Ninth draft: January 19, 2012

Structural failure of composite pipes – a trilogy

Part 3 – Strain corrosion of deflected pipes

Presented at the 2011 ACMA conference in Las Vegas
Antonio Carvalho

Abstract – This is the third paper in a trilogy addressing the structural life of composite pipes. The first paper dealt with burst rupture. The second focused on weep failure. The present paper covers strain corrosion of pipes under bending loads. It opens with a discussion of how water and other chemicals can cause strain corrosion rupture. The small water molecules can penetrate into laminates and strain-corrode pipes under tensile strains. Unlike water, the large molecules of industrial chemicals cannot penetrate the laminates and cause strain-corrosion only in pipes under bending strains. The time to strain-corrosion rupture is obtained by adding the time taken by the chemical to reach the fibers with the time the chemical takes to corrode them. The delaying effect of the liner is recognized and accounted for.

Introduction – Composite pipes display three long-term modes of structural failure. Of these, the most prominent and best documented is the weep mode, which results from the passage of fluid through cracks in the pipe. Other modes of failure involve pipe rupture by burst or by strain-corrosion. We have developed a series of three papers addressing each of these modes of failure. The first paper shows that the long-term burst failure is controlled by the hydrolytic stability of the glass, with no influence from the resin. The second paper shows that the weep failure is dominated by the glass-resin interphase, regardless of the composition of the glass fibers. The present paper will discuss the long-term rupture by strain-corrosion.

Strain-corrosion is important in designing deflected underground pipes. The pipes that carry plain water are evaluated for strain corrosion as described in ASTM D 5365. The pipes carrying sewage are evaluated for strain corrosion in accordance with ASTM D 3681. The negative aspect of these methods is the high strains that are required to complete the test in reasonable times. In both test methods, the pipes are subjected to different levels of bending strains while in contact with the corrosive chemical. The pipes under higher strains fail first and regression lines are developed to predict the bending strain that ruptures the pipe in the long-term. In both tests the deflected specimens fail by strain-corrosion.

1 - The ASTM D 5365 test is performed on deflected pipe specimens immersed in water. It determines the strain-corrosion effect of water on the corrosion barrier. The extrapolated long-term strain from this test is known in the industry as Sb.

2 - The ASTM D 3681 test is conducted on deflected pipes immersed in a 5% solution of sulfuric acid. The test simulates the strain-corrosion effect of acids in the corrosion barrier. The long-term rupture strain from this test is called "Corrosion Design Basis", or CDB, in analogy with the "Hydrostatic Design Basis", or HDB value.

There are four types of strain-corrosion in composites which the engineer should be aware of. They are:

- *Strain-corrosion of the resin-rich liner.* This type of strain-corrosion is known in the literature as environmental stress cracking and is observed when resin-rich liners under tensile strains are placed in corrosive chemicals.

- *Strain-corrosion of the UD structural plies.* Water is a penetrating chemical that strain-corrodes the UD glass fibers in the structural plies. This type of strain-corrosion determines the long-term burst life of pipes under tensile strain. We refer to this long-term strength as the Rupture Design Basis, or RDB value. The tests to measure the RDB value were performed by Mark Greenwood on UD rods and are discussed in the part 1 of this trilogy.
- *Strain-corrosion of the chopped fibers in the corrosion barrier.* This is caused by acid (or other chemical) that somehow reaches the corrosion barrier of pipes under bending strains. The rupture time is obtained by adding the time taken by the chemical to reach the glass fibers and the time taken by the chemical to corrode the glass. We refer to the long-term strength of the pipe in this situation as the Corrosion Design Basis, or CDB value. The CDB value is determined per ASTM D 3681.
- *Strain-corrosion of the outer plies*. This is caused by water, since the corrosive chemicals never reach the outer plies. This type of strain corrosion takes place in deflected underground pipes that have the outside surface in contact with the water in the soil. The long-term strength – designated as Sb – of the outer plies of deflected pipes exposed to water is measured by ASTM D 5365.

This paper will address the strain-corrosion rupture that occurs when pipes are deflected in contact with acids. The time to rupture is a function of both the glass composition and the toughness of resin in the corrosion barrier. This paper will show that the time to cause strain-corrosion rupture is obtained by combining the time to corrode the glass with the time for the acid to pass the resin-rich liner.

Two types of media – This section will put the aggressive chemicals in proper perspective. We define as aggressive any medium or agent that lessens the performance of the composite pipe. The aggressive media to composite pipes can be grouped in two categories.

1- The non-penetrating chemicals have limited penetrating power and affect only the layers next to the surface. Examples of such media are the chemicals found in industrial applications. The slow penetration and the aggressive nature of these chemicals determine the durability of the corrosion barrier. The corrosive chemicals do not reach the structural layers and have no effect on the structural life. However, as shown in the next section, the corrosive chemicals do affect the structural life of pipes under bending loads. This, in fact, is the essence of the strain-corrosion phenomenon that will be addressed in this paper.

2 -The *penetrating* chemicals pervade the whole laminate and reach all plies. Water is the most important penetrating chemical. In fact, the burst rupture of pipes under tensile loads (discussed in paper 1) is determined by strain-corrosion of glass fibers in contact with water. That concept validates the data generated by Mark Greenwood (ref 2) from tensile tests on water saturated UD rods.

