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Emergency Housing Systems from Three-Dimensional Engineered Fiberboard

Temporary Building Systems for Lightweight, Portable, Easy-to-Assemble, Reusable, Recyclable, and Biodegradable Structures

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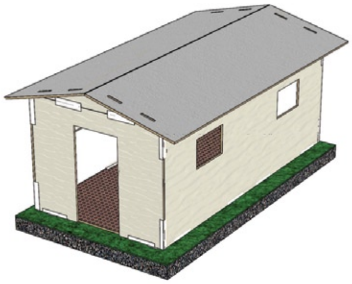

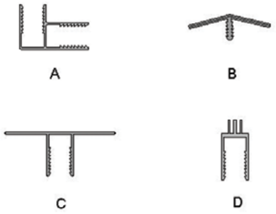

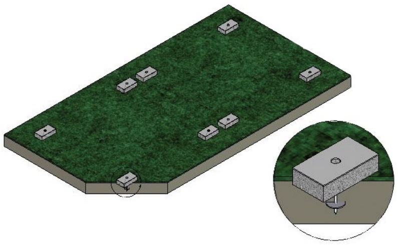

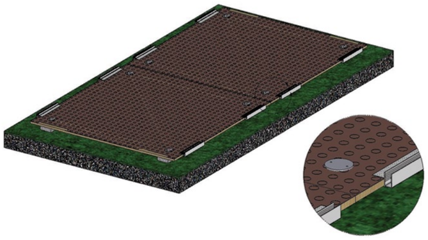

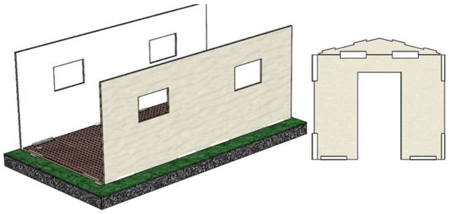

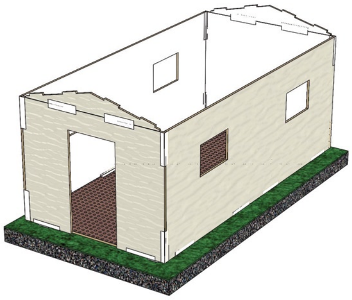

Abstract

Following natural disasters (such as hurricanes, tornados, or tsunamis), when civilians become displaced, or when military troops are deployed overseas, temporary housing is often a critical need. The USDA Forest Products Laboratory recently developed a lightweight, transportable, reusable, and recyclable biocomposite building material—three-dimensional engineered fiberboard (3DEF)—that can be used to uniquely meet this need. Once commercialized, this material can be made in large sheets—as large as the manufacturer's platen—designed to serve as single-piece prefabricated wall, floor, and roof units. These prefabricated units could be easily transported and quickly assembled into lightweight shelter structures. Pre-engineered 3DEF kits could be easily produced, shipped, and stored at strategic locations, then rapidly deployed whenever needed. Because the base material is an engineered biocomposite product, 3DEF can be designed and manufactured to provide specific levels of structural performance, durability, moisture resistance, and thermal- or acoustic-insulation characteristics. It can be made from virtually any biofiber resource, including wood, recycled paper, and agricultural residues. This report describes the basic product-processing concept for creating engineered, biobased composite panels for lightweight, rapidly deployable, temporary structures. Our next step will be to initiate a cooperative product development project to make this manufacturing technology commercially available and to design and produce advanced building systems using this new material.

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Keywords: housing, building systems, prefabricated building systems, engineered kits, temporary/intermediate housing, biocomposite building materials, three-dimensional engineered fiberboard, 3DEF.

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Introduction

Following natural disasters (such as hurricanes, tornados, or tsunamis), when civilians become displaced, or when military troops are deployed overseas, temporary housing is often a critical need. Scientists and engineers at the USDA Forest Products Laboratory recently developed a new product—three-dimensional engineered fiberboard (3DEF)—that can be used to meet this need uniquely. Three-dimensional engineered fiberboard (Fig. 1) is a biobased composite product developed to utilize alternative biobased fiber sources to produce a lightweight, high-strength alternative to products such as traditional fiberboard, double or triple corrugated paperboard, and oriented strandboard (OSB). Once commercialized, this material can be made in large sheets—as large as the manufacturer's platen—designed to serve as single-piece prefabricated wall, floor, and roof units. These prefabricated units could be easily transported and quickly assembled into lightweight shelter structures. Pre-engineered 3DEF kits could be easily produced, shipped, and stored at strategic locations, then rapidly deployed whenever needed.

