Rigidified Pnuematic Composites

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INTRODUCTION

The history of technology is a strange cascade of both accidental and intended change. Intended change comes around when current state technology is insufficient to deal with a pressing problem, accidental change on the other hand appears at random. The advent of science has brought with it a more organized fashion of study. The transfer of knowledge into useful technologies however still seems to appear at random as part of a trouble-shooting process patching up existing systems and processes. It is amazing to observe the degree of perfection we are able to accomplish by perfecting existing technologies. Think for example about the wheel evolving from its crudest form into the pneumatic fibre reinforced rubber composite it is today. The concept is primitive; the degree of perfection is amazingly high. We seem to be reluctant to deviate from a working concept unless we are forced to it by crisis, such as war. In many aspects the history of architectural technology is no different. Steel construction for example is based on the much older technology of heavy timber construction; a material replacement has occurred that refined the preceding technology.

CURRENT NEEDS

Many needs exist at the beginning of this century; most pressing is the need to house the ever-growing world population in a sustainable way. Today more than twenty percent of the worlds' population continues to live without adequate housing [1]. It is projected by United Nations demographers that human population will expand over the next fifty years from the current 6 billion to between 7.8 and 12.5 billion [1]. Considering these numbers and current state of the environment, the importance of developing more sustainable building technologies becomes readily apparent. There is also an increasing need to create a build environment more respective to human intellect, something that cannot be accomplished by technology but rather by re-establishing the understanding that cost and value are two separate things. The latter requires intelligent designers and our willingness to invest in them. The former requires advances in architectural technology and is the purpose of current research on Rigidified Pneumatic Composites.

STRUCTURAL SYSTEMS IN NATURE

Many things can be learned from natural systems, it makes sense to reason that organisms that can sustain themselves naturally are environmentally sound by fitting into the larger scheme of things. Billions of structures are being built continuously by nature without any human involvement, so most likely there is a lesson to be learned for those involved with construction. Following are a few observations [2-3]:

a) The most common building material in living natural systems, as we became to understand only in the past 65 years, are organic compounds that are polymeric and composite in nature.
b) Further, nature does not build things with screws or nails, it uses very clever chemical reactions to assemble very complex an intelligent designs. There are no blueprints to explain an assembly; instead an automated process of both information transfer and assembly is used.
c) The use of membranes and pneumatic principles are key elements in all-natural organisms, going from a single cell to the most complex plant or animal assembly.
d) Many structural systems in nature come into existence by rigidifying a more flexible one. Examples are the formation of eggshell and solidification of skull and skeleton. It is interesting to observe that most natural pneumatic structures exist in aqueous environment where decreased gravity and smooth stress situations exist. Comparable systems that exist in atmospheric condition and more stressing environment armour themselves by becoming rigid. Examples of this can be found in the differences that exist between fish eggs and those eggs laid on land by birds and reptiles. Whenever there is a need for additional protection natural structures seem to be rigid.

Bringing these observations together we can find that polymer composites, membrane structures, and pneumatic form giving concepts are well established in nature. Rigidification processes of pneumatic structures are also common. When these concepts are applied to construction they might possess some of the same merits such as, ease of assembly and efficient use or resources. A closer investigation is needed.

PNEUMATICS, THE EXPERIMENTS

Considerable interest in pneumatic structures existed during the 50s to 70s. The relation of these structures to natural systems was also recognised [4-5]. Pneumatic structures have many advantages compared to conventional building technologies, however they also have some distinct disadvantages such as high vulnerability, limited durability, and their limited appearance. As mentioned briefly, architecture is not a mere statement of some technological problem. Issues of current culture, historical tradition as well as philosophical considerations all form equal parts and explain why we have such a rich tradition in this field. Early researchers on pneumatics structures were eager in their efforts to promote this new kind of architecture, however they tended to distant themselves from the traditional roots of architecture. Bubble shape buildings coloured in orange, yellow, and pink were rather shocking to the laymen. After a period of some excited and valuable experiments interest faded away by lack of any serious audience. A lot of interest continues to exist among those involved with the design of space structures. The advantages are clear: light in weight, compact transportation volume, and ease of deployment in space are inherent to pneumatic structures making them a good choice for these applications. Current investigations on systems that rigidify in space also occur in this arena [7-11]. The usefulness of Pneumatic Composites in construction will depend on some key issues being: Will such system be more sustainable than conventional construction systems? Is it possible to develop a more intelligent architectural tradition for them? Will these structures be durable and have a good life cycle cost? Is it possible to provide a nice palette of texture and colour for these materials? Will there be sufficient market for these structures making development economical? These questions can be answered by conducting the appropriate research and are no different than those asked during the development of any other technology.

