REICHHOLD Everywhere Performance Matters

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Designing composite pipes for the long term

Part I – Burst failure

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Abstract – The long-term structural failure of composite pipes may be by weeping, burst or strain corrosion under bending strain. These modes of failure have distinct causes. The weep mode is controlled by the coalescence of cracks that form in the glass-resin interphase when the pipes are placed under tensile strains. Weeping results from the passage of water through the pathways that are formed by the coalescence of these cracks. The time taken by the water to traverse the wall depends on the length, opening and number of pathways that are formed. Weeping is controlled by the glass-resin interphase and has nothing to do with fiber rupture. The long-term burst failure of the pipes is caused by fiber rupture from strain corrosion by tensile strains in water. The long-term burst rupture is controlled by the glass fibers and has nothing to do with the resin. And finally we have the third mode of long-term structural failure, known as strain corrosion rupture. The strain corrosion rupture is similar to the burst failure in as much as both modes involve fiber rupture by strain corrosion. The differences are indeed very subtle. While burst failure is caused by tensile loads and water, the strain corrosion rupture is caused by bending loads and chemical products. The strain corrosion rupture is caused by chemical attack on fibers that are subjected to bending strains.

These three modes of long-term structural failure are discussed in separate papers. This paper will address burst failure. The second paper will discuss weeping. The strain corrosion failure under bending loads is addressed in a third and last paper.

Introduction – The weep and burst modes of failure are governed by distinct mechanisms. Weeping is a "go no-go" phenomenon. If the operating strain is lower than a threshold, weeping never occurs. If higher, weeping will certainly occur. The time to weep measures the travel time of the leaking fluid through the pipe wall. The time to weep is not a basic material property, since it depends on the wall thickness. As the part two of this trilogy will show, the times to weep should not be used to characterize composite pipes. This should be contrasted with the burst mode of failure that has no threshold strain and will eventually take place regardless of the strain on the pipe. The question may arise as to which failure occurs first, weeping or rupture. The order of occurrence is determined by the wall thickness and the strain on the pipe. If the wall thickness is small and the operating strain is high, weeping will take place prior to burst. On the other hand if the operating strain is below the threshold, the pipe will never weep and the long-term failure will be by burst. This paper addresses burst failure under the assumption that the pipes do not weep. This condition is fulfilled if the operating strain is less than the threshold strain.

The weep behavior of composite pipes is represented by a long-term parameter known as Hydrostatic Design basis, or HDB. The strain-corrosion behavior is represented by an analog of the HDB that we call Corrosion Design Basis, or CDB. The CDB measures the pipe's long-term resistance to rupture under bending loads while immersed in corrosive environments. The burst behavior is controlled by yet another long-term parameter, the Rupture Design Basis, or RDB. The RDB measures the long-term resistance of the glass fibers under tensile loads and in the presence of water. The three papers in the trilogy describe how to measure and use these parameters.

The RDB – Rupture Design Basis – is not recognized in the current pipe standards. In fact, the long-term burst failure of composites pipes was not a concern prior to the publication of a paper by Mark Greenwood (ref 6) in 2001. In this paper we will make extensive use of Mark's data to design pipes for burst failure. Our discussion will show that the RDB – Rupture Design Basis – is a property of the glass fibers that should be measured and reported by the glass manufacturer.

Note: It is customary in the composites pipe industry to refer to the short-term weep failure as "short-term burst", or STB. The pipe industry should avoid such confusing nomenclature that mixes up the distinct weep and burst modes of failure. Weep is not the same as burst. The reader is advised to read the technical literature very judiciously.

Two hypotheses – The analysis of the long-term burst failure of composite pipes is based on two hypotheses.

1. The operating strain is below the threshold strain. This excludes the possibility of weep failure.
2. Water is the only chemical capable of penetrating the laminate and causing the long-term deterioration and rupture of the fibers.

The first hypothesis excludes weep failure and assures that the long-term failure is necessarily by rupture of the glass fibers. The resin would have no effect on such a failure and the long-term burst is controlled by the fibers alone. The second hypothesis excludes any corrosive chemical other than water as a cause of long-term burst failure.

The second hypothesis may sound absurd to those familiar with composite applications in highly corrosive fluids. Experience indicates that pipes carrying aggressive chemicals fail sooner than those carrying water. This seems to contradict the hypothesis that water is the only chemical capable of affecting the structural life of the pipe. This misconception is very common and results from a confusion of service life and structural life. The service life measures the time taken by the chemical to destroy the corrosion barrier of the pipe and is not to be confused with the structural life, which measures the time taken by the water to strain corrode the glass fibers.

The durability of the pipe is determined by the shortest of the above two lives. The service lives of pipes carrying aggressive chemicals are shorter than their structural lives. And the opposite is true for pipes carrying water that do not attack the corrosion barrier. The composite pipes used in water transmission fail by rupture and not by the destruction of the corrosion barrier. This paper will not address the service life and the durability of the corrosion barrier. The reader interested in this topic is referred to (ref. 1).

Note: The aggressive chemicals do not penetrate very deep into the laminate and their effect is limited to the corrosion barrier. Water is the only molecule small enough to penetrate the laminate and affect its structural behavior. The chemical attack by species other than water is relevant in buried pipes that deflect under the soil load and are subjected to bending strains. The combination of bending strains and chemical attack leads to a strain corrosion situation that is discussed in the part 3 of this trilogy.

Static loading of isolated fibers – Isolated fibers are those not embedded in a resin matrix. This section will address the rupture of isolated glass fibers under static tensile loading. The mechanism of crack growth under cyclic loading is dealt with in the next section.

