistance of AAC homes. Furthermore, because the material is non-combustible, it provides an inherent fire-resistant structural system. According to Aecrete [45], 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 wood-based systems. Yazdani, et al. [34] also tested AAC walls for missile impact and found that there was no penetration thus AAC passed the test, but there was minor cracking.

3.6 Insulated Concrete Form Resistance

Because of the strength and monolithic construction properties of cast-in-place concrete used in ICF, it gives desirable structural integrity. Residential buildings constructed using ICF systems are expected to perform exceptionally well during wind storms and hurricanes. For example, PCA [31] reports that projectiles with a velocity of 167 km/hr (104 mph) have not been able to penetrate ICF system and that it survives 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. GAHC [47] discussed the advantages of ICF with regard to seismic and high wind performance, noting such systems have performed very favorably to resistance and human safety. Although the concrete core of the ICF can have fire-resistance rating of up to 4 hours [38], the foam forms are flammable, and therefore, GWB is needed on the interior side to achieve proper fire rating [31].

3.7 Adobe Resistance

Older type Adobe construction is associated with many disadvantages such as large weight, low strength, and brittleness that makes traditional Adobe construction is extremely vulnerable to damage in earthquakes. With renewed interest in the use of Adobe in some sustainable design circles, modern Adobe brick and mortar may include stabilizer cement or asphalt emulsion. In severe earthquakes around the world, many masonry structures built from Adobe have seen major cracking and even failure [48]. Many of these structures were built out of Adobe brick walls.
because of the availability of the material or the sustainability of the Adobe but neglected the structural behavior of the material. Of course, if cement stabilizer is used in the units and mortar and proper detailing is employed, even Adobe construction can be expected to perform as well as more engineered masonry systems [49].

3.8 Precast Concrete Panel Resistance

Precast concrete panels provide a benefit to the building as a whole under earthquake loading. Baird, et al. [50] found that panels used as wall enclosures increase the overall strength of structural system between 10-20%, depending on the panel composition and connection to the structure. From a fire resistance standpoint, 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, as this is what the fire ultimately damages. 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 [51]. The PCP itself in areas of flooding is not the issue if certain admixtures are provided in the mix to prevent water penetration. The more significant issue is the joints and sealants used between the panels, because if they do not provide waterproofing as expected, then water will penetrate and cause damage. An additional advantage that PCP has is that when damaged, individual panels can be replaced and not the entire walls [52].

4. Embodied Energy Analysis of Alternative Wall Systems

With the performance of different wall systems and their resistance to multi-hazard effects discussed as a preliminary review, this section of the paper deals with sustainable attributes of the chosen wall systems in regard to embodied energy, a metric that is robust for looking at the material aspect of load bearing wall systems.

4.1 Sustainability Basics

Efforts in the building industry to increase building energy efficiency and overall building sustainability are motivated by the goal of reducing the amount of greenhouse gas emissions (carbon dioxide and others) by processes and building operations [53]. To implement sustainability into life-cycle of design and construction, Life-Cycle Assessment (LCA) has become a standard tool in design. LCA is a method that considers a range of environmental impacts of a product over a span of its life-cycle stages [12]. US Department of Energy [54] has estimated that 40% of the country’s primary energy use comes through buildings and any method to reduce energy usage is promoted. Though a majority of this is operating energy (energy that is consumed during the building while it is in use), the materials used to construct a new building have an inherent environmental cost [55].

One of the challenges in sustainable development movements has been defining metrics that more effectively aid in making decisions and how they affect the environment [56]. More recently, embodied energy is starting to be used as a measure of sustainability and high performance attributes. Previous research by Hsu [57] has shown that the embodied energy of a building is only a fraction of the operating energy, yet it plays a critical role when operating energy can no longer be optimized. Embodied energy refers to all primary energy consumed throughout the life-cycle of a building, whether directly or indirectly; this is often referred to as the “cradle to grave” assessment [53]). However, in some cases, the energy used to manufacture the product and ready to leave the factory is referred to as “cradle to gate” part of the energy [10, 58]. The energy is accounted for within the lifecycle during the following stages: extraction/harvest of raw materials, refining, manufacturing of building materials and products, construction activities, renovations and alterations, demolition and disposal, and transportation associated with all of those stages [59]. By focusing
on the embodied energy rather than the operational energy, the inherent sustainability of a building can be assessed to a greater degree of accuracy [11].