Resin-rich liners and sacrificial corrosion barriers are built to prevent the damaging chemicals from contacting the structural plies. In some applications (storage tanks) the corrosion barrier can be replaced periodically and the chemical never reaches the structural plies. In cases like these the rupture life of the composite under tensile loads is determined by the water attack on the glass fibers. This reasoning is not valid if the laminate is placed under bending loads, as the next pages will show.

Strain-corrosion under bending loads – We open the discussion by recognizing that strain-corrosion rupture, like all ruptures of composites, is related to deterioration of the glass fibers. The glass fibers are susceptible to attack by water, acid and alkaline solutions. We might expect a uniform attack progressing from the surface to the core of the fiber. However, some surface spots on the fibers are more susceptible to attack than others and develop local micro cracks. These micro cracks expand under tensile strains and expose fresh surfaces to chemical attack. The localized corrosion concentrated in the fresh surfaces grows the crack and eventually leads to rupture of the tensioned fiber. This process is called strain-corrosion. By exposing fresh surfaces to the chemical, the strain-corrosion process causes crack growth under static loads. This finding is so fundamental that we repeat it, for emphasis. The strain-corrosion process causes crack growth under static loads. This process is unique to strain-corrosion. As a rule cracks grow only under cyclic loads.

Strain-corrosion is a chemically accelerated process of crack growth in materials under tensile static strains. It applies to all homogeneous materials like metals, resins and glass fibers. The strain-corrosion of resin-rich liners exposed to oxidizing chemicals is known as environmental stress cracking and is recognized by the mud crack appearance of the surface. As a rule, however, the strain-corrosion process in composites refers mainly to the long-term rupture caused by chemical attack on the glass fibers.

To clarify the concept, we consider a thought experiment in which a bare (not resin coated) glass fiber is tensile loaded (a) in air, (b) in water and (c) in acid. The bare fiber is not embedded in resin and makes full contact with the air, the water and the acid. The times to fiber rupture in this experiment depend on the severity of the environment. In dry air, with little moisture, the time to rupture is very long. The acid does the most harm and produces the shortest failure time. The rupture time of the bare (uncoated) fiber immersed in water falls in between these two extremes. We now do the same experiment with the fiber coated in resin, as in laminates. The presence of the resin would give different results. The times to rupture of the coated fiber in water and in air would be the same as those observed in the bare fiber. This is because the water can penetrate the resin and reach the glass that is embedded in it. The coated fiber immersed in acid, however, would have a rupture time much longer than that measured on the bare fiber. This is because the resin around the fiber retards the acid penetration.

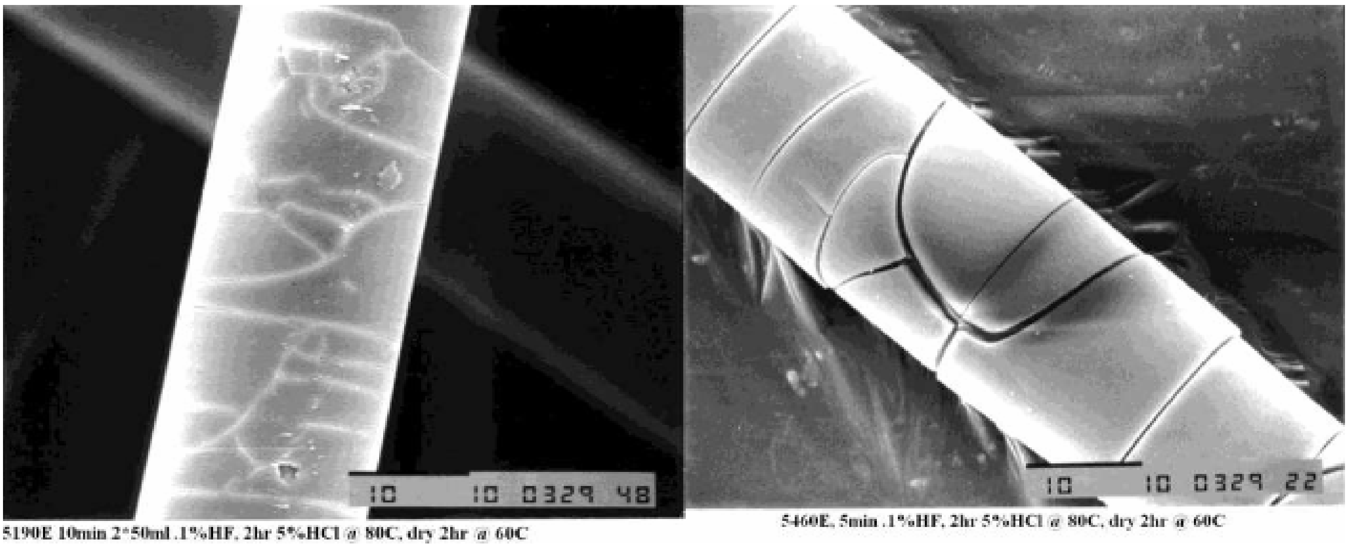


Figure 1

Spontaneous cracks from corrosion of E glass exposed for 2 hours to 5% HCl @ 60C. The open cracks indicate the existence of residual surface tensile strains. (Courtesy Owens Corning)

Figure 1 shows bare glass fibers that have been immersed for 2 hours in a 5% HCl solution at 60C. The fibers were simply immersed in the acid solution, with no externally applied tensile loading. The open surface cracks that are observed indicate the existence of residual tensile strains in the fiber surface. These residual tensile strains come from the fiber forming process and they help explain the spontaneous strain corrosion that occurs in glass fibers, even in the absence of externally applied loads. As we have said, this phenomenon is known as environmental stress cracking when observed in resins.

