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STRESSES WITHIN COMPOUND TUBES COMPRISING A STEEL LINER AND AN EXTERNAL CARBON-FIBER WRAPPED LAMINATE

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INTRODUCTION

The use of high-modulus, low-density fibers is of particular interest in two areas of pressure vessel design. Firstly, weight reduction permits improved portability of large caliber guns. Secondly, high modulus wrapping is one of the few remaining options for increasing the working pressures in Ultra-High Pressure assemblies wherein working pressure and yield strength have similar values.

The purpose of this work is to examine, using numerical models, various design and manufacture options for introducing residual stresses into a composite-wrapped tube and for minimizing damaging cyclic stresses during subsequent pressurization. Comparisons are based upon an all-steel tube of diameter ratio 2, wherein properties and behavior are well understood. This is termed the 'basis' tube and is modeled as A723 steel having a 0.1% offset yield strength of 1300 MPa. The objectives are:

1. To examine stresses within the steel 'basis' tube at the peak of autofrettage, after autofrettage and during firing.
2. To model the replacement of the steel beyond mid-wall with an 'equivalent' composite layer to reproduce stresses due to 80% overstrain, simulating various manufacturing processes, e.g.: tension wrapping of a stress-free tube, tension wrapping of an autofrettaged tube and autofrettage of benignly pre-wrapped tube.
3. To examine material behavior at each stage of simulated manufacturing and firing in order to identify critical locations and failure modes.

Elastic behavior throughout this work is described by the Lamé equations [1] whilst the non-linear numerical procedure is due to Jahed and Dubey [2], with further refinements described in [3].

STRESSES WITHIN THE BASIS TUBE

The basis tube is illustrated in Figure 1. It has a bore radius of 50 mm and an outer radius of 100 mm. The elastic hoop and radial stresses within such a tube, when pressurized to 500 MPa, are shown in Figure 2 [1].

As an alternative to shrink-fitting, autofrettage is frequently used to introduce advantageous residual stresses into pressure vessels and to enhance their fatigue lifetimes. For many years workers have acknowledged the probable influence of the Bauschinger effect [4] which serves to reduce the yield strength in compression as a result of prior tensile plastic overload.

The reduction of compressive yield strength within the yielded zone of an autofrettaged tube is of importance because, on removal of the autofrettage pressure, the region near the bore experiences high values of compressive hoop stress. This approaches the magnitude of the tensile yield strength of the material if the unloading is totally elastic. If, because of Bauschinger effect, the combination of stresses exceeds some yield criterion the tube will re-yield from the bore thus losing much of the potential benefit of autofrettage. This loss of residual compressive hoop stress has been quantified for the case of Von Mises' criterion applied to open-end tubes [3]. As a rule of thumb, for typical diameter ratios and overstrain levels, 'ideal' residual compressive hoop stress at the bore is reduced by 30% as a result of Bauschinger effect.

Figure 3 shows stresses in the basis tube at the peak of the autofrettage cycle for the case of 80% overstrain (the proportion of the wall thickness that behaves plastically during the initial application of autofrettage pressure). Note that the mid-wall pressure is 387 MPa. Figure 4 shows the same tube after removal of the autofrettage pressure; note that the Bauschinger effect has reduced the 'ideal' (elastic unloading) hoop stress by approximately 30% and that the mid-wall pressure is now 123 MPa, or approximately one-third of that at the peak of the autofrettage cycle.

MATERIAL REMOVAL POST - AUTOFRETTAGE

One of the options to be considered involves autofrettage of a steel tube followed by removal of material from the OD and subsequent wrapping. Optimization of material removal was addressed in Reference [5]; consider three autofrettage options, each of which result in 100% overstrain of a tube of inner radius 50mm and outer radius 75mm:
Option 1: Apply 80% overstrain to tube of IR 50mm and OR 100mm (k=2.0), then reduce OR to 75mm
Option 2: Apply 50% overstrain to tube of IR 50mm and OR 100mm, then reduce OR to 75mm
Option 3: Apply 100% overstrain to tube of IR 50mm and OR 75mm (k=1.5).

