Suggested Approaches for Revisions of Preliminary Performance Criteria for Tensile and Tensile Fatigue Strength Tests of Bituminous Membrane Roofing

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

Alternative approaches are reviewed for revision of the original NBS preliminary performance criteria for tensile strength and tensile fatigue strength of bituminous membrane roofing. Reviews of five approaches - elasticity theory, brittle fracture, viscoelasticity theory, strain energy and finite element techniques - were completed. Advantages and limitations of these approaches were identified and use of the strain energy approach for both tensile strength and tensile fatigue strength preliminary performance criteria was recommended.

Key Words: Bituminous roofing; built-up roofing; membranes; performance criteria; strain energy; tensile strength; tensile fatigue strength.

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1. INTRODUCTION

1.1 Background

Preliminary performance criteria for bituminous built-up roofing membranes have been used widely since their introduction in 1974 in NBS Building Science Series 55 (BSS 55) [1]. The use of preliminary performance criteria enabled product manufacturers and roofing contractors to measure properties of new and existing bituminous roofing membranes against a technically sound baseline. The criteria developed were based on a laboratory program of testing membrane specimens prepared in the laboratory and specimens obtained from roofs in service [2,3]. The results of the laboratory test program were complemented by practical experience with the performance of membranes in service.

Performance criteria for membranes are attempts to understand performance in engineering terms for one component of the roofing system. It is important that full consideration be given to other roof assembly parameters that may affect the performance of a bituminous built-up roofing membrane. For example, the type of attachment, weather extremes, roof traffic, and presence of contaminants should be considered. Preliminary performance criteria discussed in BSS 55 [1] were recommended as necessary for conventional built-up membranes to perform adequately over their service life, after installation, presuming that manufacture and application of the assembled roofing system have been completed in accordance with good practice.

The original preliminary performance criteria for bituminous membrane roofing have served the roofing industry well. The preliminary performance criterion for tensile strength was perhaps the most widely used of the twenty criteria identified and was included in the National Roofing Contractors Association

(NRCA) Roofing and Waterproofing Manual [4]. More recently, it has been included for built-up membranes testing in the NRCA Materials Reference and Guide ("the NRCA Guide") [5]. The related preliminary performance criterion for tensile fatigue strength has been less widely used.

Since the development of these preliminary performance criteria for bituminous built-up roofing membranes, many new bituminous membrane materials have been developed and introduced into the U.S. roofing market. These new materials include polymer-modified bitumens and synthetic fabrics such as polyester fibers and polyester with glass fiber. Their introduction as membrane materials has motivated proposals for new methods for evaluating their performance [6-8]. For example, the Midwest Roofing Contractors Association (MRCA) has prepared recommended performance criteria for prefabricated and reinforced modified bitumen roof membranes [6]. In a novel approach to membrane evaluation, the MRCA performance criteria address three distinct phases of membrane service: manufacture, application, and maintenance.

Since publication of the original NBS preliminary performance criteria [1] over 10 years ago, significant changes in the use and properties of bituminous membrane roofing have occurred. Some of the new membrane materials - both fabric and modified bitumens - have load-deformation properties that were not available in roofing products marketed at the time of the original study. Moreover, the types of membrane reinforcements available then are markedly different from those used today. Glass felts have gained wide acceptance for membrane reinforcements, while asbestos felts have essentially disappeared and the use of organic felts has declined.

Because of the technological changes that have occurred for bituminous roofing, it was recently suggested that review and revision of the preliminary performance criteria may be needed to address current materials use [9]. As noted in BSS 55 [1], it was expected that some of the performance characteristics for built-up membranes might be deleted or combined with others to reflect changes in the current state-of-the-art [1].

1.2 Objective

The objective of this report is to review alternative approaches that could be considered as bases for revising the existing preliminary performance criteria for tensile strength and for tensile fatigue strength of bituminous built-up membrane roofing. Several approaches are considered as candidates for both of these preliminary performance criteria. Based on a review of the advantages and limitations of each candidate approach, a recommended approach is selected. It is noted that the approaches discussed in this report have not been directly applied to built-up roofing performance. Consequently, little data are available to illustrate the application of the approaches.

