Appendix A: Step and Singularity Functions

A.1 Unit (Heavyside) Step Function

The unit or Heavyside step function is defined as,

\[
H(t) = \begin{cases} 
1, & t \geq 0 \\
0, & t \leq 0
\end{cases}
\]

and can be represented graphically as,

![Graph of the unit step function](image)

The unit step function is used to indicate a discontinuous change in another function at a particular point in time. If for example the function \( F(t) \) is given as,

\[
F(t) = f(t)H(t - t_1)
\]

It states that the function \( f(t) \) is zero before \( t = t_1 \) and is only defined for \( t > t_1 \) as illustrated graphically by,
Differentiation of the unit step function yields the singularity, or Dirac delta, function which is defined as,

\[ \delta(t) = \begin{cases} 
0, & t \neq 0 \\
\infty, & t = 0 
\end{cases} \]

and is represented graphically as,

The function \( \delta(t) \) becomes infinite in the limit as \( \varepsilon \to 0 \) and is defined such that the integral of the function yields unity

\[ \int_{-\infty}^{+\infty} \delta(t) \, dt = 1 \]

The singularity function results when the step function is differentiated, i.e.,
The singularity function has unique properties. For example, when a function such as $f(t)$ is multiplied by a singularity function, $\delta(t)$, and then integrated, the result is the function evaluated at the location of the singularity function. That is,

$$\int_0^t f(t)\delta(t-t_1)dt = \int_0^t f(t) \frac{d[H(t-t_1)]}{dt}dt = f(t_1)$$

This is known as the sifting property of the Dirac delta function.
Appendix B: Transforms

B.1 Laplace Transforms

The Laplace transform is a linear operator which is defined as,

\[ \mathcal{L}\{f(t)\} = \tilde{f}(s) = \int_0^1 f(t)e^{-st}dt \]

The above integral is easily evaluated for many simple functions which can be illustrated by finding the Laplace transform of an exponential as follows,

\[ \mathcal{L}\{e^{at}\} = \int_0^1 e^{at}e^{-st}dt = \int_0^1 e^{-(s-a)t}dt = \frac{1}{s-a} \]

The Laplace transform of many simple trigonometric, exponential and other functions results in the given function being replaced by an algebraic function. For example, the Laplace transform of the derivative of a function is,

\[ \mathcal{L}\{f'(t)\} = \int_0^1 \frac{df(t)}{dt}e^{-st}dt = s\tilde{f}(s) - f(0) \]

Because the Laplace transform of a time derivative (of any order) is an algebraic function, differential equations involving time are converted to algebraic expressions by a Laplace transformation. Thus, differential equations involving time can often be solved in the transform domain by using usual algebraic techniques provided that the result can be inverted back to the time domain.

The Laplace transform of many functions have been evaluated and the results tabulated. Extensive tables may be found in many texts on the subject. The Laplace transform of a few functions is given in the table below,
**Example of function – laplace transform Pairs**

<table>
<thead>
<tr>
<th>$f(t)$</th>
<th>$\tilde{f}(s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>$\frac{c}{s}$</td>
</tr>
<tr>
<td>$t$</td>
<td>$\frac{1}{s^2}$</td>
</tr>
<tr>
<td>$e^{at}$</td>
<td>$\frac{1}{s-a}$</td>
</tr>
<tr>
<td>$\sin \omega t$</td>
<td>$\frac{\omega}{s^2 + \omega^2}$</td>
</tr>
<tr>
<td>$\cos \omega t$</td>
<td>$\frac{\omega}{s^2 + \omega^2}$</td>
</tr>
<tr>
<td>$f'(t)$</td>
<td>$s\tilde{f}(s) - f(0)$</td>
</tr>
<tr>
<td>$f(t-a)H(t-a)$</td>
<td>$e^{-as}\tilde{f}(s)$</td>
</tr>
</tbody>
</table>

Obviously, one approach to find the inverse Laplace transform is by using the known transforms that can be found in tables. Often, manipulation of an algebraic transform (such as breaking up expressions using partial fractions) can result in a form that is easily found from a table of known transforms. When such a simple procedure is not applicable, the inversion may be possible using the inversion integral,

$$f(t) = \mathcal{L}^{-1}\{\tilde{f}(s)\} = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} \tilde{f}(s)e^{st}ds$$

This method involves contour integration in the complex plane and is beyond the scope of this text.

