TAILORED CIRCUMFERENTIAL REINFORCEMENT OF COMPOSITE CYLINDERS FOR YIELD-TYPE RESPONSE AND IMPROVED PRESSURE PULSE TOLERANCE

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Abstract

A composite materials tailoring concept for progressive failure under tensile loading has been previously developed, modeled, and experimentally validated under quasi-static and impulsive loading by one of the authors and his collaborators. The concept relies upon a sequential failure process induced in a structure consisting of a series connection of parallel redundant load path elements of tailored length and strength. The resulting yield-type response to tensile loading is characterized by an increased energy dissipation compared to a reference conventional structural element of nominally identical length and cross sectional area, and of the same composite material. In this work an application of this composite tailoring concept to provide circumferential reinforcement of thin walled cylindrical pressure vessels with the aim of providing improved pressure pulse tolerance is investigated. It is shown that the yield-type response obtained through circumferential failure tailoring results in significantly improved structural performence.

1. Introduction

A composite tailoring concept for yield-type response under tensile loading has been proposed [1], patented [2], analytically modeled, and experimentally investigated [3-5] by the author and his collaborators. The pseudo-ductile response is obtained by tailoring the 1D, unidirectional composite material structure for a tensile response consisting of a random, progressive failure sequence in a network of series-parallel redundant load paths of designed length and strength, thereby significantly increasing the fracture surface generated before ultimate failure occurs, and further dissipating energy through repeat partial load reductions and strain energy release. Models of tailored composite response under quasi-static as well as dynamic/impulsive loading have been developed and experimentally verified.

An illustration of the embodiment of the tailoring concept into a test article is provided in Fig. 1, together with the predicted corresponding normalized force vs. displacement tailored response in comparison to the untailored counterpart. The increased area under the response curve reflects the increase in energy dissipation compared to the conventional, untailored structure of corresponding length and cross sectional area.

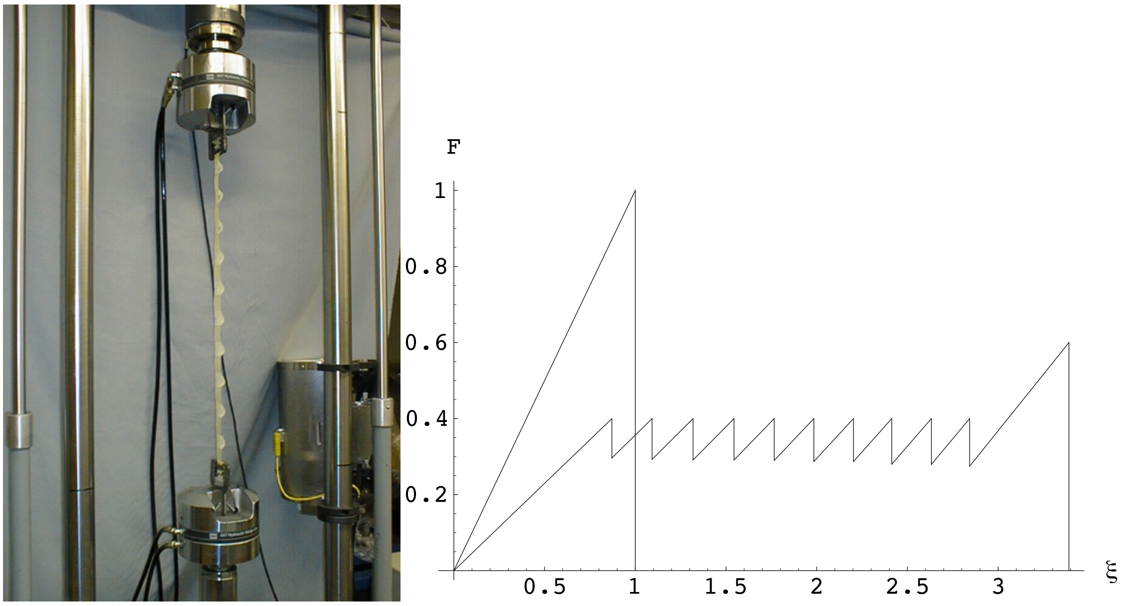

Figure 1. Tailored composite test article and modeled corresponding normalized force vs. displacement response. Conventional, untailored counterpart response provided for reference.

