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Structural failure of composite pipes – a trilogy

Part 3 – Strain corrosion of deflected pipes

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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 the strain-corrosion failure of pipes under bending loads. It opens with a discussion of how water and other chemicals can cause strain-corrosion rupture. The discussion assumes that water is the only known chemical which penetrates the entire laminate and strain-corrodes all fibers under tensile strains. Unlike water, the corrosive chemicals do not penetrate the entire laminate and therefore affect just those fibers near the exposed surface. The time taken by a chemical to strain-corrode and rupture a pipe is obtained by adding the time it takes to reach the fibers with the time it takes to corrode them. The delaying effect of the liner is recognized and accounted for in this paper.

1 Introduction – Composite pipes display three modes of long-term structural failure. Of these, the most prominent and best documented is the weep mode. This is ironic, since the weep failure is time independent and should not be included in the long-term category. 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 results from the hydrolysis of the glass fibers and is not affected by the resin. The second paper shows that the weep failure is dominated by the glass sizing and the resin matrix, 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 the design of deflected underground pipes. There are two test methods to evaluate the pipe's performance in this situation. The evaluation in water is described in the ASTM D 5365 test protocol. The evaluation in urban sewage is performed in accordance with ASTM D 3681. Both test methods use specimens deflected to different levels of bending strains while in contact with the corrosive environment. The specimens under higher strains fail first and the times to failure are annotated. Regression lines are developed linking the bending strains to the times to rupture. These lines are used to predict the strains that would fail the pipe in the long-term, say in 50 years.

1 - The ASTM D 5365 test is performed on deflected specimens fully immersed in water. The full immersion affects both the inside (weep barrier) and the outside (UD) fibers. Therefore the failure may come from the outer UD fibers or the inner chopped fibers. The test results include failures of both fibers and this may be a problem. From a statistical point of view the randomly dispersed chopped fibers should be able to sustain higher strains than the parallel UD fibers. The ASTM D 5365 should therefore produce results in between those for UD and chopped fibers. As shown in the part 1 of this trilogy, the results for UD fibers were obtained and reported by Mark Greenwood. The results for chopped fibers have never been measured. A good test method to do this would be by tensile testing pipes made exclusively of chopped fibers, replicating the rod tests performed by Mark Greenwood for UD plies. A test conducted this way would give us the RDB (Rupture Design Basis, see the first paper in this trilogy) for the chopped fibers used in the weep barrier. In the absence of such data, this paper will assume for the RDB of chopped fibers the same value obtained from the "mixed and uncertain" ASTM D 5365 protocol. The extrapolated long-term strain (RDB for chopped fibers) 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 solution is placed inside the pipe, in direct contact with the liner. The placement of the corrosive solution inside the pipe assures that only the chopped fibers in the weep barrier are affected. The acid solution

simulates the strain-corrosion effect of the acidic sewage in the weep 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. It is referred to in the industry as Sc.

2 Strain-corrosion in pipe context – There are four instances of strain-corrosion in composites pipes, which the engineer should be aware of. They are:

- *Strain-corrosion of the liner.* This type of strain-corrosion, known in the literature as environmental stress cracking, occurs in resin-rich liners that are placed in corrosive chemicals under tensile strains. This type of strain-corrosion does not rupture the pipe and will not be discussed in this paper.
- *Strain-corrosion of the UD structural plies.* Water is the only known chemical that can penetrate and strain-corrode the UD glass fibers in the structural plies. This type of strain-corrosion controls the long-term burst life of the pipes. We refer to this long-term strength as the Rupture Design Basis, or RDB. The tests to measure the RDB 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 weep barrier.* This is caused by acid (or other chemical) that somehow penetrates the liner and reach the weep barrier of deflected pipes. For rupture to occur, the pipe wall must be under bending strains. The rupture time in this case is obtained by adding the time taken by the chemical to traverse the liner with the time it takes to corrode the fibers. We refer to the long-term strength of the pipe in this situation as the Corrosion Design Basis, or CDB. The CDB is determined per ASTM D 3681. The strain-corrosion of the weep barrier in water has never been measured, and perhaps will never be, since it would produce a value much higher than that for UD plies.
- *Strain-corrosion of the outer pipe plies.* This is caused by water, since the corrosive chemicals do not reach the outer pipe 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 usual situation is for the outside surface of the pipes to be comprised of UD fibers, with the chopped fibers confined in the inner weep barrier. The strain-corrosion by water on the outer UD fibers was measured by Mark Greenwood, as we have seen in the part 1 of this trilogy. The strain-corrosion of the inner weep barrier in water probably will never be measured, since the UD plies are expected to fail sooner. Anyway, the ASTM D 5365 test method fully immerses the test specimens in water, to measure the strain-corrosion capability of both the outer surface and the inner weep barrier. The results from this test are known in the industry as Sb. The Sb is a mixture of UD and chopped fiber failures. Its significance is not relevant.

