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Affordable, safe housing based on expanded polystyrene (EPS) foam and a cementitious coating

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Abstract This paper describes an ongoing project to demonstrate an affordable, safe, and energy-efficient housing technology based on expanded polystyrene (EPS) panels with a cementitious coating. The concepts being described are (1) EPS panels embedded with galvanized steel trusses, steel mesh welded or clipped to the protruding points of the trusses and finished with a coating of cement plaster; (2) fiber-reinforced cement board panels and a core of EPS, glued together with high-strength adhesive, dried under high pressure, and connected with cellulose fiber cement board splines; and (3) EPS panels coated with a fiber-reinforced composite. The scope of this project is to model energy flows, analyze costs, simulate seismic forces, test against environmental conditions, and build pilot houses initially in California, Texas and Afghanistan. Results from air quality and energy flow analyses, preliminary cost modeling, structural calculations, and fire testing are reported. The performance goals address seismic safety; energy efficiency in extreme temperatures to reduce fuel use and indoor air quality hazards; affordability and simplicity of construction, as well as ease of expansion for future development; local employment opportunities and small-scale capital investments; and finally, cultural acceptance through education and adaptation to traditional architecture.

Introduction

Housing plays a central role in improving the quality of people's lives in both developing and developed countries. Safe and affordable housing provides personal, social, and economic benefits. Most directly, housing contributes to the health and safety of individual inhabitants. Housing re-anchors the homeless in the community and mobilizes those traumatized by a disaster, impacts especially important in a post-conflict situation. Housing also offers families a platform for economic recovery and is a means of employment generation, requiring intensive unskilled labor and local capital investment.

The approach of this housing project is to scientifically and objectively evaluate available housing designs on the basis of cost-effectiveness, seismic safety, energy-efficiency, and sustainability, in order to address the range of housing needs throughout the world. Though efforts have been directed towards demonstrating this new building technology in Afghanistan, in partnership with Shelter for Life International (SFL), and in California and Texas, with funding from the California Energy Commission (CEC) and the Department of Energy (DOE), the guiding performance goals are framed for worldwide application.

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According to the US Energy Information Administration (EIA), the average US household spent, in US Dollars (throughout the paper all dollars are US Dollars), about \$1,300 on 101 million Btu (1.07×10^8 kJ) of site energy, or the energy consumed within a housing unit, in 1997. Space heating accounted for 30% of that cost and half of that amount of energy [1]. In the US, the EIA estimates an average growth rate of 1% per year in energy consumption for 2001–2025. By 2020, the projected residential energy demand in the US is 24.5 quadrillion Btu (2.59×10^{12} kJ) [2]. Hence, the CEC and the DOE are particularly interested in developing energy efficient housing in the US.

This paper presents a rigorous list of performance goals intended to objectively evaluate available housing technologies. These specifications are applicable to both developed and developing countries in a range of environmental and economic settings, and call for materials and designs that promote health and safety while addressing cost and architectural design preferences.

Characteristics defining ideal technologies include:

- Affordability: housing should be cost effective for residents, including building cost, maintenance cost, life-cycle cost, and resale value.
- Energy efficiency: materials should have excellent insulation, offering higher comfort in extreme temperatures with minimal use of costly or scarce fuel sources.
- Durability and safety: technology should be capable of retaining structural integrity under seismic activity and natural hazards such as strong winds, fire, pests, and moisture. Any damage should be superficial and simple and inexpensive to repair. Architectural designs should promote good indoor air quality, providing adequate ventilation and air flow.
- Economically viable and beneficial: material manufacturing and housing construction should utilize intensive unskilled local labor, encourage realistic capital investments in the region, and take advantage of locally available materials.
- Cultural Acceptability: material appearance and housing designs should mimic local traditional architecture and be attractive to inhabitants.
- Rapid applicability: housing design and construction requirements should be simple enough to use as a post-emergency shelter and competitive in quality and cost with winterized tents.
- Adaptability: housing materials and designs should be easily altered to adjust to changing needs of growing families by easily transforming emergency shelters into larger permanent houses. Homes should be expandable when resources become available, especially in markets where loans and financing are unavailable.
- Environmental sustainability: materials should be resource efficient, using minimal or no wood and producing minimal waste.
- Non-proprietary: technology should use simple housing design concepts in order to significantly reduce costs.
- Easy maintenance: maintenance of technology should be simple and use readily available materials.
- Reproducibility in other markets: materials should be available worldwide, with minimal imports, and realistic capital investments in facilities employing local labor.

