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TECHNICAL REPORT ARCCB-TR-92003

WEIGHT REDUCTION OF ISOTROPIC CYLINDERS USING EQUIVALENT COMPOUND CYLINDERS

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FEBRUARY 1992

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
February 1992

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
WEIGHT REDUCTION OF ISOTROPIC CYLINDERS USING EQUIVALENT COMPOUND CYLINDERS

5. FUNDING NUMBERS
AMCMS: 6126.23.1BL0.0
PRON: 1A72ZH3HNMSC

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, SMCAR-CCB-TL
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER
ARCCB-TR-92003

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Presented at the Eighth International Conference on Composite Materials, Honolulu, HI, 15-19 July 1991.
Published in Proceedings of the Conference.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A monoblock isotropic cylinder can be reduced in weight by replacing material from its outer diameter with a lightweight stiff composite material, such that the resulting compound cylinder has a bore radial displacement (per unit of internal pressure) equivalent to that of the original monoblock design. This report is a study of the weight savings that can be achieved by using different composite materials to replace isotropic materials in cylindrical pressure vessels. The study contains a derivation of some nondimensional material parameters that can be used to characterize the effectiveness of the composite as a replacement material, including upper bounds on the weight savings that can be achieved. Furthermore, it is shown that these material parameters form the basis for the definition of three general categories of composite replacement materials. The investigation also includes results from the application of the theory to twenty different isotropic-composite systems.

14. SUBJECT TERMS
Composites, Cylinder, Jacket, Weight Savings, Design Methodology

15. NUMBER OF PAGES
17

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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INTRODUCTION

Composite materials, because of their high specific stiffness, offer the opportunity for weight reduction in many structural components. Over the last thirty years there has been a considerable increase in the use of composites as a reinforcement in pressure vessel applications. Numerous studies have been conducted to characterize the effectiveness of various composite materials in cylindrical geometries, some of which are mentioned in References 1 through 5. Many of those studies were originally motivated by the need to develop lightweight pressure containment, especially for aerospace applications. Considerable attention was given to applications where the composite material was wrapped over a metallic cylindrical liner. For many reasons it is desirable to have a metallic liner, the most common of which are to provide a pressure seal in the event of matrix cracking or crazing and to protect the composite material from the harsh environment that can exist in the pressure transmitting medium. The studies mentioned above have been primarily concerned with the design of lightweight cylinders in which strength is a major design consideration. There are, however, cylindrical applications where stiffness is a major consideration. In recent years, the Army has been interested in using composite materials to lengthen cannon, while still maintaining the inertial characteristics of the shorter cannon. In this application it is important to maintain the same bore displacement per unit of internal pressure in the lightweight design as in the original design. In a previous paper by Witherell and Scavullo (ref 6), a general approach was taken to characterize the effectiveness of a lightweight orthotropic jacket for an isotropic monoblock cylinder (IMC). That work produced an equation that predicts the amount of composite material necessary to provide stiffness equivalent to a given amount of material removed from the outer diameter of an IMC. This equation made it possible to determine both the weight savings achieved by each equivalent compound cylinder using jackets of various sizes and the one jacket size that provided the maximum possible weight savings.

Reference 6 mentioned above, however, still left some unanswered questions concerning two types of material for which the analysis breaks down. The first type is a composite that is so poor as a jacket material that it cannot produce a reduction in weight under any circumstances. The second type is a composite that is so good as a jacket material that the maximum weight savings is always achieved by replacing the IMC with a composite monoblock cylinder. The analysis below addresses the criteria for defining these two cases which, in turn, leads to the definition of three general categories of composite replacement materials.