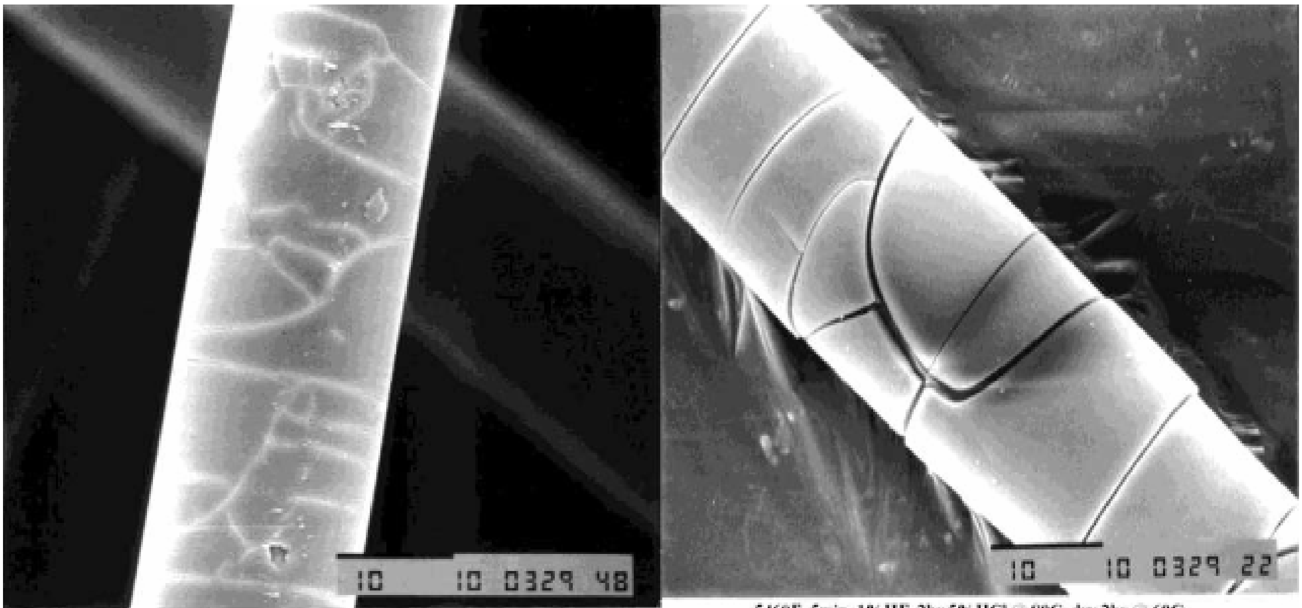
From fracture mechanics we know that the only causes of crack growth in homogeneous materials are strain corrosion and cyclic loadings. Crack growth under static loads result from strain corrosion, that is, from the combined action of corrosion and tensile strains. Corrosion initiates and grows surface flaws that eventually develop into cracks. And the tensile strain opens up the cracks to facilitate the access of the corrosive agent. The combined effect of strain and corrosion is known as strain corrosion.

1 – Crack initiation. The discussion that follows is based on the theory of fracture mechanics for brittle homogeneous materials. We begin with the statement that even perfectly smooth, pristine glass fibers develop small surface flaws in the presence of water or other corrosive environments. The number and size of these environmentally induced flaws are controlled by the chemical composition of the glass, the number of defects in the glass surface and the chemical environment. The surface flaws grow into small cracks under the combined action of the environment and the residual tensile strains present on the outer surface of the fiber. The combined action of residual strains and chemical attack explains why perfectly smooth, crack free glass fibers do not exist in the real world. Figure 1 shows environmentally induced cracks on glass fibers that have been exposed to acids.

2 – Crack propagation. The spontaneous environmentally induced surface cracks are self-limiting and arrest as soon as the driving force (the residual strains) dissipate. This situation changes, however, when the fibers are subjected to external tensile strains, over and above the residual strains. The external tensile strains are not self-limiting and act in combination with the chemical attack to grow the crack. The rate of crack growth in fibers exposed to aggressive chemicals and under tensile strains is governed by an equation of the form

$$\frac{da}{dt} = Y\left(\varepsilon\sqrt{\pi \times a}\right)^{Z} \qquad (1)$$

In equation (1) “a” is the size of the crack, “Y” is a constant that need not concern us at this time, “Є” is the sustained constant tensile strain and “Z” is a parameter that depends on the chemical environment, the temperature and the composition of the glass fibers. Equation (1) recognizes that the tensile strain, the glass composition and the temperature, all contribute to the crack growth that eventually ruptures the fiber.



5190E 10min 2*50ml .1%HF, 2hr 5%HCl @ 80C, dry 2hr @ 60C

5460E, 5min .1%HF, 2hr 5%HCl @ 80C, dry 2hr @ 60C

Figure 1
Spontaneous surface cracks from chemical attack on E glass fibers. The open cracks indicate the presence of residual tensile strains. (Courtesy Owens Corning)

Equation (1) indicates that the rate of crack growth is dominated by the total strain (residual + external) with some influence from the temperature and the composition of the glass. Together these mechanisms define the time to rupture of the fiber under static load. The time to rupture of the glass fibers in the presence of acids or water and subjected to constant tensile strains is a well documented phenomenon known in the literature as "strain-corrosion".

