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Structural failure of composite pipes – a trilogy

Part 2 – Weep failure

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Abstract – The commercial standards for composite pipes acknowledge two long-term structural modes of failure, namely strain-corrosion and weep. The importance of the weep failure is clearly demonstrated by its adoption as the basis for long-term pipe design in all commercial standards. By comparison the strain-corrosion rupture is less important, being recognized only in the special case of underground pipes used in the transmission of urban sewage. There is still a third mode of long-term structural failure, burst rupture, which is not recognized in any of the existing commercial standards.

- The long-term burst rupture occurs in pipes operating for extended periods under low strains. This failure is governed by the hydrolytic stability of the glass fibers and is quite independent of the resin matrix.
- The long-term strain-corrosion rupture occurs in pipes under bending loads in corrosive environments, such as urban sewer. It depends on the glass composition as well as on the toughness of the resin.
- The weep failure is governed by the glass-resin interface and the toughness of the resin. The weep failure is observed in pipes operating under high strains.

These are the three classical long-term structural modes of failure of composite pipes. Actually these three modes reduce to two since, as this paper will show, weep failure is independent of time. The current standards for commercial pipes, like AWWA C950, API 15HR and ISO 14692, focus mostly on the weep mode of failure, with some attention paid to strain-corrosion. The long-term burst rupture is ignored in all pipe codes.

We have developed a series of three papers addressing each of these modes of failure. The first paper recognizes water as the only chemical capable of causing long-term burst failure. The third paper explains and quantifies the elusive phenomenon of strain-corrosion. The second paper – this paper – deals with weep failure and introduces the fundamental concept of threshold weep strain.

1 Introduction – The weep failure results from the passage of water through cracks that develop in the pipe wall. The cracks start very small, as resin-fiber debonds, in response to tensile loads transverse to the fibers. The cracks grow with increases in the tensile load until eventually they coalesce and form a pathway for the passage of water. Small tensile loads generate small cracks that do not coalesce and do not let leak. It takes large loads and large cracks to allow the passage of water. It is interesting to contrast the long-term burst rupture with the weep failure. While burst comes from the slow and progressive deterioration of the glass fibers, weep results from cracks that form in the resin matrix. These modes of failure are completely independent. Pipes operating under low tensile strains never weep and eventually fail by burst. The opposite occurs in pipes operating under high tensile strains, which weep before they burst. This statement may sound preposterous. How can a pipe fail by burst under low strains and by weep under high strains? The remainder of this paper will develop the arguments that clarify this statement.

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The paper opens with a discussion of the classical weep regression line obtained from the ASTM D 2992B test protocol. Next it describes the weep mechanism and identifies the resin matrix, together with the glass-resin interface, as the governing factors for this mode of failure. The concept of threshold weep strain is then introduced as a natural and obvious result of the weep mechanism. The concept of threshold weep strain introduces two fundamental innovations into the composites pipe industry. First, it indicates that the weep performance of the pipes may be better than implied by the classical approaches. And second, it relieves the pipe manufacturers of the burden to do the expensive and time consuming tests prescribed in the ASTM D 2992 B protocol.

The commercial composite pipes are designed for weep, using a long-term allowable hoop strain known as HDB, or Hydrostatic Design Basis. The HDB is probably the most important of all composite pipe parameters. It is measured as described in the ASTM D 2992B test protocol. The test method consists in subjecting a minimum of 18 water filled pipe specimens to different constant pressures until they fail by weep. The hoop tensile strains and the corresponding times to weep are annotated and used to generate a regression line. The allowable long-term weep strain – the HDB – is obtained by applying a safety factor SF = 1.8 to the extrapolated long-term hoop strain from this regression line. The extrapolated long-term hoop strain depends on the desired lifetime, which is usually 20 years (oil pipes) or 50 years (sanitation pipes).

The HDB is, therefore, the maximum sustained, static, constant hoop strain that the pipe can take without weeping in the long-term, with a safety factor SF = 1.8. The HDB is the most important parameter used to design composite pipes. Later in this paper we will argue that the HDB should be discarded and replaced by a new design parameter, the weep threshold strain. For now, however, we proceed with our discussion of the HDB.

The weep regression line from ASTM D 2992B is shown in equation (1), where the Greek letter "€" denotes the hoop strain that weeps the pipe at the time "t". The parameter A is related to the strain that weeps the pipe in the short-term and the slope G is related to the fiber-resin adhesion and the toughness of the resin. Later in this paper we will show that the weep strain calculated from equation (1) is not a materials property, as it depends on the pipe thickness.

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

In the above regression equation the hoop tensile static strain "€" controls the number, length and opening of the cracks that form in the pipe wall. And "t" is the time that the water takes to travel the pathway formed by such cracks. If the tensile load and the strain are high, the cracks are many and widely open, reducing the time for the water to traverse the pipe wall. Higher strains produce smaller weep times.

The cracks from static loadings are stationary, meaning they do not grow. The only way to grow a stationary crack is by increasing the tensile load. If the applied load is fixed, the cracks will not grow. Contrary to general belief, the weep time "t" in equation (1) does not reflect any crack growth or progressive deterioration of the pipe. The time depicted in equation (1) is the time taken by the water to traverse the pathway formed by the stationary cracks in pipe wall. The weep time is nothing more than travel time. It has nothing to do with pipe deterioration or crack growth.

Figure 1 shows the plies that are used to make the commercial pipes used in sanitation and in oil applications. What follows is a description of each ply.

