Last revised on September 11, 2014

Designing composite pipes for the long term

Part I – Burst failure

Antonio Carvalho

Presented in 2007 at the ACMA infrastructure conference in Las Vegas

Abstract – The composites industry recognizes three long-term modes of structural failure in pipes, each governed by a different mechanism.

- The **weep failure** is caused by the coalescence of cracks that initiate in the glass-resin interface under tensile strains transverse to the fibers. The small debond cracks that form at the interface grow under increasing tensile loads and eventually link up to form pathways for the passage of water. The time taken by the water to traverse the pipe wall depends on the length, opening and number of these cracks. It also depends on the wall thickness. The resistance to weeping is controlled by the sizing that is applied on the glass, as well as by the toughness of the matrix resin. This paper will show that the weep failure is actually a short-term mode of failure that is erroneously considered as a long-term mode.
- The **burst failure** is caused by the long-term rupture of the glass fibers that are tensile loaded in the presence of water. The burst failure is governed by the hydrolytic stability of the glass fibers and is not affected by the resin.
- The **strain-corrosion failure** is similar to the burst rupture, since both involve deterioration of the glass fibers. The difference between these two modes is very subtle. In the burst mode the fibers are deteriorated by water when the pipe is loaded in tension. In the strain-corrosion mode the fibers are attacked by chemicals when the pipe is exposed to bending loads. In both cases failure comes from fiber rupture.

The above modes of structural failure will be discussed in three separate papers. The first (this paper) will address the burst case. The weep and strain-corrosion modes will be discussed in subsequent papers.

1 Introduction – The mechanism that cause burst and strain-corrosion failures are identical. Both involve the chemical deterioration of the fibers under tensile loads. The weep failure is governed by a distinct mechanism, involving the formation and coalescence of cracks that form on the glass-resin interface under tensile strains. Weeping is a “go no-go” phenomenon. If the strain is less than the threshold weep strain, weeping never occurs. If the strain is higher than the threshold, weeping will certainly occur. The time to weep is the time taken by the leaking fluid to travel through the cracks in the pipe wall. It varies with the magnitude of the tensile strains that govern the opening, length and number of cracks. It also varies with the wall thickness of the pipe. As such, the time to weep is not a fundamental material property.

By contrast, the burst and strain-corrosion modes of failure have no threshold strain. Both modes eventually fail the pipe, regardless of the magnitude of the tensile strain. The time to rupture is the time taken by the chemical product or the water to hydrolyze the glass fibers.

The classical explanation for the time dependence of the weep failure is based on the erroneous assumption that the interface cracks grow under constant loads. This interpretation is not supported by the theory of fracture mechanics which says that, in the absence of strain-corrosion, static loads do not grow cracks. Since the resin (unlike the glass fibers) is not affected by strain-corrosion, the interface cracks will not grow under tensile static loads. Composite pipes under static loads may or may not weep. If the strain is below the threshold, it never does. If above the threshold the weep time is nothing more than a measure of time for the water to travel the cracks in the wall. The weep time is not a fundamental material property and as such should not be used in designing pipes. The classical concept of the HDB and the test method described in the ASTM D2992 protocol are not relevant to the technology of composites.

The classical ideas assume the deterioration of the resin under static loads and accept the validity of the HDB. According to these ideas the weep failure is a form of long-term failure that depends on time. The question may then arise to the classical engineers as to which failure occurs first, weeping or rupture. This is a meaningless question, since the weep failure is not time dependent. The answer to this meaningless question is like follows:

If the operating strain is higher than the threshold, the travel time for the water is short and weeping occurs before 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 failures under the assumption that the pipes do not weep. This condition is fulfilled if the operating strain is less than the threshold weep strain.

The strain-corrosion mode of failure is similar to the burst mode. The similarity is in the fiber rupture by chemical attack. The difference is in the chemical that causes the attack, water in the case of burst, and sulfuric acid in the case of strain-corrosion. Another difference is that burst is caused by tensile loads, while strain-corrosion is caused by bending loads.

The Hydrostatic Design basis, or HDB, is universally used to design composite pipes against weep failure. The concept of the HDB is so entrenched in the commercial standards and in the minds of the practicing engineers that perhaps it will be maintained in our new proposal. We will from time to time refer to the threshold strain as HDB, as if they were the same thing. In fact they are not the same thing, but both are used to the same purpose.