The present paper will address the strain-corrosion rupture that occurs in pipes deflected and exposed to acids. The time to rupture is a function of the bending strain, the glass composition and the toughness of the resin in the corrosion barrier. This paper will show that the time to rupture is obtained by adding the time taken for the acid to corrode the glass fibers with the time it takes to get across the resin-rich liner.

3 Two types of chemicals – The study of the durability of composite equipment (pipes included) in aggressive chemicals can be greatly simplified by grouping the chemicals in two categories. This section will put the aggressive chemicals in proper perspective.

- **First category.** The ***penetrating*** chemicals are those that penetrate the whole laminate and reach all plies. Water is the most notorious and important penetrating chemical. In fact, as discussed in the part 1 of this trilogy, the long-term burst rupture of pipes under tensile loads is determined by the water that penetrates the whole laminate and strain-corrodes the glass fibers.
- **Second category.** The ***non-penetrating*** chemicals do not penetrate very deep into the laminate and have their effect limited to the plies next to the surface. Most aggressive products found in industrial applications fall in this category. These products are able to deteriorate the corrosion barrier (weep barrier) of the equipment and affect their service life. However, if the deteriorated corrosion barrier is

regularly replaced, the aggressive chemicals will not reach the structural plies and therefore will have no effect on the structural life. The regular replacement of deteriorated corrosion barriers is a common procedure in large diameter composites pipes and tanks. As a rule, if proper maintenance is performed, the chemical products have no effect on the structural life of the composite. However, there is one situation in which the chemical products do affect the structural life. The next section will show that this situation occurs in pipes under bending loads.

In the vast majority of the applications, the damaging chemicals are kept away from the structural plies by sacrificial resin-rich liners and corrosion barriers. The structural life of the composite is increased by the delaying effect of the sacrificial barriers. This reasoning is valid only for equipment under tensile, compressive or shear loads. It is not valid for equipment under bending loads. What makes bending loads so special? This is a topic for discussion in the next pages.

4 Strain-corrosion under bending loads – We open the discussion by recognizing that strain-corrosion rupture, like any rupture in composites, is related to deterioration of the fibers. The glass fibers are susceptible to attack by water, by acid and by alkali. This attack is not uniform. Rather, since some spots are more susceptible to attack than others, the fibers develop a few local micro cracks, that open under tensile strains and expose fresh material. The localized corrosion grows the crack and eventually ruptures the tensioned fiber. This process is called strain-corrosion, since it combines tensile strains and corrosion. The corrosion process locally weakens the fiber and the tensile strain expose fresh material to chemical attack. The strain-corrosion process is capable of growing cracks under static loads. This statement is so fundamental that we repeat it, for emphasis.

The strain-corrosion process causes crack growth under static loads. The crack growing process under static loads is unique to strain-corrosion. As a rule cracks grow only under cyclic loads, never under static 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. There are many examples of strain-corrosion in industrial applications. The strain-corrosion of resin-rich liners is known as environmental stress cracking, which are recognized by the cracked “dry mud” appearance of the corroded surface. In this paper we will not deal with this type of “mud crack” strain-corrosion. Rather, we will focus our attention on the strain-corrosion process that causes long-term rupture of the composite.

To clarify the concept, we consider a thought experiment in which a bare (not resin coated) glass fiber is subjected to equal tensile strains (a) in air, (b) immersed in water and (c) immersed 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 environment.

- In air the time to rupture is very long.
- In acid the time to rupture is very short.
- In water the time to rupture falls in between.

We next perform the same experiment with the fiber coated with resin, as they are in laminates. The resin coat produces different results.