The convolution (Faltung) integral is defined as,

$$\int_0^t f(t)g(t-\tau)d\tau = \int_0^t g(t)f(t-\tau)d\tau$$

The Laplace transform of the convolution integral is,

$$\mathcal{L}\left\{\int_0^t f(t)g(t-\tau)d\tau\right\} = \mathcal{L}\left\{\int_0^t g(t)f(t-\tau)d\tau\right\} = \tilde{f}(s)\tilde{g}(s)$$

Due to the occurrence of convolution integrals naturally in the viscoelastic constitutive law, Laplace transforms can be quite useful.
B.2 Fourier Transform

A function, $f(t)$, may be related to itself via the Fourier integral as

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} e^{i\omega t} \left\{ \int_{-\infty}^{+\infty} f(\xi) e^{-i\omega \xi} d\xi \right\} d\omega$$

and is often represented by the Fourier transform pair,

$$F(\omega) = \int_{-\infty}^{+\infty} f(\xi) e^{-i\omega \xi} d\xi$$

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} F(\omega) e^{i\omega t} d\omega$$

If the $f(t)$ in the Fourier integral has no value for $t < 0$, the integral becomes,

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} e^{i\omega t} \left\{ \int_{0}^{+\infty} f(\xi) e^{-i\omega \xi} d\xi \right\} d\omega$$

and can be shown to lead to the Laplace transform pair (Thomson 1960),

$$f(s) = \int_{0}^{+\infty} f(t) e^{-st} dt$$

$$\tilde{f}(s) = \int_{c-\infty}^{c+\infty} \tilde{f}(s) e^{st} ds$$

Similar to Laplace transforms, Fourier transforms also have special properties under differentiation and integration making them a very effective method for solving differential equations. Due to the form of the constitutive laws in viscoelasticity, Fourier transforms are quite useful in analysis of viscoelastic problems.
Appendix C: Durability and Accelerated Life Predictions of Structural Polymers

Polymers are used in many structural circumstances but due to their low modulus relative to metals and other materials they are not used alone where high modulus and high strength are required. However, in such situations they are often used as the matrix material in polymer based composites and as an adhesive in some highly stressed connections. The focus of this chapter is therefore on adhesively bonded structures and polymer matrix composite (PMC) structures sometimes known as fiber reinforced plastics (FRP). One example of a highly successful adhesively bonded structure is the Fokker aircraft F 27 developed in the Netherlands after WW II followed by the F 28 in 1965 and the F 100 in the mid 1980s. The technical director of Fokker for this effort was Rob Schliekelman whom the senior author of this text had the privilege to meet in the early 1980s at the Fokker plant in Delft. The unique feature of these planes was that they were made using thin aluminum sheets bonded together in the same manner as thin sheets of wood are bonded together to make plywood. The motivation for this development was that WW II decimated the heavy machinery industry in Holland and using the lamination technique was the only way they could build up their aircraft industry quickly. Figure C.1 is an illustration from a Fokker brochure that demonstrates the type of lamination and bonding used. Indeed the success of Fokker in building planes in this manner led to the highly funded US Air Force PABST (Primary Adhesively Bonded Structures Technology) program in the 1980s. Similarly, in the late 1990s NASA instituted a high-speed civil transport (HSCT) program where composite structures were to play a significant role. These two programs were indisputably influential in the eventual use of bonded and composite structures in both military and commercial aircraft. The Boeing 787 with over 50 % structural composite is, at least partially, a result of these two federal programs.
Of course, in both PMC and/or bonded connections as well as in any circumstance where a structure must last for many years durability is of major concern. Often durability in a structural sense is most often associated with fatigue. However, as seen in the last chapter, time dependent failure due to the viscoelastic nature of polymers is also a durability concern. In this chapter it will be shown that the time-temperature–superposition-principle (TTSP) can be used effectively to assess the durability of both adhesively bonded and/or PMC structures.