Characteristics of 3DEF

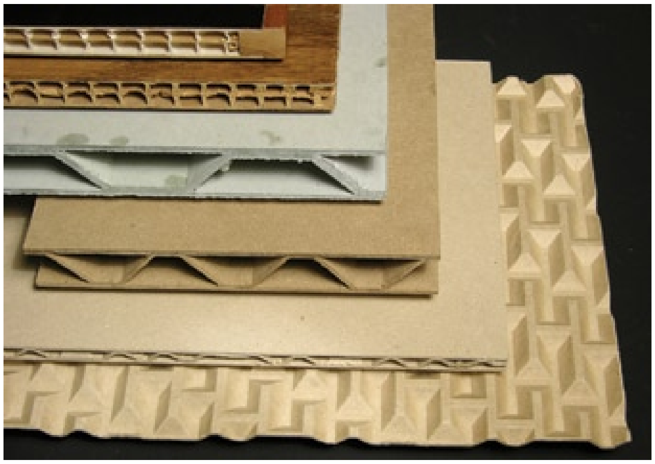


Figure 1—The 3DEF process includes combining a corrugated core and with flat biocomposite panels to produce an integrated engineered biocomposite system.

Three-dimensional engineered fiberboard is composed of a corrugated three-dimensional fiberboard core that is skinned by flat fiberboard faces. The core is engineered to provide optimum performance for the desired use with minimum weight by strategically shaping the fiberboard to be stronger in critical areas that carry higher loads while removing fiber from areas where it is not needed for optimal performance of the finished product. The shape is achieved by innovative wet-forming methods rather than cumbersome and expensive post-processing methods. Preliminary research has focused on developing a corrugated 3DEF shape that has potential applications in bulk packaging, office furniture, table tops, door cores, fiber pallets, concrete forms, and other commodity markets. The same process can easily be extended to produce specifically shaped fiberboard products for applications such as interior car parts, sound-absorbing panels, or aesthetic architectural elements.

Raw Materials

Because of the versatility of the production process, 3DEF can be made from virtually any biofiber resource, including wood, recycled paper, or agricultural residues. The FPL has already produced 3DEF from ≤4-in.- (≤10-cm-) diameter pine slash with bark (designated as hazardous forest fuel), recycled corrugated paperboard, and waste sludge from paper mills. Manufacturing 3DEF may be an innovative and practical way to add value to today's unwanted no- or low-value bioresources. Our research program has shown that 3DEF panels produced from underutilized residual material, such as hazardous forest fuels (Fig. 2) harvested off the floor of the Bighorn National Forest (Wyoming), recycled paper, or corrugated fiberboard, can be successfully used to produce this lightweight, high-performance engineered biocomposite material.

Figure 2—The process can produce 3DEF using recycled paper fiber or virgin timber or fire-prone forest residuals, such as shown on forest floor (left). When timber is used, it is chipped and then processed into various fiber types (right), depending on desired end-product properties.

Engineering and Production

In recent research projects, we have developed laboratory-scale processing methods to convert low-value biomass from low-value timber, recycled paper, or reclaimed woody or agricultural-biomass materials into wet mats that are press-dried into highly engineered three-dimensional corrugated mats (Hunt and Supan 2005, in press; Hunt and Vick 2004; Hunt and others 2004; Hunt 2004a, b; Hunt and Winandy 2002a, b; 2003). These mats form 3DEF when combined with thin, flat, face sheets. These face sheets would most often be another biobased composite material, such as wet- or dry-form fiberboard, hardboard, or oriented strandboard. However, these face sheets could also be gypsum-, phenolic-, or cementitious-based when other critical design and performance requirements are mandated, such as acoustic insulation or fire, thermal, or insect resistance.

In the critical innovation that defines the essence of 3DEF, FPL engineers developed the fundamental composite-forming technology with the specific intent of producing high-performance engineered biocomposite panels that allow both design and process flexibility and the ability to use virtually any biofiber resource. This technology may soon achieve engineering properties similar to those of hardboard and solid fiberboard but at much lower basis weight. This was accomplished by reverse-engineering, a process that first defines the necessary engineering characteristics of the final product and then uses adaptive technology capable of adjusting to the characteristics of the biofiber source.

The refining processes necessary to render optimal fibers from different sources have been studied, including different types and levels of mechanical refinement and chemical addition. Many of the inks, oils, and other waste materials that historically contaminate recycled fiber from municipal waste collection can be dealt with in 3DEF process technology without detrimental effects on engineering performance. The earliest 3DEF panels produced in the laboratory relied on natural fiber-to-fiber adhesion for bonding during the forming process (that is, no resin was added). A product of this type would be suitable only for interior use (dry conditions). Recent research has shown that 3DEF composite products can also incorporate resin binders (such as phenol–formaldehyde (PF), PF–soy, or methylene diphenyl diisocyanate (MDI) resins) to achieve performance comparable with that of current-generation "Exposure 1" engineered wood composite panels such as plywood and OSB.