- In air, the time to rupture the coated fiber is the same as that of the bare fiber. This is obvious and requires no explanation.
- In water, the time to rupture of the coated fiber is the same as that of the bare fiber. This indicates that water can easily penetrate the resin coat and reach the embedded glass. The resin coat provides no protection from water

- In acid, the time to rupture of the coated fiber is much longer than that of the bare fiber. This indicates that the resin coat around the fiber delays the acid penetration.

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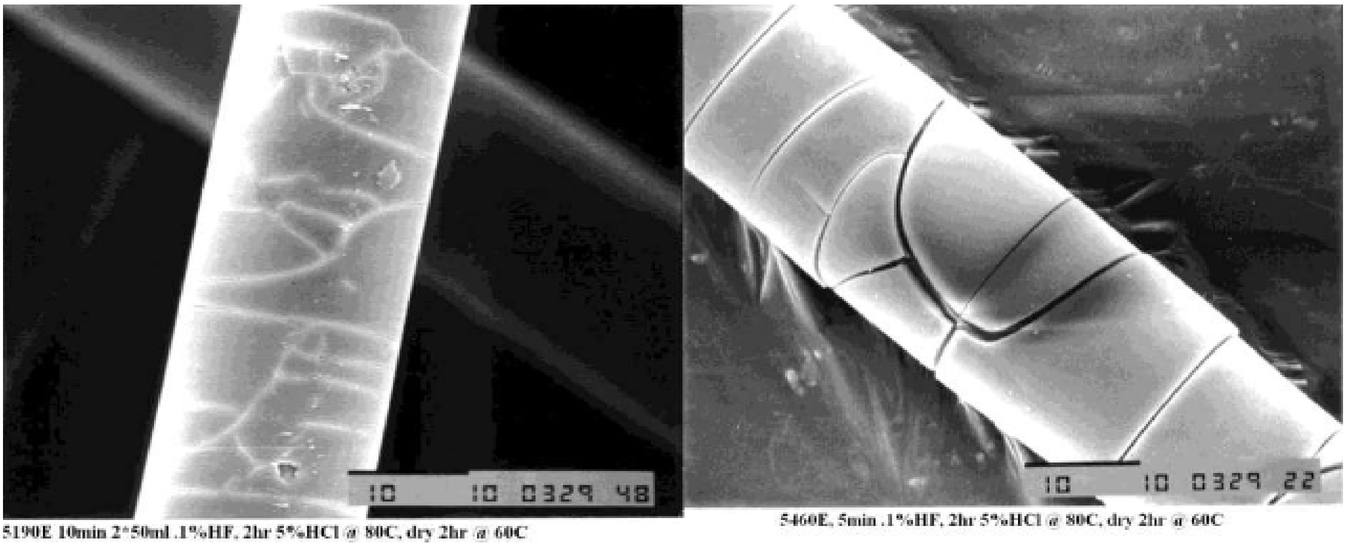

Figure 1

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% solution of HCl at 60C. The fibers were simply immersed in the acid, with no externally applied tensile load. The open cracks that are observed indicate the existence of residual tensile strains on the surface of the fiber. These residual tensile strains come from the fiber forming process and explain the spontaneous strain corrosion that occurs in glass fibers, in the absence of externally applied loads. The spontaneous cracking of the glass fibers is identical to the environmental stress cracking that is observed in resin liners.

We are assuming that water is the only chemical that can reach the fibers in the structural plies. 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 rupture 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, if this argument is true, why bother with strain-corrosion?

The above argument holds for composites under pure tensile, pure compressive or pure shear strains. Under such strains, the deterioration caused by the chemical is limited to the external plies of the laminate. The plies that are penetrated by the chemical are deteriorated and “lose” structural capability. They can be considered as structurally “lost” and their thickness can be discounted as a contributor to the laminate strength. This “loss” of structural thickness is usually misinterpreted as loss of mechanical properties. In fact, the aggressive chemical incapacitates only the part of the laminate that is penetrated, while leaving the rest intact. The structural plies that are not penetrated keep their pristine condition. What we have here is “loss” of structural thickness, not loss of mechanical properties.

We repeat that the above argument holds for tensile, compressive and shear loads. Things are different for bending loads. The difference between tensile and bending loads is explained in figure 2. The upper part of figure 2 shows that a composite under tensile load displays a minor increase in tensile strain as a result of the small “loss” in structural thickness. This is so because the tensile load is uniformly distributed on the entire cross section. If left to itself, this process goes on until eventually the corrosion barrier is destroyed, the structural 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 suffered premature failure, not because of strain-corrosion, but because of “loss” of the original structural cross section of the rods. For details, see ref. 2.