Cyclic loading of isolated fibers – The mechanism of deterioration of isolated fibers under tensile cyclic loads is different from that under static loads. The previous section showed that static deterioration is a continuous process reflecting the corrosion of the strained glass. The rate of static deterioration is strongly influenced by the strain itself, the temperature, the aggressive environment and the composition of the glass. Under cyclic loads, however, the rate of crack growth is not continuous, but proceeds in a stepwise fashion, one little bit at a time, in response to the kinetic energy delivered in each cycle, pretty much as when we drive a nail by hammering on it. The crack grows like the nail penetrates the wood, one bit at a time, depending on the kinetic energy of the blow. Cyclic crack growth is a discontinuous stepwise process described by equation (2).

$$\frac{da}{dN} = Y\left(\Delta\varepsilon\sqrt{\pi \times a}\right)^{Z} \qquad (2)$$

From equation (2) the rate of crack growth under cyclic tensile strains is cycle dependent, not time dependent. Also, the exponent "Z" in the cyclic equation (2) does not depend on the temperature, or on the aggressive chemical or on the hydrolytic stability of the glass. Temperature and moisture have no effect on the rate of cyclic crack growth. In equation (2) $\Delta\varepsilon = \varepsilon_{max} - \varepsilon_{min}$ is the range of the tensile strain.

Note: The above is valid for glass fibers only. As explained in the appendix D, the rate of cyclic crack growth in resin matrices is temperature and moisture dependent.

Static loading of UD laminas – The preceding discussion dealt with the rupture of isolated glass fibers. We continue with the discussion of the static case, assuming next that the fibers are impregnated with resin to form UD plies. The embedment of the fibers in a resin matrix has a profound effect on the short-term and the long-term strengths of the ply. Specifically, the resin matrix evens out the enormous variability found in the rupture strains of isolated fibers. This "evening out" of the fiber strength increases the overall performance of the composite and is referred to in the literature as the "composite effect".

We begin our discussion by recalling that self-similar crack growth occurs only in homogeneous materials like metals, glass fibers and neat resins. Composite materials do not grow self-similar cracks. The rare instances of self-similar crack growth in composites are observed in delamination and from debonding along the fibers of UD plies. The self-similar cracks that grow along the UD fibers play a central role in the weep mode of failure, as detailed in the part two of this trilogy.

Note: There is only one known instance of self-similar crack growth across the fibers in a laminate. That sort of thing occurs in laminates under strain corrosion, that is, subjected to bending strains and immersed in corrosive media. Examples of such failures can be found in references 2, 3, and 4. A full discussion of this topic can be found in the part 3 of this trilogy.

The following discussion is based on well documented evidence showing that composites do not propagate self-similar cracks across the fibers. To facilitate the exposition the discussion is limited to UD laminas. The cracks generated at the points of fiber rupture do not propagate to adjacent fibers. Rather, these small cracks are arrested and deflected as they grow and meet adjacent fibers. The many fiber rupture points in a ply form a myriad of isolated small cracks that do not extend beyond the neighboring fiber. The cracks do not propagate from fiber to fiber. The rupture of the composite ply results from the accumulation and eventual coalescence of many small cracks, not by the growth of one large crack. This mechanism explains the exceptional toughness and fatigue resistance of composites.

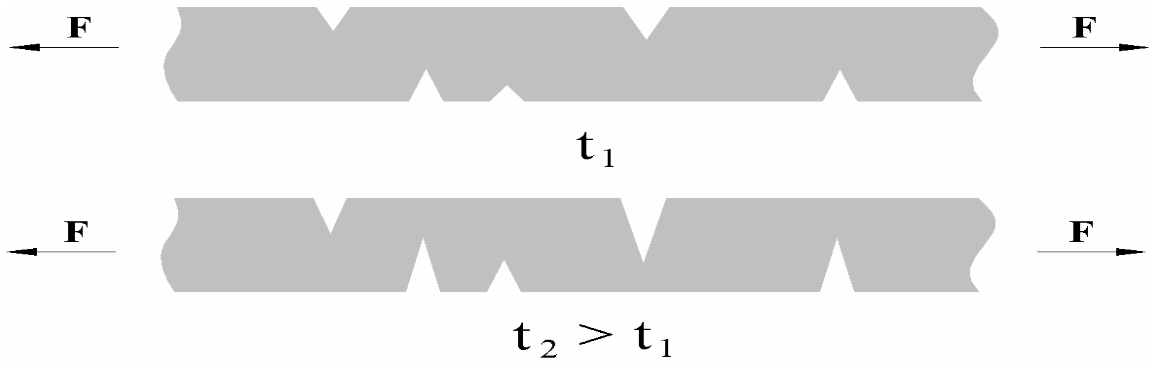


Figure 2. Self-similar crack growth occurs in homogeneous materials, like glass fibers. Self-similar cracks do not grow in composites.

The time to rupture of a UD ply under tensile strains in the fiber direction is controlled by the glass fibers. The equation to predict the time to rupture of UD laminas under static tensile strains is derived from equation (1). The mathematics involved is complicated and will be avoided here. The relationship between the static constant strain and the time to rupture is

$$\log(\varepsilon) = A_s - G_s \log(t) \qquad (3)$$

Equation (3) calculates the time to rupture of UD laminas subjected to a constant sustained static strain "Є" in the fiber direction.