Figure 2 shows model predictions of normalized force vs. time response under impulsive loading for both tailored and conventional, untailored structural members. For the particular case shown the same impulsive loading results in the complete failure of the conventional, reference structural member, while the tailored counterpart undergoes ten partial failures but preserves its overall load carrying capability.

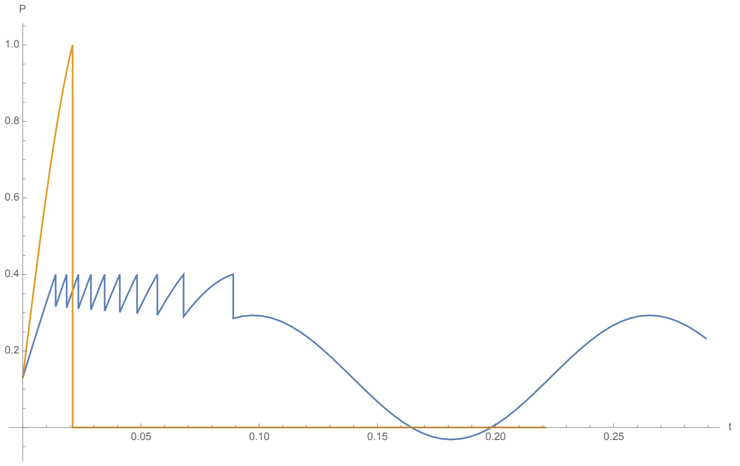

Figure 2. Model prediction of normalized force vs. time response for tailored and conventional, untailored counterpart.

Model predictions such as those shown in Figs. 1-2 have been experimentally validated for various governing parameter combinations under quasi-static loading, using a servohydraulic testing machine, and under impulsive loading, using a custom built, instrumented drop test system, thereby providing confirmation of the hypothesized progressive failure sequence – the foundation of the tailoring concept – and of the accuracy of model predictions.

Applications of the concept have been investigated, including the use of tailored composite structural elements to provide crashworthy helicopter seat stroke control [6].

2. Inflatable Space Structures

Inflatable space structures represent a solution for providing large habitabile volumes in space while overcoming size limitations/constraints associated with space launch. NASA's now discontinued TransHab is one such example of an inflatable spacecraft module intended for providing a sufficiently large air pressurized habitable volume for astronauts in Earth orbit and on the long journey to Mars and back. The module was to be launched in space in a deflated state and subsequently air inflated and pressurized outside the atmosphere.

Minimizing spacecraft weight is a top priority given the energy necessary to accelerate mass to orbital speeds and beyond, and the cascading effect of payload weight upon launch vehicle size. For an inflatable space structure a spherical configuration, providing maximum enclosed volume for a given surface area and uniform pressure loading of the wall would seem to be the ideal solution. However, a cylindrical configuration with hemispherical end caps, as illustrated in Fig. 3, was found to provide a better solution from an overall and functional standpoint. TransHab broadly fit this configuration.

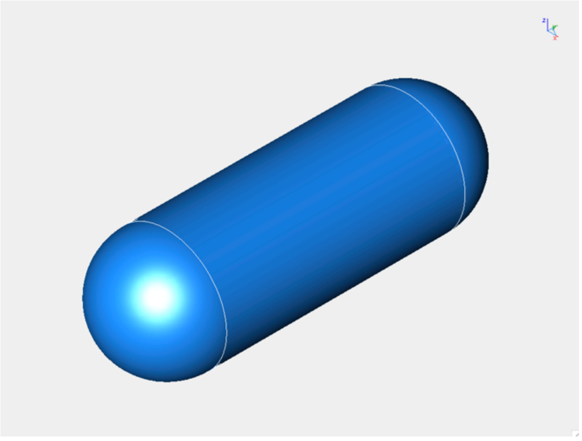

Figure 3. Generic inflatable space structure configuration – cylinder with hemispherical end caps.

