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United Consulting
625 Holcomb Bridge Road
Norcross, GA 30071
Attention: Mehdi Moazzamie

June 20, 2005

Re: Long Term Material Performance of Infrastructure Repair System, Inc.
Trenchless Technology Point Repair System

Dear Mr. Moazzamie,

As per the request of Mr. Bill Higman of Infrastructure Repair System, Inc, I am forwarding to you information regarding long term material performance of their cured-in-place composite fiberglass/epoxy resin known as Point Repair System.

Enclosed are typical wall thickness designs for the Point Repair System which utilizes an initial flexural modulus of 800,000 psi and long term flexural modulus of 400,000 psi. The typical reduction for long term flexural modulus is 50% for cured in place lining materials. These are conservative wall thickness designs that I have calculated based upon the design method and formulas outlined in ASTM Standard 1216. In addition, for a 100 year design life consideration, I have increased the factor of safety to 2.5.

The composite system utilized by Infrastructure's Point Repair System, represents a higher strength and more durable system through the use of fiberglass compared to typical felt cloth and the use of a higher strength, high temperature resistant and corrosion resistant epoxy resin as compared to a typical polyester resin. Attached is an article on the perspectives on durability of composite materials and life expectancy.

Based upon my work in the field of trenchless technology and knowledge of composite resin systems, it is my professional opinion that the sectional pipe repair system marketed as the Infrastructure Point Repair System will provide service as an intended sewer lining system for an extended period of time in excess of 100 years.

Sincerely,

Brian M. Rohan

Brian M. Rohan, PE
Member National Society of Professional Engineers

INFRASTRUCTURE REPAIR SYSTEMS, INC.

Material: Fiberglass Epoxy Resin

POINT REPAIR SYSTEM - SECTIONAL LINING
ST. PETERSBURGH, FLORIDA
PROJECT: CITY OF ATLANTA, GEORGIA

DESIGN PARAMETERS:

Existing pipe fully deteriorated
Ground water to surface

Initial Tensile Stress	19,000 psi
Initial Flexural Stress	27,000 psi
Initial Flexural Modulus of Elasticity	800,000 psi
Long-Term Modulus of Elasticity	400,000 psi
Ovality (%)	2.00%
Type of Soil	sand/clay
Soil density	120.0 pcf
Soil modulus	800.0 psi
Factor of Safety	2.5

Design Method ASTM 1216

SUMMARY OF MINIMAL SECTIONAL LINER THICKNESS (mm)							
Depth (ft)	Pipe Diameter Sizes						
	8"	10"	12"	15"	18"	21"	24"
2	7.6	10.4	13.7	20	32.1	NR	NR
3	4.6	6.1	7.8	11	14.3	18.7	24.5
4	3.5	4.5	5.5	7.4	9.4	11.8	14.6
>4 to 8	3.3	4	4.8	5.9	6.7	8.2	9.4
>8 to 12	3.8	4.7	5.6	7	8.3	9.7	10.9
>12 to 16	4.3	5.4	6.4	8	9.6	11.1	12.6
>16 to 20	4.9	5.9	7.1	8.9	10.6	12.4	14

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6/20/2005

STATE OF NEW YORK
BRIAN M. ROHAN
No. 54573
LICENSED PROFESSIONAL ENGINEER

POINT REPAIR SYSTEM

CURED-IN-PLACE

POINT REPAIR DESIGN REPORT

LINER THICKNESS
AND
FLOW QUALITY
CALCULATIONS

INFRASTRUCTURE
REPAIR SYSTEMS, INC.

CITY OF ATLANTA, GA
POINT REPAIR

8" DIAMETER PIPE/LINER
3.8 mm LINER THICKNESS
MAXIUM DEPTH 12'

Design References

Design and Construction of Sanitary and Storm Sewers
ASCE Manuals & Reports on Engineering Practice No. 37
WPCF Manual of Practice No.9, 6th Printing
7th Printing, Copyright 1969 by ASCE & WPCF
[Labeled hereafter as D.C.S.S.S.]

AWWA Standard for Fiberglass Pressure Pipe
American National Standard
ANSI/AWWA C950-88, Copyright 1989
[Labeled hereafter as F.P.P.]