1.3 Performance Criteria for Bituminous Membranes

BSS 55 [1] examined performance attributes, test methods, and preliminary performance criteria that were appropriate for built-up bituminous membranes. Twenty performance attributes were identified. These twenty attributes were considered to describe the characteristics of membrane materials necessary to resist typical modes of failure in service. Appendix A provides a brief review of major failure modes experienced by built-up bituminous membranes. Examples include blistering, splitting, ridging, slippage, delamination, alligatoring, and surface erosion. Of the twenty attributes identified in BSS 55 [1], preliminary criteria were suggested for 10 of them.

Tensile strength and tensile fatigue strength are generally recognized to be important with regard to the ability of the bituminous roofing membrane to resist splitting. Splitting is one of the most common modes of failure [10]. It is generally associated with low temperatures when the membranes are brittle. The NRCA Guide [5] notes that tensile strength tests are indicative of the ability of a membrane material to resist stresses induced by thermal changes, moisture content changes, substrate movements, and the like.

Many roofing membranes have anisotropic strength properties and, consequently, they are tested in both machine and cross-machine directions*. Tensile strength as well as other characteristics and test methods for bituminous roofing materials have been addressed by the documents given in table 1. It is noted that the European Union of Agrément directives [12,13] use tensile strength as a property for characterization and not as a performance indicator.

The performance statements presented in BSS 55 [1] consist of a requirement which is qualitative and describes what the membrane is to accomplish. This is followed by a criterion (or criteria) which expresses quantitatively the acceptable levels for adequate performance. An evaluation technique or test method is then referenced or described by which compliance with the stated criterion can be tested. Finally, a commentary is provided to explain the reason for, or the intent of, the stated criterion. In the case of tensile strength and tensile fatigue, the attributes were as follows:

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* This description refers to the orientation of the reinforcing felt with regard to the manufacturing process.

Table 1. Documents Describing Requirements Including Tensile Strength for Bituminous Roofing Materials

Material	Document	Ref.
Built-Up Membranes	NBS <u>BSS 55</u>; Preliminary Performance Criteria	[1]
Modified Bitumens	Canadian General Standards Board (CGSB); Standard 37-GP-56M	[11]
Modified Bitumens	Midwest Roofing Contractors Association (MRCA); Technical Document MB-30	[6]
APP* Modified Bitumens	European Union of Agrément (UEAtc); Special Directives	[12]
SBS** Modified Bitumens	European Union of Agrément (UEAtc); Special Directives	[13]

* APP denotes atactic polypropylene
** SBS denotes styrene-butadiene-styrene

Tensile strength - The membrane is not expected to perform as a structural member, but it must have sufficient strength to resist stresses caused by internal and external forces acting on it.

Tensile fatigue strength - Repeated stresses caused by thermal, moisture, and building movements should be resisted by the membrane. The strength of the membrane should not be significantly reduced by the applications of repeated forces.

The preliminary performance criteria for tensile strength and tensile fatigue strength, as presented in BSS 55 [1], are given in tables 2 and 3, respectively. The tensile strength requirements, presented in the CGSB [11], MRCA [6], and UEAtc documents [12,13], are given in Appendix B.

The application of the performance concept to built-up membrane performance has also been the subject of a number of papers. In 1981, Rissmiller [14] reviewed performance criteria for bituminous membrane materials and suggested a list of eleven attributes which he considered critical to performance. Included in those 11 critical attributes were tensile strength and tensile fatigue. Rissmiller noted that the tensile strength of 200 lbf/in. (35 kN/m) (as suggested by NBS [1]) at 0°F (-18°C) was a reasonable value for minimum tensile strength based on data available at that time. He noted that considerable additional work was needed to develop an acceptable fatigue test method.

More recently, Siadat et al., [7,8] have suggested a performance predictor concept for roofing systems. They defined a predictor as an indicator of the relative performance of a built-up roofing (BUR) membrane under actual exposure conditions. The performance predictors were considered functions of the viscoelastic properties of the BUR.