The lower part of figure 2 shows the bending moments carried mostly by the extreme fibers, i.e., by the fibers that are near the surface. Under such conditions, the rupture 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 significantly higher than that for tensile loads. The fast growing bending strains accelerate the strain-corrosion process, leading to a fast localized rupture. This phenomenon occurs only under bending loads. It does not occur under tensile loads.

We have just seen that strain-corrosion rupture occurs only in fibers under 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 in pipes under internal pressure should not be confused with the strain-corrosion rupture from chemicals on laminates under bending strains. Although the phenomenon is governed by the same mechanism in both cases, the rupture failure caused by water in pressurized pipes is a purely tensile situation that does not involve bending.

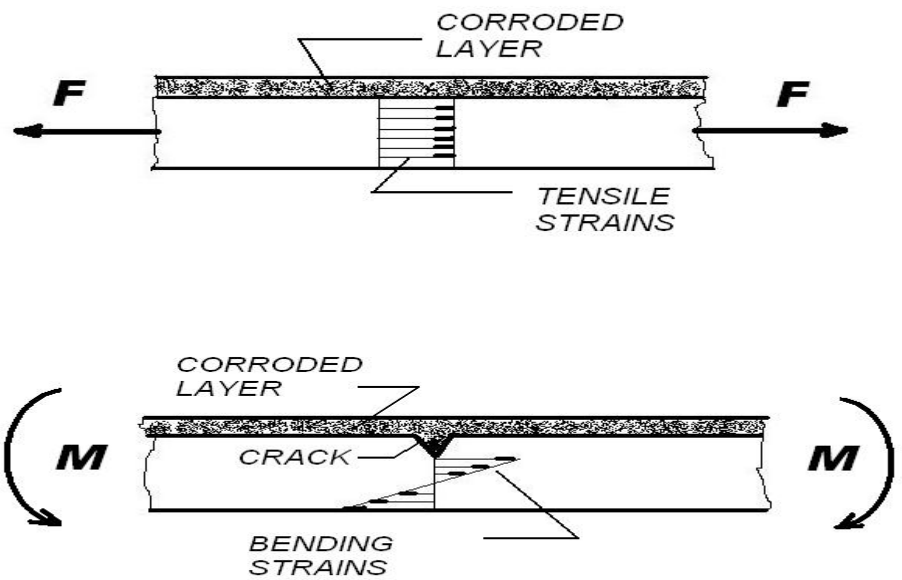

Figure 2
The tensile loads are uniformly carried by all fibers. By contrast, the bending loads are carried mostly by the extreme fibers. This idea is central to the understanding of strain-corrosion. A mathematical explanation for this can be found in any book on fracture mechanics.

Figure 3 shows a pipe that failed by strain-corrosion. The pipe carried a solution of acidic chlorine in a pulp bleaching plant. The chlorine is a strong oxidizer that corrodes the resin with little or no effect on the glass. And the acid corrodes the glass fibers with little effect on the resin. The pipe from figure 3 was supported on a rigid steel frame. The pipe operated in a deflected condition caused by the vertical compression from the 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 attack by the chlorine and the acidic media, set the stage for the strain-corrosion process. The process evolved like this.

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 rapid ingress of the acid.
3. The cracked liner exposed the fibers to the acid. The high stress intensity factor at the pipe invert promoted the 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 failed surface shows a neat, smooth fracture in the pipe wall, which is typical of strain-corrosion. It also shows that the liner was hardly penetrated by the environment. The liner ruptured and allowed the ingress of the acid only in the line along the pipe invert. This is exactly where the high bending tensile strains are.

5 Strain-corrosion tests in pipes– The strain-corrosion tests measure the hoop bending strain that leads to long-term rupture. We refer to this long-term rupture hoop strain as CDB, for Corrosion Design Basis. The CDB is sometimes referred to as Sc.

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 the corresponding times to failure are annotated to generate a regression line that is extrapolated to predict the 50 years CDB.

Figure 3
Showing 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 smooth 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 fibers.

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

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	Strain extrapolated to 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 the 50 years extrapolated strain 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:

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

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

The above equations are plotted together 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%. Figure 4 shows the short-term rupture strains approximately the same in water as in acid, as they 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.