The strength parameter "A_s" is related to the ultimate tensile strain of the lamina at t = 1 unit of time. The unit of time is irrelevant and could be 1 day, 1 minute or 1 hour. The strength parameter "A_s" adjusts itself accordingly to match any unit of time that we may choose. The parameter "A_s" has a slight dependence on the toughness of the glass-resin interphase. The interphase is a thin resin layer that forms around the fibers when the matrix blends with the sizing. We will have more to say about the interphase in the part 2 of this trilogy, when we address the weep mode of failure. The slope "G_s" in equation (3) reflects the hydrolytic stability of the fibers and is expected to increase with the temperature. To a lesser degree "G_s" depends also on the toughness of the interphase. For any given glass sizing, however, the effect of the matrix toughness on "G_s" is small and may be ignored. The effect of the resin matrix on the parameters "G_s" and "A_s" is small, so small that these parameters may be regarded as properties of the glass. Being glass properties, both "As" and "Gs" should be measured and reported by the glass fiber manufacturer.

Cyclic loading of UD plies – The equation describing the rupture behavior of UD laminas under tensile cyclic loads is similar to that for the static case.

$$\log(\Delta\varepsilon) = A_c - G_c \log(N) \quad (4)$$

As in the static case, the slope "G_c" is dominated by the glass fibers. Also, from our discussion of isolated fibers, the slope G_c should be independent of temperature and moisture. Furthermore, the parameters "G_c" and "A_c" should be measured and reported by the glass fiber manufacturer.

Two new acronyms – We will next introduce two new acronyms, developed in analogy with the HDB – Hydrostatic Design Basis. The HDB is defined in ASTM D2992 as the long-term hoop strain that fails the pipe by weeping. By analogy, we propose that the long-term hoop strain that fails the pipe by burst be called RDB, for Rupture Design Basis. Likewise the long-term hoop bending strain that fails the pipe by strain-corrosion is the CDB, for Corrosion Design Basis. From this, the three parameters that govern the long-term structural design of composite pipes are:

- The HDB – Hydrostatic Design Basis – is the long-term hoop tensile strain that causes weep failure.
- The RDB – Rupture Design Basis – is the long-term hoop tensile strain that causes burst failure.
- The CDB – Corrosion Design Basis – is the long-term hoop bending strain that causes strain-corrosion failure in chemicals.

The HDB is determined per ASTM D 2992. The CDB is determined per ASTM D 3681 (in acid) and ASTM D 5365 (in water). The RDB is measured by creep testing UD plies.

The work of Mark Greenwood - Mark Greenwood creep tested UD rods under several static tensile strains and annotated the times to rupture. The tests were done with the specimens immersed in water as shown in figure 6. The tests performed on rods (instead of on pipes) eliminate all process and geometric related distortions from the data. For example, the data from UD rods are (a) free from contamination by residual stresses and (b) independent of winding angles and other geometric features of the pipe. The regression lines generated by creep testing UD laminas provide basic properties of the glass fibers.

Figure 5
Strained rod immersed in water. (Courtesy Owens Corning)

The rods tested by Mark had a glass loading of 75% by weight and were made from a highly crosslinked isophthalic resin. The type of resin, as we have explained, is irrelevant. The rods were 6 mm in diameter. The rod diameter, like the type of resin, is irrelevant. The specimens were divided in two groups, one made of traditional E glass fibers and another of boron-free glass. The rods were immersed in water and subjected to several sustained constant tensile loads. As expected, the rods under higher strains failed sooner. The data points obtained by pairing the times to rupture with the corresponding strains were annotated and subsequently fitted to a straight line as in equation (3). The straight lines obtained by Mark are shown in figure 6.

Figure 6 shows that the boron-free glass is less susceptible to hydrolysis and holds up better in presence of water than the traditional E glass. The failure strains extrapolated to 50 years indicate a static RDB of 0.92% for the boron-free glass versus 0.41% for the traditional E glass.

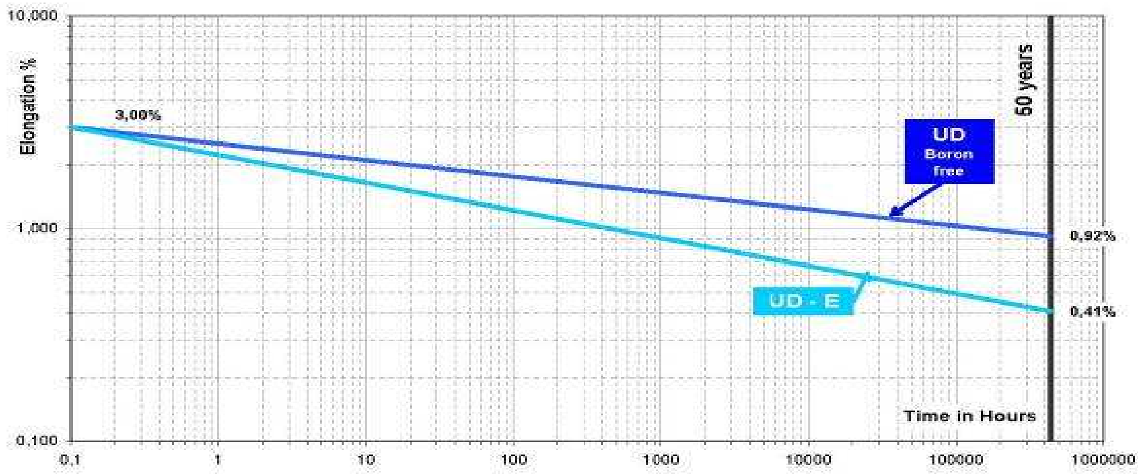


Figure 6
Regression lines adapted from the work of Mark Greenwood

Although Mark himself never published the regression equations for his data, we can do it ourselves by inspecting figure 6. The regression lines for boron-free and E glass are:

$$\log(\varepsilon) = A_s - G_s \log(t) \quad (3)$$

For boron-free glass: $$\log(\varepsilon\%) = 0{,}400 - 0{,}077 \log(hours) \quad (3A)$$

For E glass: $$\log(\varepsilon\%) = 0{,}347 - 0{,}130 \log(hours) \quad (3B)$$

The above equations indicate that under static tensile loads the UD plies of E glass lose 13% of their elongation per decade, versus a loss of 7.7% for the plies of boron-free glass. The short-term elongations of both glasses are essentially the same. The reason for this loss, as we have explained, is strain corrosion of the glass caused by the water.