The residual hoop stresses resulting from each of these alternatives are shown in Figure 5. Clearly Option 3 produces maximum bore hoop compression whilst requiring minimum effort. The reason for this behavior may be inferred from Figure 6 which shows percentage plastic strain versus radius at the peak of the autofrettage process. The loss of bore hoop stress is a direct result of the increased plastic strain which causes increased Bauschinger effect

CARBON-FIBER WRAPPING

The analysis of stresses and strains within anisotropic fiber-reinforced composite materials may appear somewhat daunting, involving 12 material properties [6]. However, various combinations of these properties are coupled (not independent) and the further simplification of 'plane' conditions reduces the problem significantly [6]. Finally, axi-symmetry and equilibrium mean that it is possible to solve the problem of a steel tube wrapped with a single (hoop) direction layer using completely conventional (isotropic) compound tube formulations (considering only hoop direction modulus) by imposing basic equilibrium and compatibility requirements at the steel-wrap interface.

It is important to select correct values of elastic modulus and Poisson's ratio within the wrapped tube. In the case of a graphite-polymer hoop-fiber laminate typical values are around E_θ = 200 GPa and $\nu_{\theta r}$ = 0.25. If $\nu_{r\theta}$ is prescribed, $\nu_{\theta r}$ should be given by the following relation [6]:

$$\nu_{\theta r} = \nu_{r\theta} (E_\theta/E_r) \quad (1)$$

The material properties E_θ and $\nu_{\theta r}$ may be 'theoretical' values calculated using volume ratios of the constituents, or engineering properties obtained experimentally [6]. *The latter are more likely to give reliable and conservative predictions*.

When layers with different orientations are combined they produce a laminate with engineering properties, sometimes termed 'smeared' properties, which differ from the single-layer case. The general case of fibers oriented at 90 deg to one another is called a cross-ply laminate. Such laminates are frequently put down such that fibers within consecutive layers are oriented at 0 deg or 90 deg to the tube axis, designated [0, 90]. One of these layers is in the hoop direction and the other in the axial direction. This produces a considerable simplification in determining 'smeared' properties [6]. Upcoming sections provide details of stress analyses for the case of hoop-only [0] wrapping. A later section summarizes the differences between [0] and [0, 90] profiles. The 'smeared' properties assumed in upcoming calculations are as follows, laminate data being taken from [7]:

A723 Steel:
E = 208 GPa, ν = 0.3, Yield (0.1%) = 1300 MPa
[0] Laminate, Hoop Fibers only:
E_θ = 200 GPa, $\nu_{\theta r}$ = 0.25, UTS = 1600 MPa
[0, 90] Laminate, Equal Hoop + Axial Fibers:
E_θ = 130 GPa, $\nu_{\theta r}$ = 0.45 - 0.5, UTS = 800 MPa

In addition, the 'crushing' strength in the radial direction (unsupported by fibers) will likely be important. This property is not well documented, since aerospace-type applications do not impose significant loadings normal to winding directions. However available data [7] indicate values in the range 120-300 MPa.

TENSION WRAP OF AUTOFRETTAGED TUBE

Wrapping consisting only of hoop-direction fibers is applied to the 75mm OR of a pre-autofrettaged steel tube (Option 3 above) whilst imposing continuity of pressure and of hoop strain at interface, Figure 7. Assuming a typical effective winding tension (one layer of fiber + matrix mix) of 800 MPa, wrapping continues until a steel-wrap interface pressure of 125 MPa is achieved at which point the outer radius of wrapping is 95mm. The 125 MPa value is almost equal to the mid-wall pressure in the autofrettaged 'basis' tube shown in Figure 4, and therefore creates residual stresses within the steel very similar to those illustrated in Figure 4. Note that, within the wrapping, residual hoop stress increases with radius. This is because the tension-wrapping process is analogous to the external shrink-fitting of a series of thin tubes.

BENIGN WRAP FOLLOWED BY AUTOFRETTAGE

An external wrapping (with no post-cure interfacial gap), consisting only of hoop-direction fibers, is applied without tension to a stress-free steel tube of IR 50mm and OR 75mm. The stress-free composite-wrap tube is then autofrettaged so that the yielded zone extends to the OR of the steel. The OR of the wrap (90mm) was selected iteratively so that at the peak of the autofrettage cycle the steel-wrap interface pressure at 75mm radius is 387 MPa, precisely the same as that during autofrettage of the 'basis' tube and the hoop stress within the laminate at the interface is 2151 MPa. The stress profile at the peak of the autofrettage is shown in Figure 8.