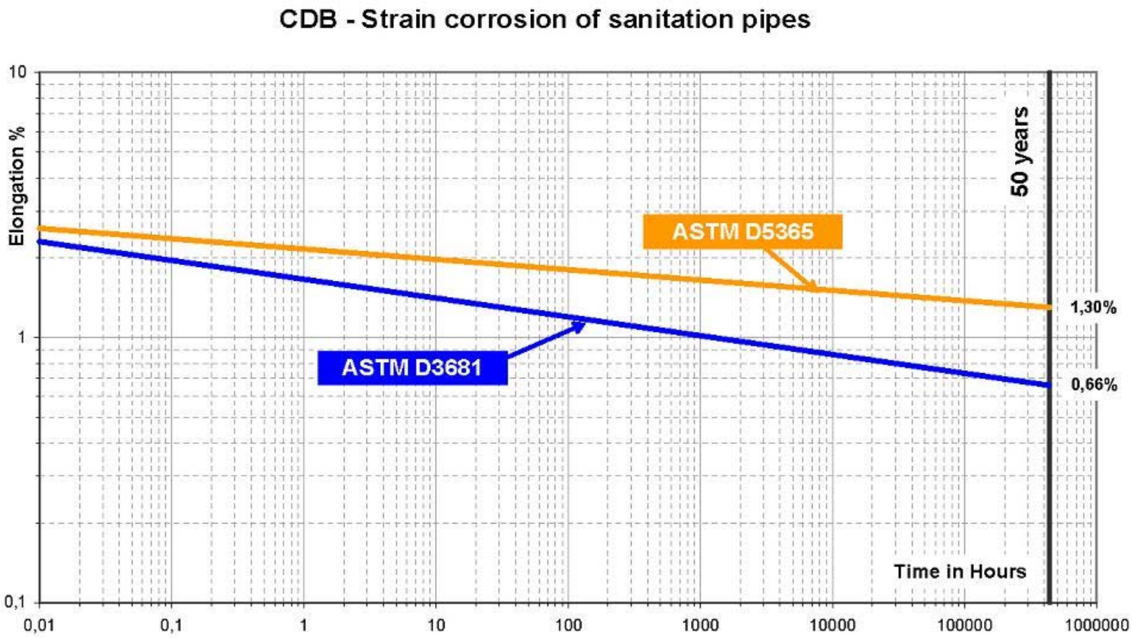

Figure 4
Strain corrosion lines for sanitation pipes in water (ASTM D 5365) and in 5% sulfuric acid (ASTM D3681).

6 Predicting the strain-corrosion times – The strain-corrosion behavior of commercial pipes is controlled by the chemical resistance of the resin in the liner, by the toughness of the resin in the corrosion barrier 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 to pipes that have a corrosion barrier of chopped glass, like those that are used in chemical processes and in sanitation. The oil pipes, that do not have a corrosion barrier, are not discussed. To initiate the strain-corrosion process, the aggressive molecules and ions must first diffuse through the liner, before they reach the corrosion barrier. Therefore, the time to strain-corrode the pipe is obtained by adding the travel time through the liner + the time 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 pipes occurs when the fibers in the corrosion/weep 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 it takes to corrode the fibers in the corrosion barrier. This is summarized in the following equation.

$$[rupture \quad time] = [penetration \quad time] + [corrosion \quad time] \tag{4}$$

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

6.1 – Travel by diffusion through the liner. This situation occurs in chemicals that do not attack the resin. The time to strain-corrosion rupture in this case is

$$\begin{bmatrix} time & to \\ strain-corrosion & rupture \end{bmatrix} = \begin{bmatrix} time & to \\ chemical & diffusion \end{bmatrix} + \begin{bmatrix} time & to \\ corrode & glass \end{bmatrix} \tag{4A}$$

Let us first say a few words about the time to diffusion of the chemical. 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. It is a pity that little is known about the diffusion times. The only information available regarding the diffusion times of chemicals in composites is that "they are very long".

In equation (4A), the time to corrode the glass is 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 in pipes made of bare E chopped fibers deflected in acidic environment. The second, by Stefanie Romhild and Gunnar Bergman (ref 4), reported the corrosion times of bare chopped fibers in flat laminates (not pipes) immersed in acid. In both cases the test laminates were made exclusively with bare plies of chopped glass, i.e., plies not protected by resin-rich liners.

