Feasibility of Rigidified Inflatable Structures for Housing

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Bibliographical Information
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Abstract: Rigidified inflatable structures (RIS) are thin, flexible membrane structures that are pneumatically deployed. After deployment, these structures harden because of chemical or physical change of the membrane. Because of this change, or rigidification, these structures no longer require pneumatic pressure to maintain their shape. With the aim of reducing the cost and examining the feasibility of RIS structures, a new material is proposed, developed, and evaluated. This material involves the formation of a semi-interpenetrating polymer network based on polyvinyl chloride and an acrylate-based reactive plasticizer. The economical and environmental performances of RIS using this new material are assessed by means of a case study. In this study, the performance of RIS technology is compared with that of a typical wood light-frame structure in the application of a small single-family house. The study indicates that the cost of ownership in present day value for the RIS is approximately 35% less than the cost of a comparable wood light-frame structure. This study also indicates that significant environmental benefits exist with the use of RIS. These structures use significantly less in terms of resources than do wood frame structures: approximately 2 times less in materials originating from nonrenewable fossil resources, approximately 2 times less in material originating from trees, and approximately 19 times less in materials originating from inorganic resources. The study concludes by delineating various means available to further increase the economical and environmental performance of RIS technology.

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CE Database keywords: Inflatable structures; Structural analysis; Polymers; Life cycle costs; Buildings, residential.

Introduction

Because of technological advances made in the 19th century, wood light-framing (WLF) has largely replaced heavy timber construction in residential buildings. Relative to heavy timber construction, a significant reduction in cost and wood consumption is accomplished by using light-framing methods. In addition, development of products such as plywood or oriented strand board further optimized these systems. This study investigates the use of rigidified inflatable structures (RIS) and the potential use of this emerging technology for residential construction. An RIS is classified as a thin, flexible polymer membrane that is inflated, then rigidified, into a structural, load-bearing system. These structures can offer reduced material usage and labor costs as compared with conventional building systems. The development of RIS systems can be considered the next optimization step in the evolution of residential construction systems. This idea is especially relevant considering that the development of cellulose-based RIS systems is both feasible and attractive. Understanding current concern for the depletion of natural resources, the resource efficiency of RIS systems could also prove extremely useful. This view is further reinforced by the fact that almost one-half of the world’s major resources are consumed by construction and related industries, and 55% of the wood cut for nonfuel purposes is used in construction (Roodman and Lenssen 1995).

Definition and Current Uses

Rigidified inflatable structures (RIS) are thin, flexible membrane structures that are pneumatically deployed. After deployment, these structures harden due to chemical or physical change of the membrane. An application of RIS can be found in the design of space structures. Reasons for this are that inflatable structures are very lightweight, are compact for transportation, and pose little difficulty when deployed in space (Cadogan and Mikulas 1998).

The development of RIS is also promising for earth-based applications. Upon initial investigation, direct transfer of this technology to earth-based applications does not seem plausible. Explanations are diverse. RIS materials developed for space applications are expensive because of the hostile conditions that prevail in space. Specific RIS curing mechanisms developed for the space environment are not always appropriate for use under normal earth conditions. So far, no concerted effort has been undertaken to identify a more appropriate material solution for use of this technology on earth. Additionally, the potential economic or environmental benefits of this technology have not yet been established.

Scope of Study

The main purpose of this paper is to (1) develop a new material to make terrestrial applications more affordable, and (2) assess the economical and environmental performance of this technology when used in a single-family house. These issues are further examined with experiments to determine materials properties and with structural analysis and comparison to existing construction techniques. The main objectives of the experiments are to collect data for mechanical properties for this material—i.e., tensile
strength and modulus of elasticity—and to determine the technical feasibility of a particular material solution. The study continues to assess the economic performance of RIS technology by comparing the life-cycle cost (LCC) of a simple RIS structure with the LCC of a comparable wood light-frame (WLF) structure. The enclosing envelope of a single-family house in its most basic form is considered. The study focuses on the relative differences in performance between these competing systems.

The second section of this paper considers various types of RIS materials currently available or under development and outlines the development and testing of new RIS material for use in residential construction. The next section examines the structural performance of a simple RIS design using Genesis, a commercially available finite-element program. Then we analyze lifecycle costs and evaluate the feasibility of RIS structures compared with existing wood frame structures. Environmental considerations and suggested additional research areas are addressed after that. Concluding remarks are presented last.

**RIS Materials**

This section highlights the different types of materials that are proposed and/or used in RIS technology. The development of a new material for use in RIS technology is also presented.

RIS membranes are typically composed of high-strength fibers embedded in a more elastic polymeric matrix. After inflation, the polymeric matrix stiffens while the fibers remain unchanged; this results in an overall increase in stiffness for the composite. Some of the RIS materials being used or proposed are the following: (1) fabric impregnated with resin that is cured by exposure to ultraviolet light; (2) fabric impregnated with resin that is cured upon the application of heat; (3) fabric impregnated with hydrophilic resin that rigidifies as the water evaporates; (4) fabric impregnated with a polymer that rigidifies when it is cooled below its glass transition temperature; (5) a laminate of aluminum foil and thin Kapton film that rigidifies when the aluminum is strained beyond its yield point; and (6) foam-inflated structures that rigidify as the foam hardens within an enveloped cavity (Cadogan 2001).