The walls of such an inflatable spacecraft need to satisfy a number of functional requirements, included among which are: gas retention, mechanical (pressure load and structural load carrying), space radiation and micrometeoroid protection, and thermal insulation. In the quest for minimum weight research has shown that a multi-layered wall solution, in which each layer fulfills primarily one specialized function leveraging the best material selection and structural configuration for that function results in minimum weight. Figure 4 shows such a generic multi-layer/multi-functional wall structure for an inflatable spacecraft.

Due to their superior specific strength and stiffness, composite materials are an ideal choice for the restraint (mechanical load carrying) layer. The primary and dominant mechanical load is due to internal pressure. The need for wall flexibility required for compact storage in a deflated state and subsequent inflation without causing restraint layer damage imposes demanding requirements upon the type of matrix material used , e.g. elastomeric, and upon the construction of the restraint layer.

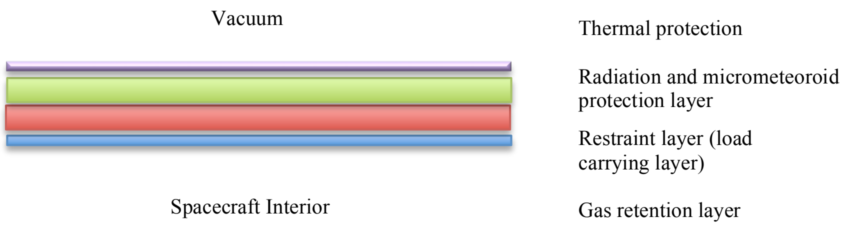

Figure 4. Generic multi-layered/multi-functional inflatable spacecraft wall structure.

A restraint layer configuration consisting of unidirectional high performance fiber composite material straps, woven in a plain weave pattern in the circumferential and the axial directions over the cylindrical region, and following meridian and parallel directions over the spherical end caps has been investigated.

Over the cylindrical region, the 2:1 ratio of stress resultants in the circumferential vs. axial directions, respectively, points to the need for a similar fiber cross sectional area ratio.

3. Pressure Pulse Tolerance

The nominal, dominant loading of the restraint layer is due to the internal pressure in the inflatable spacecraft, and the restraint layer is designed to carry the load with a certain factor of safety. In order to minimize weight, spacecraft structural factors of safety are small, typically 1.25 to failure, resulting in relatively small margins of safety.

While as a matter of design and during normal operation precautions are taken in controlling and regulating the internal pressure inside the inflatable spacecraft, it is conceivable that an accidental pressure pulse (e.g. from a small explosive-type unintended/uncontrolled chemical reaction) could occur, leading to a sudden, impulsive supplemental loading of the restraint layer, potentially resulting in structural failure with potentially catastrophic consequences.

It is essential to understand that while the margin of safety under quasistatic loading is provided by strength vs. applied load, under impulsive, shock wave loading the margin of safety is provided by toughness vs. the energy applied.

With this understanding in mind, it is clear that the increased energy dissipation capability introduced by the unidirectional composites failure tailoring concept presented above is relevant and applicable to the restraint layer of inflatable space structures. The solution envisioned is that of an oversized gas retention layer and a failure tailored retention layer such that subject to an accidental pressure pulse loading the response may involve partial failures in the restraint layer while preserving the overall pressure load carrying capacity of the restraint layer and the gas retention capability, rendering the event non-catastrophic.