It is unfortunate that none of the above authors have published their regression lines. This is understandable since their objectives were the comparison of different resins and glasses, not the quantification of the strain-corrosion problem. The equations that follow have been adapted by the 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 shown 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 author from crude graphs published by the sources.

The times to rupture are obtained by adding the travel times with the predictions from these equations, as shown in equation (4A). It is unfortunate that at the present time equation (4A) cannot be used, because the travel times are not known.

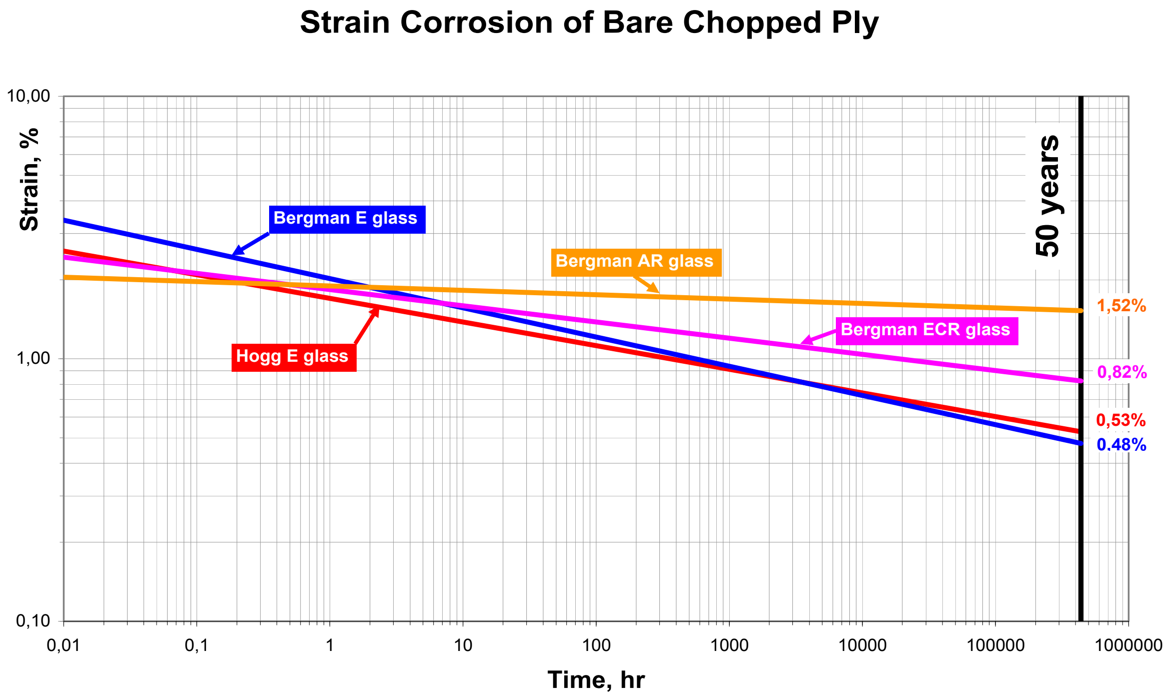

Figure 5
Strain-corrosion lines of bare (no liner) plies of chopped glass in acid.

We have just seen that the resin-rich liner delays the strain-corrosion process when the pipe is exposed to chemicals that attack the glass without attacking the resin. The delaying effect of the liner can be very high in such cases. In some cases the delay time may be so long as to give the impression that the strain-corrosion process is altogether non-existent. See ref. 5.

6.2 – Travel by 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

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

The time to strain-corrode the liner may be too short in such situations. In some cases the attack on the liner is so fast that the time to corrode it could be ignored. This is a very sobering statement, meaning that resin-rich liners are 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

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

This is the case of the pipe shown in figure 3, in which the chlorine attacked the resin-rich liner and exposed the fibers in the corrosion barrier to a direct acid attack.

Equation (9A) indicates that the time to strain corrosion rupture may be very short in environments containing chemicals that destroy the resin and are very aggressive to the glass fibers. This problem can be solved by using carbon fibers in the corrosion barrier. See ref. 9.

6.3 – Travel by infiltration through cracked liners. This situation occurs in composites that have suffered high impact loads or have been subjected to tensile strains above the infiltration threshold. Infiltration is a fast process which, unlike diffusion, carries the aggressive chemical to the corrosion barrier in a very short time. The infiltration 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. For best performance the weep/corrosion barrier should operate below the infiltration threshold, as explained in the second paper (weep failure) of this trilogy.