The materials used or proposed for RIS applications are mainly high-performance pre-preg laminates. The typical cost of a simple E-glass continuous-fiber epoxy pre-preg is approximately $22/Kg (Callister 2000). For lower-tech applications of RIS technology, such as affordable housing, material cost becomes critically important and lower-cost substitutes need to be identified. In an effort to reduce RIS material costs, a new material is proposed and tested. This material is based on the forming of a sequential semi-interpenetrating polymer network (semi-IPN). Interpenetrating polymer networks (IPNs) are a combination of two polymers in network form, at least one of which is synthesized and/or cross-linked in the immediate presence of the other (Sperring and Mishra 1996).

A number of papers have appeared in the literature that describe sequential semi-IPNs based on PVC and reactive plasticizers (Ismat 1991; Moussa and Decker 1993; Kaczmarek and Decker 1994). The formation of sequential semi-IPNs based on polyvinyl chloride (PVC) and a reactive plasticizer is of particular interest in the development of RIS technology, for several reasons. First, PVC is a low-cost polymer. Second, plastification of PVC by means of external plasticizers rendering a rubber-like material is a well-established technology. Third, many different monomers exist that can serve as plasticizers for PVC. Finally, plastisol technology, a technique to produce plastized PVC membranes or coated fabric, provides a common and inexpensive technique for making membranes. The use of photoinitiator to induce polymerization, as described by Moussa and Decker, further provides a convenient way to cure the membrane of a pneumatic structure (Moussa and Decker 1993). Unfortunately, no mechanical performance data could be found in the literature for these materials. In addition, the methods used to make plasticized PVC film involved solution-casting techniques. Plastisol coating is a much more efficient method for making thin membranes. The main objectives of this part of the study is to (1) collect data for mechanical properties for this material, i.e., tensile strength and modulus of elasticity, and (2) determine if a system (PVC + monomer + photoinitiator) can be proposed that is able to survive processing conditions encountered during the plastisol manufacturing process (≈200°C for 10 min).

**Sample Preparation and Testing Procedures**

**Mixture Preparation**

Plastisol mixes contain 100 parts by weight (pbw) of PVC, 70 pbw of reactive plasticizer, 15 pbw of epoxidized linseed oil, 1 pbw of CaZn, and 0.3 pbw of photoinitiator. Table 1 summarizes plastisol composition. All plastisol mixes were prepared in small glass beakers and were mixed by hand using a spatula. All components for the making of the PVC-based sequential semi-IPN were commercially available products, and all were used as received.

**Specimen Preparation and Test Procedures**

Specimens for tensile testing were prepared according to ASTM D638-96, a standard test method for tensile properties of plastics. An aluminum mould containing five dog-bone-shaped negative forms (Type IV) was placed on a glass plate. Plastisol mixes were poured into these moulds. Moulds sitting on the glass plate were placed in a preheated oven for 10 min at 190°C. This allowed the plastisol mixture to fuse into a solid membrane. After cooling to ambient temperature, the samples were removed from the moulds and exposed to UV light for 10 min in sets of five. A 150 W xenon lamp placed at a distance of 60 cm was used for this purpose. After cure, samples were sanded to uniform thickness. Forty-seven samples were tested for tensile strength according to ASTM D638-96 using an Instron load frame. A crosshead speed of 2 mm/min was used for samples 1 through 25, and a crosshead speed of 1 mm/min was used for samples 26 through 47. All samples were tested at room temperature.

Dynamic mechanical properties were measured according to ASTM D5418-95a, a standard test method for measuring the dynamic mechanical properties of plastics using a dual cantilever beam. Samples were prepared as follows: An aluminium mould with rectangular negative form was placed on a glass plate. Plastisol mixes were poured into this mould. The mould sitting on the glass plate was placed in a preheated oven (190°C) for 10 min in

<table>
<thead>
<tr>
<th>Component</th>
<th>Product name</th>
<th>Supplier</th>
<th>Parts by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyvinyl Chloride</td>
<td>GEON 129</td>
<td>GEON</td>
<td>100</td>
</tr>
<tr>
<td>Reactive Plasticizer</td>
<td>SB520A210</td>
<td>Sartomer</td>
<td>70</td>
</tr>
<tr>
<td>Epoxidized Linseed Oil</td>
<td>Flexol LOE</td>
<td>Union Carbide</td>
<td>15</td>
</tr>
<tr>
<td>Photoinitiator</td>
<td>Irgacur 369</td>
<td>Ciba</td>
<td>0.3</td>
</tr>
<tr>
<td>CaZn PVC stabilizer</td>
<td>Thermcheck SP239</td>
<td>Ferro</td>
<td>1</td>
</tr>
</tbody>
</table>

| Table 1. Plastisol Composition |
order to fuse the plastisol mixture into a solid membrane. After cooling to ambient temperature, the sample was removed from the mould. The obtained flexible film was cut into the desired rectangular shape of approximately $50 \times 10 \, \text{mm}$, and the sample thickness was approximately 1.5 mm. After this, specimens were exposed to UV light for 10 min, using a 150 W xenon lamp placed at a distance of 60 cm. The samples were clamped between the movable and stationary members of the dynamic mechanic spectroscopy apparatus (Seiko DMS110). A constant frequency of 1 Hertz was selected for all three tests. A linear temperature increase of $2^\circ \text{C}/\text{min}$ was used. Testing started at a temperature of approximately $-50^\circ \text{C}$ and was stopped at approximately 130°C.