Table 2. Preliminary Performance Criterion for Tensile Strength of Bituminous Membranes

Descriptor	Performance Statement[1]
Requirement	The roof membrane shall withstand, without rupture, the normal stresses imposed from internal or external causes.
Criterion	The tensile strength shall not be less than 200 lbf/in. (35 kN/m) in the weakest direction of the membrane when tested a 0°F (-18°C)[2].
Test	ASTM D 2523, testing load-strain properties of roof membranes.
Commentary	This criterion is based on performance in service. Certain membranes exhibit anisotropic behavior. Therefore, the results of tests in the weakest direction (usually transverse or "cross machine" direction as manufactured) should apply.

[1] Taken from reference [1].

[2] The tensile strength criterion is given in units of load per unit width and not stress.

Table 3. Preliminary Performance Criterion for Tensile Fatigue Strength of Bituminous Membranes

Descriptor	Performance Statement[1]
Requirement	The roof membrane shall withstand, without rupture, repeated forces causing high and low levels of tensile stress in the membrane.
Criterion	The roof membrane shall withstand without rupture a minimum of 100,000 cycles of repeated force (tension) of 20 lbf (89 N) when tested at 73°F (23°C) and a minimum of 100,000 cycles of repeated force (tension) of 100 lbf (445 N) when tested at 0°F (-18°C).
Test	Samples of the type described in ASTM Standard D 2523 are tested at 73 and 0°F (23 and -18°C). Rate of load application is 10 cycles per second (cps) for specimens tested at 73°F (23°C) and 15 cps for specimens tested at 0°F (-18°C). Maximum forces applied to the three sets of specimens were approximately 80, 60, and 40 percent of the tensile strength of the membranes. Specimens were loaded in the tension-tension mode so that the smaller force was 10 percent of the larger fatigue force.
Commentary	Certain membranes exhibit anisotropic behavior, the results of the tests in the weakest direction (usually transverse or cross-machine) should apply.

[1] Taken from reference [1].

Performance was defined as resistance to roofing failure principally through splitting in tension. Three performance predictors (designated PP-I, PP-II, and PP-III) were reported [7,8].

The first performance predictor (PP-I) was given as a measure of the membrane's ability to withstand strain without splitting [7]. This predictor was defined as a membrane's net reserve strength (ultimate strength minus the load induced by cooling a test specimen from room temperature to the test temperature) divided by the modulus (at the test temperature). Membranes having higher values of PP-I were considered to provide superior performance. Factors which either increase the net reserve strength or decrease the modulus would increase the value of PP-I.

The second performance indicator (PP-II) was given as the "ultimate strainability,"* and was considered as the reserve strain capacity of the membrane to accommodate any strains which occurred on the roof. PP-II was thus taken to be a measure of the membrane capacity to undergo strain without splitting. Siadat et al., indicated that if the strain generated on the roof is larger than the "ultimate strainability," then splitting would be sure to occur.

The third performance predictor (PP-III) was suggested based on a consideration that not all strain in a roof membrane is reversible [8]. Built-up membranes exhibit some degree of hysteresis or irreversibility in their stress-strain

* "Ultimate strainability" was the term used by the authors [8] and may be taken to be the strain capacity of the membrane.

curves during cyclical straining. PP-III was defined as the accumulated area under six hysteresis loops. It was noted that good built-up membranes should have, among other characteristics, small hysteresis or permanent damage during cyclical straining.

1.4 Scope

The scope of this report includes a review of candidate approaches that may be used to revise preliminary performance criteria for bituminous built-up roofing membranes. Only tensile strength and tensile fatigue strength performance criteria are addressed. It is recognized that any revised criteria must consider the performance of conventional materials already studied.

The study reported here does not include laboratory testing. In a second phase of the study, testing of bituminous built-up membranes will be conducted to develop levels of performance for revised criteria.