During removal of autofrettage pressure the steel unloads in a non-linear fashion, accounting for Bauschinger effect, whilst the wrapping is assumed to unload elastically. Throughout this process there is continuity of pressure and of hoop strain at the steel-wrap interface. The resulting residual stress is shown in Figure 9. The compressive bore hoop residual stress is 920 MPa, somewhat greater than that in Figure 4 (basis tube) because the autofrettage pressure is being removed from a tube which has a smaller diameter ratio than the 'basis' tube.

SUMMARY RESULTS AND DISCUSSION

The most problematic process appears to be benign wrapping followed by autofrettage. The hoop stress at the steel-wrap interface at peak autofrettage is 2151 MPa for [0] wrap and 1912 MPa for [0, 90] wrap; each of these values exceeds UTS. The radial pressure at the steel-wrap interface at peak autofrettage is 387 MPa for both [0] and [0, 90] wraps. This value exceeds the crushing strength reported earlier (120-300 MPa) and therefore appears to limit the level of overstrain, and hence of residual stress, which could be introduced using such a procedure. One caveat is that there are extremely limited data on this failure mode and even the relevance of standard crushing tests to the axi-symmetric configuration is not proven.

Autofrettage then tension Wrapping [0]

Location	Max Crushing	Max Tensile Stress
Interface (Firing)	239.4	826.0
OD (Firing)	0.0	946.0
Bore Hoop on Firing	55.0	

Autofrettage then tension Wrapping [0, 90]

Location	Max Crushing	Max Tensile Stress
Interface (Firing)	206.3	684.0
OD (Firing)	0.0	836.7
Bore Hoop on Firing	174.4	

Table 1: Stresses Within Tension Wrap During Firing with A723 Autofrettaged Steel Liner

Table 1 summarizes results for autofrettage plus tension wrapping by comparing stresses at potential critical locations during firing at 500 MPa. Table 1 also shows an equivalent summary for the case of [0, 90] wrapping. In the case of [0] wrapping tensile stresses within the wrap at interface and OR during firing are significantly less than UTS. However radial pressure at the interface falls within the possible range of crushing strength, and such strength is therefore a factor which might limit this design.

In the case of [0, 90] wrapping tensile stresses within the wrap at interface and OR during firing at 500 MPa are close to UTS, whilst radial pressure at the interface again falls within the possible range of crushing strength.

Figure 7 suggests a possible method for mitigating tensile stress problems within the wrapping. As noted previously, wrapping under constant tension produces residual hoop stresses within the laminate which increase with radius. The implication of this is that by "tuning" the wrapping tension, i.e. gradually reducing tension during wrapping, it should be possible to obtain a residual hoop stress profile within the wrap which, after application of firing pressure, creates a near-constant hoop stress throughout the laminate.

All results presented thus far relate to A723 steel with 0.1% offset yield strength of 1300 MPa. HB7 steel has recently been recognized as having certain extremely desirable properties [9]. Results for HB7 steel with 0.1% offset yield strength of 1330 MPa are presented in Table 2. These indicate that HB7 creates crushing stresses approximately 10% higher and tensile stresses approximately 6% lower than A723.

WRAPPING OPTIONS

Figure 10 illustrates various options schematically. The laminate 'crushing' problem is most serious near the interface, and decreases beyond this point as radial stress falls to zero at the OR. If it were possible to introduce fibers near the interface which are wholly or partially oriented in the radial direction, crushing strength would likely be increased and the problem alleviated.

It is clear that hoop-direction fibers make the major contribution in constraining the steel liner. Thus, if the design is for an axi-symmetric pressure vessel, maximizing the proportion of hoop winding is extremely desirable. However, in the case of a gun tube there may be a significant bending moment, and the wrap would be required to constrain such bending. In this case a proportion of axial fibers is desirable; in order to maximize second moment of area of the cross-section such fibers should be located as close to the OR as possible.