The work of Guangxu Wei – Mark Greenwood determined the static tensile regression lines and the strain corrosion effect of water on both E and boron-free glasses. The effect of cyclic tensile loads was determined by Guangxu Wei on the fiber direction as well as on the direction transverse to the fibers. The parameters that Guangxu Wei determined for the general cyclic equation (4) are:

$$\log(\Delta\varepsilon) = A_c - G_c \log(N) \qquad (4)$$

$$\log(\Delta\varepsilon) = -0.602 - 0.040\log(N) \quad \text{transverse (2) direction.} \qquad (4A)$$

$$\log(\Delta\varepsilon) = 0.519 - 0.089\log(N) \quad \text{fiber (1) direction} \qquad (4B)$$

The above equations are valid for both E glass and boron-free glass. Equation (4A) will be used in the part 2 of this trilogy, to explain the weep failure under cyclic loads. Equation (4B) will be used later in this paper to determine the long-term safety factor of pipes under the simultaneous action of static and cyclic loads.

Strain Rotation - The reader should understand that the elongations in the above equations are the static and cyclic tensile strains i*n the fiber direction (1) or in the transverse direction (2)* of the UD lamina. Why in these directions? Well, as we recall, Mark's data were developed for UD rods tensile tested in the fiber direction. And Guangxu Wei cyclic tested UD plies on the longitudinal and transverse directions. The commercial standards on pipe design usually specify the strain in the global hoop and axial directions. To comply with equations (3A), (3B), (4A) and (4B), the global strains must be rotated to the principal axis of the UD ply. This rotation is done by the equation

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \frac{1}{2}\gamma_{12} \end{bmatrix} = \begin{bmatrix} \cos^2\alpha & sen^2\alpha & 2(\cos\alpha)(sen\alpha) \\ sen^2\alpha & \cos^2\alpha & -2(\cos\alpha)(sen\alpha) \\ -(\cos\alpha)(sen\alpha) & (\cos\alpha)(sen\alpha) & \cos^2\alpha - sen^2\alpha \end{bmatrix} \times \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ 0 \end{bmatrix} \qquad (5)$$

Where:
α is the angle of the UD fibers with respect to the longitudinal (axial) direction of the pipe.
ϵ_1 is the strain in the fiber direction
ϵ_2 is the strain transverse to the fiber
ϵ_x is the global strain in the axial direction of the pipe
ϵ_y is the global strain in the hoop direction of the pipe
γ_{12} is the shear strain on the UD lamina

Expanding equation (5) we obtain the three elongations on the reference frame of the UD lamina.

$$\varepsilon_1 = \varepsilon_x \cos^2\alpha + \varepsilon_y sen^2\alpha \qquad (5A)$$

$$\varepsilon_2 = \varepsilon_x sen^2\alpha + \varepsilon_y \cos^2\alpha \qquad (5B)$$

$$\gamma_{12} = 2 sen\alpha \cos\alpha\left(\varepsilon_y - \varepsilon_x\right) \qquad (5C)$$

Equation (5A) calculates the strain in the fiber direction. This strain controls the long-term rupture of the pipe. The strain in the transverse direction to the fibers, equation 5B, controls the weep failure of oil pipes, as shown in the part 2 of this trilogy. The shear strain in equation (5C) is irrelevant in the analysis for burst or weeping.

Safety factor – The safety factor SF for long-term burst is determined from the unified equation (6). The unified equation for tensile strains in the fiber direction of UD plies (ref. 5) is

$$\left(\frac{\varepsilon \times SF}{RDB}\right)_{static}^{1/G_S} + \left(\frac{\Delta\varepsilon \times SF}{RDB}\right)_{cyclic}^{1/G_C} + \left(\frac{\varepsilon \times \Delta\varepsilon \times SF^2}{RDB_{cyc} \times RDB_{sta}}\right)^{1/G_{SC}} = 1{,}0 \qquad (6)$$

Where G_s and G_c are the slopes of the static and the cyclic regression lines, as shown in equations (3) and (4). G_{sc} is the interaction parameter that links static and cyclic loadings. Mark Greenwood has established that G_s = 0,077 for boron-free glass and G_s = 0,130 for traditional E glass. The value of G_c was determined by Guangxu Wei as G_c = 0,089. The interaction parameter G_{sc} from reference 5 is listed on table 1.

For the analysis of burst failure the strains in equation (6) are those in the direction of the UD fibers. The RDB values for the UD ply under cyclic and static loads are calculated from equations (3) and (4). The RDB values must, of course, be rotated from the global directions to the fiber directions. The strains (cyclic and static) in the fiber direction of the critical UD ply are, of course, known. The only unknown in equation (6) is the safety factor SF.

A similar analysis can be performed for the transverse direction of the ply to study the weep mode of failure. This is done in the part 2 of the trilogy.