The strain-corrosion rupture times of commercial pipes is measured as indicated in ASTM D3681 (in acid) and ASTM D5365 (in water). To shorten the test times, the pipes are tested above the threshold weep strain and most certainly are severely cracked. The regression lines developed in these tests, from specimens with cracked liners, produce very conservative results that are not representative of the real conditions under which the pipes operate. This is an undisputed fact that is recognized by almost everyone. Nevertheless, the test results from these test methods are still used in design.

7 – Limiting cases – The rupture time from strain-corrosion can be estimated by equations (4A), (9A) and (2). Equation (4A) is valid for chemicals that do not attack the resin and reach the glass by diffusion. This is the least severe of all strain-corrosion situations. Equation (9A) represents the case where the liner is attacked by the chemical and is possibly the most severe case of strain-corrosion. Equation (2) was obtained by testing specimens with cracked liners, as in ASTM D 3681. The results from this equation are too conservative and not representative of pipe performance.

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

6.1 – Sewer transmission. The sulfuric acid solutions found in urban sewers are too diluted and do not harm the resin. Furthermore, since this acid is very slow in diffusing through the resin, the liner gives good protection to the fibers. The long diffusion time of the sulfuric acid through the liner gives these pipes very long lives, regardless of the type of glass in the corrosion barrier. For further details, see ref. 5.
6.2 – Water transmission. The short diffusion time of water is not a problem, since water is not overly aggressive to the underlying glass fibers. This is confirmed by the high values of the 50 years Sb in water, which are 0.92% for UD fibers and 1.30% for chopped fibers. These values are way above the operating strains (0.35%) and assure the durability of the pipe way beyond the limit of 50 years. There are many examples of pipes that have been carrying water and urban sewage for years with no reported case of strain-corrosion failure.

From equation (9A) we conclude that the environments that attack the resin in the liner may be 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 combined with carbon fibers. This extreme situation may be found in underground pipes carrying industrial wastes. For details see ref. 9.

8 – 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 15 years as a consultant. For direct communication please contact tony.hdb@gmail.com

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Appendix A

Threshold strain – As indicated in the part 2 of this trilogy, there is a tensile strain under which the cracks in the pipe do not coalesce to allow the passage of water. This is the threshold weep strain. Pipes operating under this threshold 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 under 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 A1, report data collected over a period of 30 years from pipes deflected in 5% sulfuric acid. The 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), since dilute solutions of sulfuric acid do not attack the resin. If the test strains are below the threshold weep strain, the liner will not crack and diffusion is the only possible 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 glass composition.

Figure A1 suggests the existence of a threshold strain for strain-corrosion. However, this is a false indication, since the diffusion process remains active and eventually the sulfuric acid will rupture the pipe. There is no threshold strain for strain-corrosion. The long diffusion times of some chemicals (like sulfuric acid) may bend the regression line and give the false impression of a threshold strain.