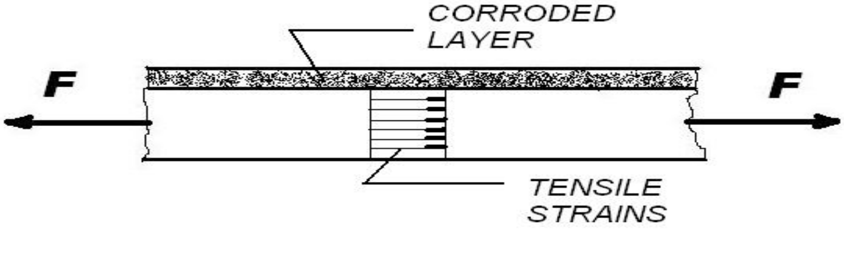
We know that water is the only chemical that reaches the structural plies of the laminate. Chemical species other than water do not penetrate deep enough to affect the structural plies. If this is so, we may conclude that the strain-corrosion process is restricted to water, as discussed in the part 1 of this trilogy. The strain-corrosion phenomenon should never be detected in pipes carrying chemicals. This is a very powerful argument. So, why bother with strain-corrosion?

The above argument holds for composites under pure tensile, pure compressive or pure shear loads. The deterioration caused by the chemical under such loadings is limited to the outer plies of the laminate. The plies that are penetrated by the chemical “lose” structural capability and the penetrated depth may be discounted as “lost” thickness. This “loss” of thickness is usually misinterpreted as loss of mechanical properties. In fact, the aggressive chemical incapacitates only part of the laminate thickness, while leaving the rest of it intact. The structural plies that are not penetrated by the chemical keep their pristine condition.

The above is valid for tensile, compressive and shear loads. Things are different for bending loads. The difference between pure tensile and bending loads is explained in figure 2. The upper part of figure 2 shows that a composite under pure tensile load will see a minor increase in tensile strain as a result of the small “loss” in thickness. This is so because the tensile load is uniformly distributed on the entire cross section of the laminate. If left to itself, this process goes on until eventually the thickness falls below a critical level and the laminate ruptures. This is in keeping with the results reported by Mark Greenwood, in which rods that were tensile tested in acid or in cement extract failed not because of strain-corrosion, but because of “loss” of structural thickness. For details, see ref. 2.

The lower part of figure 2 shows that bending loads generate moments that are carried mostly by the extreme fibers, i.e., by those fibers near the surface of the composite. Under bending loads, the strain corrosion of the extreme fibers propagates fast and leads to a sudden failure. It can be shown mathematically (see any book on fracture mechanics) that the strain intensity factor for bending loads is much higher than for tensile loads. The fast growing bending strains accelerate the strain-corrosion process, leading to a localized rupture. The same phenomenon does not occur under tensile loads.

Strain-corrosion rupture occurs only in those fibers that are subjected to bending tensile strains. This condition can be found in the inner plies of (a) knuckle areas of vertical storage tanks, (b) under the saddle supports of above ground pipes or (c) in the crown/invert of underground pipes. The strain-corrosion rupture from water on pipes under internal pressure should not be confused with the strain-corrosion rupture from chemical attack on pipes under bending tensile strains. Although the phenomenon is governed by the same mechanism in both cases, the rupture failure is very different.



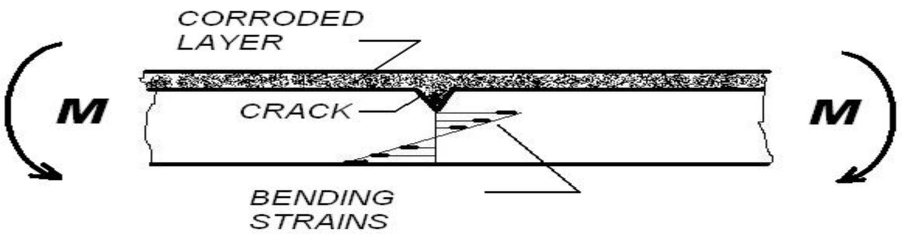


Figure 2
The tensile loads are uniformly carried by all fibers. By contrast, the bending loads are carried mostly by the extreme fibers. This idea is central to the understanding of strain-corrosion caused by chemicals. A mathematical explanation for this can be found in any book on fracture mechanics.