Features

Three-dimensional engineered fiberboard structural panels are lightweight and have structural performance characteristics similar to those of some existing wood composites but at nearly half the basis weight, a feature that could cut product shipping costs nearly in half. As an engineered biocomposite product, 3DEF can be designed and manufactured to provide specific levels of structural performance, durability, moisture resistance, insulation values, and other uses or functions. When used as a primary building system component, the hollow cavities in 3DEF formed by the corrugated web can serve as utility chases for electrical wiring; heating, ventilation, and air-conditioning (HVAC); or plumbing. These hollow cavities can also be foam-insulated to enhance energy efficiency and user comfort.

Temporary and Emergency Housing

Governments and emergency responders worldwide have historically had problems responding to emergency housing needs following catastrophic events. Such was the case after Hurricane Katrina hit Louisiana and Mississippi in August 2005 (Hsu and Williamson 2005, Riley 2005) and after the December 2004 tsunami in the eastern Indian Ocean (Walls 2005). In his assessment of conditions affecting more than 2 million homeless refugees in eight countries affected by the tsunami, Walls (2005) reported that "Six months down the line and many of the most directly affected…are still living without a roof over their head." Emergency housing is a recurring international problem, and cost-efficient, practical solutions are needed.

Emergency housing solutions based on existing wood and fiber technologies appear unable to find an appropriate

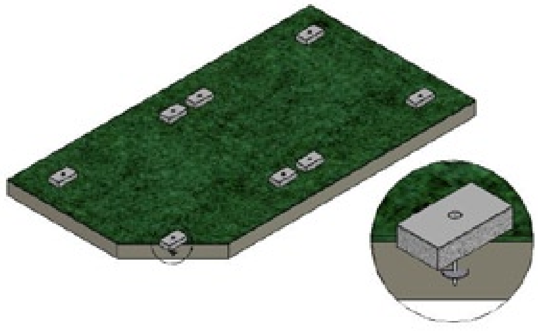


Figure 3—Foundation is set using earth anchors and concrete blocks with plastic moisture barriers.

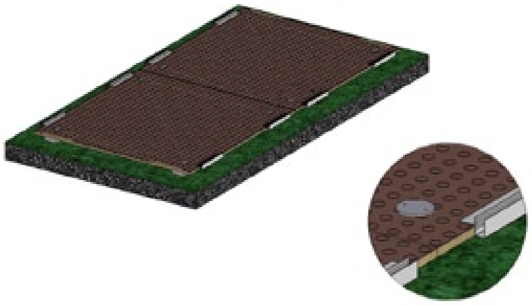


Figure 4—Floor is placed on foundation and earth anchors are connected to floor panels. Snap-in panel connectors are set in place for side walls (inset).

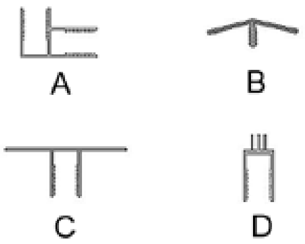


Figure 5—Examples of snap-in connectors used for construction: A, 90° panel connector; B, roof flashing; C, roof connector; and D, door and window channel.

middle ground between the traditional temporary shelter provided by tents and the semipermanent shelter of mobile homes.

Potential Application of 3DEF

One possible solution for emergency housing and shelter problems could be centered on the concept of a series of 3DEF site-assembled building system kits based on lightweight knock-down panels that could be assembled in minutes by unskilled labor using only hand tools. Although a 3DEF emergency shelter would never compete with the inherent portability and rapid deployability of a tent, a lightweight, biobased building system based on 3DEF technology could provide significant advances in weather resistance, security, life-cycle cost, user comfort, and satisfaction for many months or even years, if properly designed and maintained. A 3DEF-based system could be engineered for reuse, recycling, or biodegradation, based on user needs at the end of an initial service life of one to several years. Temporary housing solutions based on 3DEF technology could provide the weather resistance and security of steel shelters at a price point much nearer to soft-walled shelters, making it economically viable and logistically feasible to stockpile emergency shelters at regional locations for on-demand shipping to emergency housing sites.

The proposed 3DEF emergency housing system incorporates a series of wall, floor, and roof panels that can be assembled without tools by the use of press-fit connectors. Because the walls, floor, and ceiling will be produced from 3DEF, which has structural capacity, no additional framing will be necessary. The 3DEF system also creates void spaces in the walls that can be used as utility chases or be filled with insulation to facilitate heating and cooling. Those options can be included or excluded from the finished product with no change in the fundamental manufacturing process. The 3DEF configuration proposed for the structure is strong enough to withstand storm-force wind loads and cannot be cut with a knife or broken open with a hammer. The structure will be secured with off-the-shelf earth anchors designed for large canopies and tents and could be placed on cement blocks to protect it from ground moisture.