Autofrettage then tension Wrapping [0]

Location	Max Crushing	Max Tensile Stress
Interface (Firing)	261.6	818.8
OD (Firing)	0.0	914.1
Bore Hoop on Firing	25.1	

Autofrettage then tension Wrapping [0, 90]

Location	Max Crushing	Max Tensile Stress
Interface (Firing)	226.7	636.7
OD (Firing)	0.0	814.9
Bore Hoop on Firing	150.5	

Table 2: Stresses Within Tension Wrap During Firing with HB7 Autofrettaged Steel Liner

CONCLUSIONS

A723 and HB7 Steel liners produce similar stress effects within laminate.

There is no benefit in autofrettage of a steel liner beyond the radius to which material will be subsequently removed. Beneficial residual stresses are maximized and manufacturing effort is minimized by autoffretage of 'near-final' dimensions.

Because benign wrapping followed by autofrettage produces extremely high crushing and tensile stresses during manufacture it appears that the optimal procedure may be autofrettage of liner followed by tension wrapping.

The potential crushing problem at the steel-wrap interface is an inevitable feature of wrapped tube design unless radial fibers are incorporated.

Varying winding tension during the wrapping process may mitigate high tensile stresses within the laminate.

Use of a higher proportion of axial fibers near the OR ill improve second moment of area and mitigate bending effects.

Although not investigated herein, the option of shrink-fitting a composite jacket should be retained.

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[2] Jahed, H. and Dubey, R. N., 1997, "An Axisymmetric Method of Elastic-Plastic Analysis Capable of Predicting Residual Stress Field", ASME, Journal of Pressure Vessel Technology, 119, pp. 264-273.

[3] Parker, A. P., 2001, "Autofrettage of Open End Tubes – Pressures, Stresses, Strains and Code Comparisons" , ASME Journal of Pressure Vessel Technology, 123, pp. 271-281.
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[7] ASM Handbook, 2001, Volume 21, Composites, Materials Information Society, Materials Park, Ohio.
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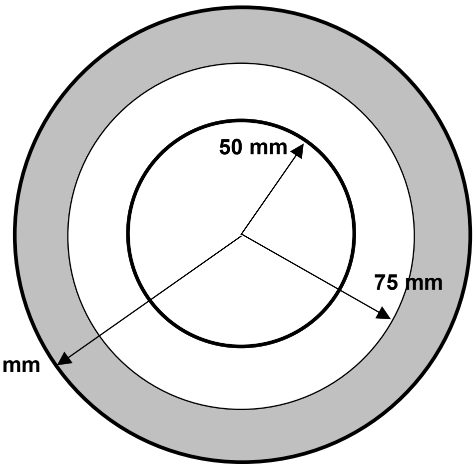

Figure 1: Monobloc Steel 'Basis' Tube, IR 50mm, OR 100mm. Wrapped Tube has Liner, IR 50mm, OR 75mm and OR of wrapping is Selected to Match Specified Criteria.