Liner: The liner is an inner, resin-rich ply which, if not broken or otherwise punctured, assures full water tightness to the pipe. In sanitation pipes the liner is made by saturating a special lightweight veil with polyester or vinyl ester resins. In oil pipes the liner is made of resin alone, with no veil. The liner thickness is typically 0.3 mm.
Weep barrier: All sanitation pipes have a ply of chopped glass – saturated with polyester resin – placed immediately on top of the liner. This ply of chopped glass develops many small cracks that do not coalesce easily and therefore increase the weep resistance of the pipe. This barrier of chopped fibers is known as “weep barrier” in the case of sanitation pipes. If the pipe is used to convey aggressive chemicals, the weep barrier is called “corrosion barrier” for obvious reasons. Typically the weep barrier is 1.0 mm thick. In industrial applications, involving corrosive fluids, the corrosion barrier is 2.0 mm thick.
Structural wall: The structural wall consists of several plies of continuous unidirectional UD glass fibers. The unidirectional fibers in the structural wall provide the high modulus required to accommodate high pressures and other loads. The thickness of the structural wall varies with the requirements of the application.
Core: The pipes used in underground sanitation applications usually have a core of sand-filled resin, to increases the ring stiffness. The plies of the sand-filled core crack easily and place stringent demands on the careful handling of the pipe components. The thickness of the sand core varies with the requirements of the application.

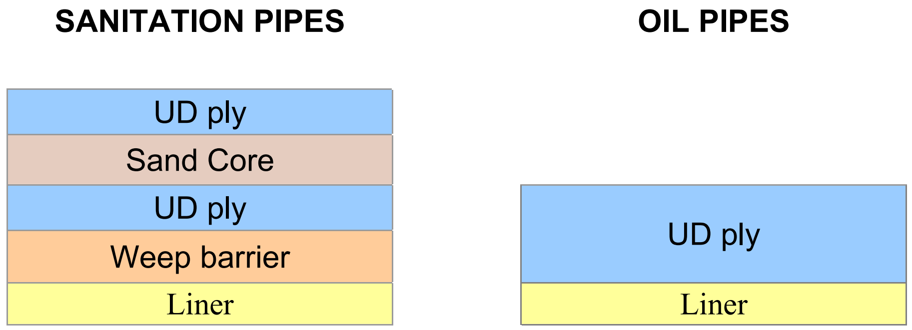

Figure 1
Typical wall construction of commercial sanitation and oil pipes.

At this point the reader may be curious to see some actual weep regression lines. These are shown in figure 2. The line with the flatter slope holds for oil pipes that do not have a weep barrier of chopped glass. And the line with the steeper slope is typical of the sanitation pipes that have a weep barrier of chopped glass.

This is the appropriate moment to correct a widespread misconception. It has to do with the effect of the liner toughness on the weep process. We all know that the liner must break before the pipe weeps. This statement seems to indicate that the resistance to weep may be increased by increasing the liner resiliency. This would be true if the liner were not bonded to the pipe wall. However, since all liners are bonded to the pipe wall, this statement is not true. The cracking of the liner – regardless of its resiliency – is controlled not by the liner itself, but by the substrate ply that is bonded to it. The liner is too thin and weak to be capable, by itself, to arrest cracks growing from the pipe wall.

Regardless of resiliency, the liner will crack immediately in response to such growing cracks. Oil pipes have a UD ply laid directly on top of the liner. Therefore, in oil pipes, the cracking of the liner is controlled by the UD

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plies. In sanitation pipes, the weep barrier of chopped glass laminated on top of the liner has the control. Increasing the resiliency of the liner will have no effect on its cracking. These unusual remarks about cracking of the liner can be easily explained by the theory of fracture mechanics.

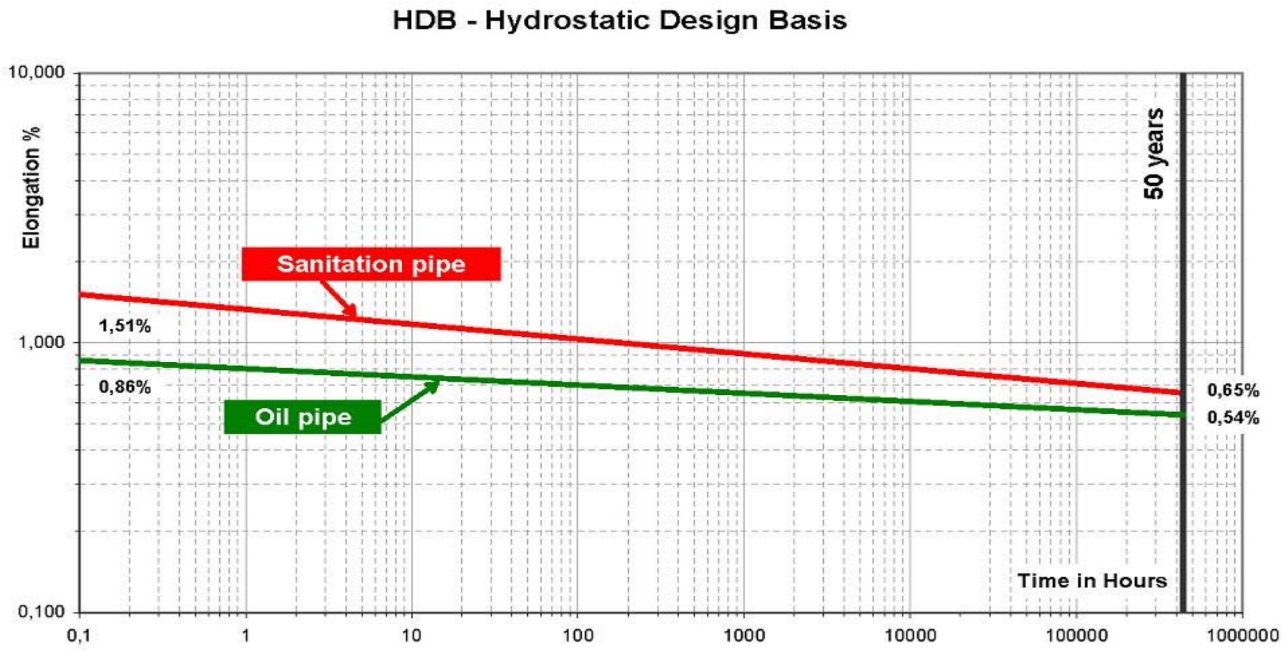

Figure 2
Typical weep regression lines for sanitation and oil pipes. Notice the flatter line for oil pipes. In oil pipes the cracking of the liner is controlled by the UD plies. And in sanitation pipes the weep barrier of chopped glass has the control.