N	*R*				
	0,0	*0,1*	*0,5*	*0,9*	*1,0*
10^3	*0,0*	*37*	*12933*	*889*	*0,0*
10^4	*0,0*	*73*	*11678*	*7012*	*0,0*
10^5	*0,0*	*142*	*9700*	*372*	*0,0*
10^6	*0,0*	*258*	*8114*	*199*	*0,0*
10^7	*0,0*	*505*	*6843*	*108*	*0,0*

Table 1
Interaction parameter G_{sc} for tensile strains in the fiber direction (ref.5).

Sample calculation – We have an oil pipe operating as indicated in table 2. It is required to determine the safety factor SF for burst failure after 20 years of continuous operation.

Winding angle	*α = ±55 degrees*
Static hoop strain	ϵ_y = 0,20%
Static axial strain	ϵ_x = 0,15%
Cyclic hoop strain	$\Delta\epsilon_y$ = 0,10%
Cyclic axial strain	$\Delta\epsilon_x$ = 0,05%
Total cycles in 20 years	$N = 10^7$

Table 2
Operating conditions of the pipe used in the sample calculation.

First we rotate the strains from the global to the ply axis.

$$\varepsilon_1 = \varepsilon = \varepsilon_x \cos^2 \alpha + \varepsilon_y sen^2 \alpha$$

$$\varepsilon = 0{,}15 \times \cos^2 55 + 0{,}20 \times sen^2 55 = 0{,}184\%$$

$$\Delta\varepsilon_1 = \Delta\varepsilon = \Delta\varepsilon_x \cos^2 \alpha + \Delta\varepsilon_y sen^2 \alpha$$

$$\Delta\varepsilon = 0{,}05 \times \cos^2 55 + 0{,}10 \times sen^2 55 = 0{,}084\%$$

Next we calculate the long-term static and cyclic strengths

Static strength for the pipes made of E glass:

$$\log(S_S) = \log(RDB) = 0{,}347 - 0{,}130 \log(20 \times 365 \times 24)$$

S_s = RDB = 0,46% for E glass

Static strength for the pipes made of boron-free glass

$$\log(S_S) = \log(RDB) = 0{,}400 - 0{,}077 \log(20 \times 365 \times 24)$$

S_s = RDB = 1,20% for boron-free glass

Cyclic strength for both E and boron-free glass

$$\log(S_C) = \log(RDB) = 0{,}519 - 0{,}089 \log 10^7$$

S_c = RDB = 0,79% for both boron-free and E glass

Next we calculate the parameter R

$$R = \frac{\varepsilon_{\min}}{\varepsilon_{\max}} = \frac{0{,}184 - 0{,}042}{0{,}184 + 0{,}042} = 0{,}63$$

Next we obtain by interpolation the interaction parameter G_{sc} = 4654 from table 1. The parameters Gs and Gc are taken from the regression equations by Mark Greenwood and Guangxu Wei. We can finally apply the unified equation.

For E glass the safety factor SF is

$$\left(\frac{0{,}184 \times SF}{0{,}46}\right)_{static}^{1/0{,}130} + \left(\frac{0{,}084 \times SF}{0{,}79}\right)_{cyclic}^{1/0{,}089} + \left(\frac{0{,}184 \times 0{,}084 \times SF^2}{0{,}46 \times 0{,}79}\right)^{1/4654} = 1{,}0$$

SF = 1,5

For Boron-free glass the safety factor SF is

$$\left(\frac{0{,}184\times SF}{1{,}20}\right)_{static}^{1/0{,}077}+\left(\frac{0{,}084\times SF}{0{,}79}\right)_{cyclic}^{1/0{,}089}+\left(\frac{0{,}184\times 0{,}084\times SF^{2}}{1{,}20\times 0{,}79}\right)^{1/4654}=1{,}0$$

SF = 3,0

The unified equation indicates that both glasses perform well for an intended life of 20 years. However, the safety factor for the boron-free glass is higher than that for E glass. For longer structural lives, the boron-free glass should be preferred.

Conclusion – This paper deals with the long-term rupture of composite pipes. This mode of failure is controlled by the glass fibers in the UD laminas. The reader is advised that other types of structural failure, such as weeping and strain-corrosion by bending strains, should also be taken into account. For details on the other types of failure, the reader is referred to the parts 2 and 3 of this trilogy. The composite pipes fail by rupture (burst) in the long-term when the operating strains are less than the threshold strain that causes weep failure. In the absence of weeping, burst is the only mode of long-term structural failure. Since the resin has no effect on the RDB, the long-term rupture is controlled by the glass fibers alone. This is an interesting conclusion in itself. This paper has other interesting conclusions:

1. The burst rupture of composite pipes is based on the long-term parameter RDB which is obtained by creep testing UD laminas.
2. The RDB is a property of the glass fibers and as such should be measured and reported by the glass manufacturer, not by the pipe producer.
3. The RDB measured on UD rods can be used directly in the unified equation (ref. 5) to determine the safety factors for the pipe’s desired structural life.
4. The effect of the resin on the RDB can be ignored.
5. The resin controls the weep failure and plays a decisive role in the strain-corrosion failure.

Biography: Antonio Carvalho is an engineer with 40 years dedicated to composites. Past experience includes 30 years with Owens Corning and 10 years as a consultant. Current position is full time consultant for Reichhold, with responsibility for technical support and market development for DION resins in Brasil. For direct messages, please contact Antonio.carvalho@reichhold.com

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Appendix A: Is there a threshold strain for rupture (burst) failure?