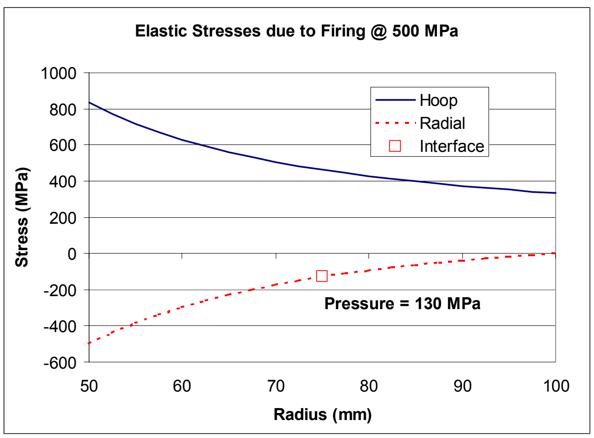

Figure 2: Elastic Stresses Due to Firing

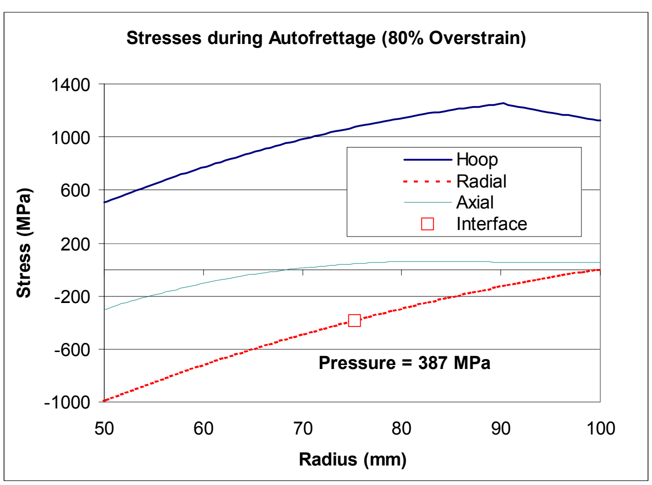

Figure 3: Stresses at Peak of Autofrettage

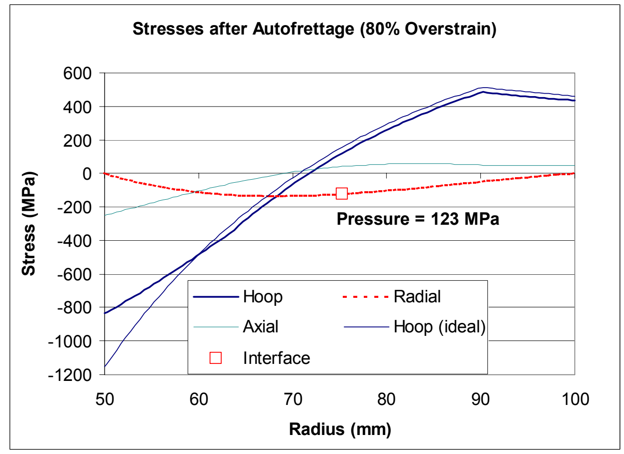

Figure 4: Residual Stresses After Autofrettage

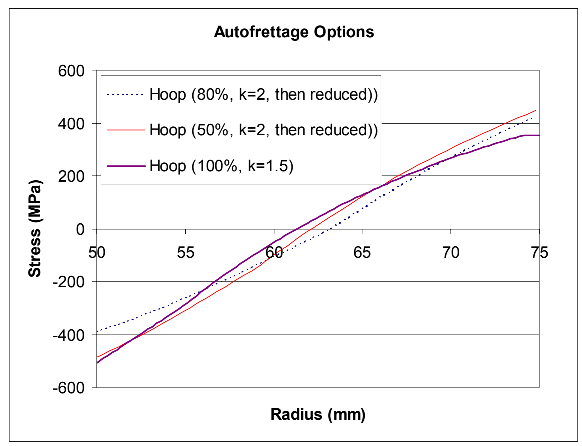

Figure 5: Various Material Removal Options Post-Autofrettage

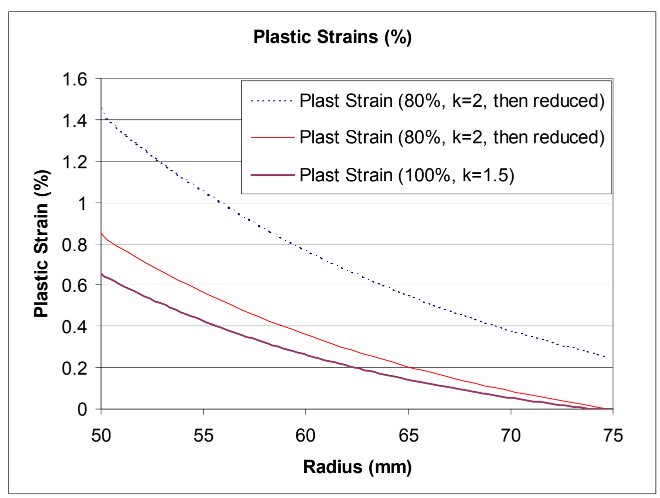

Figure 6: Initial Plastic Strains Associated with Material Removal Options Post-Autofrettage