The photograph in figure 3 shows a pipe that failed by strain corrosion. The pipe carried a solution of acidic chlorine in a pulp bleacher. The chlorine is a strong oxidizer that corrodes the resin. And the acid corrodes the glass fibers. The pipe operated deflected by the vertical compression from a rigid steel frame below and the weight of other pipes above. The vertical deflection generated bending tensile strains in the inner layer at the pipe invert. The tensile bending strain, combined with the chlorine and the acidic media, set the stage for the strain-corrosion process. The process evolved like follows:

1. The liner in the inner invert ply was subjected to bending tensile strains. This is a requirement for strain-corrosion.
2. The chlorine strain-corroded the resin-rich liner and caused it to crack. This cracking – known as environmental stress cracking – allowed the ingress of the acid.
3. The cracked liner exposed the fibers to the acid. The high stress intensity factor at the pipe invert promoted a fast crack growth that failed the pipe. The crack grew from the inside of the pipe, moving out from the inner to the outer surface.

The picture shows a neat, smooth fracture in the pipe wall, typical of strain-corrosion. It also shows that the liner was hardly penetrated by the environment. The liner was broken and the fibers were attacked by the acid in just one location, namely the line along the pipe invert, where the high bending tensile strains are.

Strain-corrosion tests – The objective of any strain-corrosion test is to measure the hoop bending strain that leads to long-term rupture of the pipe. We refer to this long-term hoop strain as CDB, for Corrosion Design Basis.

The test protocols currently used to measure the CDB are described in ASTM D 5365 (water) and in ASTM D 3681 (5% sulfuric acid). Both methods require a minimum of 18 pipe specimens subjected to different bending strains while in contact with the corrosive medium. The strains and their corresponding times to failure are annotated to generate a regression line that is extrapolated to predict the 50 years CDB required by AWWA C 950.

Figure 3
The photo shows the strain corroded invert of a pipe that operated deflected by vertical compressive loads while carrying an acidic solution. The strain-corrosion process typically ruptures the composite along a neat and well defined plane surface, instead of the jagged and splintered surface typical of other modes of rupture. Notice that the liner away from the pipe invert was hardly affected by the environment. The crack initiated and progressed from the inside of the pipe.

Equation (1) shows the regression line that is obtained. The Greek letter "Є" denotes the sustained hoop bending strain that ruptures the pipe by strain-corrosion in the time "t". The intercept A is related to the hoop short-term elongation at break of the pipe and the slope G measures the rate of attack by the chemical. The slope G depends on the operating temperature and on the chemical resistance of the glass.

$$\log \varepsilon = A - G \log t \qquad (1)$$

Table 1 shows typical values of A and G for commercial sanitation pipes tested in water and in 5% sulfuric acid. The values of A have been adjusted to give the elongation in % when the time is expressed in hours.

$\log \varepsilon = A - G \log t$	A	G	CDB (50 years)
Sanitation pipes in 5% H_2SO_4 @ 25ºC (ASTM D3681)	0.220	0.071	0.66%
Sanitation pipes in water @ 25ºC (ASTM D5365)	0.334	0.039	1.30%

Table 1
Strain corrosion parameters and 50 years CDB for typical sanitation pipes. The values of A have been adjusted for elongations expressed in % and failure times in hours. (Courtesy Amiantit)

The regression equations corresponding to the parameters in table 1 are:

$$\log \varepsilon = 0.220 - 0.071 \log t \qquad \text{(For pipes in 5\% } H_2SO_4\text{)} \qquad (2)$$

$$\log \varepsilon = 0.334 - 0.039 \log t \qquad \text{(For pipes in water)} \qquad (3)$$

The above equations are shown side by side in figure 4. As expected, sulfuric acid is far more aggressive than water. For a failure time of 50 years, the pipe can handle a hoop bending strain of 1.30% in water. The same pipe in acid would fail under a hoop bending strain of just 0.66%. The short-term rupture strains are approximately the same in water as in acid, as it should. We will return to these equations later.

The next section will show how to predict the strain-corrosion time of commercial pipes from the properties of the glass and the resin used in the corrosion barrier.