Afghanistan

Twenty-six years of almost continuous warfare coupled with major earthquakes in the past decade have damaged or destroyed much of the housing stock in Afghanistan. Pressure on existing stock is growing rapidly as many of the six million Afghans that fled to Pakistan, Iran and other nations during the war begin to return. A population of 27 million is now struggling to accommodate the estimated 1.8 million refugees who returned in 2002 alone [3]. While funding from the US and other nations is woefully inadequate and unpredictable, some progress is being made. Funds typically go to non-governmental organizations (NGOs), like SFL, with facilities in Afghanistan to assist uprooted people in rebuilding their houses, infrastructure, and communities. In an effort to use local resources and building traditions, as well as to save funds and take advantage of available skills, most of these projects rely on time honored Afghan construction methods, using handmade mud (adobe) bricks. Flat roofs are supported by wood beams covered by layers of branches, woven mats, and finally up to 40 cm of clay. Two-room houses can be built this way for less than \$1,000 [4].

Although inexpensive to build, these traditional homes present major long-term risks. Adobe structures are vulnerable in earthquakes and Afghanistan is one of the most active seismic regions of the world. More than 6,000 people died in two earthquakes 4 months apart which shook the Afghanistan/Tajikistan border in 1998 even though they measured only 6.1 and 6.9 on the Richter scale [5]. An earthquake measuring 6.1 on March 25, 2002 and an aftershock of 5.1 in the Hindu Kush region in the northern part of Afghanistan left at least 1,000 people dead, several hundred injured, and several thousand homeless in Baghlan Province [5]. At least 1,500 houses were destroyed or damaged at Nahrin and several hundred more in other areas of Baghlan Province. Houses in Afghanistan should be designed to meet roughly the same standards as in Los Angeles (4 $\mathrm{m/s^2}$ acceleration), but traditional methods founder at much lower levels. Brittle mud walls and roofs fail when shaken and their enormous weight causes disastrous injuries. Although earthquake mitigation measures as used by SFL in Afghanistan allow people more time to leave their adobe homes during seismic activity, alternative solutions need to be pro-actively explored.

Recent wood scarcities have made traditional construction more difficult. Many NGOs are forced to import wood from Pakistan, Russia, and other countries since decades of deforestation have devastated local timber supplies. Often, the wood for a roof accounts for half of the total construction costs for a house. Those not able to import wood are using inadequate and dangerous roof support structures.

Wood shortages also underscore the energy crisis facing the nation. Traditional Afghan homes are heated with wood or charcoal, but difficulty in obtaining traditional fuels has forced many to turn to expensive kerosene or imported coal. Kabul has an altitude of 1,800 m and nights are cool, but the winters are very cold (the average January temperature is 27°F or –2.8°C) [6]. These factors force a difficult choice between expensive fuel consumption and uncomfortable temperatures.

Traditional heating and cooking systems also lead to unhealthy air quality inside the homes. While the mud homes are not airtight, fires are not well vented, leading to the dangerous buildup of combustion products. Lung and eye problems resulting from these pollutants have devastating effects, particularly on women, who spend many hours indoors close to stoves and their nearby infants who are even more susceptible [7].

Design concepts

Expanded polystyrene (EPS) was found to be an attractive component in the designs. EPS begins as small pellets that contain a blowing agent like pentane or carbon dioxide. When heated to about 100°C, by steam for example, the expansion of the blowing agent creates a structure with millions of tiny air-filled cells. These pre-expanded pellets are then further expanded in a mold with steam or heat, which causes them to fuse together, creating a very strong and rigid foam structure. The end result is a twenty- to thirty-fold increase in the original volume of the pellets, depending on the density desired [8]. Toxicological tests by manufacturers have shown that fumes from burning EPS represent no greater toxic risk than fumes from natural materials, such as wood, cork, or wool. EPS is an excellent material for home construction because of its low thermal conductivity, moderate compressive strength, and excellent shock absorption [9]. Use of EPS and a reinforced concrete coating circumvents the need for expensive wood in roof construction. In Afghanistan, pellets can be imported from Pakistan or India to be expanded in Kabul at a local steam facility, when a design is to be implemented on a larger scale. This would further the goal of employing local labor and reviving local industry. In the interim, the light weight and modular nature of the panels means that they can be shipped into Afghanistan with relative ease and low cost. For housing in the United States, EPS is widely available across the country. EPS is lightweight and panels can be erected by hand without expensive equipment. Openings can be simply cut out of the EPS and fitted with windows and doors. The following are three building methods being analyzed for use as wall and roof panels.