The part 2 of this trilogy suggests the existence of a static threshold strain for the weep mode of failure. Static strains lower than the threshold strain, never weep the pipe. Could such threshold exist for rupture also? The answer is no, and the explanation follows.

The failure by weep requires the coalescence of many small resin cracks. The number of pre-existing cracks in a well made pipe is too small, in fact so small that they do not coalesce to form the pathway for the passage of water. As the static strain is increased, the size and number of cracks also increase until, eventually, the pathway is formed. It takes higher strains, over the threshold limit, to create fresh cracks that would lead to such pathway. The situation is entirely different for the glass fibers which, unlike the resin, develop fresh cracks from the attack by water. The hydrolysis of the glass creates fresh cracks all the time, regardless of the strain. Taken to the limit, this argument suggests that the glass fibers would, given enough time, hydrolyze out of existence.

Appendix B: Sudden-death and the resin effect.

This appendix addresses the interesting phenomenon of "sudden-death" and explains the influence of the resin on the regression rupture lines. We will show that (a) the long term burst rupture is governed by the glass while (b) the short term weep is controlled by the resin.

We start with a discussion of the events leading to the rupture of UD laminas in the fiber direction. To facilitate the understanding, the discussions will be conducted in terms of stresses, instead of strains. Figure B1 shows the cross section A – A of a UD lamina. The short-term strength of this lamina in the fiber direction is

$$\sigma_0 = \frac{N}{A} \times a \times (\sigma)_{fiber} + \frac{(A - N \times a) \times (\sigma)_{resin}}{A} \qquad \text{(B1)}$$

Where

N – Is the number of fibers in the section A – A
A – Is the area of the section A – A
a – Is the cross sectional area of the individual fibers
σ_{fiber} – is the short-term strength of the fiber
σ_{resin} – is the short-term strength of the resin

The resin contribution to the overall strength is small and will be ignored

$$\sigma_0 = \frac{N}{A} \times a \times \sigma_{fiber}$$

We next assume a static force F that produces a constant tensile stresses on the fibers. In accordance with the theory of fracture mechanics, this applied stress (or strain) immediately fails all fibers at the points where the crack length "a" is larger than a certain critical value. These points of immediate rupture occur at random along the fiber length, as shown in figures B1 and B2.

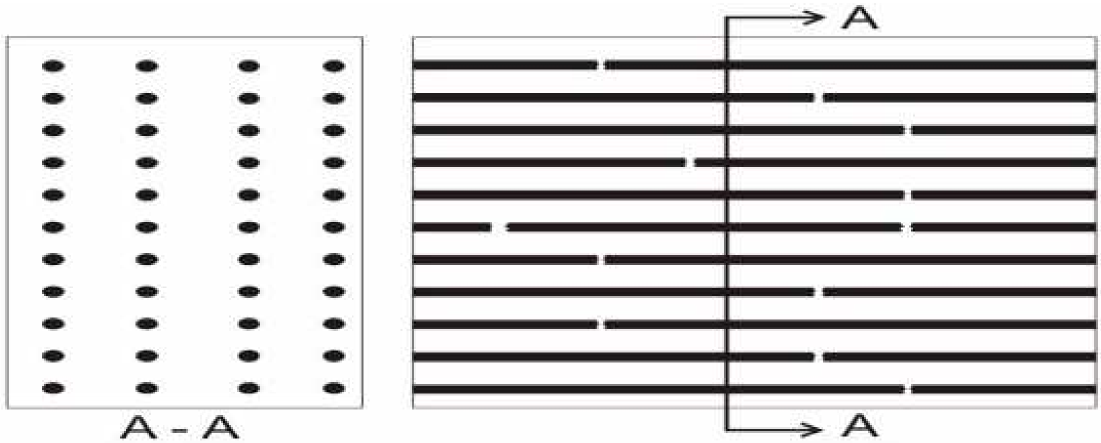

Figure B1
Rupture occurs when the fiber break points that occur randomly in the ply grow to a large number and eventually coalesce.

The load that ceases to be carried by the broken fiber is transferred by the resin to the unbroken parts of the same fiber. The load transfer takes place by shear at the glass-resin interface, as shown in figure B2. The broken fibers lose their load carrying capacity in a small segment "δ" at the ruptured ends. This small segment "δ" is called "ineffective length" for obvious reasons. The rest of the fiber, that is not broken, retains its load carrying capacity and in fact continues to play an active role in the strength of the lamina. We denote by "n" the number of ruptured fiber points that fall on section A – A. Equation (B2) gives the strength of the lamina in this condition.

$$\sigma_0 = \frac{(N-n)}{A} \times a \times \sigma_{fiber} \qquad \text{(B2)}$$

In the above "n" is the number of ruptured fiber ends that fall on section A – A. Equation (B2) is the same equation (B1), except for the discount of the load that ceased to be carried by the "n" broken fibers on section A – A. The reader will agree that while the number of ruptured points on any fiber may be very large, the number of those ruptured points falling exactly on section A – A is very small when compared to "N".

$n << N$

Entering the above in (B2) we conclude that the strength of the lamina is insensitive to the number of broken fibers and remains unchanged. This is an interesting conclusion that goes against common sense. Logic would have us believe that the strength of the ply should decrease as the fibers break but, instead, we have concluded that it remains the same.