An example of the material details, engineering design, and installation procedures for the proposed prefabricated temporary housing system is described as follows, with a corresponding materials list provided in Table 1:

- Establish a foundation using earth anchors and concrete blocks with pre-installed plastic moisture barriers (Fig. 3 inset).
- Attach lightweight 3DEF floor panels to the foundation using engineered tie-ins to the earth anchor and block assembly (Fig. 4 inset).
- Prepare floor-panel system for attachment of panelized side-wall systems using press-on panel connectors (Figs. 4 and 5).
- Set side walls in place, and prepare end walls by placing panel connectors and gables (Fig. 6).
- Complete wall assembly by attaching end walls and notched gables (inset) to the structure with panel connectors (Fig. 7).
- Set roof panels onto notched gables, lock in place with roof panel connectors (inset), and install roof flashing (Fig. 8).
- Install windows and doors by pressing standard door and window units into pre-cut locations (Fig. 9).

Table 1—Parts and materials to build a 10- by 20-ft (3- by 6-m), 8-ft- (2.4-m-) high shelter, including estimates of material weights[a]

Item	Quantity	Material	Weight each (lb)	Weight each (kg)	Weight total (lb)	Weight total (kg)
Side wall	2	Composite panel	335.7	152.27	671	305
Door wall	1	Composite panel	131	59.42	131	59
Back wall	1	Composite panel	181.4	82.28	181	82
90° panel connector	20	Extrusion grade polypropylene	1.8	0.82	35	16
Gable connector	4	Extrusion grade polypropylene	1.9	0.86	8	3
Gable	2	Composite panel	15.2	6.89	30	14
Roof panel	2	Composite panel	330.3	149.82	661	300
Roof hold down	8	Extrusion grade polypropylene	0.8	0.36	6	3
Roof flashing	5	Extrusion grade polypropylene	3.4	1.54	17	8
Window channel	8	Extrusion grade polypropylene	1.5	0.68	12	5
Window	8	Plexiglas	5.2	2.36	42	19
Door hinge	1	Extrusion grade polypropylene	6.5	2.95	6	3
Door stop	1	Extrusion grade polypropylene	4.1	1.86	4	2
Door	1	Composite panel	49.1	22.27	49	22
Foundation block	8	Concrete (gravel aggregate)	46.7	21.18	374	169
Moisture barrier	8	Extrusion grade polypropylene	1.1	0.50	9	4
Floor panel	2	Composite panel	221.9	100.65	444	201
Anchor	8	Galvanized steel	4.5	2.04	36	16
Total structure weight			–	–	2,716	1,231

[a] These values are examples and could be modified to produce stronger or lighter structural systems depending on required loads and uses.

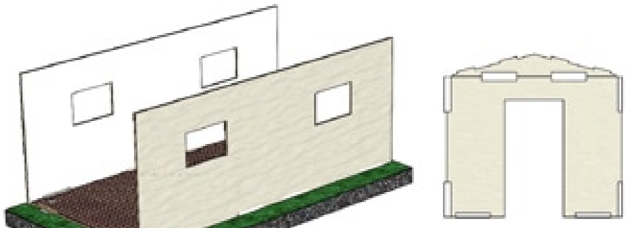


Figure 6—Side walls are set in place; end walls are prepared by attaching panel connectors and gables.

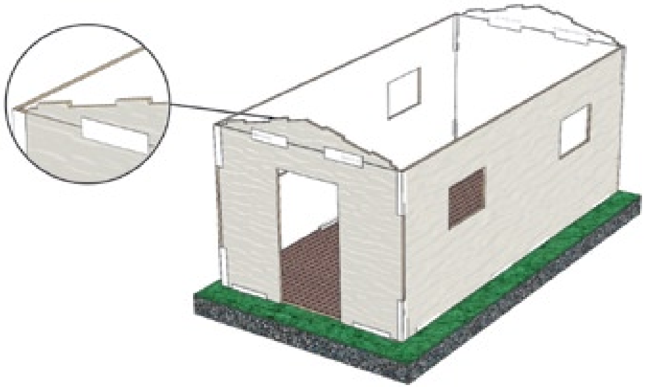
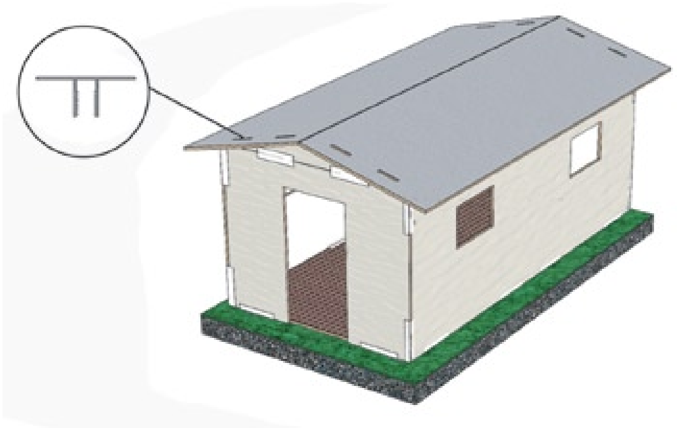


Figure 7—Wall assembly is completed by attaching end walls and notched gables (inset) to the structure with panel connectors.