The strain-corrosion behavior is represented by an analog of the HDB that we will 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, specifically a 5% solution of sulfuric acid. 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 in the presence of water. The three papers in this trilogy will describe how to measure and use these three 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 for pipe designers until the publication of a paper by Mark Greenwood (ref 6) in 2001. We will make extensive use of Mark's data in this paper. 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". We 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.

The remainder of the discussions will be specific to burst failure. The weep and strain-corrosion failures are addressed in separate papers.

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

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

The first hypothesis excludes the 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. The long-term burst is controlled by the fibers. 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 the use of composites in highly corrosive fluids. Experience shows that pipes carrying aggressive chemicals fail sooner than those carrying benign fluids like water. This seems to contradict the hypothesis that water is the only chemical causing long-term deterioration and affecting the structural life. This misconception comes from confusion between the concepts of service life and structural life. The service life is the time taken by chemical products to penetrate the corrosion barrier before they attack the fibers in the structural plies. The deterioration of the structural plies follows rapidly once the aggressive chemicals penetrate the corrosion barrier. What we have here is penetration of the corrosion barrier, followed by rapid destruction of the structural plies. The structural life in such cases is short, not much longer than the service life. However, if we replaced the deteriorated corrosion barrier by a new one every time it is penetrated, the structural fibers would not see accelerated corrosion and the structural life is defined by the water.

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. Their effect is limited to the corrosion barrier. Water is the only molecule capable of penetrating the whole laminate and affecting the fibers in all plies. 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.

3 Static loading of bare fibers – Bare fibers are those not embedded in a resin matrix. This section will address the rupture of bare glass fibers under static tensile loading. The mechanism of fiber failure under cyclic loading is dealt with in the next section.

From the study of fracture mechanics we learn that static loads do not grow cracks. Only cyclic loads are capable of growing cracks. However, fracture mechanics also tell us of a special mechanism for crack growth under static loads. This mechanism is known as strain-corrosion. It works like this. Under tensile strains the crack opens and facilitates the access of the corrosive agent to the crack tip. The corrosion process grows the crack under static loads. The combined effect of static strains and corrosion is known as strain-corrosion. It is the only process known that grows cracks under static loads.

3.1 – 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 on the fiber surface and the chemical environment. The surface flaws grow into small cracks under the combined action of the environment and the residual tensile strains on the outer surface of the fiber. This suggests that perfectly smooth and crack free glass fibers do not exist in the real world since all fibers, no matter how initially perfect, will develop cracks from the combined action of the residual tensile surface strains and the attack by water. Figure 1 shows the environmentally induced surface cracks that develop on glass fibers that have been exposed to acids.

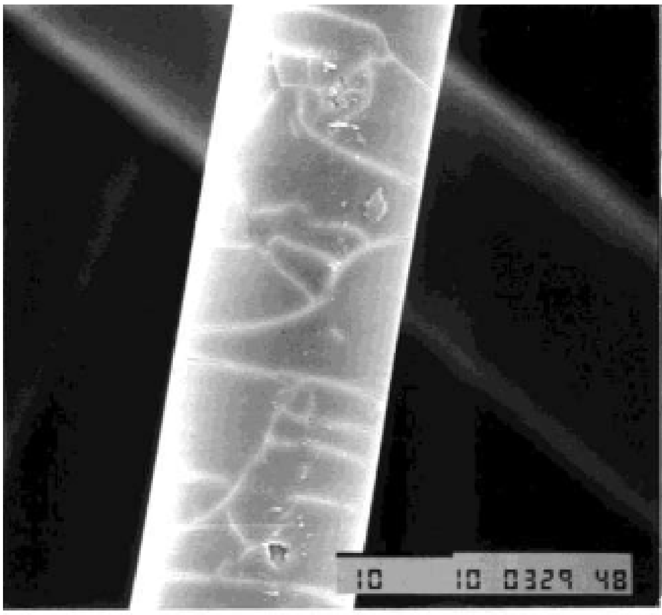
3.2 – Crack propagation. The spontaneous environmentally induced surface cracks are self-limiting and arrest as soon as the driving force (the residual strains) dissipate. This situation changes, however, if the fibers are subjected to external tensile strains, over and above the residual strains. The 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 the Paris equation, which assumes the following form