ANALYSIS

An IMC of inner radius 'a' and outer radius 'b_o' can be made lighter by replacing material at its outer diameter with a lightweight stiff composite material such that the resulting compound cylinder has a bore radial displacement (per unit of internal pressure) equivalent to that of the original isotropic design. This equivalent compound cylinder consists of an isotropic liner of inner radius 'a' and outer radius 'b' and a composite jacket of inner radius 'b' and outer radius 'c'. Both the liner and IMC are made of the same isotropic material which is characterized by Young's modulus E_s, Poisson's ratio ν_s, and density ρ_s. The composite jacket is constructed from a cylindrically-orthotropic material and has a density ρ_j. In general, an orthotropic material is characterized by nine independent material constants. A material is cylindrically-orthotropic when the principal material directions coincide with the cylindrical coordinate system of the cylinder. Also, since only internal pressure loading is considered, shear effects are eliminated, and the number of material constants necessary for the analysis reduces to six: three Young's moduli, E_r, E_θ, E_z, and three Poisson's ratios, $\nu_{r\theta}$, $\nu_{\theta z}$, and ν_{zr}. The r, θ, and z subscripts correspond to the radial, hoop, and axial directions in the cylindrical coordinate system. The Poisson's ratio ν_{ij} is defined as the strain ratio ϵ_j/ϵ_i when a stress in the i-direction is applied. The other three Poisson's ratios can be determined by taking account of symmetry in the compliance matrix, e.g., $E_r\nu_{\theta r} = E_\theta\nu_{r\theta}$.

The compound cylinder is made equivalent to the original IMC by determining the correct amount of composite necessary to replace the isotropic material that has been removed. This was already done in a previous paper by the author (ref 6) and involved equating the bore hoop strain (or bore displacement) of the compound cylinder to that of the IMC. Lamé's stress solution for an isotropic cylinder (ref 7) was used as input to both the IMC and the liner's bore hoop strain equation. The stress distribution in the composite jacket was given by Lekhnitskii's stress solution for orthotropic cylinders (ref 8) and was necessary to determine the interface pressure between the liner and the jacket. The final result of the analysis was an equation defining the wall ratio of the composite jacket (W_j) necessary to give the compound cylinder a bore hoop strain equivalent to that of the IMC:

$$W_j = \left[\frac{KA + \frac{(1+R^2)}{(1-R^2)} - B}{\frac{(1+R^2)}{(1-R^2)} - B - KA} \right]^{\frac{1}{2K}} \qquad (1)$$

where $R = W_1/W_s$

$W_1 = b/a$, wall ratio of isotropic liner

$W_s = b_o/a$, wall ratio of IMC

$W_j = c/b$, wall ratio of orthotropic jacket

and K is an orthotropic material parameter given by

$$K = \sqrt{\frac{E_z/E_r - \nu_{zr}^2}{E_z/E_\theta - \nu_{z\theta}^2}} \tag{2}$$

For plane-strain boundary conditions ($\epsilon_z=0$) for the IMC, isotropic liner, and orthotropic jacket, the constants A and B are given by

$$A = \frac{E_s}{E_\theta}\,[1 - \nu_{\theta z}\nu_{z\theta}]\,\frac{1}{(1-\nu_s^2)} \tag{3}$$

$$B = E_s\left[\frac{(\nu_{r\theta}+\nu_{rz}\nu_{z\theta})}{E_r} - \frac{\nu_s(1+\nu_s)}{E_s}\right]\frac{1}{(1-\nu_s^2)} \tag{4}$$

Once the equation defining W_j was obtained, it was then possible to determine the weight savings that could be achieved by using the composite to replace isotropic material in the original IMC. The parameter R in Eq. (1) defines the amount of material removed from the outside of the IMC. When R = 1, no material has been removed, the IMC and the liner are the same dimensions, and there is no composite jacket. When $R = 1/W_s$, there is no liner ($W_1=1$), and the compound cylinder is all-composite jacket. Therefore, for each value of R between 1 and $1/W_s$, there is a compound cylinder equivalent to that of an IMC of wall ratio W_s. The equation defining the percent weight reduction (%WR) using the composite jacket is given by

$$\%WR = \left[1 - \frac{(W_l^2-1) + W_l^2(W_j^2-1)/F}{(W_s^2-1)} \right] \cdot 100 \qquad (5)$$

where $F = \rho_s/\rho_j$.