Service-life and performance-enhancing features to the base 3DEF material for this example installation include the following:

- Floor panels have a vinyl walking surface and plastic moisture barrier underlay (Fig. 10).
- Roof panels have a heavy vinyl weathering surface and plastic moisture barrier overlay on top surface (Fig. 11).
- Wall panels have a lightweight vinyl or plastic moisture barrier or a gypsum-based fire-resistive barrier on exposed interior surfaces (Fig. 12).
- Roof or wall panels can also be manufactured as structurally insulated panels to provide increased durability and better insulation in hot or cold climates (Fig. 13).

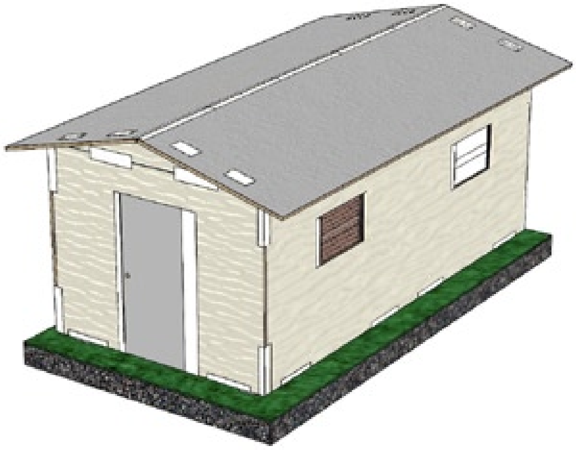


Figure 9—The structure is completed by addition of snap-in doors, windows, and roof flashing using snap-in connectors.

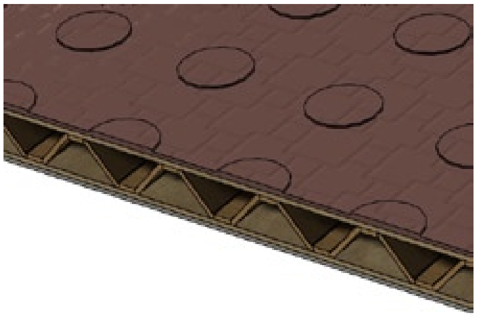


Figure 10—Floor panel with vinyl walking surface and plastic moisture barrier underlay.

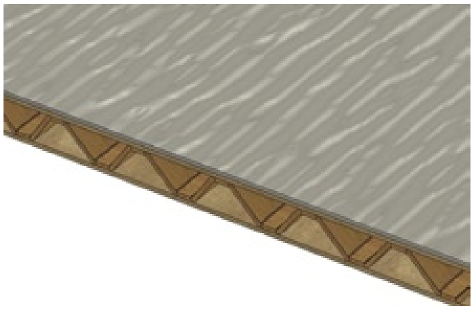


Figure 11—Roof panel (insulated or non-insulated) with weather-resistant, moisture barrier overlay on top surface and fire-resistant, inorganic–plastic moisture barrier overlay on interior surface.

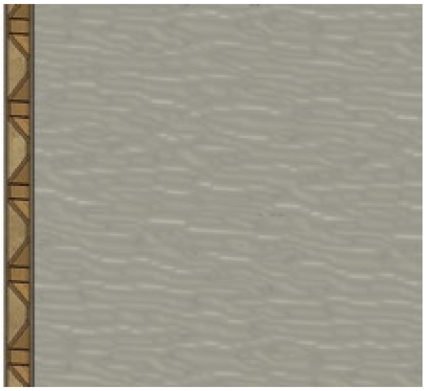


Figure 12—Wall panel (insulated or non-insulated) with fire-resistant, inorganic–plastic moisture barrier overlay on interior surface and weather-resistant overlay on exterior surface.

Existing Forms of Temporary Shelter

Traditional Temporary Shelters

Soft-walled shelters, including tents and inflatable plastic shelters, do not provide the basic levels of security and protection needed in emergency housing. Most soft-walled shelters can be compromised with a simple knife, cannot withstand intense storms, and do not meet modest heating and cooling needs.