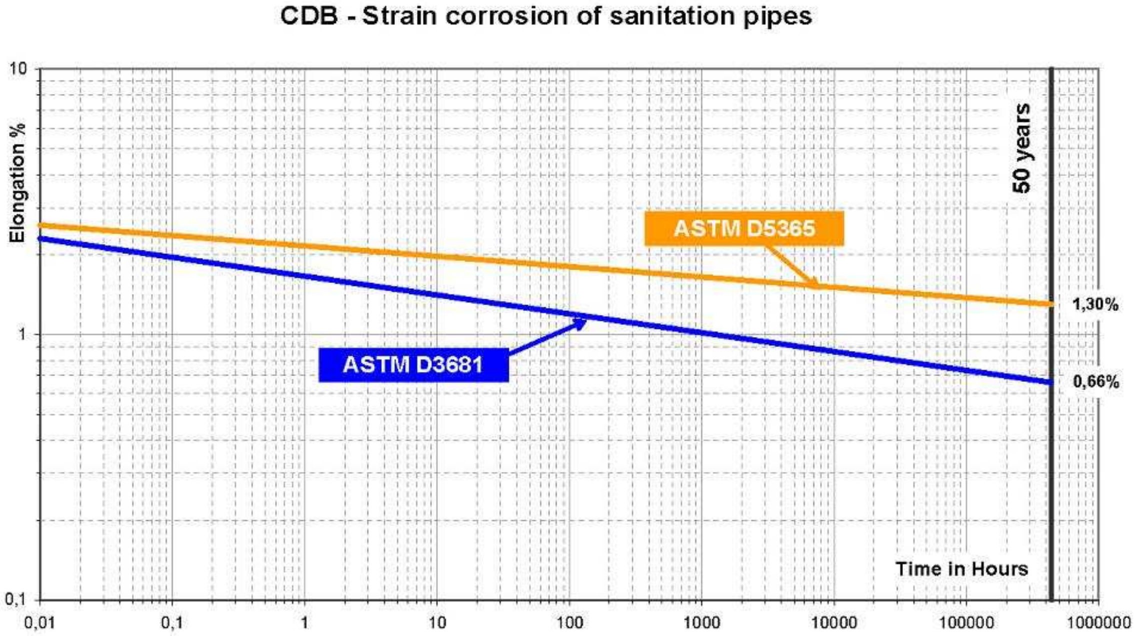


Figure 4
Strain corrosion lines for sanitation pipes in water (ASTM D 5365) and in 5% sulfuric acid (ASTM D3681).

Predicting the strain-corrosion times of commercial pipes – The strain-corrosion behavior of commercial pipes is controlled by the chemical resistance of the resin in the liner and by the composition of the glass in the corrosion barrier. This section will show how to estimate the strain-corrosion rupture time for commercial pipes. Our approach takes into account the time taken by the chemical to (a) reach the fibers and (b) to destroy the fibers.

The reader is reminded that the discussion that follows is applicable only to sanitation pipes, i.e., to pipes that have a corrosion barrier of chopped glass. Oil pipes, that do not have a corrosion barrier, are not discussed. We assume that the aggressive chemical diffuses through the liner before reaching the corrosion barrier. Therefore, the time to failure by strain corrosion is obtained by adding the time for the chemical to travel through the liner + the time that it takes to strain corrode the chopped fibers in the corrosion barrier.

Did the reader understand this? Probably not, so we will say it again in different words. The argument is like follows.

The strain corrosion rupture of commercial sanitation pipes occurs when the fibers in the corrosion barrier are degraded and ruptured. The rupture time is obtained by adding the time that the chemical takes to travel through the liner + the time that the chemical takes to corrode the fibers in the corrosion barrier. This is summarized in the following equation.

$$[rupture \quad time] = [travel \quad time] + [corrosion \quad time] \qquad (4)$$

The prediction of the rupture time is complicated by the resin-rich liner. Before doing any harm to the fibers in the corrosion barrier, the chemical must first travel through the liner. This can happen in three ways.

(a) Diffusion of the chemical through the liner. This situation occurs in chemicals that do not attack the resin. The time to strain-corrosion rupture in this case is

$$\begin{bmatrix} time \quad to \\ strain-corrosion \quad rupture \end{bmatrix} = \begin{bmatrix} time \quad to \\ chemical \quad diffusion \end{bmatrix} + \begin{bmatrix} time \quad to \\ corrode \quad glass \end{bmatrix} \qquad (4A)$$

Let us discuss the time to diffusion of the chemical product. The diffusion of chemicals in composites is a very slow process. To my knowledge nothing is known about the diffusion times of chemicals in resin castings, except maybe in the cases of water and a few solvents.

In equation (4A), the time to corrode the glass should be measured on bare (no liner) plies of chopped glass. Such corrosion times have been measured and reported in two papers. The first, by Hogg (ref 3) reported the corrosion times from pipes made of bare E glass chopped fibers deflected in acidic environment. The second, by Stefanie Romhild and Gunnar Bergman (ref 4) reported the corrosion times of bare chopped glass flat laminates immersed in acid. In both cases the tested laminates were constructed exclusively with bare plies of chopped glass, i.e., plies with no resin-rich liners.

It is unfortunate that none of the above authors have published their regression lines. This is understandable since their motivations for these tests were the evaluation of different resins and glasses, rather than the quantification of the strain-corrosion problem. The equations that follow have been adapted by the present author from the crude graphs published by Hogg, Romhild and Bergman.

$\log \varepsilon = 0.231 - 0{,}090 \log t$ (Hogg's line for bare E glass) (5)

$\log \varepsilon = 0.306 - 0{,}111 \log t$ (Bergman's line for bare E glass) (6)

$\log \varepsilon = 0.264 - 0{,}062 \log t$ (Bergman's line for bare boron-free glass) (7)

$\log \varepsilon = 0.277 - 0{,}017 \log t$ (Bergman's line for bare AR glass) (8)

The above equations are plotted side by side in figure 5. They estimate the times to strain-corrode different types of bare chopped glass in acid. The reader is again reminded that these equations are poor representations of reality, as they have been derived by the present author from crude graphs published by the sources.