2. APPROACHES FOR REVISING PRELIMINARY PERFORMANCE CRITERIA

Approaches considered for inclusion in revising tensile strength and tensile fatigue strength performance criteria are discussed in this section. The listing of approaches is not intended to be exhaustive; however, these approaches are applicable to a wide variety of mechanical response. The approaches for tension are: elasticity, brittle fracture (and notch sensitivity), visco-elasticity, strain energy, finite elements, and their tension-fatigue counterparts when applied in repeated load testing to establish fatigue life performance.

Each approach was considered as a candidate because it can provide numerical and quantitative results for evaluating test performance. Each approach can be used to deal with one or two-dimensional materials testing and each has been applied to composite sheet and membrane materials response, although direct application to roofing membranes has seldom occurred. Each approach has a significant body of background literature and a scientific basis. Measurement of loads, deformations, and predictions of load-deformation response are included in each approach.

Use of these approaches will eliminate empirical relationships. These approaches and their associated theories have a complementary inventory of standardized testing equipment and procedures.

2.1 Tensile Strength Criteria

2.1.1 Elasticity Theory

Elasticity was considered as a candidate approach because it is potentially useful in the elastic range, at low temperatures where membranes may split at relatively small deformations. At low temperatures, membrane stress and strain are approximately linearly related. Elastic theory might be applied to define loads or strains at which splits would occur at low temperatures. Factors of safety could be applied as appropriate.

The equations of elasticity for a three-dimensional homogeneous, isotropic body are given here together with their two-dimensional counterparts. The equations for the two-dimensional case are useful in membrane theory which is generally considered appropriate for roofing (plane stress). Material properties for equations of elasticity include the modulus of elasticity, E, the shear modulus, G, and Poisson's ratio, μ:

<u>Three-dimensional</u>	<u>Two-dimensional</u>	
$\varepsilon_x = \frac{1}{E}[\sigma_x - \mu(\sigma_y + \sigma_z)]$	$\varepsilon_x = \frac{1}{E}[\sigma_x - \mu\sigma_y]$	(1)
$\varepsilon_y = \frac{1}{E}[\sigma_y - \mu(\sigma_x + \sigma_z)]$	$\varepsilon_y = \frac{1}{E}[\sigma_y - \mu\sigma_x]$	
$\varepsilon_z = \frac{1}{E}[\sigma_{zX} - \mu(\sigma_x + \sigma_y)]$	$\gamma_{xy} = \frac{1}{G}\tau_{xy}$	
$\gamma_{xy} = \frac{1}{G}\tau_{xy}$		
$\gamma_{yz} = \frac{1}{G}\tau_{yz}$		
$\gamma_{Xz} = \frac{1}{G}\tau_{xz}$		

where: σ_x. σ_y, σ_z are normal stress components, τ_{ij} is a shearing stress component, ε_x, ε_y, ε_z are normal strain components, and γ_{ij} is a shearing strain component.

Although roofing membranes are dependent on time and temperature, elasticity theory is sometimes used to approximate the load-deformation behavior of membrane specimens. Fardis [15] found that the expression $S = E(e_M - e_T)$, (where E is the load-deformation modulus, S is stress, e_M is mechanical strain, and e_T is thermal strain), gives a reasonable approximation to the stress-strain behavior of the membrane in service for uniaxial loading, if 1) E is considered to be a function of temperatures and 2) the rate at which e_M increases with time is close to the strain-rate in the field. Both e_M and e_T are positive for mechanical elongation and thermal expansion, respectively. For practical purposes, Poisson's ratio may be considered to be constant. Fardis [15] calculated the thermal forces which develop in the membrane when thermal contraction is completely suppressed. For the cross machine direction (C), the force (F_C) was given as:

$$F_C = E_C(e_{CT} + \mu_{CM}e_{MT})/(1 - \mu_{CM}\mu_{MC}) \qquad (2)$$

where:

μ_{CM} = contraction of cross-machine direction divided by extension of machine-direction, due to stress in the machine direction.