This simple argument explains how the rupture of the liner is governed by the substrate ply. The events just discussed have been observed and reported by many authors. For a quick review, the reader is directed to references 3 and 8. The elongations (strains) at break of liners embedded in laminates are sometimes called “in-situ” elongations, to differentiate them from those measured on resin castings.

Note: The “in-situ” elongation of the liner is controlled by the cracks in the resin-glass interface of the substrate ply. The reader should make an effort and remember that it is the resin in the substrate ply, and not the resin in the liner, that controls the weep process. Few people realize this important concept.

So far we have been discussing the old ideas regarding the classical concept of HDB. We next move to the new ideas and the concept of the threshold weep strain.

3 The threshold weep strain – We start our discussion describing the mechanism of crack formation in the plies when the pipe is pressurized.

To facilitate the exposition we will make use of a series of drawings all labeled as figure 3. Figure 3a shows the pipe wall under low pressure and all plies free from cracks. The next figure 3b shows the glass separating from the resin as the pressure and strain have been increased. The strain leading to the onset of glass-resin debonds is governed by the interface adhesion. The subsequent figures describe the development of the cracks and can best be understood by reading the appropriate captions.

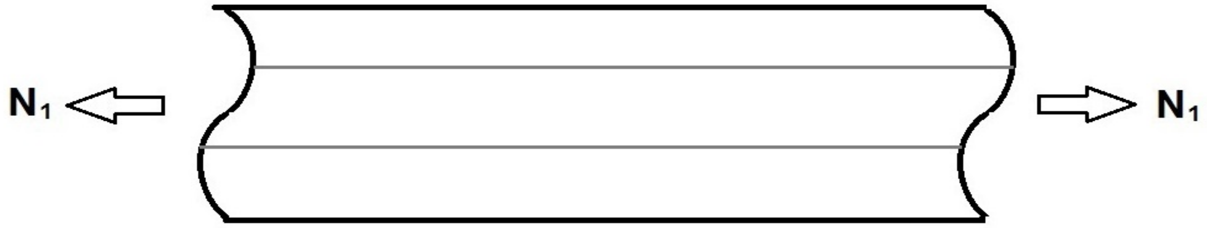

Figure 3a
Under low pressures, the strains are too low and initiates no cracks. The absence of cracks prevents the infiltration of chemicals into the laminate. The only way for corrosive chemicals, like acids and others, to penetrate the laminate is by the slow process of diffusion. The delayed penetration of corrosive chemicals substantially increases the service life of the equipment.

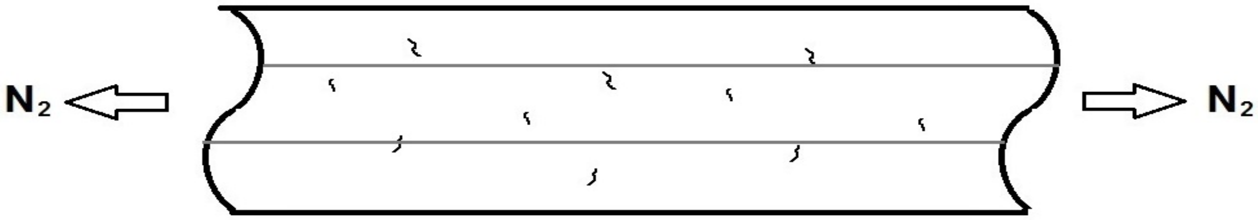

Figure 3b
At higher pressures the strains may be high enough to separate the glass from the resin. The strain that causes the first glass-resin separation, the "onset of debonding", initiates several critical events, such as emission of acoustic signals, loss of translucency and loss of linearity. At this point the laminate is susceptible to infiltration of chemicals, and these high strains may have substantial effect on the service life of the equipment. The onset of debonding marks the infiltration threshold. The infiltration threshold is a very important parameter in the design of composite equipment for corrosive environments.

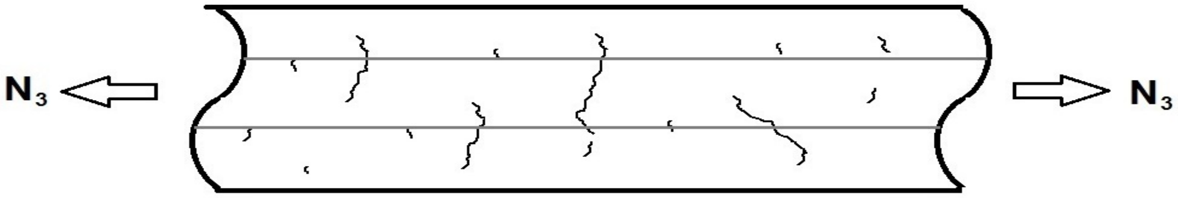

Figure 3c
Still higher pressures and strains lead to growth and coalescence of the small debond cracks. The originally sparse and small the debond cracks become larger and grow in number as the strain is increased. The reader is reminded that these are stationary cracks that do not grow under static loads. For these cracks to grow, the pressure – or strain – must be increased.