If we consider an IMC made of steel and a composite replacement material of an all-hoop wrap IM6/epoxy (60 percent fiber volume ratio), we can determine the %WR of the equivalent compound cylinders as a function of R for a specific W_s. This is shown in Figure 1 for $W_s = 1.255$ and $F = 4.621$. This curve shows that as material is removed from the IMC (from right to left on the curve) and is replaced with the composite, the %WR goes up until it reaches a maximum at a value of R = 0.866, then it declines to 0 at R = 0.83.

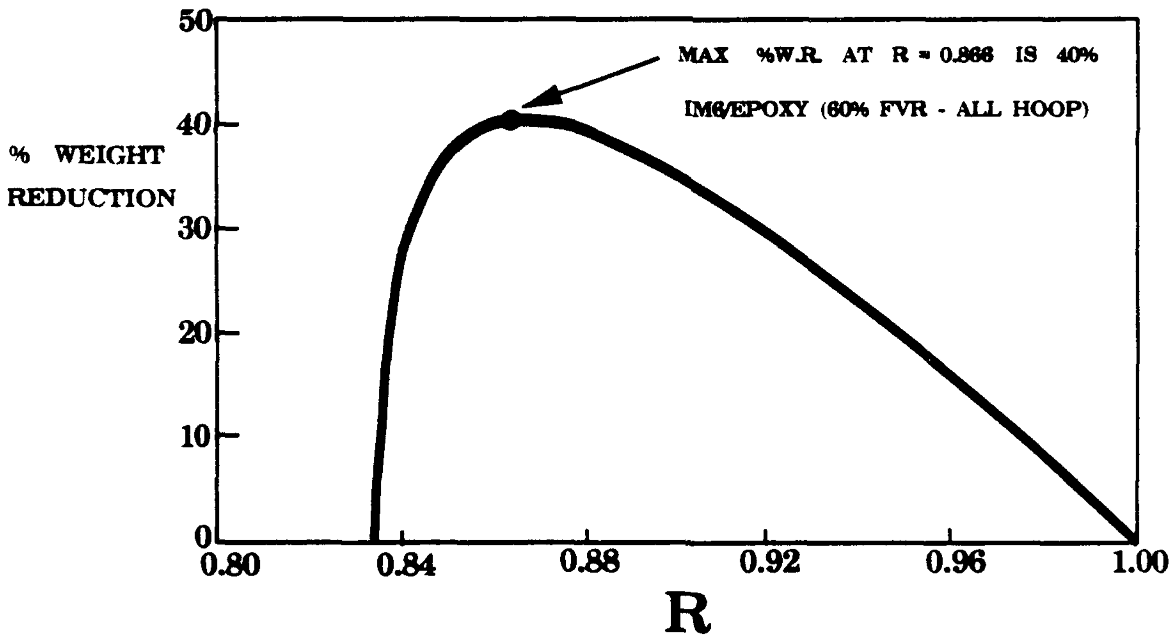

Figure 1. %WR versus R for equivalent compound cylinders using IM6/epoxy to replace material at the outer diameter of steel IMC with $W_s = 1.255$.

For this value of W_s, the maximum percent weight reduction (M%WR) possible using this composite material is approximately 40 percent. By taking the derivative of the %WR (Eq. (5)) with respect to R (for constant W_s) and setting it equal to

0, it is possible to derive an equation which defines the value of R that produces the maximum value of %WR. This was also done in Reference 6 and is given below:

$$F = (1 - RW_j \frac{dW_j}{dR} - W_j^2) \tag{6}$$

Since F is a known parameter, and W_j is a function of R and material properties, the one real value of R which solves Eq. (6) can be found by iteration.