By knowing what materials contain the lowest embodied energy, a builder or a homeowner can make a better decision when the time comes to build a new sustainable home. Limited studies are available that focus on properties related to embodied energy. In the following sections, the wall systems previously mentioned are reviewed further to see how they perform against one another from an embodied energy standpoint. Wall systems without windows and with windows were investigated in addition to their comparison if constructed in different geographic locations.

4.2 Methods to Analyze Systems for Embodied Energy

Traditionally, the most popular methods of calculating embodied energy in buildings have been “process analysis” and “input-output analysis”. Due to the wide range of products and processes that go into the construction of a home, many of these techniques have proven to be insufficient. More modern analytical platforms are becoming popular in calculating the embodied energy within a system; in particular, for this study, ATHENA® Impact Estimator [60] was used.

Process analysis involves gathering a bill of materials from architectural plans or specifications using manufacturer’s data and approximate energy requirement on a per unit mass basis for each respective manufacturing process. Extensive assumptions are made in this method due to the lack of data on these procedures. A material energy intensity database is then used to approximate the embodied energy in the materials by multiplying the database values (e.g., MJ/kg for each material) by the required amounts of the materials [61]. Input-Output analysis, on the other hand, utilizes national energy data and then groups the requirements into various sectors including construction, appliances and transportation. Each of these sectors has a respective energy intensity and total energy intensity used in the product. Each material is classified into a sector and then estimated. This method traditionally ignores the energy input from the machinery used to produce the goods, which is generally high for cement-based products [61].

ATHENA® Impact Estimator (a material and system analysis program) allows a user to analyze various parameters including energy consumption, global warming effects, and ozone depletion. Developed jointly by the ATHENA® Institute and Morrison Hershfield Consulting Engineers, the software includes a large selection of common building materials and envelope choices [60]. The program takes several lifecycle stages into account including: material manufacturing, transportation, construction, regional energy use, building type and lifetime, maintenance, demolition and disposal. Using location based data; the program is able to estimate the transportation costs associated with conveying the materials to the location of construction [60].

4.3 Wall Systems

Within this study, the load bearing wall systems defined previously were comparatively reviewed to effectively evaluate the overall energy benefit. The incorporation of wood stud walls, steel stud walls, structural insulated panels, and precast concrete panels into the ATHENA® Impact Estimator software, allowed setting the standard of measure for each wall system in question. The composition of the wall systems within ATHENA® was carefully considered, as not all of the materials to be discussed herein are preset standards. Detailed first in this section are the assumptions that went into the simulations. The model itself, shown in Fig. 9, represents a two-story residential home with both a basement and garage and with gross floor area of 207 m$^2$ (2232 ft$^2$). The home utilizes 27,300 kWh of electricity annually, with a life expectancy of 60 years.
Fig. 9 Model of the home for the simulations (by authors).

CMU has a predefined model in ATHENA® and therefore no modifications are needed when modeling. The envelope over the exterior side of the CMU wall and the interior finish was chosen to include the most common types of finishes and insulation containing a concrete brick veneer, 13 mm (½ in.) gypsum board, 51 mm (2 in.) of polyisocyanurate foam insulation, a 6 mm polyethylene vapor barrier, 13 mm (½ in.) air barrier, and latex water based paint.