As time passes, the process of "strain-corrosion" takes over and the number of ruptured fiber ends increases in the vicinity of the section A – A. Eventually the ruptured ends become too many and the lamina breaks. This description of the events is consistent with the "sudden-death" phenomenon reported by many researchers. The "sudden-death" is explained by (a) the laminas retaining their original strength even when a large number of fibers have failed and (b) the sudden rupture that takes place when a critical level of damage is reached. Mark Greenwood informs in a personal communication that *"we have tested pipes to burst after weep failure and have found the burst pressure had not significantly changed"*. This is one more testimony supporting the phenomenon of "sudden-death".

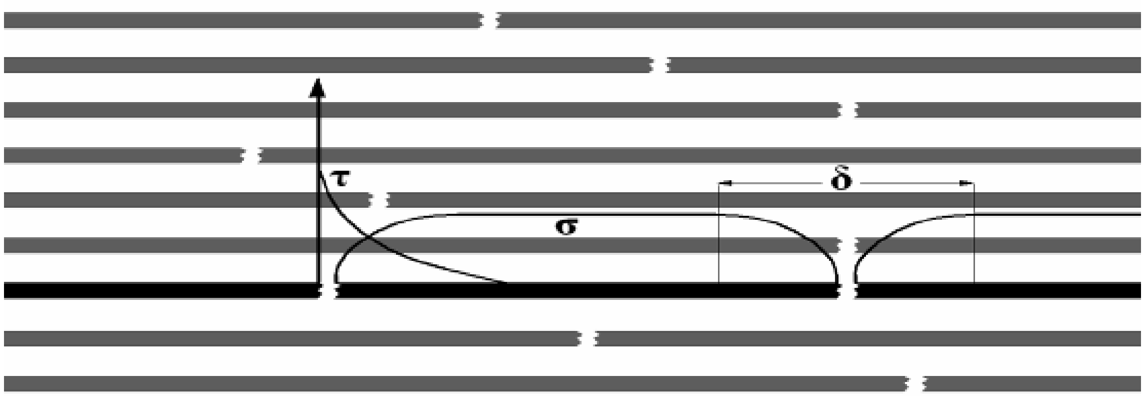

Figure B2. The shear stresses at the ruptured fiber ends transfer tensile stresses to the unbroken part of the fiber. Also shown is the ineffective length "δ".

As the number of broken ends accumulates near the section A – A, the strength of the lamina remains essentially unchanged. It is only towards the end of the process, as rupture is imminent, that the local decrease in modulus near the section A – A is felt. This local decrease in modulus, due to local coalescence, causes the lamina to rupture at the section A – A. The rest of the lamina, however, where coalescence has not been so intense (this is a random process) retains its original (or slightly decreased) modulus, elongation at break and strength. This discussion shows that the local coalescence leading to sudden-death may not be detected by testing the parts of the lamina in the vicinity of the ruptured section A – A.

We next discuss the role played by the resin. The resin contribution to the strength of the UD lamina resides not on the load that it carries, but on its ability to transfer loads from among broken fiber ends. The resin doing this trick is clearly not the matrix resin, but the interphase resin. The load transfer is done by shear stresses along the ineffective length of the broken fibers. If the shear modulus of the interphase is high, the ineffective length "δ" is small. On the other hand, if the shear modulus is low, the ineffective length "δ" is large. Large ineffective lengths "δ" have two effects.

1 – The increased "δ" expands the coalescence zone in the vicinity of the section A – A and expedites the rupture of the lamina. In other words, for the same constant stress "σ", a large ineffective length causes the lamina to coalesce and fail sooner.

2 – The increased "δ" has the additional effect of decreasing the elastic modulus of the lamina. This is a topic that we have not mentioned yet and we might as well do it now. Unlike the strength, the modulus of the UD laminas falls with the rupture of the fibers. This is to be expected and explains the slow increase in strain that takes place in creep tests.

We conclude that under constant stress "σ " the laminas with tougher interphase resins and better adhesion to the glass would have (a) longer rupture times, (b) smaller decay in modulus and (c) less creep. That is, in a nutshell, how the resin affects the long-term structural behavior of composites. The point that we have made earlier is that for any given commercial glass sizing, the effect of the resin alone is not very significant and may be ignored. That is the justification for our statement that the effect of the resin on the long-term rupture can be ignored.

Suppose we pressure test water filled pipes at increasing pressure levels. As the pressure is increased the glass-resin interphase develops cracks. If the pressure is held constant, these cracks are stationary and do not grow. If the pressure is increased the cracks grow both in size and in number. As discussed in the part 2 of this trilogy, there is a threshold strain at which the number of cracks become too large and coalesce to form continuous pathways that allow the passage of water. The pressure that weeps the pipe is much lower than the short-term burst pressure. In the short-term the pressurized pipes fail first by weep, later by burst.

We next consider the performance of the pipes in normal operation, i.e., under low pressure and low strain. If the strain is less than the threshold strain, the resin will not crack and the pipes will not weep. In this scenario the pipes fail by rupture caused by the slow deterioration of the glass. In the long-term the pressurized pipes fail by burst.

The above arguments set the foundation for the concepts of burst and weep failure of composite pipes. The reader is asked to read them again. The arguments are indeed very powerful and show that:

1 – In high strains the pipe fails by weeping, which is controlled by cracking of the resin.

2 – Under low strains the pipe fails by burst, which is controlled by strain corrosion of the fiber.

Weep and burst are independent modes of failure, governed by different mechanisms, and both should be considered in design. The current pipe standards ignore the long-term burst mode of failure. This is understandable since it was not until recently that the issue of strain corrosion by water captured the attention of the composites community.