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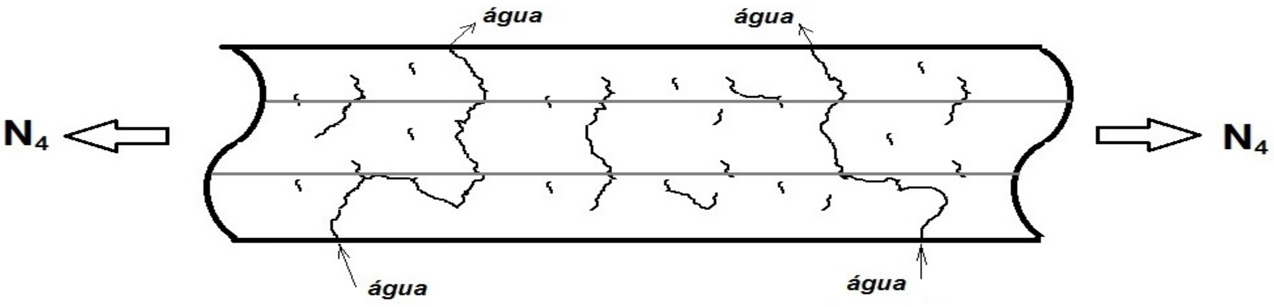

Figure 3d
Finally a critical strain is reached that allows the many small debond cracks to coalesce and span the entire ply thickness. This is the onset of ply cracking, which marks the appearance of the first through-the-thickness crack. Further increase in pressure will increase the number, size and opening of the through-the-thickness cracks. The cracks in one ply will intersect and cross over similar cracks in adjacent plies. At the intersection, or cross over points, the cracks form the passageways that allow water to move from one ply to another. This process continues and eventually the water gets through the pipe wall. The critical strain that initiates the formation of this pathway is called the threshold weep strain. If the strain is below this threshold, the pathway is not formed and the pipe will not weep. If above the threshold, the pathway is formed and the pipe will weep. The time to weep will depend on the number, opening and length of the cracks. In other words, it depends on the pressure, or strain. It depends also on the pipe thickness. The higher the pressure, or the strain, the shorter is the time for the water to traverse the pipe thickness. Again, these are stationary cracks that do not grow under static loads.

The foregoing discussion shows beyond a reasonable doubt that the length and opening of the cracks, as well as their number, increase with the tensile strain in the direction transverse to the glass fibers. When a critical transverse strain is reached, the small debond cracks coalesce and form pathways that allow the passage of fluids. The transverse tensile strain at the onset of these pathways is the threshold weep strain. The pipes never weep if strained below this threshold. And above the threshold, they will certainly weep. The time to weep depends on the pathways that are formed. If the cracks are many and their openings and lengths are large, the time to weep is short. Also, thin walled pipes weep sooner than thick walled pipes.

The concept of a weep threshold strain is in sharp contrast to the classical HDB obtained by extrapolation from regression lines. The extrapolated HDB is based on the false assumption that cracks under constant loads will grow and coalesce. This assumption is simply untenable. The theory of fracture mechanics is very clear in stating that stationary cracks do not grow.

Note: The concept of threshold weep strain is valid only for static loads. It does not hold for cyclic loads. This is because, unlike the static case, the cyclic loads cause crack growth.

4 – Inadequacy of the classical HDB. We start this section with arguments that indicate the inadequacy of the classical HDB in the design of composite pipes. Specifically, this section will show that the weep regression line developed by the ASTM D 2992B protocol is limited to high strain situations, outside the range of commercial applications. The low strain, long-term design criteria, found in commercial applications should drop the classical HDB concept and make use of the threshold weep strain. Let us elaborate on this.

The ASTM D 2992B protocol is run at high pressures and high strains in order to create many large cracks in the pipe wall and shorten the test time. The regression line generated from this protocol is valid only to predict the weep times for highly cracked pipes. It does not apply to actual pipes that do not crack because they operate at substantially lower strains. We have just seen that if the strain is below the weep threshold the pipe never weeps.

The weep threshold separates weep from non-weep. The ASTM D 2992B regression line is good to predict the weep time (actually travel time) for pipes that are strained above the threshold. Below the threshold, the regression line is not applicable, because the pipes do not weep. By ignoring the weep threshold, the regression line extrapolates unrealistic low values for the HDB, as if the pipe deteriorated and spontaneously generated cracks that would grow under static loads. As we have previously discussed this situation does not happen since the resin is not strain-corroded by water. The only deterioration in the pipe comes from strain-corrosion of the fibers which eventually ruptures, but does not weep, the pipe.

The first author to reject the classical HDB obtained from regression lines was Frank Pickering (reference 6) in 1983. Frank proposed that the classical HDB should be replaced by a parameter that he referred to as PEL, or Proportional Elastic Limit, determined by the strain at which the pipe response ceases to be linear. The loss of linearity in the pipe laminate is an indicator of resin cracking and serves as a measure for the threshold weep strain. That is the same idea advocated in the present paper, except that we propose the threshold weep strain be measured on isolated plies, not on pipes. The threshold weep strain is a ply property, not a laminate property. We will have more to say about this in the following paragraph. For now, it suffices to say that the classical HDB, obtained from regression lines, is not a good predictor for long-term weep failure.

Figure 4 shows the weep threshold superimposed on the classical weep line for sanitation pipes. The first thing to note is that the classical regression line holds for strains above the weep threshold. This is in line with what we have said earlier, that the classical line is good to predict weep above the threshold strain. However, figure 4 also shows that the regression line is obviously not valid to make long-term predictions.