1. Wire Mesh/Truss Panels—EPS panels are embedded with 10-gauge (2.6-mm diameter) galvanized steel trusses and 14-gauge (1.6-mm diameter) steel mesh is welded or clipped to the protruding points of the trusses. Once the wall and roof panels are erected and connected with wire clips, they are finished with two layers of cement plaster, resulting in a 1-inch (in.) (2.5-cm) coating (Fig. 1). Wire mesh houses have been built in Mexico, California, and Texas [10].
2. Pressed Cellulose Fiber Cement Board Panels—Panels consist of an inner and outer skin of cellulose-reinforced cement board (autoclaved fine-ground silica, cellulose, and cement) and a core of EPS, glued together with high-strength adhesive and dried under high pressure (83 kPa or 12 psi). Wall and roof panels are connected with splices of the same fiber cement board and screws (Fig. 2). Cellulose-reinforced cement board is non-combustible; durable against precipitation, wind, and temperature extremes; able to maintain its shape; and impervious to decay and pests. This type of structure has been built in Puerto Panasco, Mexico; Washington State; Sholo, Arizona; Birmingham, Alabama; and Nashville, Tennessee [11].

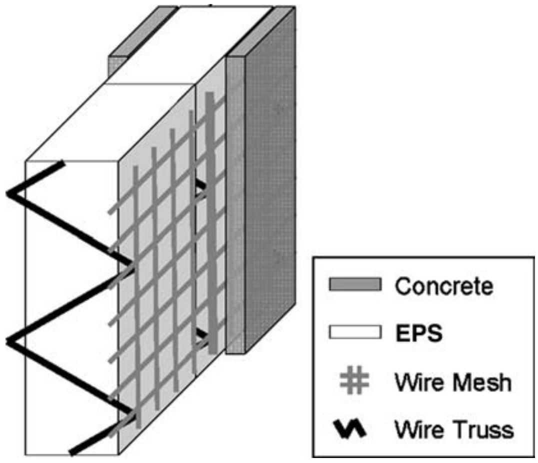

Fig. 1 Wire mesh/truss panel

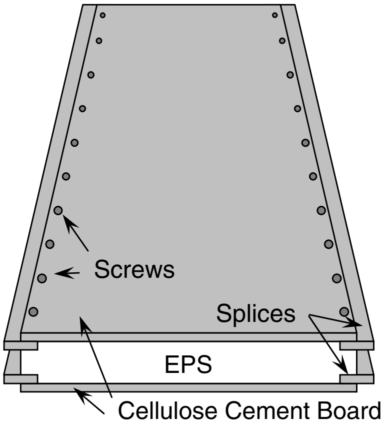

Fig. 2 Pressed cellulose fiber cement board panel

3. Fiber-Reinforced Composite Panels—EPS panels are erected and connected with an adhesive in a tongue-and-groove scheme, then coated with a layer of adhesive and a 1.3-cm (0.5-in.) thick composite of polypropylene fibers, polymers, and concrete (Fig. 3). This non-proprietary composite recipe needs to be refined with further research and testing and is not ready for implementation at this time [12].

Simulation and testing

Experts from several fields are collaborating on this project, allowing independent evaluation of the three building methods in a systematic series of simulations and tests in order to determine which design, if any, best meets the required performance specifications. The method of assessment includes,