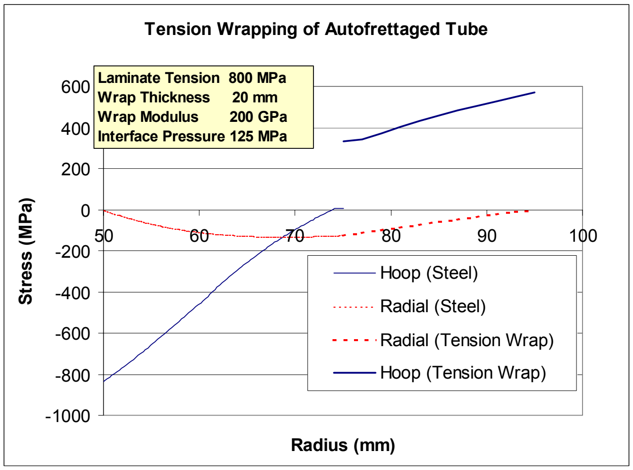

Figure 7: Tension Wrapping of Autofrettaged Tube

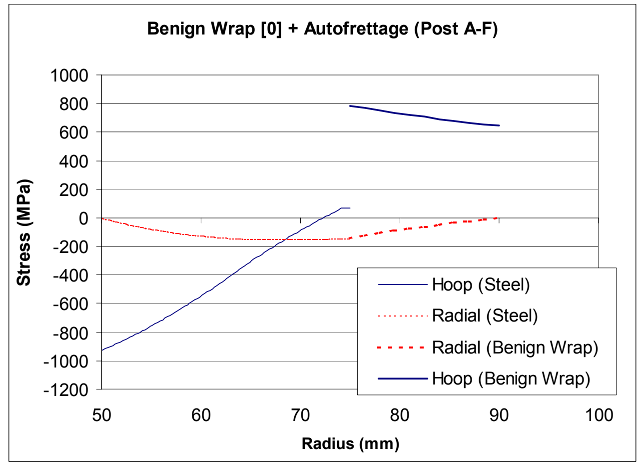

Figure 9: Benign Wrapping, then Autofrettage – Stress State After Autofrettage.

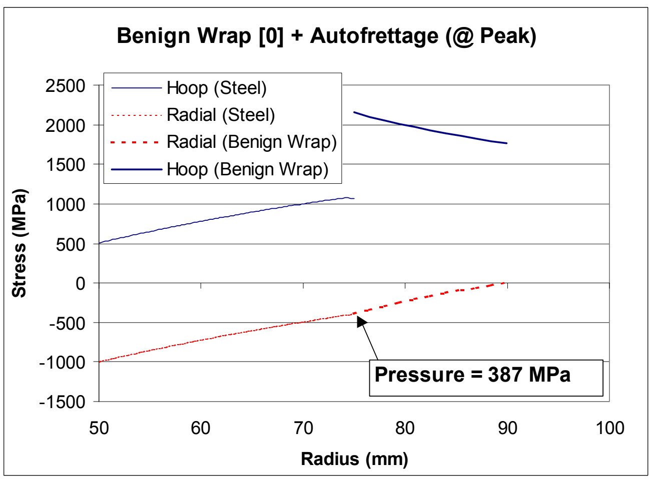

Figure 8: Benign Wrapping, then Autofrettage – Stress State at Peak of Autofrettage.

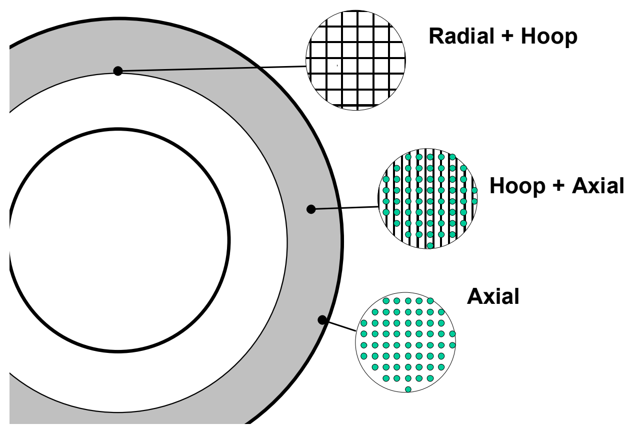

Figure 10: Some Wrapping Options