μ_{MC} = contraction of machine direction divided by extension of cross-machine direction, due to stress in the cross-machine direction.

e_{CT} and e_{MT} = thermal strains in the cross-machine and machine directions, respectively.

For the machine direction (M), the thermal force (F_M) was given as:

$$F_M = E_M(e_{MT} + \mu_{MC}e_{CT}/(1 - \mu_{CM}\mu MC) \qquad (3)$$

where the symbols are as just defined.

2.1.1.1 Possible Application of Elasticity Theory

The theory of elasticity could be applied to 2-dimensional built-up bituminous membranes by considering either one or two-dimensional stresses and neglecting strain in the thin dimension of the membrane. Testing would be accomplished under isothermal conditions. Assuming that a constant rate of extension was used, the load (stress) and deformation (strain) would be measured to determine an elastic modulus. Poisson's ratio can be obtained from measurement of transverse and longitudinal strains. Equations for plane stress in the x and y coordinate directions have been listed earlier as two-dimensional relationships (Equations 2).

Possible criteria using elasticity theory may be based on one-dimensional strains or stresses typical of those expected in service (e.g., $E_x = \sigma_x/\varepsilon_x$). Approaches using elasticity theory may only be used to develop a criterion where the stress-strain properties are linear. The criterion would possibly be based on a minimum value of strain or load (stress) which the membrane test specimen should meet or exceed based on uniaxial testing. A minimum value of strain is preferred because brittle materials, having relatively little extensibility, are not suitable for roofing materials. Testing would be accomplished at low temperatures. Since a membrane in service must remain watertight under all conditions of strain, a watertightness test should be conducted on the membrane specimen at a strain representative of the maximum strain occurring in service under normally-expected conditions.

2.1.2 Brittle Fracture (Notch Sensitivity) Theory

Brittle fracture can be used to characterize performance of membranes at low temperatures when the bituminous cement may become brittle and membrane splitting could occur when tensile stresses are imposed. Tensile stresses may be imposed by mechanical or thermal loads. Flaws or notches in a membrane may reduce its tensile strength. The study of notch sensitivity within brittle fracture theory can characterize the splitting resistance of membranes which have embedded flaws or notches. Such membranes which show high resistance to rupture would presumably be more resistant to embedded flaws or notches under service conditions.

Cracks and other flaws in elastic, brittle materials have, in general, the effect of increasing the stress in the vicinity of the imperfection. Such imperfections are called stress risers and the region around a stress riser where stress reaches a maximum is called a stress concentration. The maximum stress is sometimes expressed in multiples of the nominal or average stress, or $s_{max} = K_t s_{nom}$ where K_t is the theoretical stress concentration factor, s_{max} is the maximum stress, and s_{nom} is the nominal stress.

The severity of stress concentration induced depends on the properties of the materials and on the shape of the crack or flaw. Using the previous relation between S_{max} and S_{nom}, the severity of stress concentration is defined by means of the stress concentration factor, K_t, where

$$K_t = s_{maximum}/s_{nominal} \tag{4}$$

for tension or bending. For example, stress concentration that results from the introduction of an elliptical hole in a very wide elastic plate is [16]:

$$K_t = 1 + 2a/b \tag{5}$$

where a = major axis and b = minor axis.

When the hole is circular, $K_t = 3$. As the hole shape changes toward that of a flatter ellipse loaded in the direction of the minor axis, the maximum stress becomes much larger. Consequently, even when nominal stresses are low, portions of the material in the vicinity of cracks or flaws may be subjected to stresses considerably greater than the nominal stress.

Stress concentration factors are usually determined through the use of photoelastic methods, electrical resistance strain gages, or by the finite element method [17]. It is in the vicinity of a stress riser that cracks in a brittle material are initiated and propagated until failure occurs. For ductile or plastic materials, such as bituminous roofing membranes at higher temperatures, stress risers are not so critical because the stress is redistributed as large values of strain are attained. At low temperatures, it is likely that stress concentrations can significantly influence maximum stress and therefore the strength and service life of the roofing membrane component or system.

