RIGIDIFIED PNEUMATIC COMPOSITES: USE OF SPACE TECHNOLOGIES TO BUILD THE NEXT GENERATION OF AMERICAN HOMES

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Abstract

Developments in space technology are often driven by performance objectives very similar to those desired in home design. In contrast to home design, the extreme conditions applicable to the design of space systems calls for the development of breakthrough technologies. Hence, space technologies might have high potential to provide clues or insights for the development of breakthrough technologies useful in home design. This paper deals with rigidified pneumatic composite (RPC) technology. 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. An overview of RPC technology is provided and the anticipated benefits for use in residential construction are illustrated. Critical issues to make RPC technology useful in residential construction are further identified.

Introduction

Developments in space structure technology are often driven by performance objectives very similar to those desired in home design. For example, following research goals were recently identified as highest priority for the residential sector: 1) reduce production cost through improved technology and shortened production cycle times, and 2) improve product durability [NAHB, 1998]. These objectives are also high on the agenda for space structure design. For space systems to be affordable they need to be extremely lightweight, strong, compact for transportation, easy to deploy, energy efficient, and have a predictable service life under severe space conditions. In contrast to home design, the extreme conditions applicable to the design of space structural systems calls for the development of breakthrough technologies. Among the actions taken by the space structure design community to accomplish these objectives are: development of new materials with "designed" properties, development of self deployable systems with compact stowed volume, establishment of material databases, and development of design optimization tools and methods for assessing performance. These performance objectives are very similar to those desired for home design. Space structure technologies can therefore have high potential to provide clues or insights for the development of breakthrough technologies useful in home design. In addition, tools developed to optimize space structural systems may also be extremely useful for the optimization of home design. Hence, by harvesting developments made in space system design, significant research expenditures for residential construction can be avoided.

Considering the above, rigidified pneumatic composite (RPC) technology shows great potential for use in home design. 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 (Figure 1). [Van Dessel, 2000]. These include for example advanced panel systems, columns and beams, and complex truss systems (Figure 2). RPC systems possess many of the performance characteristics desired in home design. For example, RPC structures are extremely resource efficient, are self-deployable making possible extremely short construction times, and are very versatile in terms of design possibilities. Furthermore, they can be engineered to be very durable or to have a predictable service life. In addition, this technology lends itself well to low cost manufacturing and streamlined technology delivery. These characteristics give RPC structures high potential for accomplishing affordable and sustainable housing technologies.

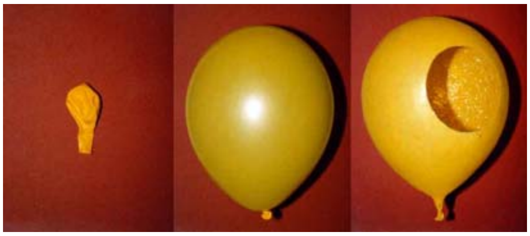

Figure 1. RPC: Illustration of concept.

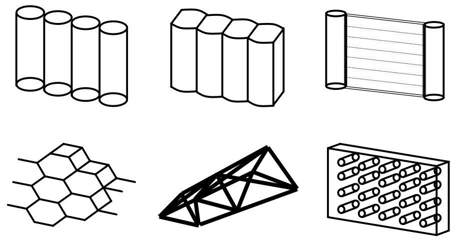

Figure 2. RPC: Some potential structural systems.

Technology Overview

Concepts for pneumatic deployable space structures have been under development and evaluation for almost 50 years [Freeland et al, 1998 and Jenkins et al, 1998]. The potential for this class of structures for achieving affordable space systems, robust deployment, very small-stowed volume, and low weight is recognized by an increasing segment of the space structure design community. A number of different technology developments have taken place over this period [Cassapakis et al, 1995]. Rigidified pneumatic composites structures (RPC) are currently at the forefront of these developments.

Current research related to RPC technology is mainly focusing on space structure design [Bernasconi, 1990, and Cadogan et al, 1998,]. 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 support structures for large solar arrays [Malone et al, 1996], complex truss structures [Guidanean et al, 1997], and large parabolic antennas [Freeland et al, 1993]. In addition, multifunctional membranes are currently under investigation that have various devices embedded in them. These new developments further extend the capacity of RPC technology to deploy complex systems in space at an affordable cost. Due to developments made in the past few decades, RPC technology has reached a state of technology maturation today that makes it a very competitive solution for future space system design.

Research on RPC structures has largely focused on two areas. The first deals with the development of appropriate materials and establishing a material database. The second deals with the development of tools and methods that can be used to accurately predict shape and performance for this class of structures.