Test Results
For the above-described matrix composition, the processing of the plastisol into a rubber-like plasticized film at 190°C for 10 min did not result in noticeable polymerization of the reactive plasticizer. All samples remained flexible at room temperature. (Samples that were stored for more than one year still remained flexible, although some discoloration and leach-out could be observed.) After exposure to UV light, all samples became rigid in just a few minutes. The average yield stress for the cured semi-IPN matrix was 25.5 MPa. The elastic modulus was found to be approximately 2.65 GPa at 25°C. The largest decrease in elastic modulus occurs between 50°C and 70°C, indicating the region for the polymer’s glass transition temperature.

Structural Modeling and Analysis of RIS Structure
This section evaluates the structural capabilities of an RIS system by considering external loads, material properties, and design criteria. A finite-element analysis (FEM) is performed to determine the behavior of a simple prismatic building composed of RIS material. Results are presented and discussed with respect to normal stress due to bending. Displacements are also considered. Discussion of the structural analysis reveals the beginning of a method for designing RIS systems in housing applications.

System Configuration
The scope of this study is limited to the analysis of one design only, being a simple prismatic building 7 m ($\approx 24 \, \text{ft}$) wide, 14 m ($\approx 48 \, \text{ft}$) long, and with a ceiling height of 2.4 m ($\approx 8 \, \text{ft}$). Although more complex building configurations are feasible with RIS technology, a conventional box shape was selected. This allowed the making of a more accurate comparison of the analysis results with the performance of similarly shaped buildings made from wood. This shape represents the enclosing envelope of a conventional single-family house in its most basic form. Fig. 1 provides a section and detail of the RIS construction placed on a concrete slab on grade. An RIS wall composed of tubular rectangular column-elements 0.2 m wide and 0.2 m deep is envisioned. The roof structure consists of a series of tubular beams with rectangular cross section 0.2 m wide and 0.4 m high. The interior ceiling height is 2.4 m (8 ft). A membrane thickness of 0.4 mm was selected for both roof and walls elements.

External Loads
The analysis accounted for a wind load of 1,050 N/m² at the windward wall, a wind load of 850 N/m² at the leeward wall, and a roof live load of 960 N/m².

Fig. 1. Diagram and cross section of wall and roof elements for RIS house

Material Properties
For the structural analysis provided in this study, isotropic material behavior was assumed in order to simplify the analysis. A semi-IPN matrix system based on PVC and reactive plasticizer as described above was used as the basis for calculation. This material was assumed to be reinforced with randomly oriented discontinuous glass fibers (volume fraction $\approx 40\%$). Isotropic material properties were calculated using a simple rule of mixtures (Callister 2000). This resulted in a modulus of elasticity of 10 GPa and a tensile strength of 100 MPa.

Finite-Element Modeling
Genesis 7.0, a commercially available structural analysis and optimization program, is used to model and analyze the RIS system. CQUAD4 plate elements are used to model the walls and the roof of the box structure (Fig. 2). These are four-node quadrilateral elements that have in-plane and bending stiffness. These elements allow loading and displacements in all directions. All degrees of freedom are released in the model, with the exception of the boundary conditions at the foundation. At the wall boundary with the foundation, displacements in $x$, $y$, and $z$ directions were fixed while the rotations in $x$, $y$, and $z$ were released. The element size is 200 by 240 mm. The model contained 16,330 elements with 69,492 degrees of freedom in all. The effects of potentially highly concentrated loads acting upon the thin membrane structure are not considered.

Fig. 2. (Color) FEM stress contours
ceilings other then plaster of the span for structural members supporting roofs or suspended members supporting roofs shall not exceed the following: 1/240 \[ \text{BOCA building code states that for wood light-frame structures, long roof; this is approximately } 1/180 \text{ of the roof’s span.} \]

The deflection of 39 mm occurs at the midpoint of the roof’s span. The displacement in the \( z \) direction is 10.5 mm, and is located near the top of the rear wall at midspan. The displacement in the \( x \) direction is negligible. The deformed shape is seen in Fig. 3.

**FEM Discussion**

**Strength**

A maximum allowable yield strength of approximately 17.2 MPa and a maximum allowable shear strength of 3.4 MPa are needed to make the above design safe. Results of the materials developed in the first section of this study indicate a tensile strength of 25.5 MPa and a modulus of elasticity of 2.65 GPa (at 25°C). When this material is reinforced with uniformly distributed discontinuous glass fibers (\( \sim 40\% \) volume fraction), strength calculations indicate a modulus of elasticity of 10 GPa and an allowable strength of 100 MPa. Hence, the maximum calculated stress (17.2 MPa) is less than the allowable stress calculated for this material. The design can further be enhanced by (1) increasing the strength of the matrix, (2) using stronger fibers, (3) increasing the fiber volume fraction, and (4) using continuous instead of discontinuous fibers. More optimal structural design could also lower stresses significantly.