The ultimate mechanical failure is fracture [17]. In a ductile material, plastic deformation precedes fracture (ductile fracture). Materials, such as glass and some metals, which fracture with little or no plastic deformation rupture by brittle fracture [18]. At sufficiently low temperatures, some asphalts behave as brittle, amorphous materials and the Griffith theory [19] of brittle fracture can be applied to study the fracture behavior of asphalts.

Toughness tests are used to measure the energy required for failure by fracture. Brittle fracture requires minimal energy, since the only energy consumption is the separation of atoms along the fracture path; that is, the energy required to form two new surfaces [20]. Ductile fracture requires appreciably more energy, since the fracture produces new surfaces and plastically deforms significant amounts of adjacent material. The amount of strain energy (see section 2.1.4) that is required per unit volume is equal to the area under the stress-strain curve.

Griffith [19] observed that for brittle materials at failure, the average strain energy was less than the theoretical value required for failure. He theorized that the strain energy was nonuniformly distributed because of the presence of small cracks or flaws. The cracks acted as stress concentrators and produced corresponding concentrations of strain energy.

Other investigators [21-24] have confirmed that the presence of small cracks or imperfections greatly reduced the tensile strength of materials that fail in a brittle manner. Griffith's formula which equates the change in strain energy to the change in work done of an infinitesimal increase of crack length c is:

$$S = (2Et/\pi c)^{1/2} \tag{6}$$

where: c = crack length

S = tensile stress

t = surface energy of the material per unit area

E = modulus of elasticity

For plane stress conditions, this expression becomes:

$$s = (2Et((1-\mu^2)\pi c))^{1/2} \tag{7}$$

where: μ is Poisson's ratio of the material.

Inglis [22] showed for plane stress that the excess strain energy of the plate containing a crack over that of a plate without a crack would be

$$U = \pi c^2 s^2/E \quad (8)$$

per unit thickness of the plate.

Differentiation of this latter equation (Eq. 8) by Irwin [24] led to the concept of the strain energy release rate:

$$G = 2\pi c s^2/E \quad (9)$$

This was considered to be the surface energy per unit area required for crack propagation. The value of the strain energy release rate at the onset of rapid crack propagation is designated as the critical strain energy release rate, G_c. Low values of G_c are undesirable. Strain energy release rates or notch sensitivities may be useful in identifying fracture susceptibility of bituminous membranes and the tendency to split under thermal or mechanical loads.

Because different loading conditions could produce the same stress concentration at the tip of the crack, the critical strain energy release rate may be considered a constant for the material, just as the modulus of elasticity is a constant for the material.

Notched beam specimens are sometimes used to determine the critical strain-energy release rate for inelastic materials subjected to different test temperatures, loading rates, and other factors. Moavenzadeh [25] used a notched beam to study the strain energy of paving asphalts subjected to different loading rates, different durations of aging and different test temperatures. He showed that for paving asphalts, the critical strain energy release rate calculated from the theory of brittle fracture is an inherent property of the asphaltic material. Its variation from one asphalt to another may be used to determine fracture susceptibility of the asphalts at low temperatures.

2.1.2.1 Possible Application of Brittle Fracture Theory

Brittle fracture theory could be applied to roofing membranes by measuring the critical strain energy release rate when the notched membrane specimen is tested in uniaxial tension at low temperatures. To evaluate the notch sensitivity, the critical strain energy release rates of bituminous membrane specimens tested at temperatures typical of those noted to be critical in service are determined. A possible criterion would identify a minimum value of the critical strain energy release rate, G_c, for a given set of test conditions. A variety of loading rates could be used.

2.1.3 Viscoelasticity Theory

Viscoelasticity was considered as an approach because roofing loads and deformations may be time-dependent. Deformations may increase with time under constant load and eventually lead to membrane splitting. For some asphalt cements used in highway construction, for example, creep compliance and relaxation moduli are useful in characterizing the materials at different temperatures. In modeling and simulation studies, it is necessary to have accurate material properties to predict responses over a wide range of loads, deformations, and temperatures. At lower temperatures, the deformation response of asphaltic built-up membranes may be approximated by use of linear viscoelasticity theory. Conditions to cause splitting of the membrane may be identified from uniaxial tests at low temperatures.

