Multiscale modeling of circular woven hoses towards the reduction of mechanically-driven in-situ performance defects

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Introduction

Woven structures are a relatively new type of product that can offer significant advantages for product durability, strength and ease of transport [1]. An example of an inflatable woven structure is shown in Figure 1, which although being compactable and easy to transport, is the foundation of many rapid deployment technologies today, especially for armed forces and disaster response teams.

Figure 1: Inflatable support structure, strong enough to support substantial loads, such as an SUV

Despite their many advantages, woven structures like this also pose many challenges, given that they have additional mechanisms that affect their behaviour, compared to classically consolidated and continuous structures. A research project with an industrial partner on woven hoses, pictured below, has helped show this.

Figure 2: 12" woven hose, with inner woven layer (white) and outer woven layer (blue)

The primary objective of this research is to investigate and summarise the modes of displacement for woven hose structures, which have been leading to failure modes that diminish the performance of the hoses. This study intends to shed light on how woven fabrics in a circular woven structure deform under external loads.

Analysis

To support this work, an extensive literature review, supported by experimental work on samples supplied by the industrial partner. The primary failure mode of concern for the hoses in this study is the phenomenon of "snaking", when a pressurized hose elongates and causes an undulation in shape, that can cause the hose to interfere with other objects around it. Figure 3 illustrates the concept, which at its core is an energy problem that presents itself as buckling.

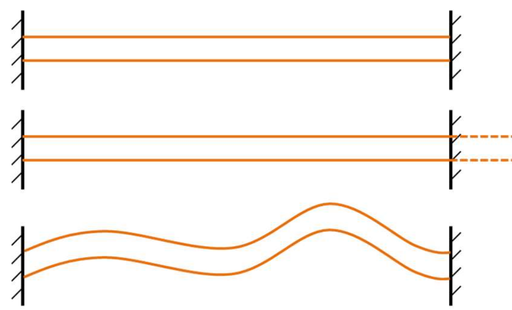

Figure 3: Snaking of pressurized hoses, which stems from elongation between two fixed boundaries, resulting in buckling

There are four factors that are deemed critical in this situation:

1. Elastic extension due to pressurization
2. Crimp in the weave
3. Straightening of filaments in warp yarns
4. State of pretension in the yarns

1 – Elastic extension due to pressurization

It is expected that as the woven hose undergoes pressurization, it will extend, due to pressure vessel phenomena of loading. This is shown in Figure 4, where the nature of the circular weaving process with fibrous material leads to different Young's Modulus' for the longitudinal (warp yarns) and radial (weft yarns) directions [2]. What is important to note here is that as soon as the hose is internally pressurized, it will elongate, the magnitude of which depends on the stress imposed and modulus of the material.

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$$\sigma_{longitudinal} = \frac{Pr}{2t}$$

$$\sigma_{longitudinal} = E_{long}\varepsilon_{long}$$

$$\varepsilon_{long} = \frac{\sigma_{longitudinal}}{E_{long}}$$

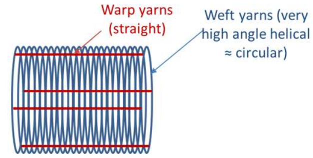

Figure 4: Elastic longitudinal strain of an internally pressurized hollow structure

2 – Crimp in the weave

Woven fabrics behave differently that solid, continuous materials, due to their nature of being assembled from discreet yarns woven together. A result of this is that there are non-conservative modes of displacement that can occur at the meso-scale. One of the most critical of these relates to the crimp of the fabric [3], where the through-thickness architecture of the weave collapses under in-plane loads. These are typically very compliant and lead to a high amount of extension for a small load, before true elastic displacement occurs.

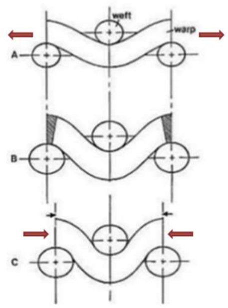

Figure 5: Illustration of crimp affecting unit cell size/displacement effects.

3 – Straightening of filaments in warp yarns

In addition to the meso-scale non-conservative nature of woven fabrics, there is similar behaviour at the micro-scale as well. Specifically, yarns are composed of many filaments, which are not closely packed together under zero load conditions. As the axial load increases, due to a Poisson's effect, the yarns radially contract and the filaments grow closer together and pack more tightly. Similar to the nature of crimp, the axial compliance of the yarns is significantly lowered by this, leading to large initial displacements, more than typical elastic behaviour for the material.

Figure 6: Radial compression of yarns, due to Poisson's effect and the compaction of filaments

4 – State of pre-tension in the yarns

An important factor to consider is the manufacturing method used, as there are many variables present in the weaving process. Specifically, in this case, the yarn pretension during weaving is a critical factor. By adding more axial pretension to yarns as they are being woven, this reduces the possible extension of the hose while pressurized, as the weave crimp and straightening of yarn filaments is lessened. This is due to the mechanical loading during weaving advancing the material beyond these non-linear, non-conservative regions of their load-displacement response. This relationship is not very well understood and should be supported by experiments.

Results and Conclusions

The sources contributing to the elongation of pressured hoses have been identified, through a combination of literature reviews and experimental work. It is still not known the relative contributions made by each factor, but this can be quantified by further testing and validation. It has been seen the irrespective of the contribution of each mechanism, overall the mechanics of the system remains the same and when a hose is pressurized, it will extend regardless. However, the amount of elongation can be reduced by controlling these factors, such that the initial highly compliant behaviour associated with non-linear and non-conservative meso-level and micro-level motion of yarns and filaments be lessened. This industrially-driven research has illustrated the value in taking a methodical and planned approach to investigating the mechanisms of a complex system, such as woven structures. By understanding such mechanisms, structures can be better optimized and fully harnessed for applications ranging from defense to disaster response.

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