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

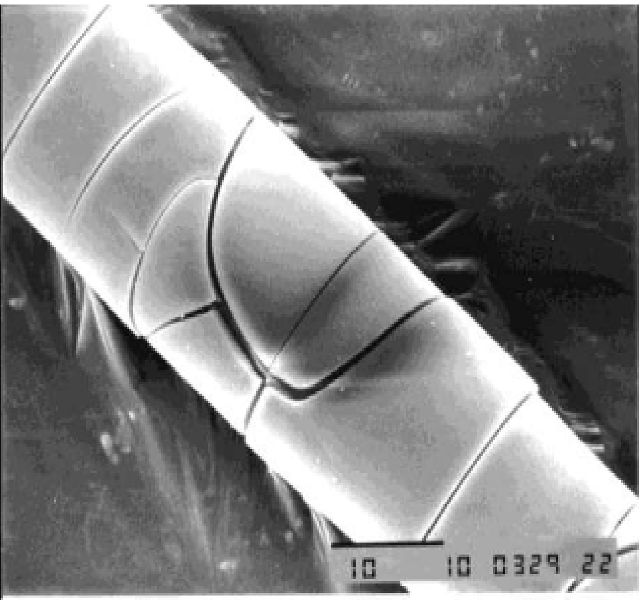
In equation (1) “a” is half the size or length of the crack, “Y” is a constant that need not concern us at this time, “Є” is the sustained constant tensile strain that would exist in the absence of the crack and “Z” is a parameter that depends on the chemical environment, the temperature and the composition of the glass fibers. Equation (1) recognizes the tensile strain, the glass composition and the temperature as contributors to the crack growth that eventually ruptures the fiber. The reader should note that the crack growth rate expressed in equation (1) is caused by strain-corrosion.

Equation (1) indicates that the rate of crack growth depends on the crack size “a”, the total strain (residual + external) “Є”, and the exponent “Z” which depends on the temperature, the chemical and the composition of the glass. Together these parameters define the time to rupture of the fiber under static load. The time to rupture of glass fibers under constant tensile strains in acids or in water is well documented.

The time to fiber rupture can be estimated by integrating equation (1) from the initial crack size “a_o” to the critical size “a”. The variability in the time to rupture of single isolated fibers is enormous, reflecting the variability in the original crack sizes.



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)

4 Cyclic loading of bare fibers – The deterioration of bare fibers under tensile cyclic loads is different from that under static loads. The previous section showed that static crack growth is a continuous process caused by corrosion of the strained glass. The rate of static deterioration is strongly influenced by the strain itself, the temperature, the nature of 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 loading cycle, pretty much as a hammer drives a nail in a piece of wood. The crack grows in the same way as 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) we see that 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.

The number of cycles to fiber rupture can be estimated by integrating equation (2) from the initial crack size “a_o” to the critical size “a”. The variability in the number of cycles to rupture of single isolated fibers is enormous, reflecting the variability in the original crack sizes.

5 Static loading of UD plies – The preceding discussion dealt with the rupture of isolated bare single glass fibers. We continue with the discussion of the static case, assuming now 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 on the long-term strengths of the ply. Specifically, the resin matrix evens out the enormous variability observed in the strain to rupture of bare fibers. This “evening out” of the fiber strength substantially increases the overall performance of the composite and is known as the “composite effect”. If the composite effect did not exist, that is, if the resin matrix did not even out the enormous variability of strength in the glass fibers, the composites industry would not be a reality.

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

Note: The only known instance of self-similar crack growth in laminates across the fibers occurs in strain-corrosion, where laminates are subjected to bending strains while 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. In the delamination and debonding mentioned above, the cracks grow parallel to the fibers, not across them.

The following discussion is based on well documented evidence indicating that composites do not grow self-similar cracks across the fibers. To facilitate the exposition the discussion is limited to UD plies. We begin by stating that the cracks generated in the composite at the points of fiber rupture do not propagate to adjacent fibers. Rather, they are arrested in their growth or deflected from their path as they meet adjacent fibers. The many points of fiber rupture in a ply form a myriad of isolated small cracks that do not extend beyond the neighboring fiber. Rather, they are arrested or diverted as they move from one fiber to the next. The rupture of the UD ply results not from the growth of one large crack, but from the accumulation and eventual coalescence of many small cracks. This mechanism explains the "composite effect" and the exceptional toughness and fatigue resistance of all fiber reinforced materials.