American Society for Testing and Materials
ASTM Standard Practice Designation: D 3839 - 89
Underground Installation of "Fiberglass" (Glass-Fiber Reinforced Thermosetting Resin) Pipe
Approved January 27, 1989
[Labeled hereafter as ASTM D 3839-89]

American Society for Testing and Materials
ASTM Standard Practice Designation: F 1216-91
Approved March 21, 1989
[Labeled hereafter as ASTM F 1216-91]

Design Parameters

Liner Dimensions

Liner diameter (in.) -- 8.0 in.
Liner thickness (in.) -- 0.148 in.
Liner SDR -- 54.0

Liner Physical Properties

Initial Tensile Stress (psi) -------------------------------------- 19000 psi
Initial Flexural Stress (psi) ------------------------------------- 27000 psi
Initial Flexural Modulus of Elasticity (psi) ------------------- 800000 psi
Long-Term Modulus of Elasticity (psi) --------------------------- 400000 psi

Existing Pipe Characteristics

Existing pipe fully deteriorated
Ovality (%)--- 2.0 %

Soil Characteristics

Type of soil --- sand
w = soil density (pcf) --- 120.0 pcf
Es = soil modulus (psi) -- 800.0 psi

Factor of Safety --- 2.500

1. Determine the Loading on the Pipe Using the Modified Marston Formula and the Boussinesq Formula

Base Equation :

Total Load (Wtot) = Wc + Wl

A) Dead Load (Wc) = Cd * w * Bc * Bd [Marston Formula, pg.187, D.C.S.S.S.]

Where :

Cd = loading coefficient
= (1 - e^(-2 * ku' * H/Bd)) / (2*ku') [pg188, D.C.S.S.S.]

Where:

H = Height of soil above crown of pipe (ft.) = 11.33 ft.
Bd = trench width (ft.), diameter of pipe = 0.67 ft.
ku' [see fig.55, pg.202, D.C.S.S.S.] = 0.130
Therefore: Cd = 3.800

w = soil density (psf) = 120.00 pcf
Bc = diameter of pipe (in.) = 8.00 in.
Bd = trench width (ft.) = 0.67 ft.

Dead Load (Wc) = 202.7 lb/ft.

B) Live Load (Wl) = Cl * P * (1 + If) [Section X1.3.4, pg.5, ASTM D 3839-89] & [Eq. A.11, pg 32, F.P.P.]

Where:

Cl = Live Load Coefficient (/ft.) = 0.002 /ft.
P = wheel load (lb) = 16000.0 lb
Imf = impact factor
= 0.766 - 0.133 * H ; 0 < If < 0.5 = 0.000

When H>3.0, Imf is 0

Therefore: Live Load (Wl) = 32.00 lb/ft.

Therefore: Total Load (Wtot = Wc + Wl) = 234.660 lb/ft

2. Determine External Pressure on Pipe

Base equation:

qa (psi) = Yw * Hw + (Rw * Wc) / D + (Wl / D) [Eg A.20, pg.39, F.P.P.]

where: Wc = vertical soil load = (Ys * H * D) / 144 [Eq A.10, pg.31, F.P.P]

Modified equation:

qa (psi) = Yw * Hw * 12 in./ft. + (Rw * Ys * H) / 144 + (Wl / (D*12 in./ft.))

where:

Yw = specific weight of water (lb/in.^3) = 0.0361 lb/in.^3
Hw = height of water (ft.), from middle of pipe to water level = 11.67 ft.
Rw = water buoyancy factor = 1 - .33(hw/H) = 0.66
Ys = soil density (lb/ft.^3) = 120.00 lb/ft.^3
H = height of soil (ft.), above crown of pipe = 11.33 ft.
Wl = live load (lb/ft.) = 32.00 lb/ft.
D = pipe diameter (in.) = 8.00 in.

Therefore: External Pressure on the pipe (qa) = 11.63 psi

3A. Thickness Required for Buckling Pressure

Base Equation:

qa = (C / N) * [(32 * Rw * B' * Es * EI)/D^3]^(1/2)

[Eq A.17, pg.38, F.P.P.])
& [Eq X1.4, pg.5, ASTM F 1216-91]

Modify the Base Equation by adding the following substitution:

EI = Pipe Wall Stiffness Factor = (El / 12) * t^3

Modified Equation:

t = 0.721 * D * [((N * qa / C)^2) / El*Rw*B'*Es]^(1/3)

where:

I = Moment of Inertia (in.^4/in.) = t^3/12
t = minimum liner thickness (in.)
D = pipe diameter (in.) = 8.00 in.
N = safety factor = 2.50
qa = external pressure on pipe (psi) = 11.63 psi
C = ovality factor

$$= \left[\frac{1 - \%\ \text{ovality}/100}{(1 + \%\ \text{ovality}/100)^2} \right]^3 = 0.836$$

El = Long-term modulus of elasticity (psi) = 400000 psi
Rw = water buoyance factor = 0.66
B' = coefficient of elastic support

$$= \frac{1}{1 + 4 * e^{(-0.065*H)}} = 0.34$$

Es = Modulus of soil reaction (psi) = 800.00 psi

Therefore: The minimum liner thickness (t) = 0.147 in

When lining ar 8.00 inch diameter pipe,
utilize ar 8.00 inch outer diameter liner with a thickness of
0.148 inches, exceeding the required minimum of 0.147 inches.