C.1 Adhesively Bonded Structures

The use of polymer adhesives in structural circumstances is many and varied. The details of specific applications with techniques and procedures are too numerous to mention in a single chapter. However, the 1992 Engineering Materials Handbook Volume: 3 Adhesives and Sealants and the 2006 Handbook of Adhesives and Sealants, 2nd Edition published by ASM International are recommended for in depth reading on chemistry, surface treatments, design procedures, equipment, etc. A more recent compendium of articles relative to adhesive selection, surface treatments and environmental effects may be found in Dillard (2010). Here only essential features relevant to durability concerns will be covered.

For engineering design, modulus and strength properties are required. For bonding of similar or dissimilar materials such properties of the adherends (the surfaces to be bonded together) and the adherent (the adhesive) must be
determined. For example, for bonding aluminum to aluminum with an epoxy requires the properties of both the aluminum and the epoxy. In most cases the properties of the aluminum can be found in the literature or can be determined experimentally. The properties of epoxy are reasonably well known but determination of the properties should be verified for the circumstances of the intended use. Stress-strain properties of an epoxy are given in Figs. 3.10 and 3.11 as well as the variation of modulus with temperature in Fig. 7.2 and a master curve using the TTSP in Fig. 7.4. However, these properties should not be used arbitrarily as the properties of another epoxy might be significantly different. Even knowledge of the correct properties for a particular aluminum and a particular epoxy would be insufficient information to assure a good bond as it is well known that there is a third material to consider – the interface or more properly the interphase. In all cases of bonding the surfaces need to be clean and dry and for best results for structural bonds surfaces need to be preconditioned with a surface treatment. Such pretreatment creates a new material called the interphase. The adhesive layer is normally very thin, usually a few millimeters or less. The interphase is much smaller and may only be tens of nanometers. The question then becomes how to correctly determine the properties of this interphase region such that the information could be used in a finite element program for a correct stress analysis. The local properties of polymers near interfaces is an active area of research, with novel methods being developed to determine glass transition temperatures and moduli as a function of distance from a surface (Rittigstein et al. 2007; Watcharotone et al. 2011). As yet, no definitive test to determine modulus and strength properties of this region has been devised.

For the above reasons many different tests have been developed to determine the properties of an adhesive joint. Some of these are:

- Lap joints (single, double and modified)
- V-notched beam (Iosipescu)
- Arcan
- Plate-twist
- Torsion of cylindrical butt joint
- Thick adherend
- Napkin ring
- Skin doubler
- Wedge
- Peel
- Blister

Details for many of these methods can be found in various sources on the internet. Also, details of each of these tests as well as other relevant information on adhesive bonding can be found at the National Physical Laboratory (NPL) website using the search term “adhesivestoolkit.” where the test
desired is inserted in the underlined area, e.g., adhesivestoolkit.peeltest. Also, ASTM or ISO standards are available for most of these tests.

C.2 Adhesive Durability Tests

The first seven tests listed above are often thought of as tests to determine the shear properties of an adhesive joint. However, in most cases the stress state is not pure shear but a combined stress state. Indeed in all the lap shear tests significant peel stresses exist (see Anderson et al. 1982 and Strozier et al. 1988). It has been shown that the Arcan and the Iosipescu tests are close to the case of pure shear. However, the lap shear test is most often used due to its simplicity.

One durability test that has been used is shown in Fig. C.2. In this test a chain of lap joint specimens are loaded in tension by a compressed spring attached to

![Schematic of 3M durability tester](image_url)
the fixture. Often as many as 10 or more fixtures are placed in an environmental cabinet where the temperature and humidity is controlled. In this manner numerous specimens can be tested under different stress levels at one time. Filby and Wightman (1988) used such a test to evaluate the effect of various surface treatments on titanium to titanium single lap shear specimens bonded with an FM-300 adhesive. The results are shown in Fig. C.3. As may be observed results varied significantly depending on the surface treatment. Obviously, from this test the CAA (chromic acid anodization) would be preferred. Filby and Wightman (1988) also performed wedge durability tests that indicated that CAA and TURCO were the same with very little crack growth over time. In their study they used a number of surface analysis techniques including XPS, AES, FTIR STEM to evaluate the surface treatment before and after failure. Their conclusion was that the anodization (CAA) was superior to the etches (P/F, TURCO) as the former was more porous than the latter.