- Air quality and heat loss calculations to determine the optimal EPS thickness for the walls and roof, in order to maximize energy efficiency and minimize materials costs. Calculations were made for various levels of airflow and insulation for a typical house with five occupants. These calculations show an optimum level of insulation which minimizes the total of fuel and materials costs.
- Cost modeling to provide an elemental comparison of the three design methods, plus a proprietary method, for two contrasting markets. Cost information was itemized for each of the elements of the house, allowing for simple evaluations of the relative costs of the various technologies. There was no analysis of any volume discounts that might occur, and further examination of housing costs using large-scale production is planned.
- Structural calculations to determine gross behavior and stress and deflection patterns under gravity, wind, and seismic loads. The structural simulations used a combination of dead loads, live loads, snow loads, wind loads, seismic loads, and construction loads in modeling potential stresses on the panel homes. Dead loads for the structures were determined based on the panel mass. Live loads, winds loads, and snow loads were standardized for each simulation, with the live and snow loads of 0.96 kN/m^2 (0.14 psi) used according to an American Society of Civil Engineers standard[1]. Appropriate regional wind loads conformed to ASCE Standard 7-2002. Construction loads of a standard 344.7 kN/m^2 (50 psi) were defined as the pressure applied by two individuals exerting a force of 517 kN/m^2 (75 psi) each across a standard 762 mm (30 inch) width.
- Fire testing to examine the materials' resistance to flames and heat and determine the level and toxicity of smoke production. The first fire test, which conformed with Uniform Building Code Testing Standard 26-3, was intended as a basic comparison of the panel's performance to the performance of other materials also used in building applications. The standardized test also served the purpose of completing the certification of the material for use in the United States. The second test was intended to demonstrate the safety of the material during a fire when the oxygen supply to the fire was increased and when the structural integrity of one of the panels directly exposed to the flames was weakened before the fire. This test was accomplished by adding a window cutout in one of the panels that formed the corner where the fire was built.

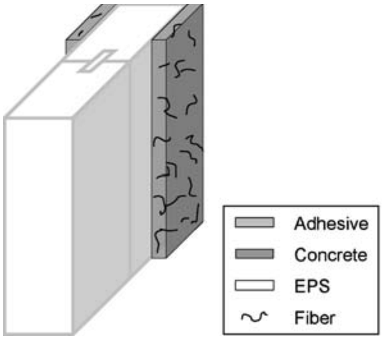

Fig. 3 Fiber-reinforced composite panel

Planned assessment activities for the near future include,

- Three-dimensional finite element analysis of wall corners and openings, e.g. doors and windows, to provide detailed simulations of loads in regions more likely to fail.
- Shake table testing of a representative three-dimensional structure at Trentec Laboratory in Cincinnati,

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[1] ASCE 7

Ohio. This is used to simulate a recorded earthquake from the Northern Afghanistan area, with visual documentation and measurements of damage.

- Building pilot homes in Houston, Texas; Borrego Springs, California; and Afghanistan.
- Monitoring and documentation to educate and encourage participation by intended inhabitants. Demonstration pilot houses will be closely monitored and documented to illustrate their advantages over conventional buildings. Feedback from intended inhabitants will be closely followed and considered.
- Laboratory development of non-proprietary fiber composite coatings for future implementation. Non-proprietary coatings are currently susceptible to small cracks and need to be further developed, possibly in collaboration with a university or government laboratory.
- And finally, outreach to EPS and building materials manufacturers and government agencies to encourage capital investment and large-scale construction.

Results and discussion

Indoor air quality and energy efficiency modeling

Preliminary air quality and heat loss modeling assumed a typical SFL house, 65 m^2 in gross area, or 42 m^2 of living space in four rooms (see Fig. 6 for similar floor plan). Windows and doors were assumed to be insulated to half the level of the walls and the foundation insulated to a level that matches heat flow through walls, with a lower bound of 2.5 cm of EPS. Air quality calculations and fuel cost estimates assumed an average of five occupants, a heating stove efficiency of 50%, and an annual operating cost of \$0.26/l (\$1/gallon) for #6 oil. Materials cost estimates assumed an EPS cost of \$26.50/m^3 (\$0.75/ft^3), EPS cost annualized at 10% of total, and no charge for the windows, doors, surface treatment, or foundation. Calculations were made for three levels of airflow per person: 7.5 l/s (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62), 5.0, and 2.5; and five levels of insulation thickness: 16.5 cm (6.5 in.) (wall)/25.4 cm (10 in.) (roof), 25.2 cm (6 in.)/20.0 cm (8 in.), 11.4 cm (4.5 in.)/15.2 cm (6 in.), 7.6 cm (3 in.)/10.0 cm (4 in.), and 3.8 cm (1.5 in.)/5.1 cm (2 in.). Results are presented in Fig. 4. There is a shallow total cost minimum, suggesting an initial specification of 15.2-cm (6-in.) walls and 20.0-cm (8-in.) roofs under the above assumptions. Somewhat less insulation, 11.4-cm (4.5-in.) walls and 15.2-cm (6-in.) roofs, is only slightly less attractive on a life-cycle cost basis. More detailed energy calculations incorporating specific heating sources and fuels and ventilation methods are needed to further this air quality and energy analysis.