3B. Check Thickness For Deflection

Base Equation (Modified Iowa Formula):

$$y = Dl * \frac{(K * (Wc + Wl) * r^3)}{(EI + 0.061 * E' * r^3)}$$

[Eq.15, pg.218, D.C.S.S.S.]
& [Eq.A.9, pg.29, F.P.P.]

Modify the Base Equation by adding the following four substitutions:
(1) $r * 2 = D$, (2) $SDR / t = D$, (3) $I = t^3$, (4) $Wtot / 12 = Wc + Wl$

Modified Equation :

$$\mathbf{y = (Dl * K * Wtot) / ((EI / (1.5*(SDR^3))) + 0.061*E')}$$

where:
y = deflection (ft.)
Dl = deflection lag factor = 1.50
[Section A.3.4.2.1, pg.30, F.P.P.]
K = bedding factor **[Table A.2, pg.31, F.P.P.]** = 0.11
Wtot = load on unit cross section of pipe (lb/in.) = 19.55 lb/in.
El = Long-term modulus of elasticity (psi) = 400000.0 psi
SDR = ratio of liner diameter to liner thickness = 54.0
E' = Modulus of soil reaction (psi) = 800.0 psi

Therefore: The deflection (y) = 0.064 in.

As a standard requirement, deflection should not exceed a 5% change in the vertical cross-section of the pipe. **[Eg A.8, pg 29, F.P.P.]**

y / D = 0.0080 in./in.

0.80 % < 5.00 %

Therefore the thickness is within acceptable limits.

3C. Check Thickness for Ring-Bending Stress

Base Formula:

$$Ob = Df * El * \left(\frac{ya}{D}\right) * \left(\frac{t}{D}\right) \leq \frac{Sb}{FS}$$

[Eq A.6, pg.27, F.P.P.]

where:

Ob =	maximum ring-bending stress due to deflection (psi)			
t =	liner thickness (in.)	=	0.148	in.
Df =	shape factor **[Table A.1, pg28, F.P.P.]**	=	8.0	
El =	long- term modulus of elasticity (psi)	=	400000	psi
y =	deflection (in.)	=	0.064	in.
ya =	maximum allowable deflection (in.)	=	0.400	in.
Sb =	ring-bending strength of pipe (psi)	=	27000.0	psi
FS =	factor of safety	=	2.50	
D =	liner diameter (in.)	=	8.000	in.

$$Df * El * (ya / D) * (t / D) = 2962.96 \text{ psi}$$

$$\frac{Sb}{FS} = 10800 \text{ psi}$$

$$2962.96 \text{ psi} < 10800 \text{ psi}$$

Therefore the liner thickness is adequate to resist ring-bending stresses.

3D. Check Thickness for Minimum Stiffness

Base Equation:

$$\frac{EI}{D^3} = \frac{El}{12 * (SDR^3)} \geq 0.093 \text{ psi}$$

[Eq X1.4, pg.5, ASTM F 1216-91]

where:

El = Modulus of elasticity (psi) = 800000 psi

SDR = ratio of liner diameter to liner thickness = 54.0

$$\frac{E}{12 * (SDR^3)} = 0.423 \text{ psi}$$

$$\underline{\underline{0.423 \text{ psi} > 0.093 \text{ psi}}}$$

Therefore the liner thickness is adequate for the required minimum stiffness.

4. Calculate Increase In Flow Capacity

Base Equation:

$Q = V * A$ [pg.80, D.C.S.S.S.]

(1) $V = \frac{(1.486)}{n} * R^{(2/3)} * s^{(1/2)}$

where:

n = Manning's Coefficient

a) Exisiting host pipe (pg.84, D.C.S.S.S.) n = 0.013

b) Liner pipe n = 0.010

R = Hydraulic Radius $= \frac{\text{pipe diameter (ft.)}}{4}$

R (original pipe) = 0.1667 ft.

R (lined pipe) = 0.1605 ft.

s = slope of pipeline $= \frac{\text{change in invert elevation}}{\text{distance between manholes}}$

M.H.#A invert depth = 12.000 ft.

M.H.#B invert depth = 11.000 ft.

Distance = 10.000 ft.