Once the value of R that gives the M%WR is found (R_{MAX}), a graph of M%WR versus W_s can be made. Because W_s has no upper bound, it is more convenient to graph M%WR as a function of C_s, where $C_s = 1/W_s$ and has values between 0 and 1. This is shown in Figure 2 for the same isotropic and composite materials used to generate Figure 1 with $R = R_{MAX} = 0.866$. The vertical dashed line at $C_s = 0.866$ in Figure 2 separates the curve into two regions. The portion of the curve to the left of the vertical line is defined by $R = R_{MAX}$, whereas the portion of the curve to the right of the vertical line is defined by $R = C_s = 1/W_s$. The reason for the transition is that when $C_s = R_{MAX}$, the value of W_1 must be equal to 1, which means the lightest equivalent compound cylinder is actually an all-composite cylinder. For C_s larger than R_{MAX}, the lightest equivalent compound cylinders are all-composite cylinders defined by $W_1 = 1$ (W_1 can never be less than 1) and $R = C_s$. Two points of interest on the curve in Figure 2 are the limits for the M%WR as C_s approaches either 0 or 1. Both of these limits indicate how well this composite material performs in replacing steel in large (C_s=0) or small (C_s=1) wall ratio steel IMCs. The value for the M%WR as C_s approaches 1 (Eq. (5) with $R = C_s$) necessitates the use of Hopital's rule and results in the following relation:

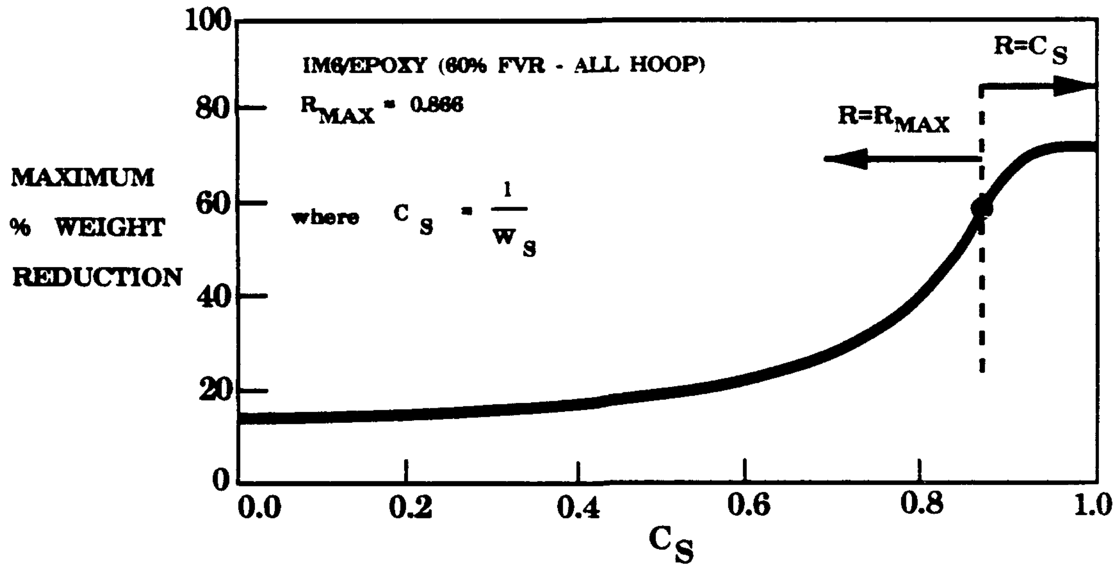

Figure 2. M%WR as a function of C_S for equivalent compound cylinders using IM6/epoxy to replace material from the outer diameter of a steel IMC.

$$\text{For } R=C_S, \ \lim_{\text{as } C_S \to 1} \text{M\%WR} = 100\ (1-A/F) \tag{7}$$