AAC is not one of the predefined wall structures found within ATHENA®. For this analysis, it was modeled as a 200 mm thick, 20 MPa compressive strength tilt up concrete wall with 35% fly ash without consideration of aluminum powder in the mix. The thin depth and high fly ash content are used to give the structure a more lightweight attribute. Additionally, AAC often comes in 6.1 m (20 ft.) long panels, which will be approximated as a large tilt up concrete structures. This assumption is also reasonable because AAC requires additional concrete structural support. The envelope was chosen to contain an outer layer of stucco, 13 mm (½ in.) gypsum, 6 mm polyethylene vapor barrier and latex water based paint.

ICF’s are a predefined building material within ATHENA®, and therefore no assumptions are needed in their modeling. In this analysis a layer of stucco is used on the outside, while 13 mm (½ in.) gypsum and water based latex paint is used on the interior.

ATHENA® does not contain a predefined Adobe wall configuration, and therefore several assumptions were made in its modeling. The envelope chosen is traditional clay brick veneer which has a similar thermal efficiency to adobe. Also, the construction of brick walls is done in much the same way as an adobe house is made, where the adobe is formed into rectangular units and then connected using grout. Additionally, a 13 mm (½ in.) gypsum board and latex water based paint is applied to the interior. Adobe also has higher maintenance costs due to the upkeep required on the earthenware materials [11].

For the embodied energy portion of this preliminary study, the wall types were broken into two groups. These groups are: panelized systems including the wood and steel studs (as they can be panelized) and the masonry unit systems. This separation allowed comparison of wall with similar construction methods, while also allowing a comparison between each construction method.

4.4 Embodied Energy of Walls with no Windows

Wood stud walls proved to require lesser amounts of energy during lifecycle stages due to materials being available in nature, where manufacturing is minimal. The lumber used within the wood stud applications is traditionally kiln-dried, which refers to the drying method when the wood is force dried in order to reduce issues caused by the inherent moisture in wood products. A comparable product, green lumber is also often used in wood-based structures, where the lumber used is recently cut and naturally dried. A comparison between green and kiln was carried out where the only difference was in the manufacturing energy. Kiln-dried lumber requires 510 GJ of energy as compared to green lumber at 507 GJ, a 3 GJ difference due to drying techniques.

Aggregate based materials (concrete and cements) are produced in a very energy intensive manner. The materials must be extracted from the earth and then processed in high temperature kilns. These kilns are most often times coal fired, which further increase fossil fuel consumption and the associated negative impacts. CMUs require the additional process of forming the concrete into symmetric units, and therefore consume the second most fossil fuel in their
production. AAC contains a large amount of air, and thus requires the least amount of fossil fuel because it contains the lowest percentage of cement per unit area.

The adobes walls, not surprisingly, have minimal fossil fuel consumption in the manufacturing stage, since they are sun dried. Energy consumption for transportation though can be higher due to where these units are produced may not be local. The ICF system, in addition to a large amount of concrete, also requires synthetic insulation in large quantities causing this system to require the most fossil fuel.

The PCP systems are thought to have the greatest levels of fluctuation for construction, maintenance, and end of life embodied energies, as they roughly require 24% more embodied energy than the wood stud home. These higher levels can be explained by the procedure in which PCP are incorporated into residential structures. Since PCP systems needs to be cast at a plant, then delivered to the building site, the inherent construction as well as demolition energy costs to implement these sizable panels is greater than other wall systems.

Both the PCP and SIP homes require a considerable amount of energy in order to manufacture and implement, while the wood and steel stud homes demonstrate lesser amounts of required energy by 18%. Fig. 10 compares the embodied energy of precast concrete and the wood and steel material based wall systems, as an example comparison of an aggregate based material, with wood stud, steel stud, and sandwich SIP panels. The maintenance, end of life, and annual operating energy categories remain constant for each of the basic wall systems (wood, steel, and SIP). Construction is nearly the same for wood and steel studs including SIPs (45 GJ) but for PCPs the energy is 80 GJ, a 43% increase. This can be attributed to the need for more industrial machinery to install the system, while the others are capable of being manually constructed. In looking at steel stud and SIP systems, they are at a comparative level to be beneficial to greenhouse gas emissions reduction. Renewable wood stud walls reduce carbon dioxide emissions (not plotted) by nearly 38% when compared to a precast concrete home.