Therefore: s = 0.1000

(2) A = flow area of the pipe

= 0.85 * (D^2) / 4 * (pi) , [0.85 = 85% of pipe's full capacity]

A (original pipe) = 0.297 sq.ft.

A (lined pipe) = 0.275 sq.ft.

Modified Equation:

$$Q = \frac{1.486 * A * R^{(2/3)} * s^{(1/2)}}{n}$$

Q (V.C.P.) = 3.25 cu.ft./sec. = 1470.04 gal/min

Q (Lined pipe) = 3.82 cu.ft./sec. = 1728.09 gal/min

Q (Increase) = 0.57 cu.ft./sec. = 258.04 gal/min

Therefore: Increase in Flow Capacity (Q) = 17.55 %

SUMMARY OF RESULTS

1. Buckling Pressure

Minimum Liner Thickness t = 0.147 inch
Actual Liner Thickness t = 0.148 inch
3.8 mm

2. Computed Deflection y = 0.064 inch
Allowable Deflection 5% = 0.400 inch

0.064 < 0.400

Deflection is within acceptable limits.

3. Computed Ring Bending Ol = 2963 psi
Maximum Ring Bending Ol (max) = 10800 psi

2963 < 10800

Ring Bending is within acceptable limits.

4. Computed Minimum Stiffness = 0.423 in-lb
Allowable Minimum Stiffness = 0.093 in-lb

0.423 > 0.093

The liner thickness meets the minimum
Long-Term Stiffness requirements.

5. Percent Increase In Flow Capacity = 17.55 %

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Professional Profile
Trenchless Technology Work

Name: **BRIAN M. ROHAN, P.E.**

Position: Consultant – Sanitary Sewer Collection Systems

Education: Bachelor of Civil Engineering, Manhattan College, 1972
Master of Business Administration, Long Island Univ., 1975

Registration: Professional Engineer - New York, 1977
Professional Engineer - New Jersey, 1977
Professional Engineer - Connecticut, 1977
Professional Engineer - Massachusetts, 1993

Affiliations: National Society of Professional Engineers
Practicing Institute of Engineering
American Society for Testing and Materials, ASTM
NASSCO – Certified Pipe Evaluator

Experience:
Brian M. Rohan, P.E. provides professional engineering services for pipe evaluation and replacement, and "trenchless" pipe rehabilitation throughout North America. With over 30 years of pipe design experience, Mr. Rohan is established as an authority on evaluation, design and construction supervision for micro tunneling, slip-line, roll-down, cured-in-place, deformed/reformed, folded/formed, pipe bursting, and shotcrete technologies. Mr. Rohan's expertise includes evaluation of field inspection data, pre-bid analysis of project designs, contractor pre-qualification, and construction phase services, including submittal review. He has been responsible for recommendation and design of the most appropriate and cost effective "trenchless technology" for various pipe rehabilitation applications. These projects include host pipe materials such as brick, vitrified clay, reinforced concrete, transite, asbestos cement, cast iron, ductile iron, and steel. Rehabilitation and replacement materials have included: polyvinyl chloride, polyethylene, resin/cloth, resin/fiberglass, and fiberglass/sand/resin matrix. Mr. Rohan's experience includes 4" to 6" sewer lateral pipe rehabilitation by lining, 8" to 16" pipe replacement by pipe bursting, 6" to 18" pipe rehabilitation by folded/formed and deformed/reformed, 4" to 84" pipe rehabilitation by cured-in-place, 42" to 84" pipe rehabilitation by shotcrete, 8" to 24" pipe rehabilitation by slip lining and roll-down, and 24" and 84" pipe replacement and rehabilitation by micro-tunneling.

PERSPECTIVES ON DURABILITY OF COMPOSITE MATERIALS STATUS AND PROMISE

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Department of Engineering Science and Mechanics
Virginia Tech, Blacksburg, VA, USA

Abstract

The field of durability of composites has made remarkable strides in the last ten years. The Failure Analysis and Prevention Special Interest Group in SPE is evidence that this progress is now impacting the applied community. It is appropriate that we assess the status of the field and set directions for the future growth and application of this important field. The present discussion will attempt to outline the current capabilities and approaches that have shown promise, and to discuss the related experimental techniques that are available to support them. Then, comments on the gaps in those modeling and experimental capabilities ill be identified and possible directions for future research and development will be suggested.

Durability - the Concept

The basic concept of durability and damage tolerance is illustrated in Fig. 1. Durability is an engineering definition that requires one to specify the applied conditions and environments, and is generally defined by the life of the component under those applied conditions. A complementary concept, to be discussed later, is damage tolerance, the ability of a material or engineering component to retain strength (or performance) over a given life. Historically, something is said to be durable if it lasts a long time. In Fig. 1, the ordinate is normalized, so that the performance that defines "lasts" (or "fails") may be something other than strength, i.e., mechanical failure is not the only useful criterion for durability.