This is an important equation because it defines the upper limit on the M%WR for a material similiar to that used in Figure 2. The use of the word similiar is defined more precisely later. For the material used in Figure 2, the limit on the M%WR, as given in Eq. (7), is 72 percent. It can also be seen in Eq. (7) that if

$$A \geqslant F \tag{8}$$

for an isotropic-composite system similiar to the one used in Figure 2, weight reduction is not possible at all, since the M%WR curve is monotonically decreasing as C_S decreases from 1. It is also observed that the material parameter A is strongly dependent on the ratio of the isotropic modulus to the hoop modulus of the composite (E_S/E_θ). An approximate relation to Eq. (8), which can be used as a rule of thumb, is if

$$E_S/E_\theta \geqslant \sigma_S/\sigma_j \qquad (9)$$

no %WR can be attained using this composite for any value of C_S. It will be seen later that there are materials that do not produce a positive slope at C_S = 1 for the type of curve shown in Figure 2, but are actually monotonically decreasing for increasing C_S. Therefore, it is useful to determine the sign and magnitude of the slope for the curve in Figure 2 as C_S approaches 1. The result of this limit, which necessitates the use of Hopital's rule twice, is given below:

$$\text{For } R = C_S,\ \lim_{C_S \to 1} dM\%WR/dC_S = \frac{100\ A(A+B-1)}{F} \qquad (10)$$

Equation (10) shows, since A is always positive, that if

$$A + B > 1 \qquad (11)$$

the slope of the M%WR curve at C_S = 1 is positive. From experience it has been found that a positive slope at C_S = 1 results in a positive slope at all points on the curve. If A + B < 1, then the curve has a negative slope at C_S = 1, and higher weight reduction is possible at smaller values of C_S. The other point of interest in Figure 2, referred to earlier, is the limit of the M%WR equation (Eq. (5) with $R = R_{MAX}$) as C_S approaches 0. The result of taking this limit is given below:

$$\text{For } R = R_{MAX},\ \lim_{C_S \to 0} M\%WR = 100\left[1 - \frac{R^2(F+W_j^2-1)}{F}\right] \qquad (12)$$

For the material used in Figure 2, Eq. (12) produces a value for M%WR of about 15 percent at C_S = 0.

Finally, it should be mentioned that the slope of the M%WR curve as C_S approaches 0 is always 0.

CHARACTERIZATION OF REPLACEMENT MATERIALS

The analysis of the previous section enabled us to calculate the value and slope of the M%WR at values of C_S equal to 0 and 1. These findings, along with an investigation of various isotropic-composite systems, led to the discovery of three general material categories which define a composite material's ability to replace material in an IMC. Although it was not always possible to rigorously prove the conditions which define each of the three categories due to the complexity of some of the equations, the author has yet to find a realistic material that violates these conditions. The three categories are explained below, with examples of two of these categories given in Figure 3.