For all wall systems, the manufacturing stage is responsible for the largest amount of fossil fuel consumption. Construction also has an impact because of the machinery required to put the heavy masonry units into place. The end of life stage is relatively low because the materials within the wall can be disposed of in a landfill without any additional processing necessary. The finished products must then be transported to the construction site, requiring diesel powered trucks, trains or ships.

![Embodied energy comparison between PCP, WF, SIP, and SS.](image-url)
4.5 Embodied Energy of Walls with Window Considerations

Window applications and considerations have a substantial effect on energy consumption during lifecycle stages. As such, it was felt that this may also have an effect on embodied energy so a comparison between solid walls (no windows) and walls containing windows were compared. To model these, ATHENA® was used again and the wall was based solely on the exterior first story wall with and without windows. Polyvinyl Chloride (PVC) framing was used around each window with Low-E Tin Argon Filled Glazing. Pittsburgh, PA USA was the location assumed for the comparison. The annual operating energy was not considered in this case, since as mentioned earlier, it is not assumed to fall under the category of embodied energy.

For ATHENA® analysis, 14 windows were chosen based on the number of windows in typical homes of equal size for this study; this resulted in a total window area of 21.5 m² (231 ft²). Fig. 11 (a) and (b) shows the embodied energy in GJ for each wall system with and without a window in place to show the effects of windows. In all cases, the addition of a window affects the energy consumption for maintenance by an increase...
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in the range of 78-97%, while for manufacturing the increase has a wider range of 9-38%. The results here reflect the window quantity chosen for this study, and these numbers can change if different window types and quantities are selected. If the window had been installed after the completion of the project, these costs would have gone up due to the difficulty of adding an opening in the materials; yet this was not possible to simulate in the software. The end of life energy consumption is also constant with and without windows for each wall type yet remains different between wall systems.

For all wall systems, the manufacturing stage was responsible for the largest amount of embodied energy consumption. The production of aluminum and glass requires energy intense processes, which accounts for the added manufacturing stage fossil fuel consumption. Additionally, there is a certain amount of upkeep required on window systems, which is reflected in the increased fossil fuel consumption associated with the maintenance stage of the wall with window analysis. Manufacturing requirements increased by an average of 13% across wall systems based on the additional energy used for the windows. Maintenance energy requirements are also increased by an 83% average across the wall systems. This is attributed to energy loss around and through including the upgrades needed over time for new sealant and window replacements. The PVC framing production of essential plastics and coatings needed for windows is relatively high in the impact on embodied energy based on comparisons in Fig. 11.

4.6 Embodied Energy and Location Variance

Site location and locally available resources also contribute to embodied energy modifications. In order to gain a fundamental understanding and to compare the effect of geographical location on fossil fuel consumption, a residential home built in Pittsburgh, PA, USA was compared to that of the same model relocated to Los Angeles, CA, USA. This variation will allow for testing of material availability, transportation, and construction methods impact into the embodied energy. Simulations were run to fully examine each lifecycle based on the same configurations with the only variance being the location. By analyzing the energy consumption of an entire house, a more realistic comparison could be made between varying wall structures. The integration of a foundation and roof has various implications, which would have affected the results. To minimize this, these areas were not modeled except for the mechanism that connects the two. For both locations, simulations were run with homes constructed of CMU, AAC, ICF, Adobe, and standard 51 mm × 102 mm (2 in. × 4 in.) wood stud construction.