For plastics and polymer based composites, it is necessary to address the question of durability in a variety of structures and engineering components that are important to our everyday lives, and to the economy of our country. Modern applications of polymers and polymer composites of special importance include bridges (especially reinforcements for earth quake damage remediation), off shore structures and piping, a wide variety of components for vehicles (including tires), turbines (including jet engine components), pipes, tanks, and boats.

Indeed, it is these applications that define and frame the present discussion of the status and promise of durability as a discipline in the polymer and polymer composite community. Historically, durability in this community has been defined in of one of two ways, by the time to physical failure under a fixed constant set of applied (often environmental) conditions, or by the number of times an applied condition can be applied before physical failure occurs (as in freeze-thaw tests). However, present day applications require more general definitions that are more precisely associated with the function of the materials in the components in which they are found. It is not always good enough to know that a polymer or composite part did not fracture during a specific period of time in a laboratory test, for example. It may be necessary to know how the properties and performance of the materials are changing during the application of the actual time-variable conditions that occur during service life, and to relate those changes to the manner in which the materials are made, especially to the internal constituents and micro- or nano-structure of the materials.

One can think of this definition of durability as being defined by material state changes. An easy example of this type of change is illustrated in Fig. 2. The data shown in that figure represent the creep compliance of a carbon reinforced polymer composite as a function of aging time. One can see that the compliance is rather strongly affected by the aging process, which is physical aging in this case. As it happens, this variation in stiffness is important not only to the material itself, but to the determination of the stress and strain state in the engineering component that is made from the composite.

Figure 3 illustrates another example of material state change that influences properties and performance, and therefore, durability. That figure shows tensile break strength (normalized by cross link density, and temperature) vs. strain to break for a wide range of polymer materials including the Epon 828/Jeffamine system examined by Shan, et al.[1] As it happens, there is a nearly universal relationship between durability and break strength in a wide range of materials. The normalization of the break strength by cross link density and temperature in Fig. 3 suggests a direct relationship between those variables and durability of polymers.

Indeed, when material fracture is the event that defines durability, the material state changes that control durability can generally be represented by either changes in stiffness or changes in strength. We will illustrate this fact, and indicate how it provides a key to determining the relationship between measureables and engineering properties and performance.

Viscoelastic behavior changes stiffness, as we have seen in Fig. 3. So the classical phenomenon of creep can be represented as a stiffness change. In the case of composites, that change affects the compliance in matrix-controlled directions, only, if the fibers are not viscoelastic. However, creep may also be a phenomenon that affects strength, since, as shown in Fig. 4, creep of a material may lead to failure. This type of behavior, called creep rupture or stress rupture is common in high temperature materials such as ceramics. It is less common in fiber reinforced polymer matrix composites. Still, it is quite possible for high volume fraction carbon reinforced polymer composites to show time dependent failure at elevated temperature, even when loaded uniaxially in the direction of the fibers.[2] Unidirectional specimens under end-loaded compressive bending fail in seconds at temperatures of the order of 60 percent of the Tg, when loaded to fractions of their failure strain of the order of 50 percent. This type of out of plane failure is not uncommon in industrial applications.

Fatigue is another common phenomenon in engineering components. A typical damage mode associated with fatigue is matrix cracking and fiber failure, as shown in Fig. 4. In general, this type of damage causes a stiffness change that is small in fiber directions (a few percent, commonly) and a significant stiffness change in directions controlled by matrix properties. It is interesting, however, that there is typically very little if any strength change caused by such damage. The reason for that is the fact that when the strength of the composite is measured, the cracks in the matrix and the fiber breaks occur during the quasi-static loading process to the fracture load, so the fracture strength reflects their presence. It should be mentioned, however, that the density of fiber fractures and matrix cracks is typically greater under fatigue loading than under quasi-static loading. Still, the strength is typically not altered until quite close to the end of life.

It should also be noted that the tensor values of strength in the different material directions may change differently, under any given applied condition. Figure 6 shows an example of this for the dependence of strength on temperature for a polymer based composite. In that figure, it is not surprising that the compressive strength in the matrix-controlled direction perpendicular to the fibers is most greatly affected. But it is surprising that the tensile strength has a maximum as a function of temperature.