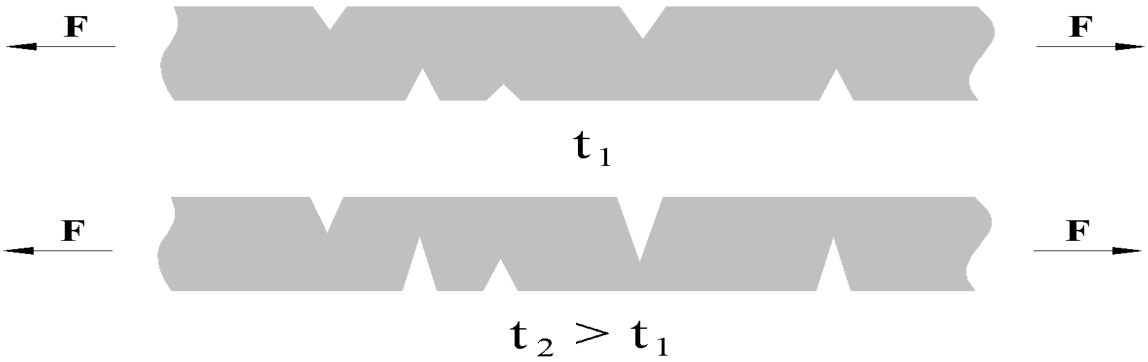


Figure 2
Self-similar crack growth occurs in homogeneous materials, like glass fibers. Self-similar cracks do not grow in composites.

The time to rupture of single bare fibers under static tensile loads can be predicted by integrating equation (1). In UD plies, however, there are many fibers, all failing according to equation (1). The equation to predict the time to rupture of UD plies is a statistical version of equation (1). The relationship between the global static tensile strain in the fiber direction and the time to rupture UD plies is

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

Equation (3) calculates the time to rupture (t) of UD plies under sustained static tensile strain "Є" acting in the fiber direction. The fitting parameters As and Gs are determined by experiment.

The parameter "A_s" is related to the ultimate tensile strain of the ply at t = 1 unit of time. The unit of time is irrelevant and could be 1 day, 1 minute or 1 hour. The parameter "A_s" is adjusted to match any unit of time that we may choose. The slope parameter "G_s" reflects the hydrolytic stability of the fibers and is expected to increase slightly with the temperature. The effect of the resin matrix on the parameters “G_s” and “A_s” is small, so small that they are regarded as properties of the glass. Being glass properties, both “As” and “Gs” should be measured and reported by the glass fiber manufacturer.

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

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

As in the static case, the slope “G_c” is dominated by the glass fibers. Also, from our discussion of bare fibers, the slope G_c is independent of temperature and moisture. The parameters “G_c” and “A_c” are measured and reported by the glass fiber manufacturer.

7 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 largest hoop strain that the pipe can sustain for a defined number of years without weeping. By analogy, we propose that the largest long-term hoop strain that the pipe can sustain without bursting be called RDB, for Rupture Design Basis. Likewise, the largest long-term hoop bending strain that can be sustained without strain-corrosion rupture 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 static hoop tensile strain that controls weep failure.
- The RDB – Rupture Design Basis – is the static hoop tensile strain that controls burst failure.
- The CDB – Corrosion Design Basis – is the static hoop bending strain that controls strain-corrosion failure.

The HDB is determined per ASTM D 2992B. 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.

8 The work of Mark Greenwood - Mark Greenwood creep tested pultruded UD rods under a variety of static tensile strains. The times to rupture varied inversely with the tensile strains and the data collected were used to generate regression lines to predict the times to rupture for any strain. The tests were done with the specimens immersed in water as shown in figure 5. 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) are independent of winding angles and other geometric features of the pipe. The regression lines generated by creep testing UD plies reflect the basic properties of the glass fibers.

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

The rods tested by Mark Grenwood were 6.0 mm in diameter, had a glass loading of 75% by weight and were made from a highly cross linked isophthalic resin. The rod diameter and the type of resin are not relevant. The specimens were divided in two groups, one made of E glass fibers and the other made of boron-free glass. The rods were immersed in water and subjected to different levels of 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 strain of 0.92% for the boron-free glass and of 0.41% for the traditional E glass.