Steel structures, ranging from modified cargo containers to full-sized mobile homes (Fig. 14), also do not provide adequate emergency housing. Even the most basic steel structures are difficult to transport because of their weight, and one truck is usually required for transporting each structure to the emergency location. In most regions, mobile homes are not considered temporary structures, and thus require permits and land dedicated to “trailer parks.” The Federal Emergency Management Agency (FEMA) spent over $1 billion to purchase mobile homes in the wake of Hurricane Katrina, but because of logistical difficulties of establishing mobile homes, only 105 families could be placed in that type of housing (DuraKit 2005). No type of steel structure has the combination of economic viability and transportability necessary to meet housing needs in emergency situations within the United States, let alone in more remote locations around the world.

The U.S. military recognizes the limitations of existing soft-walled and steel structures and is working to develop new solutions using composite panels and other novel technologies (Rollo 2005).

Other Wood and Fiber Temporary Shelters

Other innovative approaches to emergency and temporary housing systems based either on wood, wood composites, or wood fiber have been offered. The following descriptions

Figure 13—Examples of foam-in-place insulated roof or wall panels.

represent a few such innovations but in no way constitute a comprehensive overview. In summary, none of these shelters is comparable to the proposed FPL 3DEF emergency shelter, and available information indicates that these existing products suffer from many of the same drawbacks as traditional temporary shelters.

DuraKit Shelters

DuraKit Shelters, Inc. (Bradford, Ontario), offers an 8- by 12-ft (2.4- by 3.7-m) Disaster Relief Building Unit (DuraKit 2005). The unit is framed in solid wood and sheathed in corrugated fiberboard. It comes packaged in an 8- by 5- by 2-ft (2.4- by 1.5- by 0.6-m) crate that unfolds to form the unit's floor. Although other DuraKit products have cyclone wind ratings, the Disaster Relief Building Unit has no foundation and is not wind rated. Weather resistance is provided by a coating on the corrugated fiberboard and a plastic tarpaulin to cover the roof; no insulation or utility connection capabilities are offered. The wood frame construction without an inner skin would make the addition of utilities impractical—pipes and electrical wires would be difficult to mount and would be left exposed. The unit has a solid floor and solid door; however, the walls are skinned between the solid wood joists by corrugated fiberboard, which offers no security or weather protection advantage over existing soft-walled shelters. The 8- by 12-ft (2.4- by 3.7-m) unit is fairly lightweight at 300 lb (136 kg) but offers no utility connection capability, insulation, or tamper-proof security. Tools are required for construction and deconstruction.

Visy Shelter

According to news reports (Moore 2005), the Australian company Visy, a large manufacturer of packaging materials, is developing an emergency shelter very similar to the DuraKit Disaster Relief Building Unit. The estimated manufacturing cost of the Visy shelter is $1,500 Australian. Although the Visy shelter includes steel spikes for footing and uses plywood and heavy 2-in. (50-mm) corrugated panels for floors and walls, it apparently has no provision for utilities or insulation. No information is available on whether the Visy will require tools to assemble, but it does not appear to be a panelized system.

Figure 14—One- and two-story commercial steel buildings designed as site-assembled kits and made in China for use as temporary commercial and emergency structures.

NRRI Rapid Response Housing

The Natural Resources Research Institute (NRRI) at the University of Minnesota–Duluth has developed a rapid response housing system (NRRI 2005) that can be assembled from an 8- by 20-ft (2.4- by 6-m) container into a 20- by 24-ft (6- by 7.2-m) shelter "by a half dozen people in about four hours using little more for tools than mallets to tap the wall panels into place." Electrical and plumbing systems are built into the wall panels, which are constructed of solid wood frames and conventional wood composite panels, much like modular home construction. The rapid housing unit comes with installed sink, toilet, shower, hardwood flooring, and multiple internal rooms. (It is not clear whether the sink, toilet, and other amenities shown with the unit fit into the containerized system or whether they are accounted for in the build-time estimates.) Pat Donahue, project leader, refers to the rapid housing system as a "somewhat permanent structure." The initial price point of $24,000 puts the rapid response housing system in competition with steel-based mobile homes. Although NRRI expects the price to come down substantially with mass production, it will not likely be able to match the $8,333 per unit that FEMA paid for mobile homes after Hurricane Katrina. Because of the semi-permanent nature of the NRRI units, potential users may encounter the same difficulties in finding suitable locations for mobile homes that FEMA faced placing mobile homes following Hurricane Katrina. The containerized units can be stacked up to three high, so three units could potentially be transported in the same space required for a single mobile home, depending on whether extra space is required for the amenities. That narrow advantage in transportability over mobile homes may not be enough to overcome the disadvantages of substantial build time and higher manufacturing cost.

