Rigidified Pneumatic Composites:
Environmental Performance of Structural Skins Made from Fiber Reinforced Polymers

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INTRODUCTION

Rigidified pneumatic composites (RPC) structures are defined as thin flexible membrane structures that are pneumatically deployed. After deployment, these structures harden due to chemical or physical change of the membrane. Because of this change, such structures no longer require pneumatic pressure to maintain their shape or provide structural stability. As a result, a structural skin is obtained that can be used to construct a variety of structures[10] (figure 1).

These include for example advanced panel systems, simple columns and beams, and complex truss systems (figure 2). Current research related to RPC technology is mainly focusing on space structure design[1-3]. In these applications, the minimum of materials and labor that is needed to deploy such systems makes them ideal to build large space structures at an affordable cost. Examples of applications that have been successfully demonstrated include large solar arrays, complex truss structures, and large parabolic antennas[2-3]. In addition, multifunctional membranes are currently being developed that have various devices embedded in them[2-3]. These new developments further extend the capacity of RPC technology to deploy complex systems in space at an affordable cost.

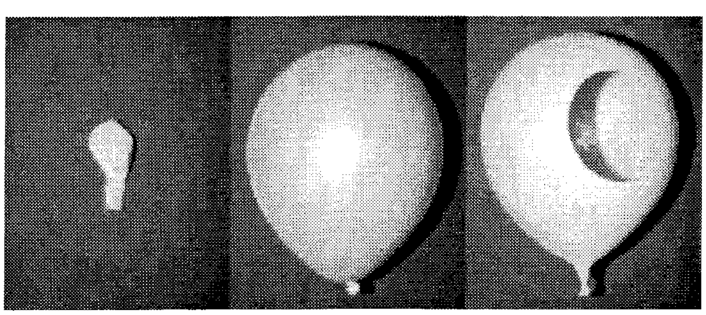

Fig. 1. RPC: Illustration of concept

RPC systems possess many of the performance characteristics desired in home design. For example, RPC structures are self-deployable making possible extremely short construction times. RPC systems can further be engineered to be very durable or to have a predictable service life. In addition, RPC technology lends itself well to low cost manufacturing and streamlined technology delivery (by using manufacturing processes well known to the textile industries). These characteristics give RPC structures high potential for accomplishing affordable and sustainable housing technologies. In order to assess the usefulness of RPC technology for architectural applications, economic and environmental performance need to be considered. In our previous study, a systematic listing of the various means available to develop polymeric materials useful in RPC technology was presented. With the aim to reduce cost, a new material was also proposed, tested, and evaluated[10, 11]. The objective of current study was to assess the environmental performance of RPC technology by considering the amounts and types of resources used.

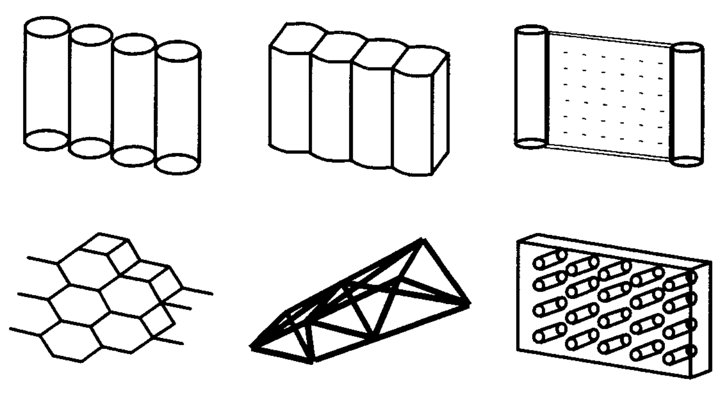

Fig. 2. RPC: Potential structural systems

SCOPE & METHODS

Various methods exist that can be used to asses the environmental performance of construction technologies, these include for example; the embodied energy method, the 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. In many occasions however, 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 [4]. 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 RPC technologies (no relevant historical data available), we decided to adopt such a streamlined assessment method. The method adopted in our 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. We 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 our study did not reveal any differences that may exist within one class of materials due to for example different methods of extraction, processing, manufacturing, or design.

We compared the performance of an RPC system with the performance of a more conventional wood light framing system (WLF) that served as a standard base case. Our 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 & weight). Second, materials for each system were classified into categories of materials having similar origin or nature. Categories used were: a) materials coming from wood, b) materials coming from fossil resources (petroleum, coal, natural gas), and c) materials coming from inorganic matter. Materials present in small quantities were not included. Finally, results were used to assess the resource efficiency of RPC structures relative to the wood light frame system.