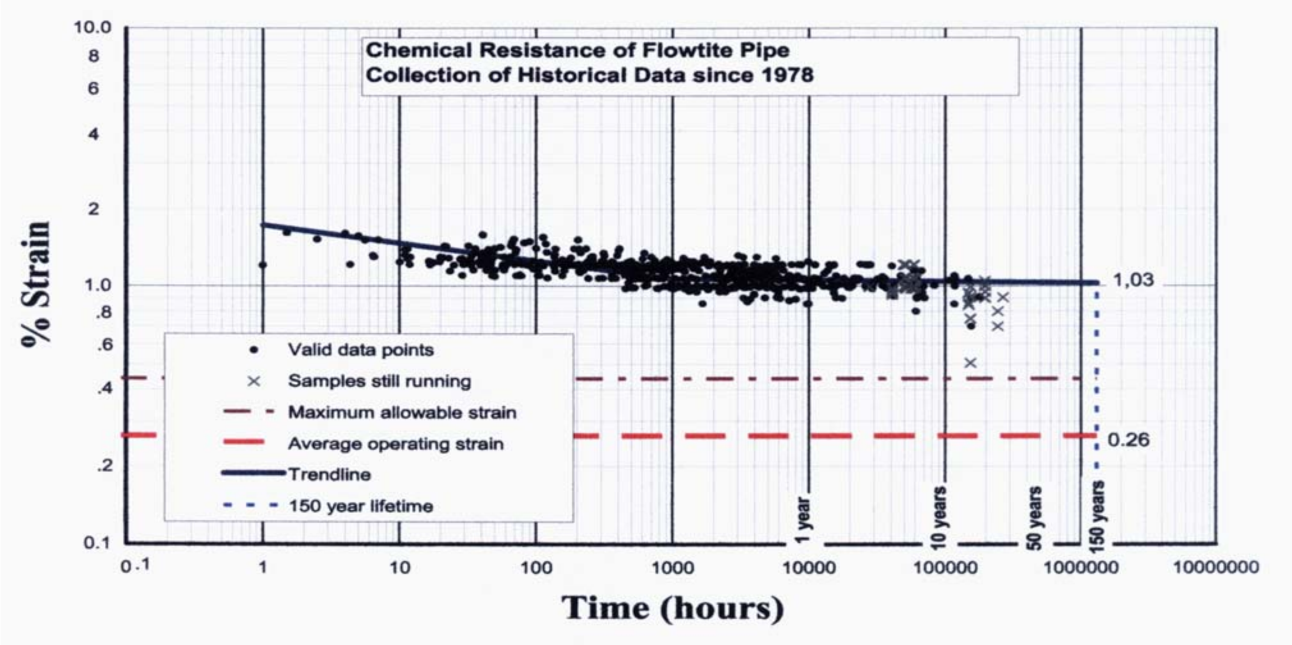

Figure A1
The long-term strain-corrosion tests of composite pipes in sulfuric acid shows a flattening of the regression line. This, however, is not proof of a threshold strain for strain-corrosion. (Courtesy Amiantit).

Appendix B

Cyclic strain corrosion – The discussions presented in this paper are applicable to static loads. The extension of the strain corrosion concept to cyclic loads is very simple and can be 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.

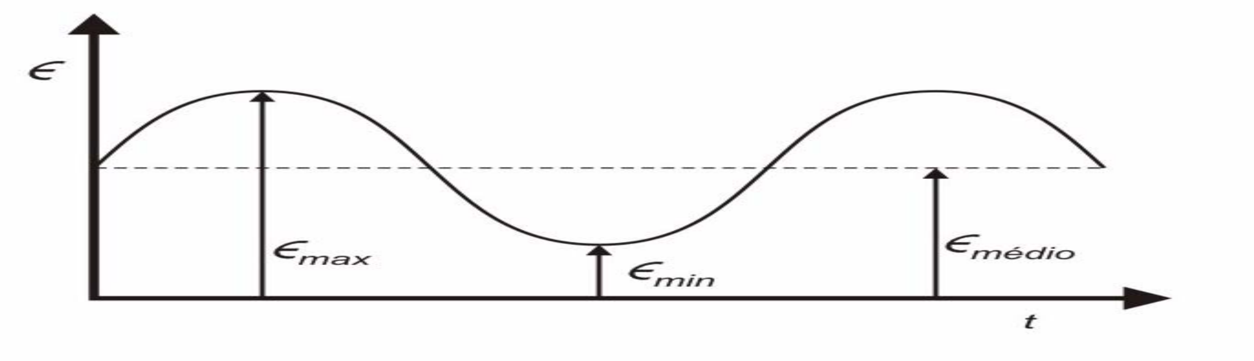

Figure 10 – The strain wave. The strain corrosion phenomenon is defined only for tensile bending strains. Compressive strains do not cause strain corrosion.

The time to rupture by strain-corrosion is affected only by the static component of the strain wave. The cyclic component causes fatigue rupture, but do not cause strain-corrosion.

Mandell (ref 7) mentions a very interesting example of strain-corrosion associated with cyclic fatigue. The application consists in composite UD rods used as high voltage insulators in electrical 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 the electric field. The stage is thus set for the strain-corrosion process. The bending strains come from the vibrations, and the corrosive product is the nitric acid.

Mandell reports that rods made of E glass have a short life in this application. This is due to (1) the absence of a 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 good description of rupture by strain-corrosion. Should the rods be 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.

Of course, the fatigue and crack growth from the cyclic vibrations helps speed up the process. But this is a separate phenomenon, not related to strain-corrosion. The simultaneous action of static and cyclic loads is addressed by the unified equation (ref. 8).