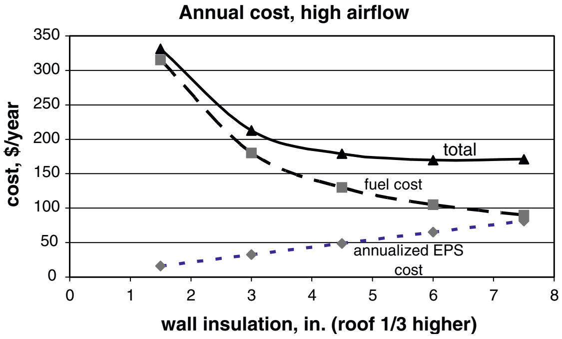

Fig. 4 Heat loss calculation results

Cost analysis

Cost estimation was performed in order to evaluate and compare the affordability of the three building methods, and in addition, a proprietary and commercially manufactured fiber-reinforced composite coating. Calculations include building materials, capital investment for EPS pellet steam expansion and panel construction, and labor.

The key components of the cost analysis:

1. EPS material cost, based on the dimensions of the house and the volume of material necessary. EPS costs are for 4-in. (10.0-cm) wall and 6-in. (15.2-cm) roof panels in California; 10-cm wall and 15-cm roof panels in Afghanistan.
2. Additional materials costs associated with the particular method of construction
   a. Wire Mesh/Truss Panels—wire, trusses, joints, concrete
   b. Pressed Cellulose Fiber Cement Board Panels—cellulose fiber cement board
   c. Fiber-Reinforced Composite Panels
      i. proprietary composite
      ii. non-proprietary composite—polypropylene fibers, masonry sand, cement
3. Labor, divided into skilled and unskilled labor, in both Afghanistan and California (Sacramento area) with available data from contacts in Afghanistan, published US residential construction handbooks [13], and quotes from local suppliers.
4. Capital costs—Capital costs per house are based on simple division of total estimated cost by 10,000 planned houses. In Afghanistan, where materials supplies are limited, there is a capital cost associated with an EPS pellet steam-expansion facility (approximately

$100,000) and either a press to sandwich and glue the EPS to the pressed cellulose cement board (approximately $500,000, including other equipment to cut panels) or a facility to manufacture the mesh/truss from raw coils of galvanized wire (approximately $100,000), depending on the chosen method of construction.

The calculations for two locations, Afghanistan and California, illustrate the differences in costs for materials and labor in developing and developed countries. Costs in Afghanistan are for a 35.5-m^2 starter (Fig. 5) and a 72-m^2 expanded house (Fig. 6); and in California, a 408-ft^2 (38-m^2) starter and an 828-ft^2 (77-m^2) expanded house (floor plans similar to Figs. 5, 6). These floor plans are based on houses that SFL has built in Afghanistan so that structures will be similar in appearance to traditional adobe homes. The starter house can be expanded easily as the resident family grows or achieves the financial capability for expansion. Other details of cost are difficult to quantify precisely (e.g. transportation to site), but effort was made to determine a relative (not absolute) comparison between designs. For example, foundation costs have not been included, based on assumptions that the four building methods would use the same foundation. (In Afghanistan, the cement necessary to add to a dug-hole foundation filled with rocks costs approximately $30.) A more sophisticated accounting of capital costs per house will be performed later. Costs are summarized in Table 1.

The costs of some of the systems are difficult to determine exactly because the figures depend on some proprietary information. Based on reasonable assumptions, the non-proprietary fiber composite panel design is the least expensive; however, it is not as fully developed as the other methods. There may be additional polymers necessary to prevent cracking and ease application. Although this composite is not ready for implementation at this time, further research and testing should be pursued because of its potential affordability.

The commercially available composite is the most expensive compared to the other designs, because it is a proprietary technology. In Afghanistan and other developing countries, where labor rates are lower, more labor intensive construction, like the wire mesh panels, appears to be appropriate, in order to keep costs low and stimulate the local economy. In California and other developed countries, where labor is relatively more expensive and materials like cellulose cement board are readily available, the pressed cement board technology is more suitable, with most of the assembly completed in a factory.