RPC: Material Development

The criteria used for developing RPC materials for application in space are to accomplish: a) high flexibility for dense packaging and ease of deployment (before rigidified), b) high modulus of elasticity for structural stiffness (after rigidified), c) process reversibility for testability, d) zero coefficient of thermal expansion for thermal stability, e) resistance to the space environment, f) predictable surface contours before and after structures rigidify, and g) control over the stiffening process [Freeland et al, 1998].

Multiple materials and rigidifying techniques are currently available that can be used to construct RPC structures. The most common of these are: a) fabric impregnated with resin that is cured by exposure to ultraviolet light, b) fabric impregnated with hydrophilic resin that rigidifies as the water evaporates, c) fabric impregnated with a polymer that rigidifies when it is cooled below its glass transition temperature, d) thermo-set resin that is cured upon the application of heat, e) a laminate of aluminum foil and thin Kapton film that rigidifies when the aluminum is strained beyond its yield point, and f) foam inflated structures that rigidify as the foam hardens within the enveloped cavity. [Cadogan et al, 1998; Cassapakis et al, 1995; and Derbes, 1999].

RPC: Design

Many applications for pneumatic space systems require accurate prediction of surface contours. These include for example parabolic solar concentrators, X-ray antennas, and large telescopes. While standard finite element method codes can be used to analyze pneumatic structures, they cannot be used to predict surface contours very accurately. A number of computer codes that allow more accurate shape predictions have therefore been developed. These include FAIM, a code developed for the finite element analysis of inflatable membranes [Palisoc, A., and Huang, Y. 1995]. AM, a high precision tool for the study of pressurized axisymmetric membranes capable of modeling wrinkling and determining initial shapes which inflate to desired pressurized contours [Greschik et al, 1998]. Structural behavior of pneumatic systems is currently also being investigated at the Compliant Structures Laboratory at the South Dakota School of mines and Technology [Jenkins, C. and Marken, D., 1998] and at the Jet Propulsion Laboratory at the California Institute of Technology [Freeland et al, 1998]. While standard FEM codes should be used cautiously when analyzing pneumatic systems, they can be used with higher levels of confidence to analyze RPC structures after they have become rigid. In addition, simple cases can also be handled analytically. Design optimization of RPC systems is mostly concentrated on conducting comparative analysis, the objective of these studies is to emphasize the advantages of RPC technology relative to more conventional mechanically deployed space systems [Mikulas, M., and Cassapakis, C., 1995].

RPC: Residential Applications

The use of RPC technology for residential construction has been suggested occasionally [Dent, R., 1972, DiTomas, E. 1996]. Meaningful technological advances however remain to be established. Plausible explanations are that RPC technology has only recently accomplished a sufficient level of technology maturation for space structure design. In addition, application in residential construction differ significantly from space applications, no direct displacement into home building is therefore possible. For example, thermal stresses are a main controlling factor in design of space structures. For residential construction, loads generated by gravity, wind, and occupation is usually more important. In addition, space structures often require high surface accuracy while less accuracy can be accepted in housing design. Further, severe space conditions, including space radiation and particle impact pose many restrictions on the type of materials that can be used in that environment. Most of these conditions are less severe on Earth; hence the range of available materials is largely expanded possibly accommodating lower cost solutions.

RPC: Anticipated Benefits for Residential Construction

RPC technology appears to possess many of the performance characteristics desired in home design. For example, RPC structures are extremely resource efficient, are self-deployable making possible extremely short construction times, and are very versatile in terms of design possibilities. Furthermore, they can be engineered to be very durable or to have a predictable service life. RPC technology also lends itself well to low cost manufacturing. Some of the anticipated benefits that RPC technology can provide for residential construction are explained. These include: 1) expected efficiency to mitigate the impact of natural disasters, 2) expected ability to reduce residential construction work illness and injuries, and 3) expected energy efficiency. While many indications exist to support the claims presented in the following section, physical performance testing of RPC systems will be necessary to make more conclusive recommendations.

RPC: Potential to Mitigate the Impact of Natural Disasters

Mitigate damage due to hurricane/tornado:

Damages caused by hurricanes and tornados can be devastating. In 1992 for example, hurricane Andrew caused an estimated $15.5 billion in damage to insured property [Ayscue, J., 1996]. Because less engineering oversight is applied to design and construction of residential structures, houses are especially vulnerable to damage during hurricanes or tornados. Fully engineered construction, on the other hand, performs well because of the care given to connections and load paths [Perry, D., 1991]. Since RPC structures are completely manufactured, proper design features can be incorporated to mitigate damages. In addition, RPC structures can be designed to allow significant deflections before structural failure occurs. This is very difficult to accomplish with traditional wood light framing (WLF) were deflections are largely limited by the fragility of the interior finishes. In RPC structures, both materials and connections can easily be engineered to allow significant elastic structural movement without failure. To take full advantage of these characteristics, proper detailing and connection with the foundation system is needed.