**Deflection**

The deflection of 39 mm occurs at the midpoint of the 7,000-mm-long roof; this is approximately 1/180 of the roof’s span. The BOCA building code states that for wood light-frame structures, “The deflection due to live, snow or wind loads of structural members supporting roofs shall not exceed the following: 1/240 of the span for structural members supporting roofs or suspended ceilings other than plaster” (BOCA 1996). The deflection of the RIS system exceeded these criteria. The relative large deflection is due to the low modulus of elasticity that was used in the analysis (10 GPa). Proper design, such as aligning continuous fibers along the length of the roof, can result in increased stiffness and reduction in deflections. In addition, the roof structure could also be given an initial curvature to compensate for these deflections. Changing the design could also lower maximum deflection significantly.

**Assumptions and Limitations**

The analysis provided considered only the effects of a limited number of structural loads. In addition, several assumptions were made to arrive at these results. A more complex analysis—including, for example, thermal effects, creep, concentrated loads, and an isotropic material response—is needed before a more conclusive recommendation can be made. A detailed study of structural connections between foundation and the RIS is also required to address such issues as wind uplift and concentration of local stresses. This study does not consider the effects of buckling; a buckling analysis is recommended.

**Life-Cycle Cost**

This section addresses life-cycle costs (LCC) of RIS and WLF houses. WLF construction is analyzed instead of light-gauge metal framing mainly because WLF methods are more popular where housing issues are concerned. Furthermore, construction time estimates are provided and compared.

**Base Case Assumptions**

The scale of the two houses to be compared is that of a small prismatic single-story house 7 m wide, 14 m long, and with a ceiling height of 2.4 m (approximately 48x24x8 ft). The building foundation, a frost-protected shallow concrete slab, was held constant for both systems. Operation costs for heating and cooling of the building were not considered. These were considered to be identical assuming similar thermal performance for both systems. The only variables were materials and methods of construction (exterior walls and roof), and costs for maintenance. Superstructure and relevant finishing systems are considered. The study did not cover wall openings, mechanical or electrical systems, and issues related to land acquisition; however, some of these topics are addressed in the Additional Research section. A typical service life of 40 years and a discounted rate of 10% were selected. Since significant structural differences exist between the compared systems, only the primary function of enclosing space was considered. Nonprimary functions, such as absolute load-bearing capacity of each wall assembly, are not considered. The present-worth method was used for LCC calculations (Dell ’Isola 1997).

**Wood Light-Frame Construction**

Fig. 4(a) depicts a cross section of a typical wood light-frame structure placed on a concrete slab on grade. A 2×6 stud wall was selected; studs are placed at a spacing distance of 60 cm (24 in.) on center. Exterior 10-mm-3/8 in.-thick plywood sheathing, Exposure 1, is nailed directly to the stud wall, providing permanent lateral bracing to the structure and a substrate for placing siding. The siding consists of a PVC exterior cladding system. The interior finish consists of gypsum wallboard nailed to the studs. Two coats of paint are applied to the gypsum wallboard and serve as the final finishing surface.

A simple gable roof with a slope of 5:12 is selected. Roof trusses are also placed at a distance of 60 cm on center. A 13-mm-(1/2 in.)-thick plywood sheeting is applied to the trusses, providing permanent lateral bracing to the roof and a substrate for placing the asphalt shingles. The shingles are made from die-cut heavy sheets of asphalt-impregnated felt faced with mineral granules that act as a wearing layer. The interior finish of the ceiling consists of gypsum wallboard panels that are nailed to the bottom chord of roof trusses. The ceiling insulation consists of a cellulose...
insulation system. Two coats of paint are applied and serve as the final finishing surface.

**RIS Construction**

Fig. 4(b) depicts a cross section of an RIS construction placed on a concrete slab on grade. A 0.2-m-thick wall composed of tubular-rectangular column elements 0.2 m wide and 0.2 m deep is envisioned. No effort was made to resemble the shape of a gable roof. The roof structure consists of tubular-rectangular beam elements 0.2 m wide and 0.4 m high. The top of the beams is slightly curved to allow for rainwater drainage. The interior ceiling height is 2.4 m (8 ft). A single-ply butyl-rubber membrane covers the exterior surface of the wall and roof and provides protection against environmental elements (rain, UV light, puncture). No interior finishes are included; the membrane will provide these functions. The insulation consists of a blown-in cellulose system within the cavities of the structure. A membrane thickness of 0.4 mm was selected according to the structural analysis provided earlier.

**Cost Components**

**Wood Light-Frame**

**Construction Cost.** The estimated construction cost for the wood light-frame construction is provided in Table 2. The table provides a cost breakdown for materials, labor, equipment, total cost, and total cost including overhead and profit. The time needed to perform each task is also provided. The total construction cost to erect the wood light-frame structure was estimated to be approximately $17,000, not including the foundation system. Cost data were obtained from the *Dodge Metric Unit Cost Book* (Dodge 1997).