As a first step in investigating the potential of applying the tailoring concept to inflatable space structures a simple configuration is analized in this work. It is assumed that a small explosive chemical reaction occurs at the central location on the axis of the cylindrical region, away from the end caps, resulting in a spherical shock wave that propagates outwards, as illustrated in the sequence depicted in Fig. 5.

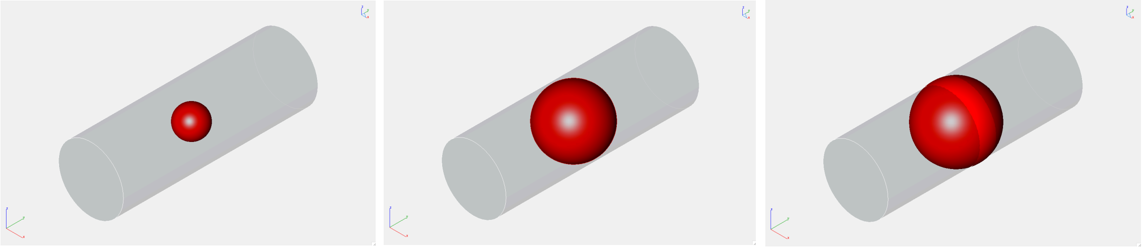

Figure 5. Spherical shock wave propagating from the center of the cylindrical region.

It is well established that the amplitude of the shock wave pressure overload decreases rapidly with propagation distance. Therefore it becomes apparent from Fig. 5 that for this problem the restraint layer cylindrical region/ring in the middle will be impacted first by the shock wave and will be subject to the highest overpressure load. Furthermore, as the intenal pressure shock wave loading is applied, the primary stress induced will be in the circumferential direction. It is therefore the hoop direction tailoring that will be relevant.

Figure 6 shows conceptually a tailored composite material hoop ring. While this specific configuration would not necessarily be practically implementable, other functionally equivalent tailoring configurations, not discussed in this work, are available.

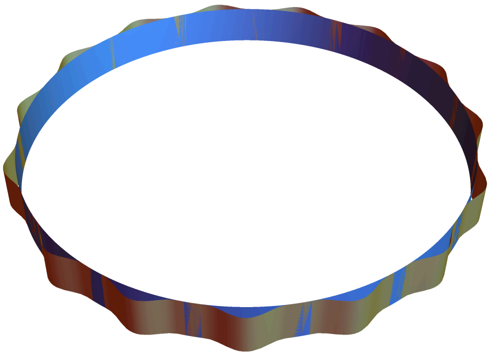

Figure 6. Tailored hoop ring configuration.

A shock wave pressure pulse loading is a very short duration event, typically lasting ms or less, resulting in the application of an impulsive loading. A typical normalized time variation of normalized overpressure is given by Friedlander's shock wave form, Eq. 1, where t=1 represents the zero crossing time. Figure 7 represents the variation of Eq. 1.

$$\frac{P(t)}{P_s} = e^{-bt}(1-t) \tag{1}$$

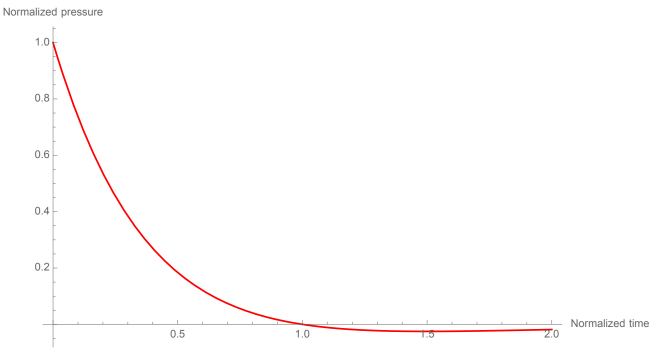

Figure 7. Shock wave normalized pressure vs. normalized time.

The variation of normalized area specific applied impulse can be obtained by integration of (Eq. 1) for $0 \le t \le 1$, and is shown in Fig. 8.