Fig. C.3 Time to failure windows for the stress durability test at 40 % strength to break load at 80 °C and 95 % r.h.
Clearly it is possible to use the TTSP to obtain master curves of the adhesive modulus and strength properties obtained through the use of lap shear (or other specimen) and thereby make an effort to establish long term design data experimentally. However, this does not provide accurate information about the properties of the interphase that can be used in a finite element analysis. One possibility is to estimate the ratio of the interphase properties to that of the adhesive to give an estimate of how the variation of properties might affect the analysis. Botha (1983) used this approach to estimate the effect of the interphase properties on the shear stress distribution in a single lap shear specimen as shown in Fig. C.4. (See also, Brinson and Grant 1986.) As may be observed the interphase property has a significant effect on the stress distribution.

It is clear from the above that better measurement technique need to be developed to determine properties of materials in the nanometer range and on the interior of an adhesive bond.

![Diagram showing shear stress distribution](image)

**Fig. C.4** The effect of different interphase to adhesive moduli ratio on the stress distribution along the bondline
C.3 TTSP Applied To PMC Structures

An early use of the TTSP to produce a storage modulus master curve for a Boron-Epoxy composite was reported by Heller et al. (1975) using forced oscillation tests at different frequencies and temperatures. Cardon and Hiel (1981) also used forced oscillation tests to study the viscoelastic behavior of composites. Yeow (1978) performed a large number of creep tests at various elevated temperatures (30 temperatures between 23 °C and 210 °C) at fiber angles (10°, 15°, 30°, 45°, 60°, 75°, 90°) on unidirectional T300/934 tensile specimens. The creep tests were of short duration (16 minutes) and were used to produce a master curve at each fiber angle using the TTSP. In turn, the master curves for axial, transverse and shear compliance were found such as the one given in Fig. C.5 for 1/S66 for T = 180 °C. A similar master curve was produced for 1/S22.

Also included were tests measuring the coefficient of thermal expansion to determine the glass-transition temperature, Poisson’s ratios and linearity. Constant strain-rate tests were used to ascertain strengths for various fiber angles. Shift factors were found and compared for all fiber directions tested but unlike expectations little variation of shift factor with fiber angle was found. The shift factor variation with temperature was found to match the WLF equation above the glass transition temperature and be in agreement with an activation energy type shift factor below the glass transition temperature. The results were then used with laminated plate theory to predict the response of multidirectional composite laminates. The foregoing efforts led to the development of an accelerated life prediction methodology outlined in Fig. C.6 and first presented by Brinson et al. (1978) and later in a series of publications with colleagues in the early 1980s (See, Morris et al. 1980; Brinson et al. 1981, 1982; Hiel et al. 1983.) This approach makes it possible to determine long-term (years) behavior over the lifetime of a polymer based composite structure from data taken over a short time interval (minutes or days) and could include the effects of a number of environmental parameters including time, temperature, stress, moisture and, perhaps, other environmental parameters. It was suggested that this method could be used to produce a multidimensional property surface that could be modeled analytical and used with various computational procedures such as laminated plate theory or finite element analysis to ascertain the lifetime of a composite structure.
Fig. C.5 Reciprocal of compliance, $1/S_{66}$, and portion of master curve at 180 °C for T300/934 epoxy laminate. (*Upper:* short-term data and portion of master curve. *Lower:* complete master curve and long-term, 25 hour, test)
C.4 Time Dependent Failure Master Curves

Time dependent failure has long been of concern to design engineers. For an interesting description and an extensive reference list of early time dependent aging and accelerated life prediction techniques including the Arrhenius and Eyring’s models (See Carfango and Gibson 1983).