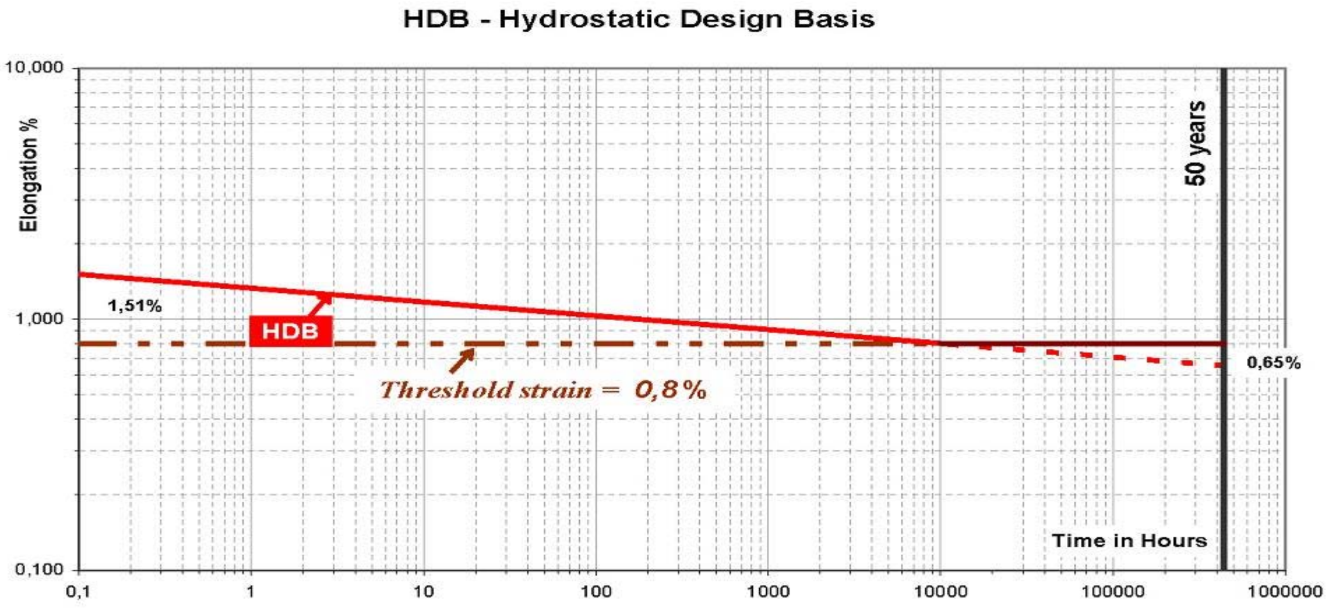

Figure 4

Weep regression line of sanitation pipes superimposed on the threshold line. The threshold strain is assumed to be 0.8%, which is reasonable for matrix resins with elongation of 3.0%. The threshold strain of 0.80% is substantially higher than the HDB extrapolated at 0.65%.

5 Measuring the threshold weep strain. The threshold weep strain should be measured on plies, not on pipes. The reason is the difficulty to separate the response coming from different plies in the pipe. Also, shear strains should be avoided in the test protocol, since shear cracks cause loss of linearity, loss of translucency and are a source of acoustic emissions, but they do not open cracks that cause weep. As explained earlier, we are interested in the response of the ply that serves as substrate for the liner. That substrate ply is the critical one, meaning the one which causes the liner to crack when it cracks. To make sure the measured signals come from this critical ply, the test specimens should be made exclusively with that ply. And the test specimen should be designed to eliminate all shear strains.

The test specimens made exclusively with the critical ply will eliminate the spurious response from other plies. This is true for both sanitation and oil pipes. For example, the test specimens for sanitation pipes should be made of chopped glass plies. And those for oil pipes should be made exclusively of cross-ply UD plies. The use of cross-ply laminates is necessary in order to eliminate shear strains.

The tests should be performed on pressurized pipe specimens to measure the onset of debonding (infiltration threshold) as well as the onset of ply cracking (weep threshold). Table 2 shows the onset of debonding from acoustic emission measured by Norwood and Millman (ref 3) on plies of chopped glass or of woven roving. The onset of debonding marks the “infiltration threshold strain”, not the “threshold weep strain”, which should be higher than the values in table 2.

Elongation at break of resin castings	Threshold debond strain measured by acoustic emission	
	Chopped glass ply	Woven roving ply
2.5%	0.4%	0.3%
3.8%	0.8%	0.6%

Table 2
Infiltration threshold strain values reported by Norwood and Millman from tensile tests performed on plies of chopped glass or woven roving. The above are the infiltration threshold. The weep threshold should be higher.

We recall that the weep barrier in sanitation pipes is made of chopped glass saturated with polyester resins having a minimum elongation of 3.0%. From table 2 such pipes would have a threshold weep strain higher than 0.8%. We will take 0.8% as the threshold weep strain for sanitation pipes made of polyester resins with 3.0% elongation.

Work done at the University of Liverpool (ref. 11) indicates a threshold infiltration strain of 0.4% for oil pipes made with a brittle polyester resin (1.6% elongation at break) and a 55 degrees winding angle. Again, the threshold weep strain is higher than 0.40%. As before, we will conservatively assume 0.4% to be the weep threshold strain for oil pipes.

These are the only values available in the literature at this time for the threshold weep strain:

For sanitation pipes	*0.8%*
For oil pipes	*0.4%*

The above strains are expressed in the hoop direction of the pipe. The reader should recall that both the classical HDB and the threshold strains are referred to the hoop direction of the pipe. The threshold strain in the direction transverse to the fibers is calculated by rotating the global strains to the local reference frame. This is easily done using the rotation matrix from classical laminate theory.

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

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 local shear strain on the UD ply

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

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

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

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

Equation (2A) calculates the strain in the fiber direction when the global hoop and axial strains are known. The strain in the transverse direction to the fibers, equation (2B), controls the weep failure of oil pipes. The shear strain in equation (2C) is irrelevant.