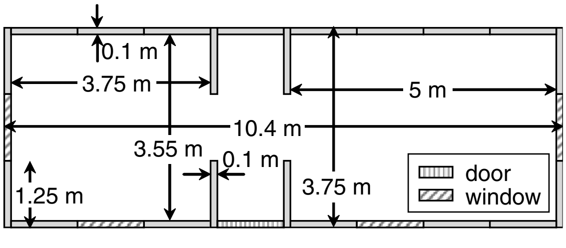

Fig. 5 Afghanistan starter house, 35.5 m^2

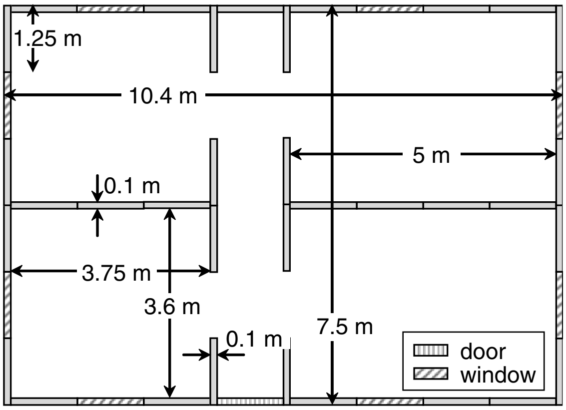

Fig. 6 Afghanistan expanded house, 72 m^2

Structural calculations

Linear calculations were performed for loads under worst case assumptions for the floor plan in Fig. 5. The simulations consisted of three types of loads (gravity, wind, and seismic) applied to the four systems: wire mesh, pressed cement board, fiber composite, and the proprietary composite. Gravity loads included dead loads (material weight), live loads, and Afghanistan snow loads. Wind loads used American Society of Civil Engineers (ASCE) Code 7-2002. The seismic load design followed the 2003 Universal Building Code, using a seismic importance factor of $I_E = 1.0$, seismic use group *I*, a site soil classification of Class D, seismic design category E, R = 2, $S_S > 1.25$ g, and $S_1 > 0.75$ g. Table 2 lists the specific design criteria used in the calculations and Table 3 outlines the results. All designs performed satisfactorily, with the wire mesh/truss design results slightly better than the other construction methods.

Fire testing

Standardized fire testing was performed to determine the panels' ability to retain structural integrity under extreme heat loads. Two tests were designed to compare the structure's performance in alternative circumstances as might be present in a residential home. The testing protocol in both tests followed the Uniform Building Code fire safety testing standard 26-3 for residences, with modifications to the building structure included in the second test.

Table 1 Cost comparison of the four building methods

		Wire mesh	Pressed cement board	Fiber composite	Proprietary composite
Afghanistan, starter house, 35.5 m^2	EPS	\$300	\$300	\$300	\$300
	Materials	\$680	\$1,390	\$170	\$2,960
	Labor/capital	\$160	\$100	\$150	\$150
	Total	\$1,140	\$1,790	\$620	\$3,410
	\$/m^2	\$32	\$50.40	\$17.50	\$96.10
Afghanistan, expanded house, 72 m^2	EPS	\$530	\$530	\$530	\$530
	Materials	\$1,120	\$2,260	\$300	\$5,130
	Labor/capital	\$270	\$120	\$250	\$250
	Total	\$1,920	\$2,910	\$1,080	\$5,910
	\$/m^2	\$26.70	\$40.40	\$15.00	\$82.10
California, starter house, 408 ft^2	EPS	\$710	\$710	\$710	\$710
	Materials	\$1,680	\$1,670	\$530	\$3,090
	Labor/capital	\$2,430	\$1,670	\$2,280	\$1,800
	Total	\$4,820	\$4,050	\$3,520	\$5,600
	\$/ft^2	\$11.80	\$9.90	\$8.60	\$13.70
California, expanded house, 828 ft^2	EPS	\$1,250	\$1,250	\$1,250	\$1,250
	Materials	\$2,950	\$2,900	\$930	\$5,460
	Labor/capital	\$4,570	\$2,870	\$3,850	\$3,460
	Total	\$8,770	\$7,020	\$6,030	\$10,170
	\$/ft^2	\$10.60	\$8.50	\$7.30	\$12.30