CASE STUDIES

The environmental performance of RPC technology was compared with the environmental performance of a typical wood light frame structure in the application of a small house. The enclosing envelope of a single-family house in its most basic form was considered. The scale of the two houses being compared was that of a small prismatic single-story house 24 feet wide, 48 feet long, and a ceiling height of 8 feet (about 14mx7mx2.4m). The building foundation, a frost protected shallow concrete slab, was held constant for both systems. Operation costs for heating and cooling of the buildings 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). Only superstructure and relevant finishing systems were considered. The study did not cover wall openings, and mechanical or electrical systems. A typical service life of 40 years was selected. Since significant structural differences exist between the compared systems, only the primary function of enclosing space was considered. Non-primary functions such as the absolute load bearing capacity of each wall assembly was not considered.

Case 1: Wood Light Frame System

Figure 3 gives a section through the wood light frame construction adopted for this study. A 2x6 stud wall with studs placed at a spacing distance of 24 inches on center was selected. A single pressure treated sole plate, and a double top plate is used. Exterior 3/8 inch thick plywood sheeting, 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 board nailed to the studs. Two coats of paint are applied to the gypsum boards and serve as the final finishing surface. An R-19 mineral fiber bat insulation system faced with paper was selected for the walls. A simple gable roof with a pitch of 5/12 was selected. Trusses are also placed at a distance of 24 inches on center. A ½ inch thick plywood sheeting is applied to the trusses providing permanent lateral bracing to the roof and a substrate for placing the asphalt shingles. The exterior sheeting is covered with a layer of asphalt saturated felt paper prior to placing the 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 5/8-inch thick gypsum board panels that are nailed to the truss bottom chords. Two coats of paint serve as the final finishing surface. Roof edges are provided with aluminum drip edges. An R-19 mineral fiber bat insulation system faced with paper was placed between the truss bottom chords. Figure 3 provides the inventory of the important components necessary to construct the superstructure of the WLF house.