This completes our discussion of the classical HDB versus the threshold weep strain. Our conclusion is that the classical HDB should be replaced by the weep threshold. This substitution would bring the following advantages:

- The concept of weep threshold is consistent from a materials point of view
- The weep threshold is easy to measure
- The weep threshold is higher than the classical HDB, allowing the production of lower cost pipes.

In closing, we say that the classical HDB has been around for so long and is so deeply rooted in the minds of the design engineers that we propose to maintain the nomenclature HDB to designate the weep threshold. After all, that's what the weep threshold really is: a Hydrostatic Design Basis.

The next question is what happens if the loading is not static and the cracks can grow. The concept of weep threshold is not valid for cyclic loads. What happens in cyclic loads?

6 Cyclic loadings – We next discuss the difficult problem of estimating the time to weep of pipes under cyclic loads. Unlike static loads, cyclic loads can grow cracks. As a result, there is no weep threshold for cyclic loads. Given enough time (or better, enough cycles) the cyclic loads will grow the initially small debond cracks until eventually they coalesce and cause the pipe to weep.

The total time to weep pipes under cyclic loads may be estimated by adding two distinct times

$$\begin{bmatrix} total & time \\ to & weep \end{bmatrix} = [coalescence \quad time] + [travel \quad time] \qquad (3)$$

Where "coalescence time" refers to the number of cycles (expressed in time) required to grow the originally small debond cracks to the point where they are large and plentiful enough to coalesce. The weep process is set in motion once the coalescence is completed. The "travel time" is computed from equation (4), which is the cyclic version of the static regression equation (1). Equation (4) is determined as indicated in the ASTM D 2992A test protocol.

$$\log \Delta\varepsilon = A - G \log N \qquad (4)$$

The reader will notice that equation (4) is cycle, not time, dependent. It gives the number of cycles N that weeps the pipe under a known cyclic loading. As we have seen in our discussion of the static case, equation (4) holds for cracked pipes.

Equation (3) indicates that the total time to weep is determined in two steps. The first step computes the time for the cracks to grow and coalesce under cyclic loads. The second step computes the time for the water to travel through the cracks. The travel time is determined from equation (4).

Equation (4) is maybe not necessary in pipe design, since it computes the travel time in pipes that have already cracked, that is, have already failed. This is the same situation that we encountered in the static case. The travel time is a measure of the delay in the weeping process on pipes that have already failed.

If we ignore the travel time equation (3) becomes

$$\begin{bmatrix} total & time \\ to & weep \end{bmatrix} = [coalescence \quad time] \qquad (3A)$$

The problem that we face in using equation (3A) is how to calculate the coalescence time when static and cyclic loads act simultaneously. The solution to this problem requires the use of the unified equation and is beyond the scope of this paper. The reader may find details on the unified equation in ref. 10. A numerical example illustrating the use of equation (3A) and the unified equation can be found in ref. 12.

We repeat that the concept of weep threshold strain is valid only for static loadings. There is no weep threshold strain for cyclic loadings. Given enough time, or enough cycles, all cyclically loaded pipes will eventually weep.

A worked example to illustrate how cyclic loads affect the weep time will not be given at this point, since we have not yet discussed the unified equation. The reader interested in a worked example is referred to ref. 12.

9 Conclusions – We have described two approaches to predict the weep failure of composite pipes.

- *The classical approach* proposes that the few small cracks that develop under typical pipe operation grow under static loads to form pathways for the passage of water. Regression lines are used to predict the long-term allowable strain (HDB). The underlying assumptions for this approach are not supported by the theory of fracture mechanics.
- *The threshold strain approach* proposes that all pipes have a static weep threshold strain below which weeping never occurs.

A conclusive experiment to discriminate between these two proposals would require long periods of time. Such tests have never been performed. The best evidence in favor of the threshold strain was published early in 2009 by Hogni Johnson, who reported the results of 30 years of tests on deflected pipes under strain-corrosion. See reference 4. Figure 5 shows the flattened strain-corrosion line published by Hogni in exactly the same fashion as proposed in this paper. This is the best evidence available at this time to prove the reality of the threshold weep strain concept.