When comparing the two locations, it can be seen that CMU wall systems have significantly higher fossil fuel consumption for the Los Angeles location at 1.9 GJ compare to 1.18 GJ in PA (Fig. 12 (a) and (b)). Based on Werner and Burns [53], this is most likely attributed to the fact that the east coast is more plentiful in cement plants, and that CA must import the concrete cement and aggregates a farther distance driving up transportation embodied energy. AAC walls have similar fossil fuel consumption regardless of location. The manufacturing energy for both CMU and steel stud systems increase (42% and 27%) when the home is relocated to CA. This increase can be contributed to concrete and steel industries being more centralized around the eastern coast of the United States.

Regardless of the system considered, the manufacturing stage has the highest fossil fuel consumption. CMUs are the highest fossil fuel users in both locations due to the energy intensive process of producing concrete block. ICFs contain the second highest fossil fuel consumption because this type of structure is primarily composed of concrete. The construction methods for the wall structures only slightly vary due to the similar processes and equipment used. Except in the case of CMUs in Los Angeles, where a higher input of fuel is necessary for
construction [61, 62], the operational energy consumption of each building is the same regardless of the type of wall used due to the thermal capacity of the masonry type structures and the additional insulation in the envelopes.

By using the wood stud home as a basis, the difference in percentage of fossil fuel used can be seen in Fig. 13 where 100% is the wood stud home baseline. This baseline was chosen because it is the most widely used form of residential construction in North America. While CMU and AAC homes have slightly higher values overall (1.33 time larger for both), Adobe and ICF have relatively the same embodied energy as the wood frame (90% and 95% of wood in CA) based on the tradeoffs between maintenance, manufacturing, and materials (Fig. 13). Furthermore, the transport distance required for these materials likely played a role and could change as new plants and factories open and close. Since the assumptions made are reasonable for this type of analysis, it can be inferred that these wall structures have comparable fossil fuel consumptions with the wood frame design. The results presented here support the justification as to why the majority of homes are constructed with wood frame systems as only two systems (Adobe and ICF for CA) scored lower than the baseline in both locations. Now depending on the location, there are possible benefits for choosing an alternate load bearing wall system such as Adobe (with a 90% of baseline in CA and 106% in PA) and AAC (with a 101% of baseline in CA and 133% in PA) (Fig. 13 (a) and (b)).
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(a) By Lifecycle Stage for PA

(b) By Lifecycle Stage for CA

Fig. 13 Embodied energy for by lifecycle phase for various wall systems (with wood being the baseline).

When all forms of energy input are considered (hydro, nuclear, etc.), the results are slightly different. It then becomes necessary to consider the contribution of other sources of energy besides fossil fuel consumption in estimating the overall embodied energy of these structures. Table 1 contains summations of all sources of energy input for both locations for different lifecycle phases. Instead of ICF requiring the most energy, based on the volume of concrete, CMUs at both locations has the most embodied energy (2.70 GJ for CA and 1.94 GJ for PA). This is attributed to the drying of the units in production as being an extra component where ICF does not have this stage (ICF ranks second).

Additionally, the wood stud system has the lowest energy consumption in Pittsburgh (1.66 GJ for PA) due to the abundance of local lumber yards, while adobe has the lowest in Los Angeles (1.84 GJ for CA) due to natural materials being closely available.

4.7 Comparison in Embodied Energy

Based on the results presented in Figs. 10-13 and Table 1 on the embodied energy of these load bearing wall types under different conditions, it is evident that the embodied energies of each wall system, whether comprised of concrete, polymer foams, steel, or traditional wood, vary with great discrepancy from 90% to 161% of a wood baseline. Fig.14 illustrates the
Table 1  Embodied energy for east coast vs. west coast.