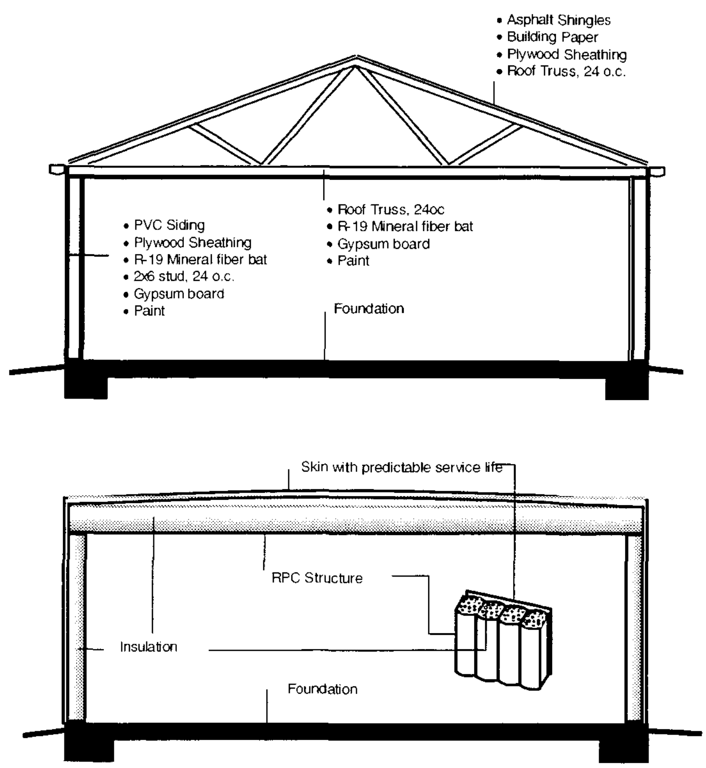

Fig. 3. Sections through WLF and RPC systems

Case 2: Rigidified Pneumatic Composite System

Figure 3 gives a section through the RPC design adopted for this study. A 20 cm thick wall composed of tubular rectangular column elements 20cm wide and 20cm deep is envisioned (figure 1). No effort was made to resemble the shape of a gable roof. The roof structure consists of similar tubular rectangular beam elements 20cm wide and 40cm high. The interior ceiling height is 8 feet. A single-ply butyl-rubber membrane covers the exterior surface of the wall and roof structure forming a protective skin for the RPC structure. A blown-in cellulose insulation system was envisioned placed inside the wall and roof cavities. The membrane of the RPC system was assumed to consist of a semi-inter-penetrating polymer network based on poly-vinyl-chloride and reactive plasticizer[6]. The average yield strength of this matrix was 25MPa, the modulus of elasticity was 2.5 GPa[10, 11]. This matrix was further assumed to contain a volume fraction of 30 % of randomly oriented discontinuous glass fibers. Isotropic material properties were calculated using a simple rule of mixture, this resulted in a modulus of elasticity of 8.5 GPa for the rigid composite. SSTAN, a Simple Structural Analysis Program using finite elements for static load analysis of three-dimensional structural systems[5] was used to analyze this RPC-system. The total amount of material needed for safe design could be determined hereby; this resulted in a membrane thickness of 0.4 mm. The effects of highly concentrated loads acting upon the thin membrane structure were not considered. The assumption was made that local buckling of beam or column membranes is prevented by means of the cellulose insulation cavity filling. A deflection of L/100 was allowed for the midpoint of the beam. This deflection was considered acceptable since no fragile finishing systems are attached to the RPC superstructure. Figure 4 provides the inventory of the major components necessary to construct the superstructure of the RPC house.

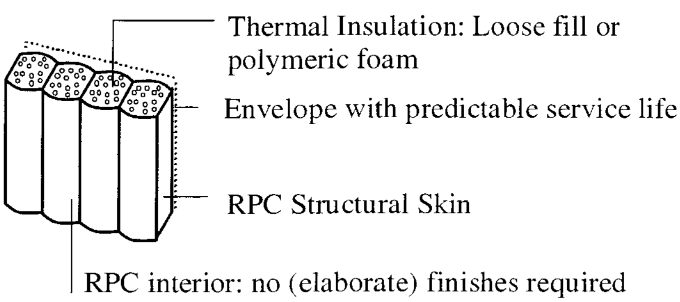

Fig. 4. Composition of the RPC wall/roof assembly used in our case study

RESULTS

WLF structure: The total mass of the WLF structure is approximately 9670Kg. The WLF structure uses a total of 1209Kg of material derived from fossil remains (petroleum, coal, natural gas). These include for example: the glues that hold the exterior plywood together (178 Kg), the Poly-Vinyl-Chloride siding (104 Kg), the interior paints (22 Kg), and the asphalt shingles on the roof (896 Kg). Combined, these make up 12% of the weight of the WLF structure. Second, a significant portion of the mass for WLF comes from inorganic matter (4692 Kg), these are the gypsum boards used to finish interior walls and ceiling (3368Kg), and the mineral fiber insulation system (1294Kg). Combined these make up 48 % of the weight of the structure. Finally, 39% of the weight of the WLF structure comes from wood. These include the 2x6 studs of the wall (1371 Kg), the wood used in the W-shape roof trusses (781 Kg), and the wood present in the plywood sheathing (1601Kg).

RPC structure: The total mass of the RPC structure is approximately 3250Kg. About 630 Kg (19 %) of the total weight of the RPC structure comes from fossil resources, this incorporates the polymeric matrix used in the RPC membrane and the rubber used as protective skin. The amount of inorganic matter present in the RPC structure is 180 Kg or 6% of the total weight, this represents the glass-fiber reinforcement present in the membrane. Finally, about 75 % of the weight of the RPC structure comes from wood (2423 Kg). This is the cellulose insulation system inserted in the cavities of the RPC structure. Figure 5 compares these results for each category used in both systems.

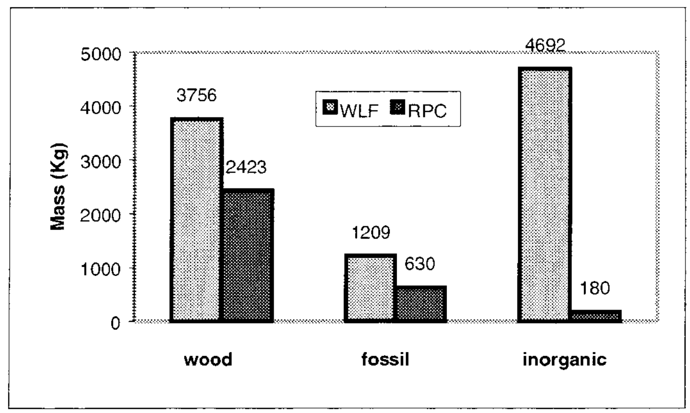

Fig. 5. Resource consumption per category for WLF and RPC systems

CONCLUSIONS

Our study indicated that the RPC system used significantly less resources compared to the WLF structure. About 2 times less materials coming from non-renewable fossil resources, about 30% less material coming from wood, and about 25 times less materials composed of inorganic matter was used in the RPC structure relative to the WLF structure (Fig. 5). On a weight basis the RPC system used almost 3 times less material compared to the WLF system. The exceptional resource efficiency of RPC 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 RPC 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 afterwards. In addition to this, RPC structures are also more homogeneous in composition facilitating the separation of wastes resulting in more convenient recycling or reuse of materials. Our study also revealed that the estimated time needed to construct the RPC system was four times less than the time needed to construct the WLF structure. This represents a 75% reduction in project delivery time. This short delivery time for RPC structures is largely explained by the ease at which RPC 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.