**Maintenance Cost.** Maintenance needs for the wood light-frame structure involve repair of exterior and interior surfaces at different points in time. One major renovation was calculated for after 20 years of service (half of the useful life). For the exterior walls, this was estimated to include replacing 50% of all the vinyl siding. Maintenance cost for the roof was estimated to involve replacing all roofing shingles after 20 years. No maintenance costs for interior walls and ceiling were included. The assumption was made that these operations would be similar in cost for both systems. Maintenance costs were considered as single expenditures at these different time intervals. The renovation cost for the wood light-frame structure was estimated to be $3,562 for the exterior surfaces (after 20 years). Maintenance and repair intervals for these activities were obtained from the RS-MEANS, facilities maintenance, and repair cost data (“Means” 1997).

**Rigidified Inflatable Structures**

**Construction Cost.** Since no historic construction cost data are available for RIS structures, surrogate data needed to be found. Cost was obtained by means of a survey of retail prices of mass-produced plasticized PVC items such as inflatable air mattresses and swimming pools. The weight of several items was obtained and divided by its retail price. From this an average cost per weight could be established. After this, the cost for raw materials (PVC + plasticizer) was obtained. From these two (raw material cost and retail price), a “product factor” could be determined. The next step involved calculating the raw material cost for materials used in the actual RIS membrane and multiplying it by the “product factor.” This cost per weight could then be used to calculate the total cost of the RIS membrane. This method assumed that the RIS structure was a mass-produced item delivered on-site ready for inflation. It was also assumed that the cost of a material with sufficient strength would not differ significantly from that of the material tested in this study. Table 3 provides an estimated construction cost for the superstructure of the RIS structure. The total construction cost to erect the RIS structure was estimated to be $10,937, not including the foundation system. Other cost data were obtained from the *Dodge Metric Unit Cost Book* (Dodge 1997).

**Maintenance Cost.** Maintenance needs for RIS structures will be different than for more conventional construction systems. Walls and roof are composed of thin membranes that are inflated and rigidified. In a second phase, an insulation system is put in place. Since membranes are structural, any damage to them can possibly compromise structural integrity. For this reason, a skin made from butyl rubber was provided to protect the exterior surface of the structure. For maintenance, this protective envelope will need to be replaced after 20 years of service (half the service life). No maintenance costs for interior walls and ceiling were included. The assumption was made that these operations would be similar in cost for both systems. Maintenance costs were considered as single expenditures at these different time intervals. The renovation cost for the RIS structure was estimated to be $3,148 for the exterior surfaces (after 20 years). Maintenance and repair intervals for these activities were obtained from the RS-MEANS, facilities maintenance, and repair cost data (“Means” 1997).

**Other Costs**

No salvage value, associated costs, tax elements, alteration costs, real estate cost, or design costs were included in this study.
The present-worth method, in which the baseline for comparison is present-day value in equivalent dollar, was used for LCC calculations. Cost elements that were similar for both systems, or were not considered significant, were removed from the analysis. The financial criteria on which the economic evaluation was based are the following:

1. interest rate of 10%;
2. labor and material escalation rate of 0% per year; and
3. life-cycle period of 40 years.

Fig. 5 represents the cost breakdown for both systems. The costs of ownership in present-day values are $30,507 and $19,658 for the wood light-frame and RIS structure, respectively, not including foundation and operation costs. Hence, the RIS structure is approximately 35% less expensive than the WLF structure. The net savings in present-day value is $10,849 for this particular design. Approximately 56% of the costs are due to initial construction, and 42% is due to financial costs. The rest accounts for the major renovation of both proposals after 20 years.

### LCC Discussion

An approximate difference of 35% in cost of ownership is fairly significant. However, considering the high risks involved with the implementation of this new construction technology, this difference may not be sufficiently compelling. In addition, a total initial cost of about $10,937 is still beyond the reach of many individuals or families living in less developed countries. The cost of the RIS structure is a result of the cost of initial construction and the resulting interests that need to be paid. Fig. 6 provides a cost breakdown for the initial construction cost of the RIS structure. Both the protective skin and the insulating filling make up a substantial portion of the total initial construction cost of the pro-