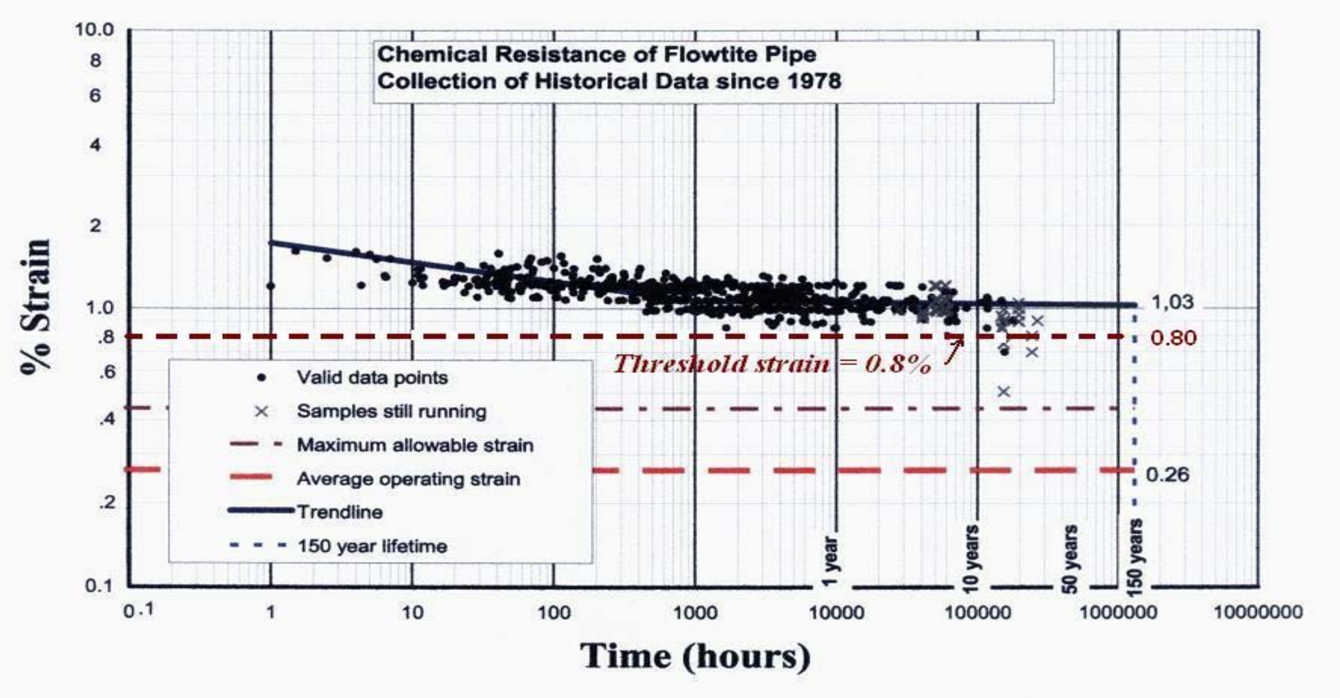

Figure 5
The long-term strain-corrosion tests of composite pipes in acidic media shows a flattened regression line. The threshold weep strain of 0.8% has been superimposed on the graph. (Courtesy Amiantit)

It may be argued that strain-corrosion tests performed on deflected pipes are not valid to vindicate a hypothesis for weep failure on pressurized pipes. A rebuttal of this argument will be presented in the third paper of this trilogy, which explains that the strain-corrosion rupture may be regarded as a special case of the weep failure that we have just discussed. Therefore, the results presented by Hogni in figure 5 are valid as proof of weep failure.

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Appendix A – Weep lines for sanitation and oil pipes.

This appendix explains the differences between the weep lines of oil and sanitation pipes. From figure 2 the points requiring explanation are: (a) the difference in slopes and (b) in the relative positions of the two lines.

We begin with the relative position of the lines. The random chopped fibers in the weep barrier of sanitation pipes do not form large and long cracks and therefore require higher strains to form the pathways. In contrast, the ± 55 degrees UD plies of oil pipes require lower strains to form the pathway. In addition, the oil pipes are pressure tested with both ends free in a biaxial strain situation. These are the reasons why the weep line of sanitation pipes plots above the weep line of oil pipes. The regression line of oil pipes could be substantially improved by introducing a weep barrier of chopped fibers under the first UD ply.

Next we address the difference in slopes. We begin by recalling that the time to weep is in fact the time for the water to traverse the pipe wall. In this discussion we assume the pipes have the same wall thickness. The UD plies of oil pipes develop long cracks, as shown in figure A1. The points where the water moves from one ply to the next are those at the intersection, or crossing, of the cracks. In oil pipes the water is forced to travel long distances, meaning long travel times, to reach the crossover points and advance from one ply to the next. By contrast, the pathways in the chopped glass of sanitation pipes are direct and shorter. It takes high strain

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increments to shorten the long travel times in the UD plies of oil pipes. That is the reason for the flatter regression lines of oil pipes.

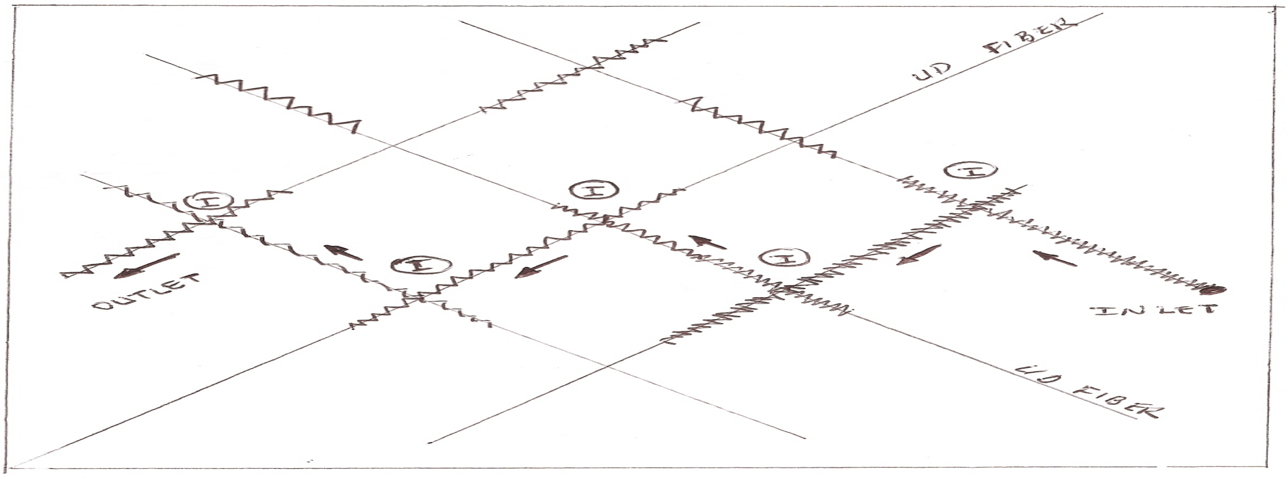

Figure A1
The crack pattern of UD plies explains the flat weep lines of oil pipes. The pathway followed by the water is shown by the arrows. The water moves to the next ply at the intersection points "I". The flat slope of oil pipes is explained by this long, tortuous pathway.