Table 2 Design criteria

		Wire mesh	Pressed cement board	Fiber composite	Proprietary composite
Dead load		1.46 kN/m^2	1.46 kN/m^2	0.50 kN/m^2	0.50 kN/m^2
Live load		0.96 kN/m^2	0.96 kN/m^2	0.96 kN/m^2	0.96 kN/m^2
Snow load		0.96 kN/m^2	0.96 kN/m^2	0.96 kN/m^2	0.96 kN/m^2
Wind load (ASCE 7-2002)	Windward	0.50 kN/m^2	0.50 kN/m^2	0.50 kN/m^2	0.50 kN/m^2
	Leeward	0.36 kN/m^2	0.36 kN/m^2	0.36 kN/m^2	0.36 kN/m^2
	Roof	0.90 kN/m^2	0.90 kN/m^2	0.90 kN/m^2	0.90 kN/m^2
Base shear		100.97 kN	100.97 kN	34.69 kN	34.69 kN

Table 3 Calculations of stress levels at specific points

			Wire mesh	Pressed cement board	Fiber composite	Proprietary composite
At base of wall panel	Bending stress	Wind	218 kN/m^2	655 kN/m^2	655 kN/m^2	655 kN/m^2
		Seismic	1,551 kN/m^2	1,641 kN/m^2	1,641 kN/m^2	1,641 kN/m^2
	Shear stress	Wind	19 kN/m^2	56 kN/m^2	56 kN/m^2	56 kN/m^2
		Seismic	132 kN/m^2	140 kN/m^2	140 kN/m^2	140 kN/m^2
	Diaphragm Force	Wind	22 kN/m^2	66 kN/m^2	66 kN/m^2	66 kN/m^2
		Seismic	104 kN/m^2	108 kN/m^2	108 kN/m^2	108 kN/m^2
At roof panel	Bending stress	At coating	744 kN/m^2	1,517 kN/m^2	1,517 kN/m^2	1,517 kN/m^2
	Shear stress	At foam	32 kN/m^2	21 kN/m^2	21 kN/m^2	21 kN/m^2
	Deflection	At mid-span	19 mm	19 mm	19 mm	19 mm

The structure's performance was evaluated through visual examination during and after the fire to determine structural integrity and material performance, through sensor observation to determine heat exposure and smoke toxicity, and through informal observations of heat flow through the outer walls of the structure.

The testing room was constructed with 2.4-m × 2.4-m (8-ft × 8-ft) panels as directed by the testing standard. The testing panels used 30.5 cm (12 in.) of EPS in the core with a 1.1-cm (7/16-in.) cement board cladding. The pressed cellulose fiber cement board panels were used as a representative example of the various panel options being studied. The structure included a standard sized door with a frame that was used as an observation point for both tests. There was also a window cutout on the right wall that measured 38.1-cm × 66.0-cm (15-in × 26-in.) supported by wood framing. The window was located 35.6 cm (14 in.) from the back wall and 1.06 m (3.5 ft) above the floor of the structure. To pass the examination, the structure had to remain intact for 15 min after the fire was ignited. The panels had to maintain structural integrity under the applied load of the ceiling panel. Additionally, smoke production as measured by a photometer located in the duct above the door cutout could not be excessive, and there could be no visible charring on the outer extremities of the wall or ceiling panels. The standardized test design uses a fire ignited in the vulnerable corner joint of an 2.4-m × 2.4-m × 2.4-m (8-ft × 8-ft × 8-ft) room constructed entirely of structural insulated panels.

The test results showed that the panels exhibited significant resistance to the heat and flames. In both tests, the flames did not spread beyond the wood crib and ignite the panels, and the foam melted only in those areas exposed to the most extreme heat, ensuring structural integrity in spite of the heat stresses. Damage to the cement board was limited to some cracks near the areas of highest heat and on the ceiling. At the points where the cement board fell away from the EPS core, the foam did not ignite because a thin cellulose skin remained over the foam, protecting the EPS from direct flame (Fig. 7). The heat flow to the outside of the panel was extremely limited, with the exterior cement board remaining cool to the touch as observed informally.

In the second test featuring the window cutout, the most significant difference from the first fire test was the damage in the area under the window frame. The number and surface area of exposed joints, which were unsealed at the point where the cement board skin intersected the wooden window frame, was much greater than in the previous test. As a result, there was a significant increase in the loss of foam under the window frame.