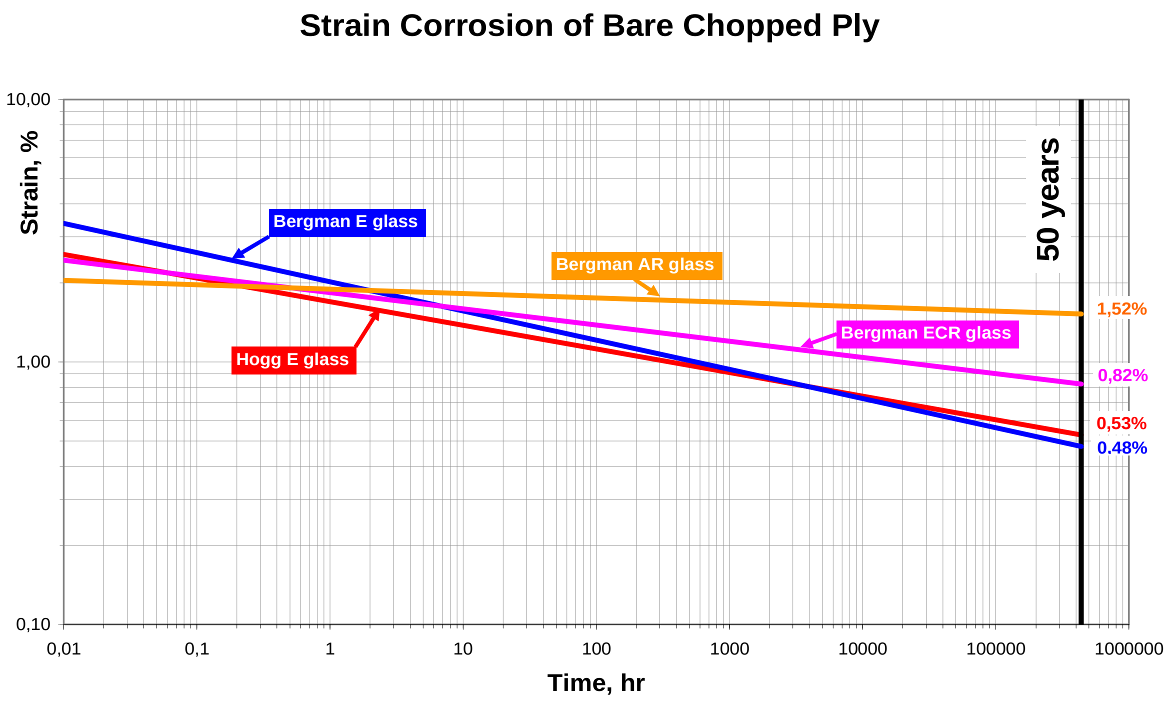


Figure 5
Strain-corrosion lines of bare (no liner) plies of chopped glass in acid.

The resin-rich liner delays the time for strain-corrosion rupture in chemicals that attack the glass, but not the resin. In some cases the delay time from the resin-rich liner may be so long as to give the impression that the strain-corrosion process is altogether eliminated. See ref. 5.

(b) Strain-corrosion of the resin-rich liner. This situation occurs in chemicals that attack the resin. The time to strain-corrosion rupture in this case is like follows

$$\begin{bmatrix} time & to \\ strain-corrosion & rupture \end{bmatrix} = \begin{bmatrix} time & to \\ strain-corrode & liner \end{bmatrix} + \begin{bmatrix} time & to \\ corrode & glass \end{bmatrix} \qquad (9)$$

The time to strain-corrode the resin-rich liner is very short and may be ignored. This is a very sobering statement, meaning that the resin-rich liner is not a deterrent for strain-corrosion in applications where the environment attacks the resin. If we ignore the time to strain corrode the liner the rupture time equation becomes

$$\begin{bmatrix} time & to \\ strain-corrosion & rupture \end{bmatrix} = \begin{bmatrix} time & to \\ corrode & glass \end{bmatrix} \qquad (9A)$$

This is the case of the pipe shown in figure 3, where the chlorine strain-corroded the resin-rich liner and exposed the fibers in the corrosion barrier. The strain corrosion problem of the liner can be solved by using the split liner technology. For information on the split liner technology, please contact the author.

(c) Migration of the chemical through cracked liners. This situation occurs in composites that have suffered high impact loads or have been under high tensile strains. Migration is a fast process which, unlike diffusion, carries the chemical to the corrosion barrier in a very short time. The migration of the chemical is facilitated by voids and cracks in the liner. Cracked and defective liners can be very detrimental to pipes under bending loads and subject to strain-corrosion.

The strain-corrosion rupture times of commercial pipes under high strains is measured as indicated in ASTM D3681 (in acid) and ASTM D5365 (in water). The regression lines developed in such tests, however, are not representative of the real conditions under which the pipes operate. The regression lines generated this way should not be used in pipe design.

Limiting cases – The time to strain-corrosion rupture is estimated by equations (4A), (9) and (10). Equation (4A) is valid for chemicals that do not attack the resin and reach the glass by diffusion. This is possibly the least severe of all strain-corrosion situations. Equation (9) represents the case in which the resin is attacked by the chemical and is possibly the most severe case of strain-corrosion. Our analysis will ignore the regression equations obtained from pipes with cracked liners, as in case (c) above, as unrealistic and not representative.

From equation (4A) we derive two scenarios for applications in which the chemicals do not attack the resin:

1 – Sewer transmission. The sulfuric acid solutions developed in urban sewers do not harm the resin. The liner gives good protection to the underlying fibers, since sulfuric acid is very slow in diffusing through the resin. The long diffusion time of sulfuric acid through the liner gives these pipes very long lives, regardless of the type of glass in the corrosion barrier. For further details, please refer to ref. 5.

2 – Water transmission. The short diffusion time of water is not a problem, since water is not overly aggressive to the underlying glass fibers. There are many examples of pipes that have been carrying water for years with no reported case of strain-corrosion failure.