Early failure strength master curves were developed by Lohr (1965) and Halpin and Polley (1967). In the former, yield strength master curves were formed using constant strain rate tests from 0.003 to 300 min\(^{-1}\) and from 15 °C above the glass transition temperature to 100 °C below the glass transition temperature for poly(methyl methacrylate), polystyrene, polyvinyl chloride, and polyethylene terephthalate. In the latter, the creep rupture strength for an SBR Gum polymer at different temperatures was shifted to form a master curve that could be fitted with a modified power law. The master curve had the traditional sigmoidal shape of a modulus master curve but was actually formed from data plotted as the ratio of the number specimens (out of 60) that did not fail for each temperature and stress level and as a result represented survival rates rather than failure rates.
C.5 Time Dependent Modulus, Fatigue and Failure Master Curves

At a durability conference organized by Albert Cardon, et al. at the University of Brussels (VUB) Miyano (1996) introduced a procedure to predict long-term static, creep and fatigue strengths of carbon reinforced polymer composites based on the TTSP. Following this introduction Miyano and his colleagues in an excellent series of publications reported the details of a comprehensive procedure to develop master curves using the TTSP as the foundation for the accelerated life or durability prediction of various fiber reinforced polymer-based composites (See, Nakada et al. 1996; Miyano et al. 1999, 2002, 2008). Included were not only modulus or compliance master curves but also strength and fatigue master curves as well for temperatures above and below the glass-transition temperature. They found that the same TTSP approach was applicable for the resin and its composites for modulus (compliance) and for strength from constant strain-rate tests. Fatigue strengths were found to exhibit linear dependence on the stress ratio of the cyclic loadings and Robinson’s time fraction rule (linear cumulative damage) was applicable for monotonic increasing loads. Figure C.7 gives a schematic of Miyano’s accelerated life prediction procedure reproduced from Miyano et al. (2008). This method was verified for a large number of resins such as; epoxy, PAN, PI, BMI, and vinylester, and composites made with the resins and such fibers as carbon, pitch, and glass.

Tsai et al. (2003) reported on an accelerated insertion program developed for composite materials. The fundamental concept was that a procedure was needed to shorten the time required for a new material to be used in primary structural applications. They relied on Miyano’s TTSP based accelerated life prediction method combined with micromechanics analyses together with a 3-D finite-element based analysis of complex composite laminates and structures which included a strain invariant failure theory. They too evaluated a wide spectrum of resins, fibers and laminates. Most impressively they presented initial and final failure data on an AS4/3501-6 [0/90/45/−45] biaxial laminate superimposed on predicted initial and final failure envelopes. Data and theory correlated extremely well. As the program (AIM-C) under which this research was accomplished was led by a Boeing team, it is encouraging to know that most likely the design of aircraft using polymer-based composites has an integrated experimental and analytical basis for making rational long-time predictions of structural performance including delayed time dependent failure due to the viscoelastic nature of such materials.
Topics of current composite research importance are biological tissues, nanocomposites and fuel cells. Insight to the viscoelastic behavior of these materials can be found in the literature, including for biological materials (Garner et al. 2000; Ma et al. 2012), nanocomposites (Fisher et al. 2004, 2006 and fuel cells (Lia et al. 2009). The extent of the use of superposition techniques such as the TTSP, TSSP, etc. for this research involving these materials is certainly possible but their use is still in its infancy at this time.

Fig. C.7 Schematic of Miyano’s accelerated life prediction procedure (Redrawn from Miyano et al. 2008)
Appendix D: Herbert Leaderman: A Master of Polymer Physics and Mechanics

Herbert Leaderman (1913–1965) (Photo 1948: Courtesy of NIST Archives)