That result brings us to our next fundamental point. Durability is becoming a science, and not just a phenomenological observation. As it happens, there is a very good reason why there is a maximum in the fiber-direction tensile strength, as shown in Fig. 6. If the matrix around a fiber fracture is very stiff, then the stress concentration around a fiber fracture is very high and the chance that the fiber next to the break will also rupture – and the next, and so on, to cause brittle fracture of the specimen – is also very high. This is the situation at low temperatures, or at least the tendency at such temperatures. At very high temperatures, the matrix is so compliant that a broken fiber cannot be reloaded by matrix shear, so that the entire length of the fiber becomes "ineffective," i.e., there is a very long ineffective length. At some intermediate temperature (for a well designed composite) the best combination of fiber and matrix properties are achieved, and the best "composite effect" is obtained. This is true for short term or long term properties.

The science of this sort of effect can often be represented by micromechanics. It is, of course, possible to estimate the stress concentration near a broken fiber, and many papers have been written on this subject. And if that type of calculation is combined with a good philosophy of composite strength, a maximum in the strength dependence on temperature is predicted, as shown in Fig. 7. In that figure, low temperature corresponds to small ineffective lengths and high temperature corresponds to large ineffective lengths. [3]

This science is not complete (for example, there are not well established micromechanical representations of all of the tensor strength values, but good representations of tensor stiffness are available). Figure 7 shows a representation of stiffness with temperature across all transitions for a polymer, another essential element.[4] If such representations are used, composite strength can be predicted across such transitions as well (Fig. 9).

Closure

We have outlined the status of durability, with a focus on polymer composites. We have seen that the field is maturing quickly, from phenomenological observations to materials science, from descriptive "rules" over limited ranges of variables to predictive, robust science and philosophy that embraces the full range of conditions and variables that are expected in the operating environment(s).

Which leaves us with the question of "what is the promise?" The promise is that the science and engineering of the newly emerging field of durability will bring us cost effective, safe, and reliable engineering components and systems that make the best use of resources, and enable us to use and depend on the latest technical advances in materials science (especially newly developed materials). The promise is an enabling science that replaces the "after the design fact" rules and practices that now pervades the field. The promise is support for a better life and stronger economy for all of us.

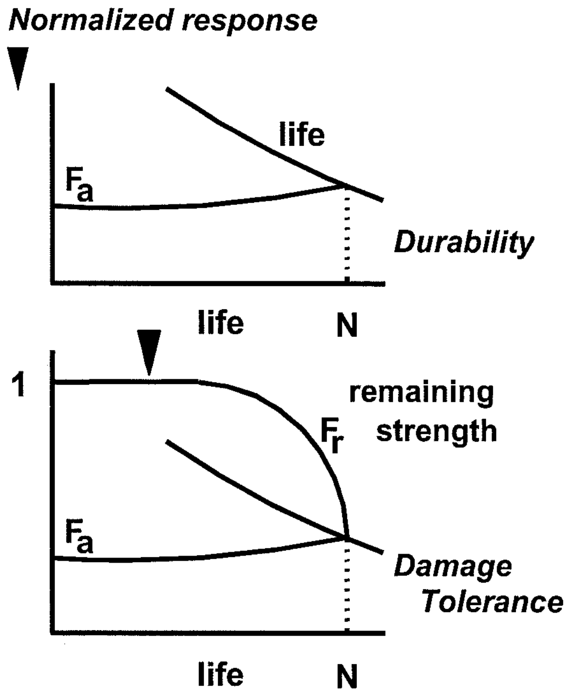


Figure 1 Basic durability concepts.

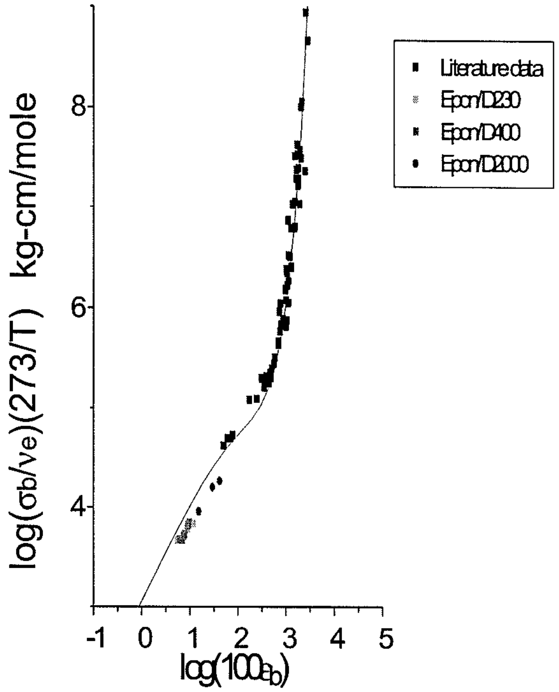


Figure 3 Literature data and Epon 828/Jeffamine network systems fitted on the expression in an analog of the MRS equation.