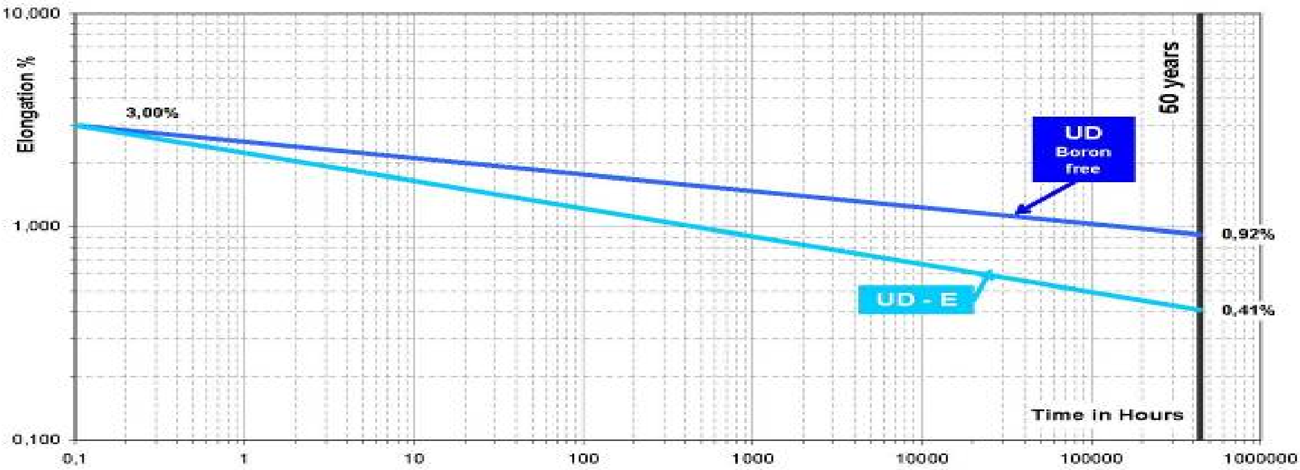


Figure 6
Regression lines adapted from the work of Mark Greenwood

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

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

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

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

Figure (6) indicates that the two rods have essentially the same short-term strain to rupture. The two glasses tested differ in the long-term, not in the short-term. This is so because the strain corrosion process requires some time to take effect.

9 The work of Guangxu Wei – Mark Greenwood determined the static tensile regression lines for both E and boron-free glasses. The cyclic tensile regression lines were determined by Guangxu Wei both in the fiber direction and in the direction transverse to the fibers. The equations determined by Guangxu Wei for the general cyclic equation (4) are:

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

$\log(\Delta\varepsilon) = -0.602 - 0.040 \log(N)$ for the transverse (2) direction. (4A)

$\log(\Delta\varepsilon) = 0.519 - 0.089 \log(N)$ for the fiber (1) direction (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 calculate the number of cycles to weep failure. Equation (4B) will be used later in the present paper to study the long-term rupture of pipes under the simultaneous action of static and cyclic loads.

10 Strain Rotation - The reader should understand that the strains in all previous equations are expressed either *in the fiber direction (1) or in the transverse direction (2) to the fiber.* As we recall, both Mark Greenwood and Guangxu Wei developed their data in these directions. Mark's data were developed using UD rods tensile tested in the fiber direction. And Guangxu Wei tested UD plies in both the longitudinal and the transverse directions to the fibers. This is correct.

However, the commercial standards for pipes specify the strains in the global hoop and axial directions. To comply with equations (3A), (3B), (4A) and (4B), the global strains should be rotated to the principal axis 1 and 2 of the UD ply. This rotation is done by equation (5)

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

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 ply

Expanding equation (5) we obtain the three elongations expressed on the local reference frame 1 – 2 of the UD ply.

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

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

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

Equation (5A) calculates the strain in the fiber direction when the global hoop and axial strains are known. 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 discussed in the part 2 of this trilogy. The shear strain in equation (5C) is irrelevant in the analysis of burst or weeping.

11 Safety factor – Equations (3) and (4) are applicable to pipes under static or cyclic strains acting alone in the fiber direction. They are not valid when the two loadings act simultaneously. The combined effect of the two loadings acting simultaneously is calculated using the unified equation (6).

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

In the above equation G_s and G_c are the slopes of the static and the cyclic regression lines, as shown in equations (3) and (4). These parameters are known. The static and cyclic RDB's are determined from equations (3) and (4) and are known. The interaction parameter G_{sc} links the static and the cyclic loadings.

Mark Greenwood established 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. Some interaction parameters G_{sc} from reference 5 are listed on table 1. For the analysis of burst failure, the strains in equation (6) are those in the direction 1 of the UD fibers. They are obtained by rotating the global strains as indicated in equation (5A). The global strains (cyclic and static) are, of course, known. The only unknown in equation (6) is the safety factor SF.

To study the weep mode of failure, a similar analysis can be performed for the transverse direction of the ply. This is done in the part 2 of this trilogy.

Interaction parameters Gsc

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). The R parameter is defined in the usual way as $R = \epsilon_{min}/\epsilon_{max}$.