### Table 2. Summary of Estimated Construction Costs for Wood Light-Frame Structure

<table>
<thead>
<tr>
<th>Item description</th>
<th>Quantity</th>
<th>Unit of measure</th>
<th>Person-hours (h)</th>
<th>Labor cost ($)</th>
<th>Material cost ($)</th>
<th>Equipment cost ($)</th>
<th>Total cost ($)</th>
<th>Total cost including overhead and profit ($)</th>
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</thead>
<tbody>
<tr>
<td><strong>Rough Carpentry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Studs 2 x 6, 60 mm o.c.</td>
<td>190</td>
<td>M</td>
<td>14.25</td>
<td>342</td>
<td>274</td>
<td>0</td>
<td>616</td>
<td>760</td>
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<tr>
<td>Sole plate 2 x 6</td>
<td>44</td>
<td>M</td>
<td>3.30</td>
<td>79</td>
<td>63</td>
<td>0</td>
<td>142</td>
<td>176</td>
</tr>
<tr>
<td>Double-top plate 2 x 6</td>
<td>88</td>
<td>M</td>
<td>5.19</td>
<td>122</td>
<td>197</td>
<td>0</td>
<td>319</td>
<td>383</td>
</tr>
<tr>
<td>Plywood sheathing 10 mm</td>
<td>107</td>
<td>m²</td>
<td>13.80</td>
<td>334</td>
<td>507</td>
<td>0</td>
<td>841</td>
<td>1,013</td>
</tr>
<tr>
<td><strong>Exterior Finish</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vapor barrier, polyethylene</td>
<td>107</td>
<td>m²</td>
<td>3.42</td>
<td>58</td>
<td>104</td>
<td>0</td>
<td>162</td>
<td>196</td>
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<tr>
<td>Vinyl siding (0.635 mm)</td>
<td>107</td>
<td>m²</td>
<td>50.72</td>
<td>1059</td>
<td>1117</td>
<td>0</td>
<td>2,176</td>
<td>2,672</td>
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<td><strong>Interior Finish</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Blown cellulose, 6 in.</td>
<td>107</td>
<td>m²</td>
<td>12.63</td>
<td>288</td>
<td>449</td>
<td>104</td>
<td>841</td>
<td>1,002</td>
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<tr>
<td>Gypsum board 16 mm, taped and spackled</td>
<td>107</td>
<td>m²</td>
<td>21.94</td>
<td>461</td>
<td>346</td>
<td>0</td>
<td>807</td>
<td>1,013</td>
</tr>
<tr>
<td>Paint (water based) 2 coats</td>
<td>107</td>
<td>m²</td>
<td>6.96</td>
<td>126</td>
<td>138</td>
<td>0</td>
<td>264</td>
<td>322</td>
</tr>
</tbody>
</table>

| **Rough Carpentry**                   |          |                 |                  |               |                   |                   |               |                                             |
| "W" roof trusses, 5 in 12 slope, 60 cm o.c. | 25      | Each       | 33.53            | 766           | 1258              | 273               | 2,297         | 2,725                                      |
| Plywood sheathing on roof, 13 mm thick| 112      | m²           | 14.45            | 349           | 651               | 0                 | 1,000         | 1,194                                      |
| Plywood sheathing (gable ends) 10 mm  | 10.5     | m²          | 1.36             | 33            | 50                | 0                 | 83           | 99                                         |
| **Exterior Finish**                   |          |                 |                  |               |                   |                   |               |                                             |
| Building paper                        | 112      | m²           | 2.46             | 48            | 48                | 0                 | 96           | 121                                        |
| Asphalt shingles #240                 | 112      | m²           | 15.57            | 302           | 381               | 0                 | 683           | 870                                        |
| **Gable**                             |          |                 |                  |               |                   |                   |               |                                             |
| Vapor barrier, polyethylene           | 10.5     | m²            | 0.34             | 6             | 10                | 0                 | 16           | 19                                         |
| Vinyl siding (0.635 mm)               | 10.5     | m²            | 4.98             | 104           | 110               | 0                 | 214           | 262                                        |
| **Roof edges**                        |          |                 |                  |               |                   |                   |               |                                             |
| Aluminum flashing 0.4 mm              | 45       | M            | 11.97            | 263           | 459               | 0                 | 722           | 853                                        |
| Vinyl gutter and down sprouts         | 29.3     | M            | 5.10             | 120           | 93                | 0                 | 213           | 266                                        |
| **Interior Finish Ceiling**           |          |                 |                  |               |                   |                   |               |                                             |
| Blown cellulose, 9 in.                | 107      | m²            | 16.16            | 368           | 564               | 92                | 1,024         | 1,233                                      |
| Gypsum board on ceiling               | 107      | m²            | 25.36            | 530           | 691               | 0                 | 1,221         | 1,486                                      |
| Paint (water based) 2 coats           | 107      | m²            | 10.38            | 208           | 126               | 0                 | 334           | 415                                        |
| **Totals**                            |          |                 |                  |               |                   |                   |               |                                             |
|                                      |          |               | 274              | 5,966         | 7,636             | 469              | 14,071        | 17,081                                     |
posed design (51%). The identification of lower-cost fillings, such as foam-plastic waste used in packing, could reduce this cost. If insulation is not critically important, the exclusion of filling, or a lower-cost filling such as sand, can further reduce the cost. Similar thoughts apply to the external protective skin, which makes up a substantial portion of the total construction cost. The main purpose of this skin is to protect the structural RIS membrane from environmental degradation. The identification of lower-cost skins or other means of protecting the membrane may eliminate or reduce this cost. Development of lower-cost RIS materials and materials having higher strength and stiffness can further reduce cost significantly. Finally, more appropriate designs can also reduce construction cost.

Another important factor in LCC estimates involves construction time. The estimated time for construction for the WLF structure is 274 person-hours, compared with 64 person-hours for the RIS structure. This represents the potential of a 75% reduction in project delivery time. Fig. 7 depicts Gantt charts that approximate the sequence of tasks for each method of construction. The short delivery time for RIS structures is largely explained by the ease at which RIS structures are manufactured and deployed, and by the fact that no elaborate interior finishes are required. Considering the possibility of developing multifunctional membranes (with embedded communication, illumination, energy distribution, and energy-collecting devices), further reductions in project delivery times are possible.