<table>
<thead>
<tr>
<th></th>
<th>Embodied energy consumption for material (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CMU</td>
</tr>
<tr>
<td>For Pittsburgh, PA</td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td>1.140</td>
</tr>
<tr>
<td>Construction</td>
<td>0.062</td>
</tr>
<tr>
<td>Maintenance</td>
<td>0.700</td>
</tr>
<tr>
<td>End-of-Life</td>
<td>0.034</td>
</tr>
<tr>
<td>Total</td>
<td>1.936</td>
</tr>
<tr>
<td>For Los Angeles, CA</td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td>1.670</td>
</tr>
<tr>
<td>Construction</td>
<td>0.285</td>
</tr>
<tr>
<td>Maintenance</td>
<td>0.700</td>
</tr>
<tr>
<td>End-of-Life</td>
<td>0.048</td>
</tr>
<tr>
<td>Total</td>
<td>2.703</td>
</tr>
</tbody>
</table>

Fig. 14  Embodied energy by material composition.

Figures the range of the embodied energy for the PCP, SIPS, steel stud, and wood stud wall systems. As the figure shows, wood studs require the least embodied energy. Differences between non-renewable materials (ICF and Adobe) and renewable materials (wood and steel) can be distinguished, based on this preliminary study.

The wall systems composed of renewable materials require roughly 24% less embodied energy when compared to non-renewable materials for baseline walls with no openings. Such a difference is due to the energy-intensive manufacturing of non-renewable sources, which result in both greater emissions as well as greater costs for production of materials. On comparison, wood stud wall systems require 15-16% less total embodied energy than thermally comparable homes employing alternative steel or concrete based systems [62]. Renewable materials require roughly 2% less embodied energy than non-renewable systems with solid walls. With the inclusion of windows, 62% less embodied energy is required in solid walls as compared to walls with windows. Since the number of windows directly affects embodied energy (the more windows the higher the energy), then a limitation should be put on the number of openings within a home to limit the amount of extra embodied energy added to the system. This is a viable option to reduce the overall energy impact if the design is exclusively focused towards embodied energy. However, if a more holistic scope is conducted, say looking at day lighting the results, then the energy impact may be different, particularly in the operations phase of the lifecycle [14].

The procurement of energy during manufacturing and also for maintenance of the system during the life-cycle was clearly identified as the leading impact mechanisms that defined the embodied energy for the systems. Improving of these aspects can prove beneficial to minimize the carbon dependence throughout all stages within a products lifecycle as new projects are developed. It is clearly discernible that residential homes composed of non-renewable
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Materials have a higher impact on energy emissions during lifecycle stages that contribute to the greenhouse gas effect as compared to renewable materials. Based solely on an embodied energy and life cycle assessment of various wall systems, it can be concluded that wood stud wall systems demonstrate the most sustainable properties. Despite the sustainability of a building material, there are many factors that need to be taken into consideration for a more complete understanding to select the overall best system.

5. Overall Wall System Discussions

With the attributes of the chosen load bearing wall systems now reviewed based on literature for multi-hazard resistance and evaluated for embodied energy, a matrix (Table 2) was developed to suggest a rating of the performance of the systems in a side-by-side manner considering both performance aspects. The values assigned in the matrices are subjective as more quantitative research is needed to develop a more objective ranking system. More refined ratings can be developed by conducting surveys and averaging the rating values suggested by professional and manufacturers.

The different wall systems mentioned here for residential homes take on a variety of attributes from a sustainability aspect and from a multi-hazard resistance. In each respected category, comparatively, there are clearly systems to provide the best lifecycle performance. 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).

Across the board, ICFs are the best to provide resistance to hazards. On the other hand, ICFs fall in the middle of embodied energy consumption (171 GJ below the average of all walls at 2,500 GJ by Fig. 13), which can be attributed to the embodied energy from the production of the cements and the insulation materials. Another example is wood frame walls, where from sustainability and embodied energy standpoint, it is one of the best systems (15-24% energy reduction); however for hazards they are only superior for earthquakes. These examples and others discussed show that what is best for one wall system is not necessarily the best for all wall options based on multi-criteria metrics.