From equation (9A) we see that the environments that crack the liner are very dangerous. We advise in such cases that the liner be prevented from cracking by using the split liner technology. And in those situations where the environment is extremely aggressive to the fibers we recommend the split liner technology with carbon fibers in place of the glass fibers. This extreme situation may be found in underground pipes carrying industrial wastes. For details, please contact the author.

Conclusion – We have presented arguments indicating that the strain-corrosion process occurs in composites under bending loads while immersed in corrosive chemicals. Our discussions led us to equations to predict the durability of composites under strain-corrosion.

Biography: Antonio Carvalho is an engineer with 40 years dedicated to composites. Past experience includes 30 years with Owens Corning and 9 years as a full time consultant for Reichhold. His current responsibility includes technical support and market development for Reichhold`s DION resins in Brazil and Latin America. For direct communication please contact Antonio.carvalho@reichhold.com

References:

1 – A new method to predict the service life of corrosion barriers, by Carlos Marques and Antonio Carvalho, in ACMA Composites conference and trade show, 2006, St Louis.

2 – Pultruded composites durability: A key value, by Mark Greenwood, in CFA (now ACMA) Composites Conference, 2001.
3 – Stress Corrosion of GRP, by P. J. Hogg, J.N. Price and D. Hull, in the 39th Conference of the SPI, 1984
4 – Corrosion resistance of glass fiber materials – A crucial property for reliability and durability of FRP structures aggressive environments. By Stefanie Homhild and Gunnar Bergman, in NACE Corrosion 2004, paper 04612.
5 – Chemical resistance of GRP pipes measured over 30 years. By Hogni Jonsson in Munich, march 2009.
6 – Effect of internal stress on corrosion behavior of glass fibers, by A. Schmiermann, M. Gehde and G. W. Ehrestein in the 44th Conference of the SPI, 1989
7 – Fatigue behavior of fiber-resin composites, by F. Mandel, in Developments in Reinforced Plastics, vol. 2, edited by G. Prichard, Applied Sciences Publisher.
8 – The unified equation. Antonio Carvalho. Unpublished

Appendix A

Threshold strain – As argued in the part 2 of this trilogy, there is a tensile strain below which the cracks that develop in the pipe do not coalesce to allow the passage of water. This tensile strain is known as threshold strain. Pipes operating below the threshold strain do not weep. The concept of threshold strain is valid for weeping. The questions that we ask are:

Is there a threshold strain for strain-corrosion?
Is there a strain below which the pipes never fail by strain-corrosion?

Hogni Jonsson has recently (ref 5) published data which strongly supports the existence of a threshold strain for strain-corrosion. His findings, shown in Figure 9, report data collected over a period of 30 years from pipes deflected in 5% sulfuric acid. Hogni's data show the strain-corrosion line flattening out and turning horizontal, as predicted by the concept of threshold strain. This amazing data apparently validate the concept of threshold strain for strain-corrosion rupture.

The flattening of the regression line reported by Hogni can be explained by equation (4A). Given that dilute solutions of sulfuric acid do not attack the resin-rich liner, the time to strain-corrosion rupture is controlled by diffusion and may be very long. If the strains in the deflected pipes are below the threshold strain, the liner will not crack and diffusion is the only way for the acid to reach the fibers. The diffusion time for sulfuric acid is very long and the regression line gives the impression of turning horizontal, regardless of the type of glass. In fact the diffusion process is active and will eventually rupture the pipe.

We conclude that there is no threshold strain for strain-corrosion, even though the long diffusion times of some chemicals that do not attack the resin may give that impression.