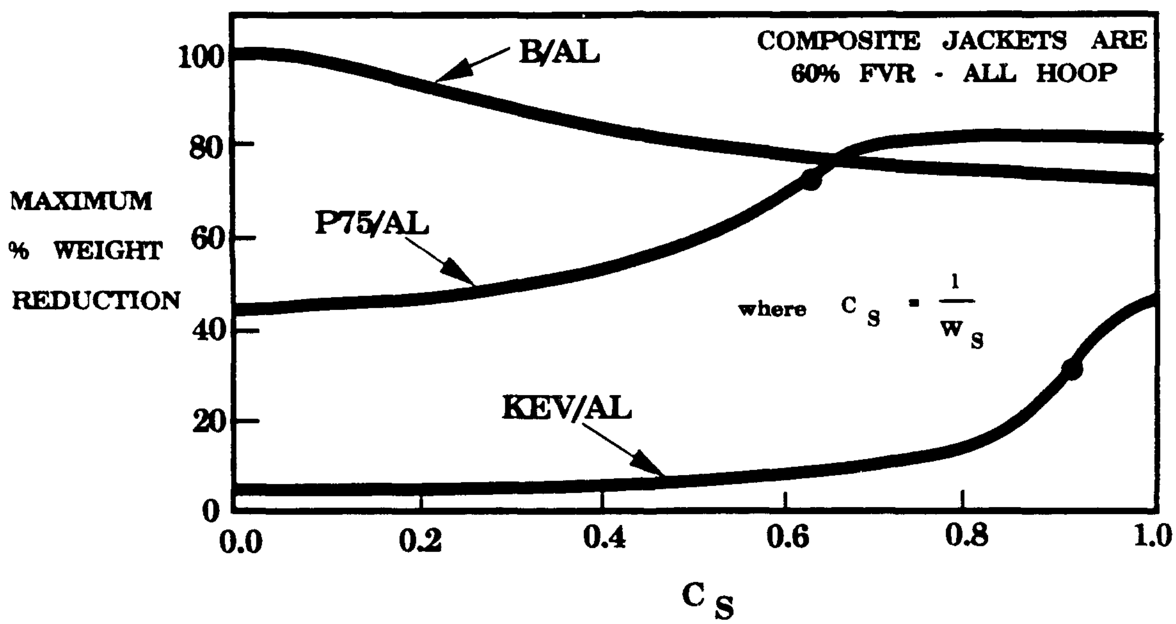

Figure 3. M%WR as a function of C_S for equivalent compound cylinders using three composite materials to replace material at the outer diameter of a steel IMC.

Non-Replaceable Material (NRM)

An NRM is an orthotropic material for which there is no value of C_S between 0 and 1 that can produce weight savings when it is used to replace material at the outer diameter of an IMC. This class of material is defined by

$$A \geqslant F \tag{13}$$

One observation that has been made of orthotropic materials for which an R_{MAX} does exist is that the slope of the M%WR curve for C_s smaller than R_{MAX} is always positive. We also know the equation that predicts the M%WR at $C_s = 1$, and that if $A \geqslant F$, this value is less than or equal to 0. As mentioned earlier, there are materials that produce a negative slope for the M%WR curve for C_s greater than R_{MAX}. This can be seen in Figure 3 for curve 2. Now if the material for which R_{MAX} equals 1 can be determined, there will be no value of M%WR greater than at $C_s = 1$, as is given in Eq. (7). The result of setting $R_{MAX} = 1$ in Eq. (6) is that $A = F$. Therefore, if $A \geqslant F$, the M%WR will always be less than or equal to 0 because its largest value, at $C_s = 1$, is less than or equal to 0.

Partially-Replaceable Material (PRM)

A PRM is an orthotropic material which always produces a positive M%WR for values of C_s between 0 and 1 and has a value of R_{MAX}, as determined from Eq. (6), between 0 and 1. For values of C_s less than R_{MAX}, the M%WR is always achieved with $R = R_{MAX}$, and for values of C_s greater than R_{MAX}, the M%WR is always achieved with $R = C_s$ (see Figure 2). The word partially appears in the name because the cylinders that achieve the M%WR for C_s less than R_{MAX} are partially isotropic and partially orthotropic as defined by R_{MAX}. A PRM is defined by the following two conditions:

$$A < F \tag{14a}$$

$$KA + B \geqslant 1 \tag{14b}$$

The first condition is necessary due to the constraint already discussed for NRMs. The second condition is arrived at as a consequence of obtaining the conditions for an FRM as discussed below. Figure 3 shows two PRMs with a negative and positive slope at $C_s = 1$ (curves 2 and 3).

Fully-Replaceable Material (FRM)

An FRM is an orthotropic material for which the M%WR is always positive for values of C_s between 0 and 1 and is achieved by fully replacing the isotropic material (see curve 1 in Figure 3). This implies that the equivalent compound cylinders that produce the M%WR are actually all-composite cylinders defined by $R = C_s$. This material type is also characterized by a limit on the M%WR as $C_s \rightarrow 0$ of 100 percent. An FRM is defined by the following two conditions:

$$A < F \tag{15a}$$

$$KA + B < 1 \tag{15b}$$

Again, the first condition is due to the constraint already discussed for NRMs. For FRMs there is no liner (W_l=1), and the R that maximizes the weight savings is a variable given by $R = C_s$. Also, we know that the M%WR is always greater than 0, and by observation of Eq. (12), goes to 100 percent as C_s goes to 0. However, if C_s goes to 0, R also goes to 0. By setting $W_l = 1$ and $R = 0$ in the %WR equation, we arrive at the following equation:

$$\%WR = \left[1 - \frac{(W_j^2 - 1)}{F(W_s^2 - 1)} \right] \tag{16}$$

Since C_s going to 0 implies W_s going to infinity, the above equation only needs to have a real value of W_j greater than 1 and less than infinity to have a value of 100 percent. The W_j equation with $R = 0$ is given below:

$$W_j = \left[\frac{1 + KA - B}{1 - (KA+B)} \right]^{\frac{1}{2K}} \tag{17}$$

Recalling that K and A are always positive, the only way W_j can have a value greater than 1 and less than infinity is to have $KA + B < 1$. Consequently, any material that is neither an NRM nor an FRM must be a PRM and have as one of its conditions $KA + B \geqslant 1$.

NUMERICAL RESULTS AND CONCLUSION

The theory of the preceding section was applied to twenty different isotropic-composite systems. Two isotropic materials, steel and aluminum, were considered for the IMCs. Their properties are given in Table I and consist of Young's modulus (E_s), Poisson's ratio (ν_s), and density (ρ_s). Two matrix materials (epoxy and aluminum) and five types of fibers (S-glass, Kevlar, IM6, Pitch-75, and boron) were used to construct the ten different composite replacement materials to be used in the jackets. The laminate material properties for these ten different composite materials are given in Table II. Each of the laminates was considered to be an all-hoop wrap layup with a 60 percent fiber volume ratio. The material properties are given for a cylindrical system and consist of the hoop modulus (E_θ), radial and axial moduli (E_r, E_z), two Poisson's ratios ($\nu_{\theta z}, \nu_{zr}$), and density (ρ_j). The laminate properties given in Table II are the average of five different micromechanics models. The Poisson's ratio $\nu_{r\theta}$ is equal to $\nu_{z\theta}$, where $\nu_{z\theta}$ can be determined from Eq. (2).

TABLE I. MATERIAL PROPERTIES FOR ISOTROPIC MONOBLOCK CYLINDERS

Name	E_s (GPa)	ν_s	ρ_s (g/cm^3)
Steel	206.8	0.30	7.600
Aluminum	72.4	0.33	2.723

TABLE II. LAMINATE MATERIAL PROPERTIES FOR ALL-HOOP WRAP WITH 60% FVR

Name	E_θ (GPa)	E_r, E_z (GPa)	$\nu_{\theta z}$	ν_{zr}	ρ_j (g/cm³)
Sg/Ep	52.9	12.9	0.258	0.358	1.982
Kev/Ep	79.4	5.8	0.350	0.395	1.368
IM6/Ep	175.1	8.9	0.259	0.362	1.645
P75/Ep	311.6	6.7	0.259	0.349	1.645
B/Ep	241.3	14.3	0.258	0.365	2.063
Sg/Al	80.5	81.4	0.253	0.257	2.584
Kev/Al	107.0	24.4	0.340	0.320	1.970
IM6/Al	202.8	33.6	0.261	0.272	2.247
P75/Al	339.3	26.5	0.265	0.288	2.247
B/Al	268.9	186.8	0.251	0.319	2.665

*FVR: Fiber volume ratio

Tables III and IV contain the results of applying the analysis to the twenty isotropic-composite systems. The results of the composite replacement materials for steel and aluminum IMCs are given in Tables III and IV, respectively. The first column in the tables gives the name of the fiber and matrix used to form the composite material. The nondimensional material parameters K, F, A, B and the nondimensional geometry parameter R_{MAX} are also shown and are defined by the equations discussed earlier. As is shown in the tables for NRMs, R_{MAX} does not exist, and for FRMs, $R_{MAX} = C_s$. The values for W_j are calculated with $R = R_{MAX}$. For FRMs, W_j is a variable because R_{MAX} is a variable. The M%WR at $C_s = 1$ and $C_s = 0$ is also given, along with the slope of the M%WR curve at $C_s = 1$. The last column tells which of the three classes of replacement materials this composite falls into.