Leaderman was born in London and matriculated at both the University of Cambridge and the University of London in 1934 with an Honors B. A. from the former and a B. S. in Engineering from the latter. He later worked for Aero Research Limited as an Assistant to the Director from 1936 to 1937 on “Research and Development – Plastics” according to a bio obtained by courtesy of the NIST Archives. He was awarded a Robert Blair Fellowship from the London County Council (termed a “Traveling Fellowship” in his NIST bio) that he used to attend MIT in 1937–1938 engaged in studies and research toward an S.M. degree in Mechanical Engineering. His thesis title was: Creep, Elastic Hysteresis, and Damping in Bakelite and was concerned with evaluating the energy lost in materials that could be attributed to elastic hysteresis and/or damping. The motivation was that a distinction between the two effects in metals was small and hard to measure but in polymers (such as Bakelite) differences would be larger and measurable. Hence, he elected to do his studies on Bakelite and received materials from both Bakelite Limited of England and the Bakelite Corporation of America. Another focus of his S.M. was to ascertain if the
Boltzmann Superposition Principle was valid for the case of creep of Bakelite, a concern that carried over to his later Sc. D. studies at MIT. Temperature was not a consideration in this study and there is no mention of time-temperature shifting. Indeed, he listed only seven references and the only one that was later used in his Sc. D. was Boltzmann’s 1876 paper relative to the superposition principle. There was no mention of papers by Kobeko (1937) or Hetenyi (1938, 1939) that were prominently featured in his Sc. D. thesis. It is safe to say that his efforts relative to the time-temperature-superposition-principle were only a result of his Sc. D. research.

Leaderman’s S.M. thesis advisor was Alfred V. de Forest an associate professor in the mechanical engineering department. De Forest was an innovator and an entrepreneur. He had earlier founded Magnaflux, Inc. that marketed “stress coat” and a “carbon strain gage”. Brittle coatings such as “stress coat” were applied to models of various engineering structures made of metal or other materials to determine the regions of high tensile stress because the coating would exhibit cracks perpendicular to such areas. The most successful coating was made from “wood rosin” extracted from pine trees, a natural polymer. Sometimes models were made of brittle polymers such as PMMA, Bakelite, etc. that would exhibit surface cracks in regions of high tensile stress. (See Hetenyi 1950 for in-depth information.) The carbon strain gage was a thin carbon rod sanded down to a flat sheet and bonded to a structure to be tested. When stressed the resistance change in the carbon was measured and, when calibrated, would provide a measure of the surface strain. However, the carbon gage was only useful for dynamic applications and could not be used for static circumstances. As a result there was a keen interest in developing a better strain gage. Magnaflux is still in business though their focus has shifted to more modern products.

Author C. Ruge was an assistant professor in civil engineering interested in seismology and the associated equipment for related laboratory studies. (He later became the first professor of seismology at MIT.) Ruge was interested in developing very sensitive instrumentation that could be used in equipment to simulate earthquakes and was undoubtedly familiar with the carbon strain gage produced by de Forest at Magnaflux. In 1938 he experienced, by his own admission, a “eureka moment” and invented the forerunner of the SR-4 electrical resistance strain gage. This was essentially four thin tungsten filaments sandwiched and glued between thin sheets of paper and bonded to a structure to be tested under load. When stretched the resistance in the wires changed and could be related to strain at that location. Ruge and de Forest collaborated to form a company, Ruge-deForest Inc., to patent and market the new strain gages. As it turned out another person, Edward E. Simmons a laboratory assistant for Donald S. Clark (an Assistant Professor at Cal Tech) had invented a similar
electrical resistance strain gage in 1936. (For more information on Simmons see: “Simmons and the Strain Gage”; Engineering and Science, Volume 50:1, September 1986. This can be found at: http://resolver.caltech.edu/CaltechES:50.1.0) Ruge and de Forest were very generous and included Simmons in their patent. The patent was for an SR-4 strain gage where the S and the R stood for Simmons and Ruge and the 4 was for the two of them plus their collaborators, Donald S. Clark and Alfred V. De Forest. A modern electrical resistance strain gage is shown in Fig. 2.6c. Ruge-deForest, Inc. was sold to Baldwin-Lima-Hamilton Corporation in 1955 but a division of Ruge-deForest that marketed temperature measurement products was retained and the name changed to RdF, Inc. and still remains today as a closely held company. (For more information on the history of the strain gage, see: Tatnall, Frank G.; Tatnall on Testing: An Autobiographical Account of Adventures Under 13 Vice Presidents; ASTM, 1967.)