Environmental Considerations

This section addresses environmental issues and considerations associated with RIS structures. Resources for both RIS structures and WLF housing units are compared and assessed. Environmental performance results are discussed.

Various methods exist that can be used to assess the environmental performance of construction technologies. Methods include the embodied energy method, emergy method, and life-cycle assessment methods using input-output analysis. These methods enable designers to compare, evaluate, and make proper recommendations regarding the environmental performance of competing technologies. However, in many structures, the practical use of these methods is hindered by a lack of readily available and reliable data concerning the materials or processes under consideration. To avoid this problem, streamlined assessment methods become more commonplace (Graedel 1998). The idea in these methods is to limit the scope of the assessment while retaining sufficient levels of confidence. Scope can be limited in various ways—for example, by considering only a limited number of system components or by limiting the study to some but not all of the system life-cycle steps. While these methods have their limitations, they tend to be much more useful in revealing major environmental concerns or issues in a manageable way. Hence they provide a good basis for decision making and can reveal areas to conduct more targeted studies.

Considering the emerging character of RIS technologies (no relevant historical data available), it was decided to adopt such a streamlined assessment method. The method adopted in this study builds on the argument that when comparable resources are used to construct buildings, systems will perform better environmentally when lesser quantities of these resources are used to accomplish the same objective. It was assumed that when similar material resources are used in different systems, the environmental impact of the systems should be proportional to the amount of resources used. Hence, this study did not reveal any differences

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**Table 3. Estimated Construction Costs for RIS Unit**

<table>
<thead>
<tr>
<th>Item description</th>
<th>Quantity</th>
<th>Units</th>
<th>Person-hours (h)</th>
<th>Labor cost ($)</th>
<th>Material cost ($)</th>
<th>Equipment cost ($)</th>
<th>Total cost ($)</th>
<th>Total cost including overhead and profit ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane</td>
<td>175</td>
<td>Kg</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td>2,496</td>
<td></td>
</tr>
<tr>
<td>Blown cellulose, 9 in.</td>
<td>106</td>
<td>m²</td>
<td>16</td>
<td>364.6</td>
<td>559</td>
<td>91</td>
<td>1,015</td>
<td>1,221</td>
</tr>
<tr>
<td>Protective envelope, butyl 1/16 in.</td>
<td>125</td>
<td>m²</td>
<td>8</td>
<td>511.3</td>
<td>808</td>
<td>0</td>
<td>1,319</td>
<td>1,574</td>
</tr>
<tr>
<td><strong>Walls</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Membrane</td>
<td>200</td>
<td>Kg</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td>2,852</td>
<td></td>
</tr>
<tr>
<td>Blown cellulose, 9 in.</td>
<td>106</td>
<td>m²</td>
<td>16</td>
<td>364.6</td>
<td>559</td>
<td>91</td>
<td>1,015</td>
<td>1,221</td>
</tr>
<tr>
<td>Protective envelope, butyl 1/16 in.</td>
<td>125</td>
<td>m²</td>
<td>8</td>
<td>511.3</td>
<td>808</td>
<td>0</td>
<td>1,319</td>
<td>1,574</td>
</tr>
<tr>
<td><strong>Roof</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Totals ($)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10,937</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 5.** Cost breakdowns for WLF and RIS houses

**Fig. 6.** Cost breakdown of initial construction cost of RIS house
that may exist within one class of materials due to, for example, different methods of extraction, processing, manufacturing, or design.

The performance of an RIS system was compared with that of a more conventional wood light-framing system that served as a standard base case. The study compared the amount and type of materials used to build a single-family house. First, the quantities needed to construct both structural systems were estimated and translated into a common denominator—volume and weight. Second, materials for each system were classified into categories of materials having similar origin or nature. Categories used were (1) materials coming from wood, (2) materials coming from fossil resources (petroleum, coal, natural gas), and (3) materials coming from inorganic matter. Materials present in small quantities were not included. Finally, results were used to assess the resource efficiency of RIS structures relative to the wood light-frame system.

Environmental Performance Results

WLF Structure
The total mass of the WLF structure is approximately 10,411 kg. A significant portion of the mass of the WLF structure originates from fossil remains (petroleum, coal, natural gas). These include, for example, the glues that bond the exterior plywood (178 kg), the polyethylene vapor barrier (11 kg), the polyvinylchloride siding (104 kg), the interior paints (22 kg), and the asphalt shingles on the roof (896 kg). Combined, these constitute 12% of the weight of the structure. Second, a significant portion of the mass for WLF originates from inorganic matter (3,397 kg). These are the gypsum boards used to finish interior walls and ceiling. Combined use constitutes 33% of the structure. Finally, 55% of the weight of the WLF structure originates from wood, it being the structural framework. These include the 2×6 studs of the wall (1,371 kg), the wood used in the W-shaped roof trusses (781 kg), the wood present in the plywood sheathing (1,601 kg), and the cellulose insulation (2,038 kg).