Remarks: It is clear that the results of our study could be quite different when different system components were selected. This is true for both the WLF and RPC structures. For example; Substituting the PVC siding with a 10mm wood siding and replacing the mineral fiber insulation with a cellulose insulation system reduces the use of fossil resources to 10%, increases the use of wood to 59%, an reduces the use of fossil resources to 31% of the total weight of the WLF structure. Figure 6 compares these results with the RPC system. Replacing the asphalt shingles with another roof material can further reduce the use of products derived from fossil resources. Similar substitutions can be done for the RPC structures. For example, replacing the poly-vinyl-chloride of the RPC matrix system with a cellulose based polymer (coming from wood or other plants), and replacing the acrylate based reactive plasticizer with one derived from natural oils (such as soybean or linseed oil) can result in a matrix system in which no petroleum derived polymers are used. Also, when replacing the glass reinforcement with a natural reinforcing fiber (such as cotton, flax, or hemp) an RPC membrane can be developed that is completely based on renewable resources. Additional research is needed to assess the performance of such systems.

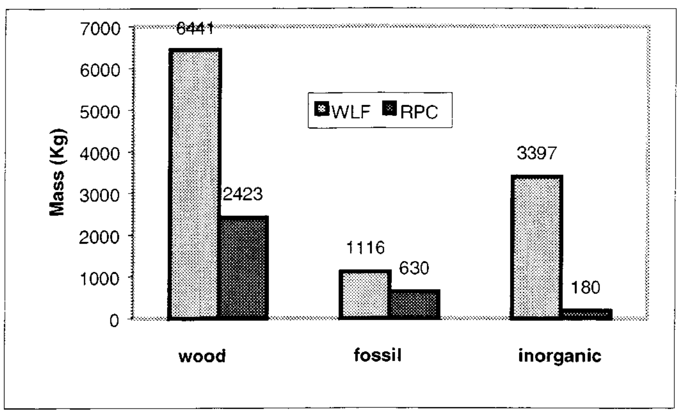

Fig. 6. Resource consumption per category for WLF and RPC systems (using more material derived from wood for the WLF system)

DISCUSSION

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 extend, the high cost of fiber-reinforced polymers rises from the labor-intensive methods used to fabricate large structures from them. Considering the simplicity of fabrication methods that can be used in RPC technology (using low cost manufacturing processes well known to the textile industries), a reduction in cost can be expected. Our 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).

It is interesting to observe that most biological systems are composed of fiber-reinforced polymers[7]. Furthermore, material properties in biological systems are specifically tailored to perform optimum in a given application or condition[9]. The use of similar materials for construction purposes may therefore be of promise in light of sustainable development goals. This notion could be particularly relevant considering that biological systems have for long accomplished many of the sustainable goals currently aimed for. It should be acknowledged however that wood light frame structures also rely on fiber-reinforced polymer systems (being wood). A tree however is not a house. So while a piece of wood serves it purpose well in a tree system, it may not perform as efficiently in an enclosure system.

Historical note: It is also interesting to notice that due to technological advances made in the 19th century, wood light framing has largely replaced heavy timber construction in residential buildings. Relative to heavy timber construction, a significant reduction in cost and wood consumption was accomplished hereby. In addition, development of products such as plywood or oriented strand board further optimized these systems. The development of RPC systems can be considered as being the next optimization step in this evolution. This idea is especially relevant considering that the development of cellulose-based RPC systems is both feasible and attractive[10]. Understanding current concern for the depletion of natural resources, the extreme resource efficiency of RPC systems could proof to be very useful. Even more so knowing that almost one-half of the world's major resources are consumed by construction and related industries and fifty five percent of the wood cut for non-fuel uses are used in construction[8]. While our study indicated that architectural applications for RPC technology are promising, we acknowledge that it will require a great deal of development to realize full technological potential. Nevertheless, we hope that our research will lead to the development of commercially viable and environmentally conscious housing technologies that utilize state-of-the-art materials and manufacturing processes. In the near future, we foresee demonstration of RPC technology for architectural application and development of multifunctional RPC membrane systems based on renewable resources. These are envisioned to have embedded in them: communication, illumination, energy-distribution, and energy-collecting devices.

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