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Investigation of a fast mechanical self-repair mechanism for inflatable structures

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ABSTRACT

The self-repair mechanism of flexible cellular as well as dense polyurethane coatings applied on the internal side of a commercially available membrane for inflatable structures was investigated. In a dedicated test setup the coated membrane was punctured with a spike of 2.5 mm in diameter and the flow of the leaking air was measured. Parameters such as the coating thickness and coating weight as well as the mechanical properties and microstructure were varied and their influence on the repair efficiency of the coatings analysed. The mechanism underlying the self-repair effect was identified and found to be the result of compressive strains in the coating layer, mostly induced by the curvature of inflated membranes. The strain situation in the coating layer is for a given curvature most exclusively dependent on the thickness of the applied coatings. With respect to a minimum in coating weight, flexible closed cell foam coatings yield the most promising repair efficiencies (>0.99).

1. Introduction

Pneumatic structures such as rubber boats or Tensairity® structures are a category of light weight constructions whose functionality is the result of the synergetic cooperation between a membrane body and an internal pressure (Luchsinger, Pedretti, & Reinhard, 2004; Luchsinger, Pedretti, Steingruber, & Pedretti, 2004). One relevant drawback of pneumatic structures is the vulnerability of the inflatable membrane body. If no extra pressure supply is provided, already small local fissures and leaks in the membrane body of an inflatable structure cause the pressure and hence the integrity of the whole structure to decrease continuously until failure. A membrane being resistant against fast pressure drops caused by small fissures could help to increase the life cycle as well as to increase the reliability of inflatable structures. There is only very few research published on the restoration of the barrier properties of membranes for inflatable structures. Nagaya et al. presented (Nagaya, Ikai, Chiba, & Chao, 2006) a self-repair system for tires based on a water saturated expanding polymer gel and Yamagiwa et al. described a puncture resistant tire based on a double tube technique (Yamagiwa, Nakayama, Kiyota, Tanaka, & Makisaka, 1997). However, as it is the case with the multitude of commercially available products designed to seal leaks in tires for cars or bicycles, this approach is suitable only to a limited extend for pneumatic light weight structures. The drawbacks of all the commercially available products are either the significant weight or a mechanism which relies on centrifugal forces which are absent e.g. in rubber boats or in a Tensairity® roof structure. So far, solely Beiermann et al. presented an approach suitable for non rotating light weight structures (Beiermann, Keller, & Sottos, 2009) which was also considered for space applications (Brandon, Vozoff, Kolawa, et al., 2011). They developed a self-healing flexible laminate based on

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microencapsulated liquid polydimethylsiloxan (PDMS) resin and curing catalyst dispersed in the PDMS layer of a thin laminate. However, this system is only practical for structures which may remain under no pressure for a period of 24 h before reuse, since the microencapsulated PDMS takes time to cure and to recover the barrier property of the membrane. To make inflatables such as rubber boats or airbeds immune to pressure drops caused by small puncture damages a fast working self-repair mechanism is very important. A promising approach, inspired by a fast mechanical self-repairing mechanism found in vines (Busch, Seidel, Speck, & Speck, 2010) and adequate for inflatable light weight constructions, was recently presented by Rampf, Speck, Speck, and Luchsinger (2011). PU foam coatings applied on the internal side of a commercially available PVC-PES membrane helped to reduce the air flow through the fissures after being dotted by a spike of 2.5 mm in diameter. On the one hand the air flow could be reduced by increasing the coating weight per unit area and on the other hand curing the two component (2C) polyurethane (PU) foam coatings under an overpressure of 1 bar helped to enhance the self-repairing effect significantly (Rampf et al., 2011). However, the detailed mechanical effect underlying was assumed to be the result of the complex interplay between various parameters, but could not be identified in more detail, yet. In addition, curing foam under overpressure displays a quite complex process within industrial production routes.

The aim of the present work was to gain a detailed understanding of the mechanisms involved in the repair effect. The influence of parameters such as the coatings thickness, the mechanical properties as well as the foams microstructure on the air flow through a puncture damaged membrane was investigated. Based on this knowledge a proposal for the design of membranes for inflatable light weight structures with self-repair effect was made.

2. Experiments

2.1. Raw materials

A PVC (polyvinyl chloride) coated polyester fabric (Ferrari Précontraint 1002, La Tour du Pin, France) was used as reference membrane. The membrane has a thickness t_M of 0.8 mm and a mass per unit area of 1050 g/m^2. The elastic modulus E_M in the warp and fill direction is 1027 N/mm^2 and 1124 N/mm^2, respectively, and the Poison's ratio v is 0.235. For the experiments, circular pieces with a diameter of 85 mm were cut from the membrane material. A two component polyurethane foam system (RAKU-PUR 33-1024-3, Rampf Giessharze, Grafenberg, Germany) was used as raw material for the extra foam coating. Furthermore, two sample series were coated with a two component PU elastomer (RAKU-PUR 80-L70/38-4, Rampf Giessharze, Grafenberg, Germany).

2.2. Sample preparation

The membrane samples were coated with PU foam using an automatic mixing and dispensing system (Rampf Giessharze, Grafenberg, Germany). The foam components were mixed by the machine and dispensed in the centre of a reference membrane using a mold. The stirring rate as well as the air load in the foam components could be precisely controlled this way. Subsequently, before the foaming and curing reaction of the foam system starts, the so far prepared samples were either put in a pressure vessel to perform the reaction under a certain amount of overpressure p_{cure}, or the reaction was performed under ambient conditions. The overpressure was maintained for 30 min, before removing the samples from the pressure vessel. A number of 10 samples each series was produced and tested. Foam coatings with a weight per unit area of 0.10 g/cm^2, 0.12 g/cm^2 and 0.16 g/cm^2 cured at ambient conditions, 1 bar and 2 bar overpressure were produced.

Performing the foaming and curing reaction of two component polyurethane foams under an overpressure p_{cure} of up to 2 bar influences predominantly the relative density ρ_{rel}, and hence, the mechanical and structural properties of the foam material (Rampf, Speck, Speck, & Luchsinger, 2012). A linear correlation between the extent of overpressure applied during curing and the foams relative density as well as its modulus of elasticity was found in previous investigations (Rampf et al., 2012; Cloakaerts & Mortelmans, 1994). Furthermore, the microstructure of the foam was found to be strongly connected to ρ_{rel}. The rather open pore structure of foams alters to a closed pore structure by increasing the relative foam density from ca. 50% above 60%. In this way, membrane coatings with various thicknesses and Young's moduli at certain coating weights, as well as foam coatings with open as well as closed pore structures were produced for the present investigation. This provides the possibility to analyse the influence of the coating thickness and the coatings mechanical properties as well as the microstructure on the air flow through a fissure in a coated membrane.

The dense elastomer coatings were mixed and dispensed by hand. Coatings with a weight of 0.12–0.16 g/cm^2 were prepared. The curing reaction of the PU elastomer was performed at ambient conditions.

2.3. Experimental procedure

2.3.1. Standard test procedure

The foam coated membrane samples were mounted on a purpose built setup (Rampf et al., 2011). The setup consists basically of a pressure vessel with an opening on its top where the samples can be mounted to as shown in Fig. 1a. The samples can be inflated through the generation of an overpressure in the pressure vessel. A spike with a diameter of 2.5 mm, mounted on a rail, is used to puncture the samples. After the puncturing process a flow sensor can be mounted to detect the air flow