Mitigate earthquake damage:

According to a study released by the Federal Emergency Management Agency, earthquake losses in the United States add up to about $4.4 billion dollars a year [FEMA, 1999]. Lateral forces generated in buildings due to an earthquake are mainly responsible for catastrophic failure of buildings. These forces are directly proportional to the building's dead loads [Ambrose, J., and Vergun, D., 1999]. Reducing these dead loads by using building materials that are light and strong is therefore an effective way to reduce earthquake damage in small residential structures. In addition, lighter materials are less likely to cause injury or death in case small residential structures do collapse. RPC structures are made from fiber reinforced polymer composites. These materials are among the strongest materials available today and have specific strength properties that exceed those of structural steel or concrete many times [Mallick, P., 1995]. RPC structures can thus be engineered to be both extremely strong and light. In comparison to wood light framing, RPC structures can again be designed to allow significant deflections before structural failure occurs. As already mentioned, this is very difficult to accomplish with traditional wood light framing were deflections are largely limited by the fragility of the interior finishes. In addition, connections used in WLF structures often do not allow large deflection without failure. In RPC structures, both materials and connections can easily be engineered to allow (elastic) lateral structural movement without failure. Because of this, RPC structures can more readily be engineered to resist lateral earthquake forces.

<u>Mitigate flood-damage:</u>

According to the hydrologic information center, flood losses totaled \$5.45 billion in 1999 [HIC, 2000]. The most cost-effective way to reduce damages due to flooding is to incorporate mitigation measures into site planning and the design and construction of buildings. The first can be accomplished for example by not constructing new houses in floodplains. When this cannot be avoided, minimizing the impacts of those risks through proper design is recommended. Such measures can include for example raising the house above the expected flood line. In addition to these measures, mitigating the impacts of water on structures when contact does occur is highly recommended. This can be accomplished through selection of building systems that are less prone to water damage. RPC structures are composed of fiber-reinforced polymers. These materials have replaced wood and steel in many applications were prolonged contact with water is needed. Example can be found in the applications for ship hulls and storage containers. In light of this, RPC structures can be expected to outperform traditional home building materials such as wood, plywood, and gypsum board since the constituent RPC materials have a proven record of being durable in applications where prolonged contact with water is needed.

RPC: Potential to Reduce Residential Construction Work Illness and Injuries

<u>Non-fatal injuries and illnesses:</u>

Non-fatal work related injuries and illnesses strongly depend on the industrial sector under consideration. For the construction sector in general, the incidence rate (number of injuries and illnesses per 100 full-time workers) for non-fatal injuries and illnesses is about 8.6. In addition, the incidence rate for manufacturing lumber and wood products, currently the prevailing materials used for residential construction, is approximately 13. In contrast, the incidence rate for textile and mill-products is approximately 6.4, while the incidence rate for apparel and other textile products is approximately 5.8. The incidence rate for manufacturing chemicals and allied products is about 4.4 [US department of labor, bureau of labor statistics, 2000]. Based on these statistics, adoption of RPC technology can possibly reduce work related non-fatal injuries and illnesses in residential construction by more then 30%. This reduction will come first from the use of manufacturing processes that cause less injury and illness among the US work force. And second, since materials are used that also cause less injury and illness among the US work force during extraction and processing.

Fatal injuries:

The construction sector is known as one of the most dangerous industries in the US. While construction workers comprises only 1% of the US labor force, the sector accounts for 5% of all fatal injuries [Toscano, G., 1997]. In general, occupations at highest risk of fatal injuries perform work outdoors or in other environments that are harder to control. In contrast, those workers that perform in conditions that are easier to control, such as a manufacturing plant, are at much lower risk [Toscano, G., and Windau, J., 1998]. For example, the rate of fatal occupational injuries (number of fatal injuries per 100,000 workers) is approximately 13.9 for the construction sector while the same rate is only 3.5 for the manufacturing industries [US Department of Labor, 1999]. Since RPC structures will be manufactured indoors by means of largely automated processes, they require a minimum amount of on-site manual labor. The total rate of fatal occupational injuries can hence be expected to reflect statistics for fatal occupational injuries, possibly reducing construction fatalities in homebuilding by more than 50%. Also, RPC structures will out-perform more traditional home manufacturing practices since manufacturing processes lend themselves better to automation. In addition, less mass of material is transferred to and on the construction site reducing the risks involved during maneuvering. This is especially true considering that most fatal construction accidents occur by workers being struck by hard and heavy objects or being caught in between such objects [OSHA, 1990]. Since RPC structures are self-deployable (including roof), no scaffolding is needed to build small residential buildings. Death due to fall, another major cause of fatal construction injury, will hence also be significantly less [OSHA, 1990].