Appendix B – Is there a weep threshold strain?

This appendix addresses an interesting objection to the validity of the weep threshold. The argument against the existence of the threshold weep strain can be divided in four parts:

1 – All plies have a large number of pre-existing "flaws" that serve as starting points for cracks.

True.

2 – Under constant tensile loads these pre-existing cracks will grow and eventually weep the pipe.

Not true. Static, constant loads do not grow cracks. According to fracture mechanics, only the few cracks above a certain length would grow under static loads. And their growth would be arrested by neighboring plies and fibers. The number and length of these arrested cracks are not enough to coalesce and form a pathway.

3 – Therefore, there is no threshold strain.

Not true. There is a threshold strain, below which the stationary cracks are too few and too small to coalesce.

Composite pipes weep not because they develop many small cracks, but because they develop few large cracks. And in order to develop large cracks, they must be placed under high tensile static strains. Cyclic strains are different since, unlike static strains, they can grow cracks.

Appendix C – Rupture versus weep

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This appendix compares the weep and burst regression lines for sanitation pipes made with E glass and boron-free glass.

The weep failure is governed by the resin-fiber interface and is not affected by the composition of the glass. The burst failure is governed by the glass composition. The following discussion is valid for "hoop-chop" pipes, which have the UD plies in the hoop direction. This simplification is not necessary and will not cause loss of generality.

Before reading this appendix, the reader should be familiar with the ideas of burst failure, as proposed in the first paper of this trilogy. Figure C1 shows the rupture lines for pipes made of E glass and boron-free glass superimposed on the weep regression line. Also shown is the threshold weep strain line of 0.8%. Figure C1 shows that if the strains are higher than the weep threshold, the pipes always weep before they burst. And for strains below that threshold the pipes always burst before they weep. In fact, below the weep threshold the pipes never weep. It should be noted that the E glass pipes burst at 1200 hours when strained at 0.8%. By contrast, the pipes made of boron-free glass can sustain 0.8% strain for 50 years without bursting.

Figure C1 shows the dramatic impact of the glass composition on the long-term rupture strains. The boron-free glass extrapolates to a rupture strain of 0.92% at 50 years, versus 0.41% for the standard E glass. The weep line and the threshold weep strain, however, are independent of the glass composition.

The reader is advised that the graphs in figure C1 are applicable to sanitation hoop-chop pipes. They do not apply to oil pipes or to sanitation pipes other than hoop-chop. Also, the reader should be aware that if the applied strain is too high, the test time may be too short and the pipe may burst (rupture) before the water has time to weep. This is the situation of pipes tested per ASTM D 1599.

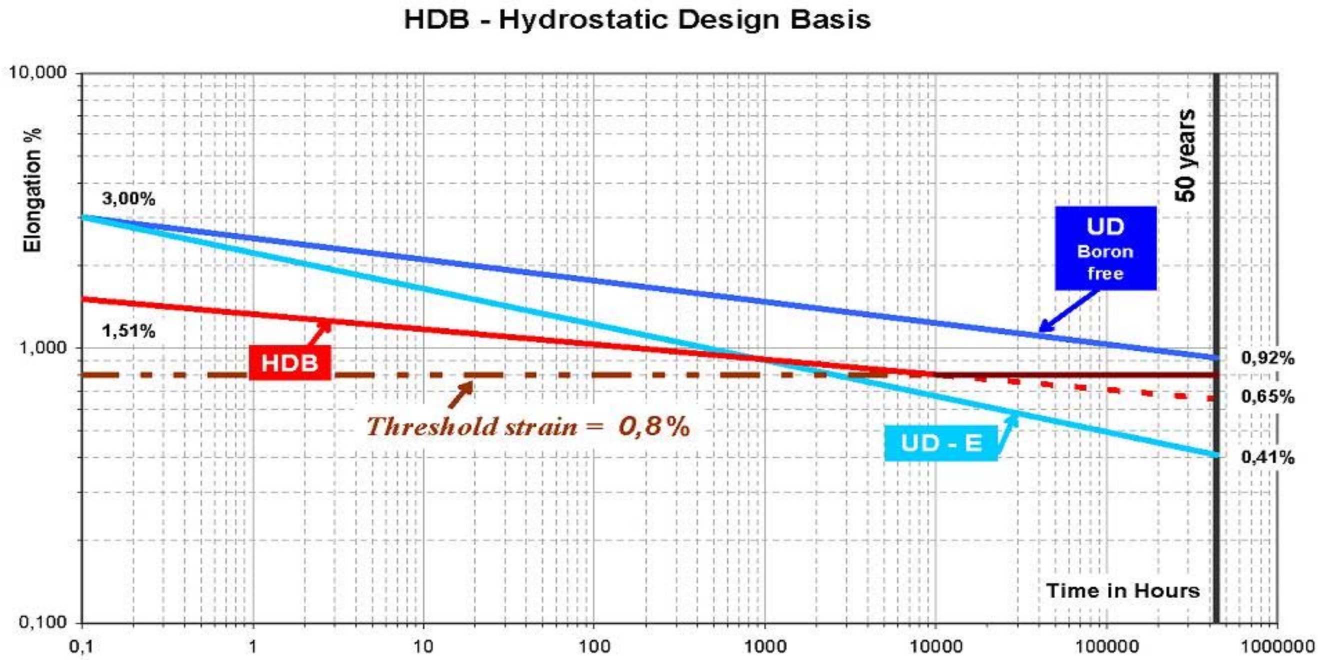

Figure C1

Weep and rupture lines for "hoop-chop" sanitation pipes. Rupture data from Mark Greenwood. Weep data from Amiantit. The threshold line is my suggestion.

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