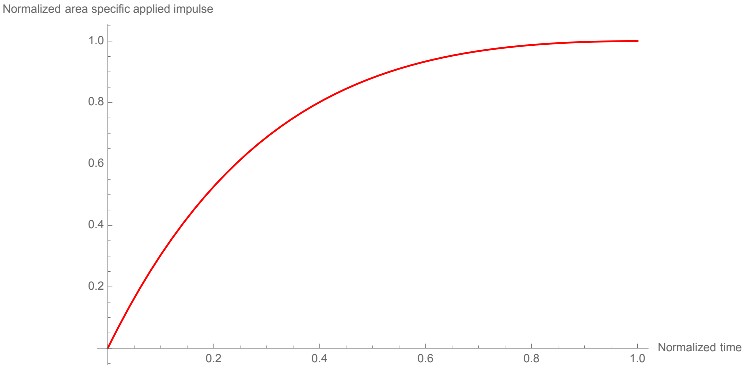

Figure 8. Normalized area specific applied impulse vs. normalized time.

The cumulative area specific applied impulse up to t=1 is given by (Eq. 2):

$$\frac{P_s(e^{-b}+b-1)}{b^2} \tag{2}$$

For the problem at hand, given the short duration of the shock wave impingement a simpler yet accurate enough approximation can be obtained by using a Dirac-delta function to describe the pressure variation and a Heaviside step function to characterize the applied impuse.

The area specific impulse given by (Eq. 2) is applied in a radial outward direction upon the inflatable structure wall. Considered in conjunction with the areal density of material in each wall layer, the step change in radial velocity of the wall can be deterimined, together with the corresponding area specific kinetic energy imparted to the wall by the shock wave impingement. This in turn can be used to determine the kinetic energy imparted to a ring region of the wall.

Using the conservative assumption that it is only the tailored composite restraining layer that can be relied upon to absorb this energy, this information can next be used to determine if the tailored restraint layer is capable to resist a given shock wave/blast loading. The approach is illustrated graphically in Fig. 9, in which the brown area represents the normalized strain energy stored in the tailored composite ring as a result of the quasi-static loading due to the nominal pressure. The remainder area under the response curve, represented in blue in Fig. 9, corresponds to the residual capacity of the tailored composite ring to dissipate energy. Therefore a comparison of the corresponding amount of energy provided by the shock wave loading against this reference will provide a criterion for determining if overall failure results.

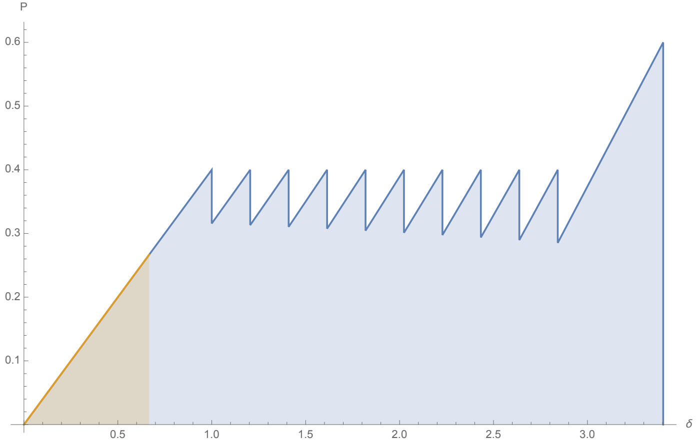

Figure 9. Energy based determination of shock wave tolerance.

3. Conclusions

In this paper a first step in analysing the applicability and benefits of a composite material failure tailoring concept to the restraint layer of a multi-functional/multi-layered inflatable space structure wall is presented. A process and associated criterion are provided for determining if a given baseline pressure loading combined with a shock wave overload result in overall failure of the wall. An experimental verification of predictions made using this approach is necessary.

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