Other Uses for 3DEF

A critical concept is that 3DEF production starts by engineering the production process to (1) the base materials and (2) the desired performance characteristics of the final product. For example, 3DEF could be produced with engineered damping characteristics to eliminate vibrations or noise. Pallets, or entire truck or rail car floor systems, could be made with specially designed 3DEF that could eliminate or greatly reduce damage to products during shipping. Walls—or door systems, office partitions, and room dividers—of 3DEF could be engineered to virtually eliminate room-to-room noise and vibration transmissions from voices, music, or low-frequency-emitting equipment.

Housing

Residential construction is one of the largest economic engines of the U.S. economy. The FPL has long been an international innovator for prefabricated–manufactured residential and light-commercial construction technology. The first prefabricated house was built at FPL in the mid-1930s (Fig. 15, left, Luxford 1958). The post–World War II housing demand continues into the early 21st century, and the ever-increasing acceptance of manufactured housing systems and engineered components in part stems from early FPL research. The FPL has also long been a leader in developing new biobased wood and biofiber composite technologies for housing (Winandy 2002).

Recent research led to the development of a concept for using large 3DEF panels as prefabricated structural elements (such as interior walls and partitions) and even whole structures (Fig. 15). Prefabricated 3DEF interior wall systems could be pre-wired and sheathed with gypsum board at the factory and then delivered to the job site. The relatively lightweight panels could be easily handled by a two- or three-person crew. On-site carpenters using portable saws

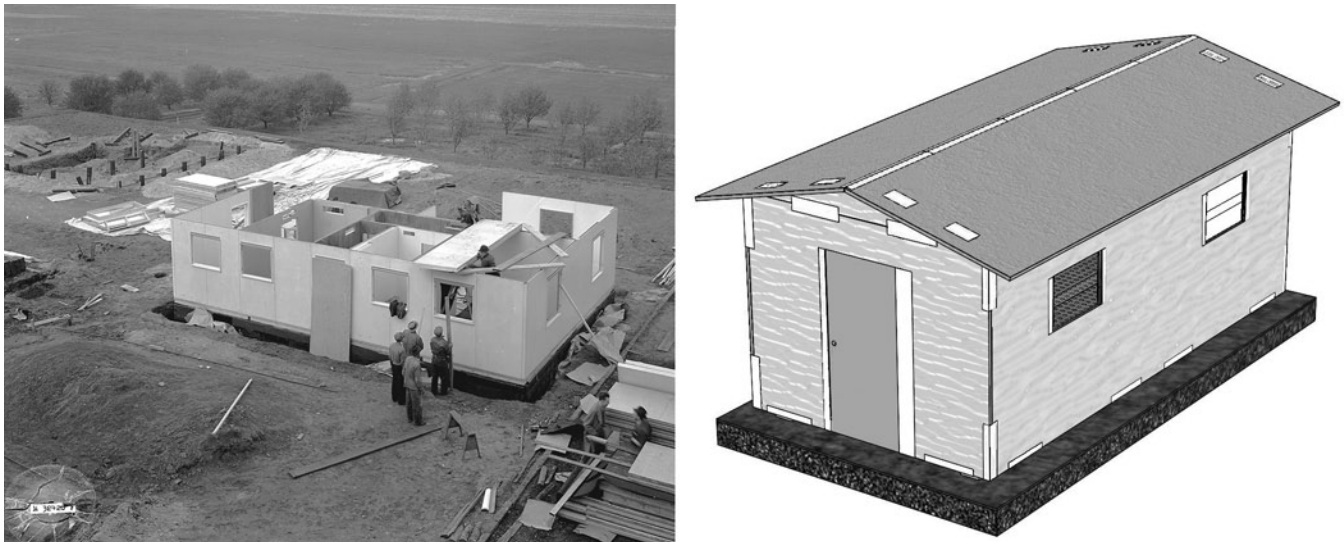


Figure 15—Prefabricated housing research at the USDA FPL: circa 1930s (left) and tomorrow (right).

would cut the panels to size, cut in door and window openings and HVAC chases, and erect an entire lightweight wall system in minutes rather than hours or days. The corrugated interior web construction of 3DEF would allow for foam-in-place thermal insulation and specific design of utility chases, simplifying subcontracting requirements and expediting the work.

Furniture

Over the past 20 years, knock-down furniture has become a staple of the U.S. domestic furniture market. Many major building supply centers annually sell thousands of these pre-engineered, ready-to-assemble kits for bookcases, desks, and cabinets. Most of these kits are relatively heavy to handle because they are made with a heavy particleboard core with vinyl-plastic or wood-veneer overlays. Pre-engineered, ready-to-assemble kits based on lightweight 3DEF technology in place of heavy particleboard corestock would allow manufacturers and retailers to offer furniture kits that are equally strong but 40% to 50% lighter.