RPC: Energy Efficiency

Approximately 20% of all energy produced in the US is consumed by residential buildings [DOE/EIA, 2001]. Space conditioning (heating & cooling) accounts for over 50% of the energy used in the average American home [DOE/EIA, 1999]. Hence, energy expenditures for space conditioning are a significant environmental and economical factor if calculated over the complete service life of a house. Energy expenditures due to space conditioning are affected by many factors. These include for example thermal properties of materials, air infiltration rate, efficiency of HVAC systems, exposed external surface area, and climate conditions. Increasing thermal performance of walls and roof and reducing air infiltration rate are the most efficient ways to increase the overall performance of the external envelope for conventionally shaped buildings. In light of this, RPC structures can be expected to perform well. First, since RPC structures are manufactured from continuous airtight membranes, less air infiltration due to joints are to be expected. Secondly, inflation cavities can easily be filled with insulating materials after the RPC structure becomes rigid (Figure 3). Thermal insulation can be inserted as a loose fill cavity filing or by means of injecting polymeric foam into inflation cavities. Such foam can provide both increased thermal insulation and structural stiffness. When a high performance RPC envelope is coupled with an efficient HVAC system, significant energy savings can be accomplished.

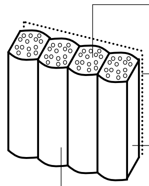

Figure 3. Plausible RPC Wall Assembly

Future Outlook

In light of sustainable development goals, RPC technologies appear to have great potential. Successful implementation however will require substantial research effort, especially focusing on the following areas:

Cost of Ownership

RPC technologies are currently being developed almost exclusively to serve the needs of the space industry. 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. The cost of materials in space applications however usually represents only a minor fraction of the total system cost, material costs are therefore often not of primary concern. For residential construction however material cost is critically important. Also, the service life of residential structures spans several decades while space system usually serve less than a decade (although under severe conditions). Hence the long-term performance of RPC structures is also important. Ideally, RPC structures will be affordable and durable. If not, then they should not require substantial financial and material resources for maintenance. In addition to developing low cost RPC materials, means to increase long-term performance or to identify environmentally sound maintenance and repair practices need to be developed. In addition to this, continued effort should be spent to identify and develop new materials that rely less on non-renewable resources and more on the utilization of renewable resources (such as agricultural by-products).

Fire Safety

In 1999, fire killed more Americans than all other natural disasters combined, approximately 82 % of all these fire deaths occurred in residences [Karter, M., 2000]. Considering the importance of fire safety in residential construction, measures aimed to reduce the impact of fire on RPC structures and occupants need to be identified. Considering that RPC structures are composed of thin skins made from organic materials, they are potentially prone to fire. Ability to increase fire resistance, reduce flame spread, smoke development, and toxicity in RPC structures need to be evaluated. Plausible solutions to increase fire safety may include: In-capsulation of structural composite with materials that are more fire resistant, fire retardants blended with the polymeric matrix, intumescent systems, use of fire resistant/retardant polymeric foam cavity fillings, use of low cost sprinkler systems, or combinations of the above [Refs. 1,6,22,31].

Indoor Air Quality

Fifty percent of new buildings today suffer from the so-called sick building syndrome caused for example by off-gassing of volatile organic compounds (VOC's) [Roodmann and Lenssen, 1995]. These VOC's are composed of low molecular weight compounds that are present in most building materials and that diffuse to the material surface over prolonged periods of time. Distribution of these compounds into the indoor air may in turn adversely effect human health. It is important in the development of RPC technologies for residential construction to assure that no hazardous off gassing occurs. This can be accomplished for example by selecting RPC material components that are safe to humans and the environment (such as products that are approved for prolonged contact with food).

Conclusion

The space technology of rigidified pneumatic composites has great potential in addressing some of current needs in residential construction. While architectural applications of RPC technology are promising, a great deal of research and development is needed to realize full technological potential. Use of new materials that rely less on non-renewable resources and more on the utilization of renewable resources (such as agricultural products) in the development of RPC membrane systems is beneficial from an ecological viewpoint.

Acknowledgment

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