Smoke production was minimal in both tests, and the smoke that was produced had limited toxicity. The level of smoke production was interpreted by the testing lab to be significantly below the non-quantified threshold, defined loosely as not ‘‘excessive.’’ The products of EPS combustion are typically carbon monoxide and styrene, with the styrene decomposing further in high heat into carbon and water. The inclusion of a window cutout in the second test did not affect the production of smoke, but informal observations revealed that the concentration of the smoke in the structure was decreased in the second test as a result of air flow through the window. Fig. 8 shows that the maximum smoke production at any time during the first test (where air flow was restricted in the testing room) did not exceed 0.28 m^2/s, which occurred at approximately 13.5 min into the test, 1.5 min before the fire was extinguished [14].

Demonstration home

Two demonstrations of the EPS panel homes are planned to field test the technology’s energy, structural, and cost performance. The initial test in the United States is planned for Houston, Texas. The goals for this 2,000-ft^2 (186-m^2), single story, single-family home include a \$10/ft^2 (\$108/m^2) cost reduction and a 50–70% reduction in energy use below an equivalent stick built home. Additional goals include long-term mold and termite resistance, as well as durability against fire and extreme weather, including hurricanes and high winds.

Prior to design completion, a detailed energy analysis using EnergyGauge software will be performed to determine optimal wall thickness and HVAC unit sizing. Following construction, planned observations include blower

Fig. 7 Fire damage to panels

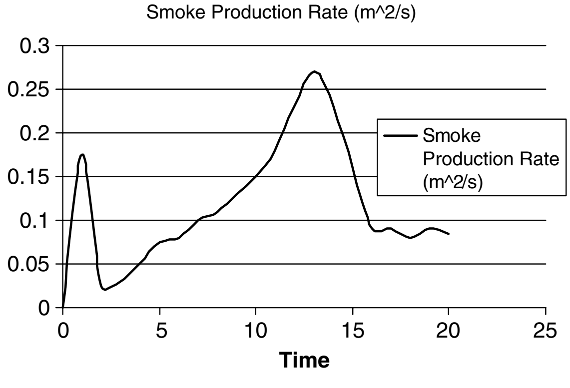

Fig. 8 Smoke production rate

door testing, interior temperature and relative humidity monitoring, long term energy use monitoring, and an occupant survey to reaffirm comfort, ease of maintenance, and cost savings.

The second demonstration is planned for construction in the near future in Mazar-i-Sharif or Kabul, Afghanistan. This home will demonstrate the viability of the technology for mass production in Afghanistan by determining if panel homes can be built at the same or lower cost as the traditional mud brick homes. The model home will also demonstrate the durability and energy efficiency of the panel technology, and will serve to prove that the panel appearance does not deviate significantly from cultural norms for housing design.

Local collaborators from international housing groups will provide observations on the housing technology's acceptance among the local population. Additionally, observations from homeowners will be used to determine if the model home is meeting the efficiency and durability goals.

Summary

Preliminary test results indicate that houses constructed from EPS structural insulated panels with a cementitious coating meet the defined needs of populations in many parts of the developing world. The testing regimen, including structural and fire safety, energy use, and cost analysis, showed that panel homes met the necessary criteria of safety and affordability. Structural simulations demonstrated that the technology was highly resistant to ordinary and extreme forces, such as high wind, snow loads, and earthquakes. The panel homes were also shown to be safe in fires, and damage was easy and inexpensive to repair. Affordability concerns were addressed through cost analysis and energy modeling, which demonstrated that the panel design is inexpensive to build and maintain. Design comparisons with traditional architecture also show that panel homes are highly likely to be accepted by populations in the developing world.

Concluding remarks

Future work on this project beyond modeling energy flows, analysis of construction costs, simulation and testing of seismic forces, environmental conditions, and hazards, and building pilot houses in California, and Afghanistan, includes application in other regions of the world and other building types (e.g. schools, hospitals, community centers). Another important application of EPS and reinforced concrete is retrofit or addition of roofs to damaged houses, as they are the least stable component of a building in an earthquake. It will be important to involve global companies with the ability to implement new building technologies in the future of this project. This project is ongoing and continued research and development involving NGOs, scientists, engineers, and industry will be required to meet all the performance specifications.

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