Alternative Structural Concepts

The 3DEF panelized system is really more of a concept than a specific product. The critical system element is the designable core structural component, which offers many possible features. The potential for modifying the face skins further expands the possibilities.

Nested Panels

Panelized system components could be designed and manufactured to be nested (that is, packed closely together) before final assembly. This feature would allow for more efficient storage and transport of components, especially when structural efficiency of a panelized system requires significant “air-space” in the core design. Once on site, final fabrication of the structural components could be completed using simple tools. If foaming is required for exterior insulation, the foam could serve as a panel adhesive and a reinforcing agent for the core’s ribbed structure.

Stackable Core

A single core system could be designed with “stackable expansion” capability. In other words, a single core could be used for thinner structural components (such as furniture components or interior walls) or stacked to produce thicker panels for structural components requiring greater strength (such as longer span floor and roof systems). Another possibility is adding complete single panels (core and skins) together in various combinations—similar to double- or triple-wall corrugated packaging material—to produce thicker floor, roof, or wall panels with increased panel or column strength for heavier load-bearing needs.

Fire-Resistant Skin

The panelized system could be designed with integral gypsum-, phenolic-, or cementitious surfaces to provide sufficient heat and fire resistance to prevent flash fires or sufficient fire retardation to allow safe occupant egress. The fire requirements may allow for use of a thinner fire-resistant material then the 0.5-in.- (12.7-mm-) thick wallboard system used in conventional housing construction. The thinner the gypsum requirements, the lighter the panelized system. Advanced intumescent paint could also be integrated with the thinner gypsum surface to provide optimum fire performance while minimizing weight and thickness.

Research Needs

We are in the early stages of research and development of the 3DEF structural panelized component system. We have already demonstrated the ability to form 2- by 2-ft (0.61- by 0.61-m) three-dimensional corrugated core sections without the torn rib sections that have plagued traditional three-dimensional embossed hardboard panels. Panelized systems have been fabricated with flat faces glued to a corrugated core. These panels are currently being tested.[1] The ranges of material properties of the components are critical factors in designing 3DEF structural performance characteristics. The FPL is currently analyzing structural and physical material properties of the material over a range of densities and resin contents.[2] These property values are critical as input variables for analysis using three-dimensional finite-element computer modeling of the 3DEF structure.[3] Computer modeling and analysis are critical to optimal design for given performance criteria. Our research goal is to develop an integrated approach to designing a 3DEF panel and the appropriate forming mold based on (1) desired performance criteria, (2) fiber type, and (3) fiber processing parameters. An economic assessment of 3DEF process and production costs is nearing completion.[4]

The FPL is in initial stages of designing a 2- by 8-ft (0.61- by 2.4-m) forming station that will allow full-length core sections to be formed and manufactured on our 2- by 8-ft- press then mated with 4- by 8-ft (1.2- by 2.4-m). Fiber processing and forming data will be collected and reported to help industry move this technology to commercialization. Full-size panels will be made and tested in several different configurations.

Partnership

Providing emergency housing following catastrophic events is a recurring national and international need. The Forest Products Laboratory has developed a new concept for producing safe, secure, weather resistant, and energy-efficient emergency shelters that could be efficiently stored in strategic locations and transported to emergency housing sites as needed. Government (USDA, DOD, FEMA, DHS, and HUD) and industrial partners must work cooperatively to develop this technology to commercial viability. This research and development effort must include an assessment of the economic feasibility of using this type of material for both emergency housing and for panelized construction in traditional light-frame wood house construction in North America. We are seeking partners to co-direct this research on fabrication and performance characteristics and the economics of using 3DEF structural panels for advanced lightweight building systems.

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[1] The following related paper is under development for publication: Hunt, J.F.; O'Dell, J.; Turk, C. 3-D engineered fiberboard panel properties.

[2] The following related papers are currently being prepared for publication: Hunt, J.F.; Turk, C.; and O'Dell, J. Thin wet-formed flat panel constitutive properties—Bending Properties. Hunt, J.F.; O'Dell, J.; Turk, C. Thin wet-formed flat panel constitutive properties—In-plane tensile properties. Hunt, J.F.; Turk, C.; O'Dell, J. Thin wet-formed flat panel constitutive properties— Z-direction tensile properties. O'Dell, J.; Hunt, J.F.; and Turk, C. Thin wet-formed flat panel press processing considerations.

[3] The following related paper is planned for publication: Hunt, J.F.; Turk, C. Finite element analysis and evaluation of 3D engineered fiberboard panels.

[4] The following related paper is planned for publication: Bilek, T.; Hunt, J.F. An economic assessment for process and production costs of 3DEF.

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