<table>
<thead>
<tr>
<th>Wall type</th>
<th>Tornado</th>
<th>Hurricane</th>
<th>Flood</th>
<th>Earthquake</th>
<th>Fire</th>
<th>PA</th>
<th>CA</th>
</tr>
</thead>
<tbody>
<tr>
<td>WF</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>III</td>
<td>III</td>
</tr>
<tr>
<td>SS</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>II-III</td>
<td>II-III</td>
</tr>
<tr>
<td>SIP</td>
<td>2-3</td>
<td>1-2</td>
<td>1-2</td>
<td>2-3</td>
<td>1</td>
<td>II</td>
<td>II</td>
</tr>
<tr>
<td>CMU</td>
<td>2-3</td>
<td>2-3</td>
<td>3</td>
<td>1-2</td>
<td>3</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>AAC</td>
<td>2-3</td>
<td>1-2</td>
<td>1</td>
<td>2-3</td>
<td>3</td>
<td>II</td>
<td>II</td>
</tr>
<tr>
<td>ICF</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2-3</td>
<td>3</td>
<td>I-II</td>
<td>I-II</td>
</tr>
<tr>
<td>Adobe</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>II</td>
<td>II-III</td>
</tr>
<tr>
<td>PCP</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2-3</td>
<td>3</td>
<td>I</td>
<td>I</td>
</tr>
</tbody>
</table>

3-level multi-hazard rating where: 1=poor, 2=average, and 3=good;
3-level embodied energy rating where: I=poor, II=average and III=good;
PA is Pittsburgh embodied energy rating and CA is Los Angeles embodied energy rating.
To understand these 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. It was observed that the embodied energy changes for different locations and so do the hazards. Tornados often do not happen in Maine but do in Kansas. Looking at local conditions will help to narrow down the options to select from. 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.

6. Conclusions

Several concluding remarks can be drawn from the literature review and from this study with regards to embodied energy and multi-hazard resistance:

Considering multi-hazard resistance:

The residential buildings suffer moisture penetration that normally leads to rotting of WF members and mold growth but there is not significant structural damage in flood situations.

With respect to high winds, the main failures result from connection failure between elements, debris impact, and envelope breaching.

In seismic applications, nearly all wall systems function well except for CMU (in particular unreinforced) and adobe. 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.

Considering embodied energy:

Geographic location, in particular, related to material availability in the region can significantly drive the manufacturing and the construction energy due to transportation from material source to plant and plant to construction site.

Maintenance energy requirements also increased by an 83% average across the wall systems when windows were used; this is attributed to energy loss around and through them including the upgrades needed over time for new sealant and window replacements.

Energy consumption in the manufacturing stage of the lifecycle is the highest followed by maintenance stage of the lifecycle. Energy in these phases is independent of location except for the transportation components in manufacturing.

Concrete Masonry Units contain the most embodied energy due to high manufacturing energies through material production and supportive equipment. Traditional wood-frame designs provide the lowest embodied energies based on their low manufacturing and construction efforts in the field and in the lumber plants.

Considering both metrics:

Wood and Steel stud framed walls have the most contradictory performance and conflicting attributes as they are excellent for energy yet perform the poorest across multiple hazards.

In earthquake hazard zones the best system for both sets of performance is with wood or steel studs as both have high performances.

When high wind hazards are the dominating factor then the most comparative system energy wise is AAC.

For flood and fire situations the best matching wall type would be ICF. ICF was chosen as it has lower energy consumption than PCP.

The concluding remarks presented provide a good indication into how each wall system performs for the various metrics. The metrics presented here (embodied energy and multi-hazard resistance) should not be used as the sole criteria for selecting a wall system in new construction situations though. Many other factors impact the environment and human well-being besides embodied energy and multi-hazard resistance; these include: resource use, smog potential, respiratory effects, global warming potential, thermal comfort, day lighting, insect infestation, mold resistance, and aesthetics. 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 the various materials, composite systems that utilize multiple of these systems, and a more robust simulation tool based on a large research database. Moving away from the current scope, studies should also include the comparison of parameters like: thermal performance, moisture response, and product repair.

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