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

Winding angle	$\alpha = \pm 55$ degrees
Static hoop strain	$\epsilon_y = 0,20\%$
Static axial strain	$\epsilon_x = 0,15\%$
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 for the pipe in the sample calculation.

First we use equation (5A) to rotate the global strains to the fiber direction.

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

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

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

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

Next we determine the long-term (20 years) static and cyclic strengths. These strengths are also known as RDB's.

The static strength for the pipes made of E glass is:

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

S_s = RDB = 0.46% for E glass

The static strength for the pipes made of boron-free glass is

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

S_s = RDB = 1.20% for boron-free glass

The cyclic strength for both E and boron-free glass is

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

Sc = RDB = 0.79% for both boron-free and E glass

Next we calculate the parameter R

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

The interaction parameter $G_{sc} = 4654$ is obtained by interpolation from table 1. The parameters Gs and Gc are taken from the regression equations by Mark Greenwood and Guangxu Wei.

We have determined all the relevant inputs to the unified equation (6).

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 predicts that both glass compositions perform well for the intended structural life of 20 years. However, the residual safety factor for the boron-free glass is higher than that for the E glass. For structural lives longer than 20 years, the boron-free glass should be preferred over the regular E variety.

13 Conclusion – The long-term structural failure of composite pipes may occur by burst or strain-corrosion. The weep mode of failure is not a long-term problem. This paper argues that the long-term burst is caused by rupture of the glass fibers exposed to tensile loads in water. Water is the only chemical capable of penetrating the pipe wall and attacking the glass fibers. The weeping and strain-corrosion failures are addressed in the parts 2 and 3 of this trilogy.

Composite pipes fail by burst in the long-term only if the operating strains are lower than the threshold weep strain. Otherwise they weep before they burst. In the absence of weeping, burst is the only remaining possible mode of failure. The long-term rupture is controlled by the glass fibers alone. The resin matrix has no effect on the long-term bust rupture.

This paper offers other interesting conclusions:

1. The long-term parameter – RDB – controlling burst rupture is obtained by creep testing UD pultruded rods immersed in water.

2. The Rupture Design Basis – 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 desired structural life.
4. The resin effect on the RDB can be ignored.
5. The weep failure is controlled by the resin and the sizing on the fibers.

Biography: Antonio Carvalho is an engineer with 45 years dedicated to composites. Past experience includes 30 years with Owens Corning and 15 years as a consultant. For direct messages, please contact tony.hdb@gmail.com

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

The part 2 of this trilogy proposes the existence of a static threshold strain for the weep mode of failure. Could such a threshold exist for rupture as well? The answer is no, and the justification is like follows.

The failure by weep requires the coalescence of many cracks in the resin matrix. As the static strain is increased, the size and number of cracks also increase until, eventually, they coalesce. The cracks in the resin are not strain-corroded by water and do not grow under static loads. Therefore, if the static loads are below the threshold, the pipe will never weep. The cracks in the resin are stationary and do not grow.

The situation is entirely different for the glass fibers which, unlike the resin, are attacked by water and grow cracks by strain-corrosion. The strain-corrosion of the glass grows the cracks on a continuous basis. The cracks in the fibers grow with time and eventually rupture the pipe.

In conclusion:

- There is a threshold strain for weep.
- There is no threshold strain for rupture.

Appendix B: Weep versus burst

Suppose a monotonically increasing pressure inside a water filled pipe. At first the pressure is not large enough to grow cracks in the transverse direction to the fibers. As the pressure is increased, the transverse cracks grow and eventually link up to form pathways that allow the passage of water. If the pressure is held constant, these debond cracks are stationary and do not grow. Why would these cracks not grow? Because, unlike the glass fibers, the resin is not attacked by water and do not grow cracks by strain-corrosion. The only possible way for these debond cracks to grow is by increasing the internal pressure in the pipe.

As the pressure is increased, the transverse cracks grow in size, in opening and in number. As discussed in the part 2 of this trilogy, there is a critical strain that link up the transverse cracks and form pathways that allow the passage of water. This is indicated by droplets on the outside surface of the pipe. The pressure that weeps the pipe is much lower than the short-term burst pressure.

We next consider the performance of pipes under low pressure and low strain. If the operating strain is less than the threshold weep strain, the debond cracks do not coalesce and the pipes do 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 under low strains 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 beyond a reasonable doubt that:

1 – Under strains higher than the threshold weep strain, the pipe fails by weeping
2 – Under strains lower than the threshold weep strain, the pipe fails by burst.

Weep and burst are independent modes of failure, governed by different mechanisms. 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.