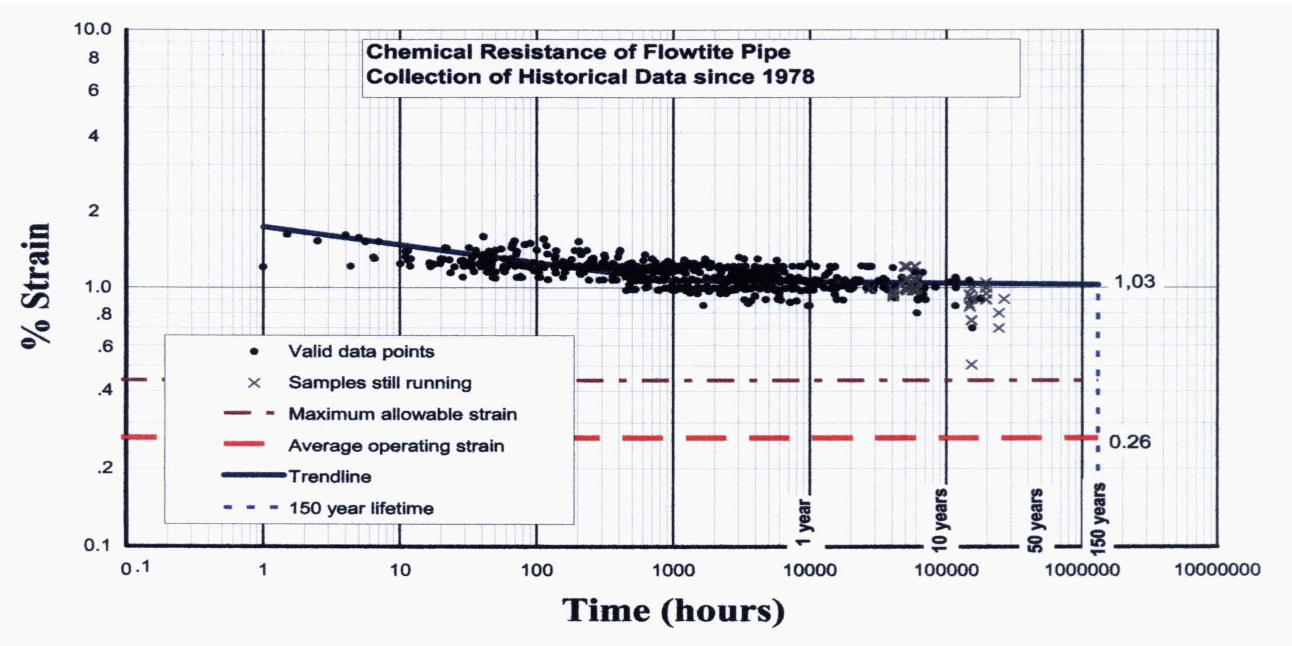


Figure 9
The long-term strain-corrosion tests of composite pipes in sulfuric acid shows a flattening of the regression line. (Courtesy Amiantit). This, however, is not proof of a threshold strain for strain-corrosion.

Appendix B

Cyclic strain corrosion – The preceding discussion is applicable to static strains. The extension of the strain corrosion concept to cyclic strains is very simple and is summarized in the following statement:

Cyclic tensile loads do not cause strain corrosion.

This interesting statement is well explained by the unified equation proposed in ref. 8. The unified equation resolves the strain wave in a static and a cyclic component as shown in figure 10 and represented in the following equations.

$$(\varepsilon)_{static} = \varepsilon = \frac{\int_0^T \varepsilon(t)dt}{T} \qquad \text{(Static component)}$$

$$(\varepsilon)_{cyclic} = \Delta\varepsilon = \varepsilon_{\max} - \varepsilon_{\min} \qquad \text{(Cyclic component)}$$

Where ϵ_{max} and ϵ_{min} are the extreme values taken by the tensile strain and T is the period of the cyclic strain wave.

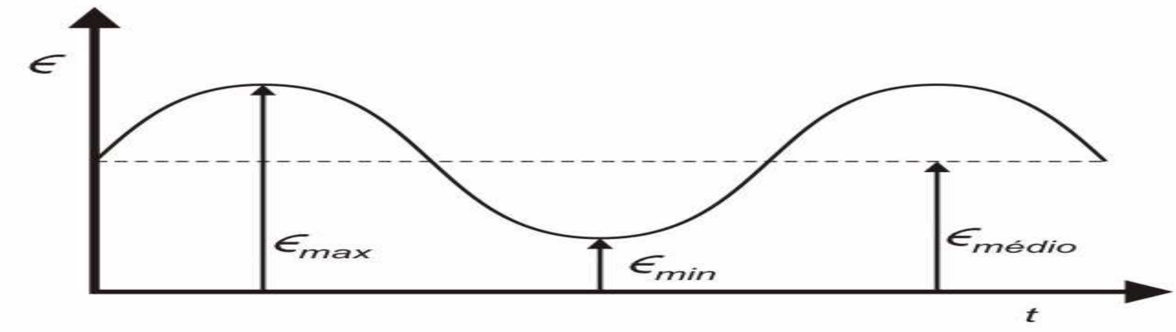


Figure 10 – The strain wave. The strain corrosion phenomenon is defined only for tensile bending strains. Compressive strains do not cause strain corrosion.

The tensile static component of the strain wave has a strain-corrosion effect. The tensile cyclic component does not cause strain corrosion. The simultaneous action of the static and cyclic components is beyond the scope of this paper. For details, please refer to the unified equation (ref. 8).

Mandell (ref 7) mentions a very interesting example of strain corrosion associated with cyclic fatigue. The application is UD rods used as high voltage insulators in transmission lines. The rods are subjected to static tensile strains as well as to high frequency wind induced vibrations. The wind vibrations generate the bending strains that are required by the strain corrosion process. The corrosive chemical in this case is nitric acid generated by electrical discharges. The stage is thus set for the strain corrosion process. E glass rods have a short life in this case due to (1) the absence of the protective liner, and (2) to the direct attack by the acid to the highly strained UD fibers. All that, of course, induced by the bending moment from the high frequency cyclic vibrations. We quote from Mandell himself:

"Some failures occur at strains which appear to be less than 10% of the short term value (the quality of the UD rods appears to be very good and the strength near the cracks is close to the initial values). The aspect of these field failures which is most unusual is the mode of crack growth. Cracks propagate in a planar fashion perpendicular to the fibers, with no significant splitting or debonding along the fibers. The fracture surfaces are almost perfectly flat over most of the 2 cm rod diameter, with fracture surface features which can be traced back to crack origin, as with many homogeneous materials. Along with the main failure crack, there are often several small cracks which have grown a short distance in from the surface".

The above is a perfect description of rupture by strain corrosion. It should be noted that if the rods were subjected to pure tensile strains, with no wind induced vibration, strain-corrosion would not occur. The induced vibration provides the bending loads required by the strain-corrosion process.