There is no mention of electrical strain gages in Leaderman’s M.S. thesis but it is certain that he was aware of the strain gage activity of both de Forest and Ruge and likely participated in the development to some degree as he coauthored the following NACA Report and book on the subject with de Forest:


Forest, A.V and Leaderman, H., Die Entwicklung elektrischer Dehnungsmesser (The development of the electrical strain measure), Dessau: Junkers Flugzeug-und Motorenwerke AG, Stammwerk, Werkstoff-Forschung, Germany, 1941.

The NACA Report is available on NASA’s publication website and can be downloaded. A look at that report indicates that de Forest and Leaderman designed a reusable electrical resistance strain gage for the aircraft industry. The following abstract details their objective:

The design, construction, and properties of an electrical-resistance strain gage consisting of fine wires molded in a laminated plastic are described. The properties of such gages are discussed and also the problems of molding of wires in plastic materials, temperature compensation, and cementing and removal of the gages.

Further work to be carried out on the strain gage, together with instrumentation problems, is discussed.

De Forest and Leaderman published an earlier preliminary NACA report in 1939 that is referenced in the above publication. On his brief NIST bio Leaderman gives the following description of his position at MIT for the period
1938–1943: “Research Assistant (a) Physics of plastics and textile fibers, (b) Wire stain gage development”. So it is certain de Forest and Leaderman were working together on an electrical resistance strain gage soon after Ruge’s inspiration and likely with his approval. It is curious that Ruge’s name does not appear on these publications.

The 5th IUTAM Congress was held at MIT in Cambridge, MA in September of 1938. At this congress, Miklos Hetenyi of Westinghouse (and a former Ph. D. student of Professor Steven P. Timoshenko at the University of Michigan) made a presentation on “Photoelastic Studies of Three-Dimensional Stress Problems” which almost certainly Leaderman attended (see references, Hetenyi et al. 1938, 1939). This presentation and paper was the first effort that explained in detail the frozen stress procedure for determining the three-dimensional stress field within structural models made of Bakelite, BT-61-893. In this study Hetenyi presented creep data at various temperatures for this photoelastic model material that Leaderman later referenced and used in his Sc. D. thesis. (In fact in a footnote in his thesis, Leaderman thanked Hetenyi for providing his creep data on Bakelite.) This data together with the creep studies of Kobeko led Leaderman to his statement quoted in Sect. 7.2.1: “...it is not unreasonable to suppose that the creep curves are identical in shape but displaced relative to each other along an axis of logarithmic time; the effect of increases in temperature would then be to contract the time scale.” Indeed, Hetenyi in his efforts recognized that the same deformations observed at low temperature would be observed at a high temperature only faster. Using a Kelvin model and estimating the viscosity of Bakelite every $10^{14}$ C, he calculated that it would take on the order of 10,000 years for Bakelite at room temperature to reach the same level of deformation obtained in only a few minutes at high temperature.

After completing his S.M. in 1938 Leaderman switched advisors and completed his Sc. D. with Edward R. Schwarz a professor in Textile Technology at MIT a group within the mechanical engineering department. This was likely due to funding and the fact that de Forest and Ruge were heavily involved in creating a new company. Leaderman and de Forest were obviously still collaborating as evidenced by their publications in 1940 and 1941. It is clear that Hetenyi’s work on Bakelite was a stimulus and an aid to Leaderman’s Sc. D. thesis completed in 1941. On the other hand it is doubtful that Hetenyi was aware of his contribution to Leaderman’s work as the senior author of this text had many conversations with Hetenyi on the subject of master curves and the shifting procedures without a connection being made (see Brinson 1965). This is a classic example of how one person’s efforts contribute to the work of another and the connection between the two is lost in the haze of time!
Between 1943 and 1946 Leaderman was a staff member at the MIT Radiation Lab, a physicist at the Firestone Tire and Rubber Co. from 1946 to 1948 with a brief stint as an instructor for a few months in 1947 at the University of Akron. He joined the Physics group at NIST in 1948 and published numerous papers and reports relative to the temperature effects on polymers throughout his career. He was awarded a Fulbright Fellowship in 1956–1957 to give lectures on the physics of high polymers at the Gakushiu University and the Tokyo Institute of Technology. He was awarded the Bingham Medal by the Society of Rheology in 1955.


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