RIS Structure
The total mass of the RIS is approximately 3,250 kg. Approximately 630 kg (19%) of the total weight of the RIS originates in fossil resources. These include the polymeric matrix used in the RIS membrane and the rubber used as protective skin. The amount of inorganic matter present in the RIS structure is 180 kg, or 6% of the total weight; this represents the glass-fiber reinforcement present in the membrane. Finally, approximately 75% of the weight of the RIS structure originates from wood (2,423 kg). This is the cellulose insulation system inserted in the cavities of the RIS structure. Fig. 8 compares these results for the categories used in both systems.

This study indicates that the RIS system used significantly less in resources than the WLF structure. Approximately two times less material originating from nonrenewable fossil resources, approximately two times less material coming from wood, and approximately 19 times less material composed of inorganic matter was used in the RIS structure relative to the WLF structure (Fig. 8). On a weight basis the RIS system used almost three times less material than the WLF system. The exceptional resource efficiency of RIS structure can be explained by the favorable distribution of material through the wall thickness and the absence of an elaborate finishing system. The above results can be considered significant in several ways. First, since comparable resources are used in lesser amounts, the environmental impacts of resource consumption can be assumed to be less. Second, since no wood is used as structural material in the RIS system, no trees need to be cut for this purpose. This could have significant environmental benefits, since more land could become available for natural forests. Third, the use of fewer resources will also ease the waste...
management problem. In addition to this, RIS structures are also more homogeneous in composition, facilitating the separation of wastes and resulting in more convenient recycling or reuse of materials.

Discussion of Environmental Performance

Fiber-reinforced polymers are usually associated with applications in the automotive, aerospace, and sporting sectors. The particular benefits for these applications rise from the high specific material properties (strength or stiffness-specific gravity). When properly applied, high specific properties can result in better overall performance, reducing for example fuel consumption for automobiles or airplanes. Hence, fiber-reinforced polymers directly provide environmental benefits in these applications. For the construction of buildings however, this argument does not apply. Specific strength is usually not as important as specific cost (strength or stiffness/cost). Since fiber-reinforced polymers are currently more costly than traditional construction materials, they are not commonly considered for general construction purposes. To a great extent, the high cost of fiber-reinforced polymers arises from the labor-intensive methods used to fabricate large structures from them. Considering the simplicity of fabrication methods that can be used in RIS technology (which uses low-cost manufacturing processes well known to the textile industries), a reduction in cost can be expected. This study indicated that a sharp decrease in primary resource consumption can exist when fiber-reinforced polymers are used for structural enclosures. The true benefits of fiber-reinforced polymers for application in construction can therefore once again be found in their environmental performance (again related to the high specific strength properties of these materials).

Additional Research Areas

Although RIS systems seem promising for future applications in housing, there are many issues that remain to be addressed. Some areas for additional research include further development and optimization of RIS materials, architectural design and optimization of RIS systems, physical testing of RIS systems, optimal detailing of door and window penetrations, and the incorporation of utilities. Furthermore, implementation barriers, such as the lack of applicable building codes, need to be addressed.

Materials

Considering that houses are permanent structures, this study examines materials that permanently rigidify once the material property change has occurred. Reversible materials exist and could be used where the advantages of deflation are beneficial, perhaps disaster relief or military situations. The specific physical material properties might also be enhanced to meet specific design needs. For example, the RIS might have a controlled degree of opacity or translucency to allow for natural means of lighting and heating in the finished product.

Architectural Design

The shape studied here is a simple box in order to make a direct comparison with existing WLF houses. Another possible area of research could be the architectural design of the structure. The optimal use of a membrane material often occurs when the membrane is placed in tension. Considering this, tensile roof systems may prove to be more efficient. Further investigations into the form of the structure would uncover additional issues such as window and door construction. Openings may be inserted in the volume as they would be into a WLF house. However, the shape and specific nature of the openings would be closely related to the nature of the RIS material in its rigidified state. The issues of utility installation and servicing also arise. Eventually, electric, water, and plumbing lines might be embedded in the membrane during the manufacturing phase. Until these issues are studied, a more temporary solution might be found by installing these lines in the foundation of the structure. Another alternative might be to install utilities in the walls, in a fashion similar to utility lines in existing WLF structures.

Concluding Remarks

The objective of the research presented herein was to contribute to the development of affordable and resource-efficient housing technologies. The emerging technology of rigidified inflatable structures (RIS) was investigated as a means to accomplish these objectives. A new material, which can be used in this technology, was proposed, developed, and evaluated. In light of sustainable development goals and issues of affordable housing, the results of this research indicate that RIS structures have great potential in addressing current needs. The study indicates that the cost of ownership in present-day value for the RIS is approximately 35% less than the cost of a comparable wood light-frame structure. The study also indicates that significant environmental benefits exist with the use of RIS. These structures use significantly less resources than do wood-frame structures: approximately 2 times less material originating from nonrenewable fossil resources; approximately 2 times less material originating from trees; and approximately 19 times less materials originating from inorganic resources. While this study indicates that architectural applications for RIS technology are promising, it acknowledges that it will require a great deal of development to realize the full technological potential of RIS materials. In the near future, it is likely that the demonstration of RIS technology for architectural applications and development of multifunctional RIS membrane systems based on renewable resources will be feasible. These structures are envisioned to have embedded in them communication, illumination, energy-distribution, and energy-collecting devices.

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