TABLE III. REPLACEMENT MATERIALS FOR STEEL

Comp.	K	F	A	B	R_{MAX}	W_j $R=R_{MAX}$	M%WR $C_s=0$	M%WR $C_s=1$	Slope $C_s=1$	Mat. Class
Sg/Ep	1.911	3.835	4.224	1.149	-	-	-	-	-	NRM
Kev/Ep	3.429	5.557	2.836	1.019	0.951	1.180	3.2	49.0	145.7	PRM
IM6/Ep	4.151	4.621	1.293	0.052	0.866	1.282	14.6	72.0	9.6	PRM
P75/Ep	6.391	4.621	0.728	-0.163	0.818	1.254	24.8	84.2	-6.8	PRM
B/Ep	3.828	3.684	0.938	-0.085	0.791	1.343	23.8	74.5	-3.7	PRM
Sg/Al	0.994	2.941	2.637	0.477	0.976	1.066	0.2	10.3	189.6	PRM
Kev/Al	2.011	3.858	2.071	0.509	0.906	1.260	5.5	46.3	84.8	PRM
IM6/Al	2.374	3.382	1.110	-0.087	0.747	1.480	24.6	67.2	0.8	PRM
P75/Al	3.434	3.382	0.667	-0.219	0.639	1.496	44.3	80.3	-10.9	PRM
B/Al	1.167	2.851	0.803	-0.131	C_s	W_j	100.0	71.8	-9.2	FRM

TABLE IV. REPLACEMENT MATERIALS FOR ALUMINUM

Comp.	K	F	A	B	R_{MAX}	W_j $R=R_{MAX}$	M%WR $C_s=0$	M%WR $C_s=1$	Slope $C_s=1$	Mat. Class
Sg/EP	1.911	1.374	1.510	0.071	-	-	-	-	-	NRM
Kev/Ep	3.429	1.991	1.014	0.025	0.833	1.242	11.7	49.1	2.0	PRM
IM6/Ep	4.151	1.656	0.462	-0.321	0.532	1.443	53.2	72.1	-24.0	PRM
P75/Ep	6.391	1.656	0.260	-0.397	0.365	1.411	78.7	84.2	-17.9	PRM
B/Ep	3.828	1.320	0.335	-0.370	C_s	W_j	100.0	74.6	-26.3	FRM
Sg/Al	0.994	1.054	0.943	-0.169	C_s	W_j	100.0	10.5	-20.2	FRM
Kev/Al	2.011	1.382	0.740	-0.158	0.510	1.726	36.7	46.4	-22.4	PRM
IM6/Al	2.374	1.212	0.397	-0.370	C_s	W_j	100.0	67.3	-31.9	FRM
P75/Al	3.434	1.212	0.238	-0.418	C_s	W_j	100.0	80.3	-23.2	FRM
B/Al	1.167	1.022	0.287	-0.386	C_s	W_j	100.0	71.9	-30.9	FRM

Table III shows that Sg/Ep cannot be used at all to save weight in steel cylinders, whereas Sg/Al can provide about a 10 percent weight reduction at values of C_s close to 1. Similiarly, Sg/Ep cannot save weight in an aluminum cylinder, whereas Sg/Al can save about 10 percent in weight at values of C_s close to 1 and even greater weight reduction at smaller values of C_s. Tables III and IV both show that for the five fibers considered, aluminum is a better matrix material for weight reduction than epoxy. It is also seen in Tables III and IV that, in general, Kevlar, IM6, and Pitch-75 fibers perform better at larger values of C_s when replacing either steel or aluminum. It is also interesting to note that B/Ep is a PRM for replacing steel, but it is an FRM for replacing aluminum, even though the specific stiffnesses of steel and aluminum are almost the same. This difference is primarily due to the higher radial stiffness of the steel relative to aluminum which allows for more effective load transfer in the steel at the larger wall ratio cylinders. Many other interesting comparisons can be made of different fibers, matrix materials, and isotropic materials by using data presented in a form similiar to that found in Tables III and IV.

In summary, a convenient method has been developed for investigating the effectiveness of any orthotropic composite material which is to be used as a replacement material at the outside diameter of an IMC.

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