RIGIDIFIED PNEUMATIC COMPOSITES

The objective of this research is to mimic the natural process of solidification of a pneumatic structure, and develop a system called Rigidified Pneumatic Composites (RPS). The exploration and development of new materials that are tailored towards application of this technology in the construction field is the main focus of the remainder of this paper. The idea to rigidify pneumatic structures is fairly new and not yet well established, research is scattered over periods of time and location [5-11]. Most of the research is concentrated in the area of space structure design. The displacement of these technologies into architectural application is not a straightforward process. Conditions of space differ significantly from those encountered on earth, and solutions presented need to be tailored towards the specific environment.

MATERIALREQUIREMENTS

Many possible reactions exist that can be used to solidify a membrane structure. However, taking under consideration the conditions necessary to come to an acceptable system, a solution does not present itself easily. This is due to the fact that a combination of performances is needed. While solving for one criterion is relatively easy, solving for all is a lot more complicated. The application of this technology in construction requires the development of unique material solutions tailored towards the specific applications. Following are some of the criteria to be accomplished: Good Mechanical Properties, Ease of processing, Low Implementation Cost, Durable, Convenient Storage & Long Shelf life, Convenient curing conditions, Safe to use, Cost effective, Sustainable, Provide a healthy environment, Able to provide a palette of different colours and textures.

CASE STUDY: SEMI-INTER-PENETRATING POLYMER NETWORK (SEMI-IPN) BASED ON POLY-VINYL-CHLORIDE AND AN ACRYLATE BASED REACTIVE PLASTICIZER, UV-INDUCED POLYMERISATION

In order to address some of the above issues, a particular material solution was designed based on plasticized Poly-Vinyl-Chloride (PVC). In this solution, small plasticizer molecules disrupt polymer-polymer interaction by forming secondary bonds with the PVC molecules. By spreading the PVC polymer chains apart, PVC molecules have more free volume to move around, providing a more plastic rubber-like mass [12]. This material, when formed into a membrane, can be used to construct a pneumatic structure. After inflation of such membrane structure, the plasticizer can be transformed into a polymer network itself providing a more rigid mass. Such materials are called sequential semi-Inter-Penetrating Polymer Network (semi-IPN). IPN's are defined as a combination of two or more polymers in network form that are synthesized in juxtaposition. Semi-IPN's consist of an intimate mixing of a linear or branched polymer with a cross-linked polymer [13]. IPN's have the advantage of creating new organic materials by combining the properties of known polymers. A number of polymers other than PVC can also be used and many reactive plasticizers can be considered [14-15]. A reactive plasticizer is really a monomer that possesses good compatibility with a given polymer regarding to its plasticizing properties. This solution was selected since it allows a high degree of freedom in selection of system components while having relative low implementation cost. An acrylic monomer is used as plasticizer for poly vinyl chloride (PVC) and a photo-initiator was used to produce free radicals upon exposure to UV-light. Polymerisation proceeds according the general scheme of free radical chain reactions transforming the plasticized film into rigid semi-inter-penetrating-network (semi-IPN) upon exposure to UV-light. Proof of concept of similar systems for different applications was found in the literature [16-17]. A pilot study was undertaken to establish initial performance data on this material. Both non-reinforced and reinforced samples where prepared. Reinforcements used where plain weave fabrics of Glass, Aramid, and Cotton fibres. Samples where tested for yield strength, and glass transition temperature. Reinforced samples where tested at 0, 22.5, and 45 degree angles relative to the fabric's warp direction.

Materials

The PVC resin was a dispersion grade PVC powder commonly used in plastisol applications. This material was obtained from the Geon Company. Reactive plasticizer was obtained from Sartomer and consisted of a blend of acrylate oligomer diluted with an acrylic monomer. Irgacure 369 from Ciba Chemicals was used as the photoinitiator. Epoxidized Linseed oil was used in combination with CaZn as PVC stabilizer. Aramid and glass fibre fabric used where untreated plain weave and were obtained from BFC. Unbleached Cotton fabric was used.

Experimental

Plastisol mixes where prepared according toTable 1

Table 1: IPN Components	Parts by weight
PVC 100	
Reactive Plasticizer	70
Epoxidized Linseed Oil	15
CaZn (PVC stabilizer)	1
Photoinitiator	0.3

Unreinforced samples

Plastisol mix was poured into moulds having a dog-bone shape according to ASTM D638-96. Moulds where put on a glass plate and heated in a regular oven for 10 minutes @ 190 degrees Celsius in order to fuse the plastisol mix into a solid membrane. After cooling down to ambient, the samples where removed from the moulds and exposed to UV-light for 10 minutes. A xenon lamp was used for this purpose. Samples where tested for tensile strength and modulus of elasticity according to ASTM D638-96 using an Instron tensile tester. Glass Transition Temperature was determined by Dynamic Mechanical Spectroscopy (DMS).