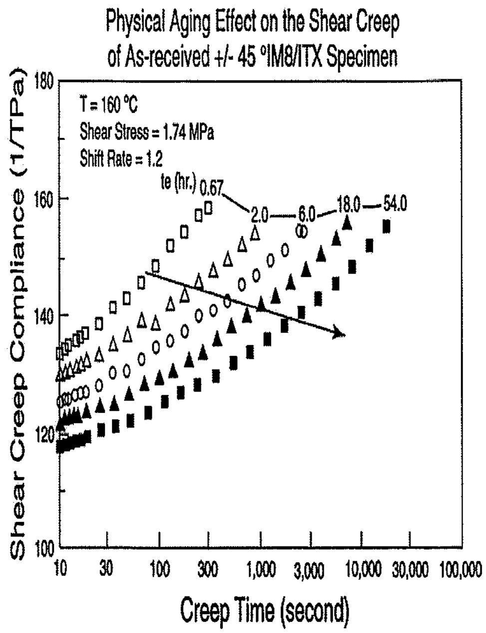


Figure 2 Effect of physical aging in a carbon reinforced polymer composite.

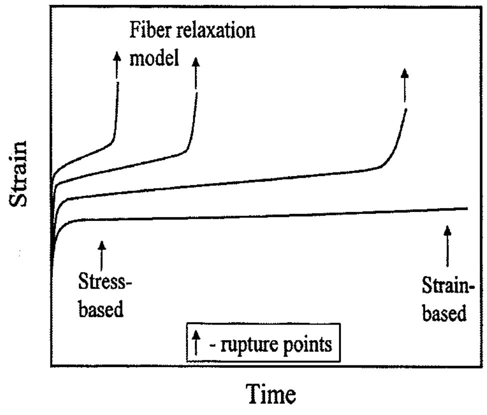


Figure 4 Time dependent failure of composite laminates.

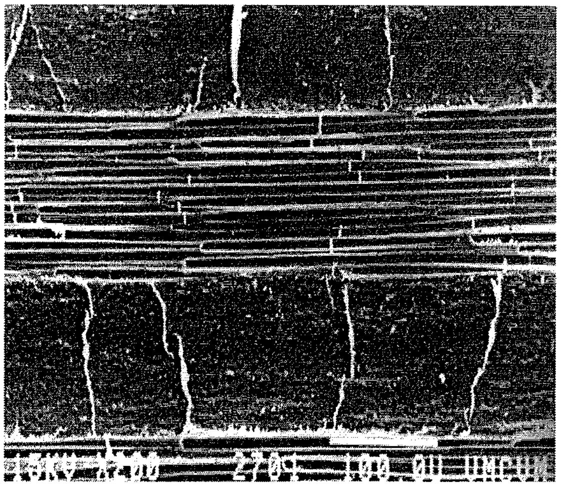


Figure 5 Micro-cracking and fiber fracture in carbon epoxy composite laminates.

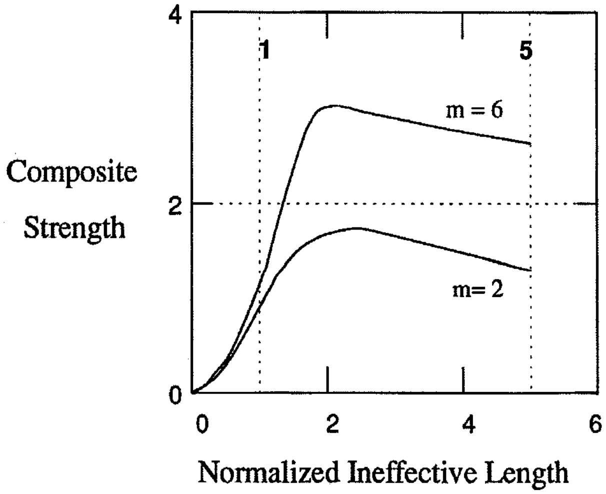


Figure 7 Predictions of unidirectional composite tensile strength as a function of ineffective length near fiber fractures.

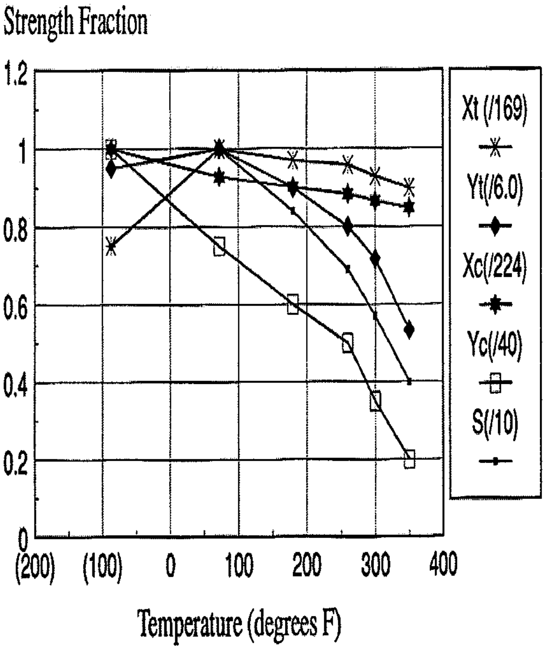
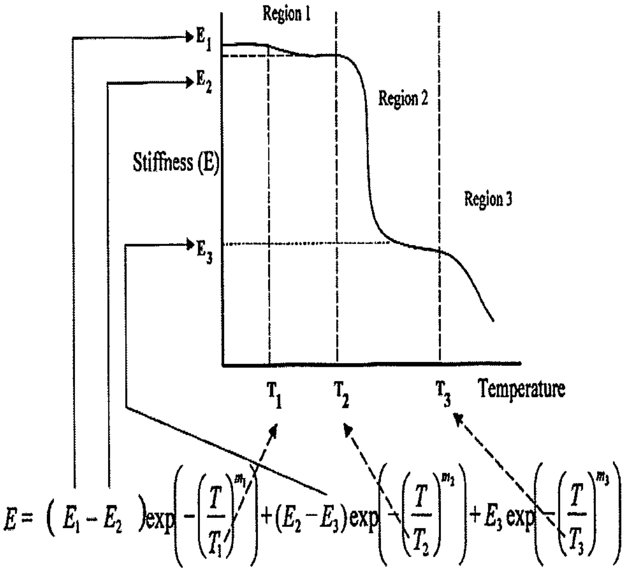


Figure 6 Changes in composite laminate tensor strength values with temperature.



$$E=(E_1-E_2)\exp\left(-\left(\frac{T}{T_1}\right)^{m_1}\right)+(E_2-E_3)\exp\left(-\left(\frac{T}{T_2}\right)^{m_2}\right)+E_3\exp\left(-\left(\frac{T}{T_3}\right)^{m_3}\right)$$

Figure 8 Representation of continuous stiffness change across transitions in a polymer or polymer composite.

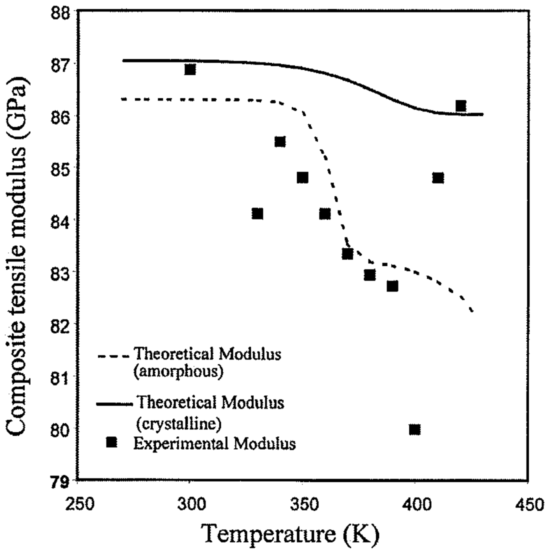


Figure 9 Predicted and observed tensile strength of unidirectional polymer composite across the secondary transition temperature.

REFERENCES

1. L. Shan, K.N.E. Verghese, C.G. Robertson, K.L. Reifsnider, 1999, "Effect of Network Structure of Epoxy DGEBA-Poly(oxypropylene)diamines on tensile Behavior," J. of Polymer Science, 37, 2815-2819.
2. C. Mahieux, B.E. Russell, and K.L. Reifsnider, 1998, “Stress Rupture of Unidirectional High Performance Thermoplastic Composites in End-Loaded Bending at Elevated Temperatures: Part I Experimental Characterization of the Failure Mode,” J. of Composite Materials, 32 (14), 1311-1321.
3. Z. Gao and K.L. Reifsnider, 1992, “Tensile Failure of Composites: Influence of Interface and Matrix Yielding,” J. of Composites Technology and Research, 14 (4), 201-210.
4. C. Mahieux and K.L. Reifsnider, 2001, “Property Modeling Across Transition Temperatures in Polymers: A Robust Stiffness-Temperature Model,” Polymer, 42 (7), 3281-3291.