Reinforced samples

Plastisol mix was applied to the fabric and spread open evenly by means of a pallet. Impregnated fabric was placed in a tension ring stretching the fabric uniformly to flat configuration. Flattened fabric was exposed for 10 minutes to three IR-light sources 250 W each at a distance of 15cm in order to fuse the plastisol mix into as solid membrane. Samples were turned continuously to avoid local overheating. After cooling down to ambient, the samples where exposed to UV-light for 10 minutes. A xenon lamp was used for this purpose. Specimens 25 mm wide and 170 mm long where cut out using a sharp knife, fibre angles where 0, 22.5, and 45 degree relative to the fabric's warp direction. Samples where tested for tensile strength using an Instron tensile tester according to ASTM D5083-96.

Results

The results for the non-reinforced and reinforced samples are given in Table 2. An average tensile strength of 25 MPa and a glass transition temperature of 70°C where recorded for the plain matrix. As expected, yield strengths for the different fabrics depend highly on fabric orientation being highest at 0° and lowest at 45°. The addition of cotton did not increase tensile strength of the matrix at the given volume fraction, however strength in all 3 measured direction where much closer to each other. Both the glass and aramid fabrics showed superior strength in the 0 angle direction compared to cotton base composite and the plain matrix, strength in all other directions was much lower.

Table 2: Yield stress, summary results

System	Test angle	Yield stress N/mm2	Fibre volume fraction %
Glass	0	191.5	0.322
	22.5	12.5	0.427
	22.5	48.8	0.102
	45	11.8	0.36
	45	18.2	0.106
Kevlar	0	290.9	0.375
	22.5	37.2	0.375
	45	21.6	0.258
Cotton	0	13.6	0.246
	22.5	12.1	0.183
	45	11.3	0.196
Plain matrix	n.a.	25.57	0

Discussion

Tensile strength of the plain matrix was close to the value predicted by the rule of mixture [18]. In general the tensile strength of a fibre reinforced polymer composite increases with increasing fibre volume fraction [18]. Results however indicate the opposite. This can be explained by the fact that laminas tested were extremely thin (0.25 to 0.35 mm), replicating envisioned thickness of final application. The fibre reinforcement consisted of plain weave fabrics of about 0.25 mm thick. The thinnest samples contained the highest volume fractions of fibre and were only slightly coated with the matrix. Transfer of stress only occurred through matrix present in-between adjacent fibres. This explains why samples with higher fibre volume fraction performed less than those with lower volume fraction of fibre. The usefulness of this material will depend on structural design and details. Properties can be further enhanced by using different components for the semi-IPN. Modulus of elasticity for example can be increased significantly if a reactive plasticizer is used that cross-links more densely. Many means exist to alter overall performance: Type of fibre reinforcement, fibre volume fraction, and fibre orientations, are key factors effecting composite properties [18]. Another way to accomplish better mechanical strength is to inject the cavities of the pneumatic composite with structural foam. Besides providing increased strength, this approach has additional merits such as outstanding insulating properties, increased impact strength, and increased durability. In this particular system PVC was used as one of the components of the semi-IPN, the reason for this is that it is a well-known polymer for which plastification technology is well established. A number of other polymers can be considered that can perform equally well. Possible candidates are cellulose or acrylate based polymers, which can also be plasticized easily [14]. When considering a cellulose-based polymer in combination with reactive plasticizers derived from natural oils such as linseed or castor oil, a matrix system can be made that is completely based on natural products. If natural fibres are used to reinforce this matrix, a system can be designed which is completely based on renewable resources. These options are very attractive considering the current need for more sustainable building technologies. Further research is needed.

CONCLUSIONS

The principle of Rigidified Pneumatic Composites can be found in many natural structures. Applying the same concepts in construction might thus possess some of the same merits such as ease of installation, reduced construction time, and efficient use of resources. The performance of such systems compared to conventional building systems highly depends upon the particular material solution. Many different IPN components can be used to tailor system properties and thus affect long-term performance. In this particular system PVC was used as one of the components of the semi-IPN. A number of other polymers can be considered that can perform equally well [14]. When considering a cellulose-based polymer in combination with reactive elasticises derived from natural oils such as linseed or castor oil, a matrix system can be made that is completely based on natural products. If natural fibres are used to reinforce this matrix, a system can be designed which is completely based on renewable resources. These options are very attractive considering the current need for more sustainable building technologies. Success of implementation in construction will also depend on the ability to develop an appropriate architectural language. Further research is needed to address all of the above issues.

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