As previously indicated, roofing bitumens and other materials exhibit time and temperature dependent properties. The mechanical behavior changes continuously with temperature and loading rate. The glass transition temperature is sometimes identified as characteristic of materials, including some asphalts. Below the glass transition temperature, the material is in a brittle, glassy state (behaves like a solid) and has nearly elastic load-deformation properties. Above the glass transition temperature, the material is in a flexible, rubbery state (behaves like a fluid) and may deform plastically under constant stress.

Some materials [26] which undergo time-dependent deformation retain some memory of past stress and strain history. That is, the strain (or stress) does not depend only on the current value of stress (or strain) but on the stress (or strain) history. For isothermal conditions, the stress-strain-time behavior of such a material is commonly characterized by its creep compliance (the time dependent strain for given stress) or relaxation modulus (the time dependent stress for constant strain).

Linear viscoelastic materials are characterized by application of the principle of superposition. If, at a given time, the strain due to a constant stress is proportional to previous strain, then the time history of stress due to a variable strain can be found by superposition. For nonlinear viscoelastic materials, no similar procedure exists for computing the stress (or strain) time history due to a variable strain (or stress).

The difference between elastic media and viscoelastic media lies in the relation between stress and strain. The least amount of analytical complexity is introduced if the material is linearly viscoelastic. This implies that, at any instant, the magnitude of the time-dependent response is directly proportional to the magnitude of the time-dependent input [26-27]. Although the use of discrete spring and dashpot element representations is conceptually convenient, quantitative accuracy over long time periods requires an inordinately large number of such elements. A spectral distribution of characteristic retardation or relaxation times is often convenient for characterization and preliminary analysis.

In general, components of deformation (or strain), for example, may include instantaneous elastic response, recoverable ("delayed") response, and irrecoverable viscous flow. These components are time and temperature dependent and must be considered in any testing program. At higher temperatures, asphalt is a nonlinear viscoelastic material.

Polymer modification of roofing bitumens [28] has been effective in reducing the low temperature brittleness and rupture temperature of membrane materials. To stay waterproof, membranes which are deformed without rupture at low temperatures must remain uncracked.

2.1.3.1 Possible Application of Viscoelasticity Theory

Viscoelasticity theory could be used by measuring time and temperature dependent creep or relaxation moduli of bituminous built-up membranes for uniaxial tensile specimens. Testing would be accomplished in the weakest direction. A possible criterion obtained from viscoelasticity theory would establish a limit on creep to prevent creep rupture. A static load may be applied, based on some specified percentage of static strength. The load would be maintained for required length of time to demonstrate creep resistance or surviveability. A watertightness test would be conducted where laboratory strain is representative of that occurring in service.

2.1.4 Strain Energy Theory

The concept of strain energy can be applied to a variety of material responses to load. Whereas historically, conventional built-up bituminous roofing membranes failed in tension at small deformations, newer bituminous membrane materials now being marketed can accommodate larger deformations without rupture. The ultimate tensile strength of newer membranes may be less than strengths of traditional built-up membranes studied as background for BSS 55 [1].

More extensible membranes which are forgiving of substrate movement at discontinuities, such as joints between insulation boards, might be evaluated readily if both failure load and deformation at failure were identified for temperatures typical of those occurring in service. Strain energy may be used to account for the relative extensibility of membranes prior to failure and can be used to combine tensile strength and elongation properties.

Strain energy of specimens can be calculated by the summation of the products of the average force and a finite incremental distance the force moves. Hence, the strain energy may be interpreted as the area under the load-elongation curve (Fig. 1). The strain energy at break (often called work-to-rupture) has been used to characterize strength and extensibility. Strain energy is dependent upon the specimen size (or gage length over which strain is measured). To eliminate the effect of specimen size, the strain energy per unit volume (sometimes called strain energy density) is often considered. For example,

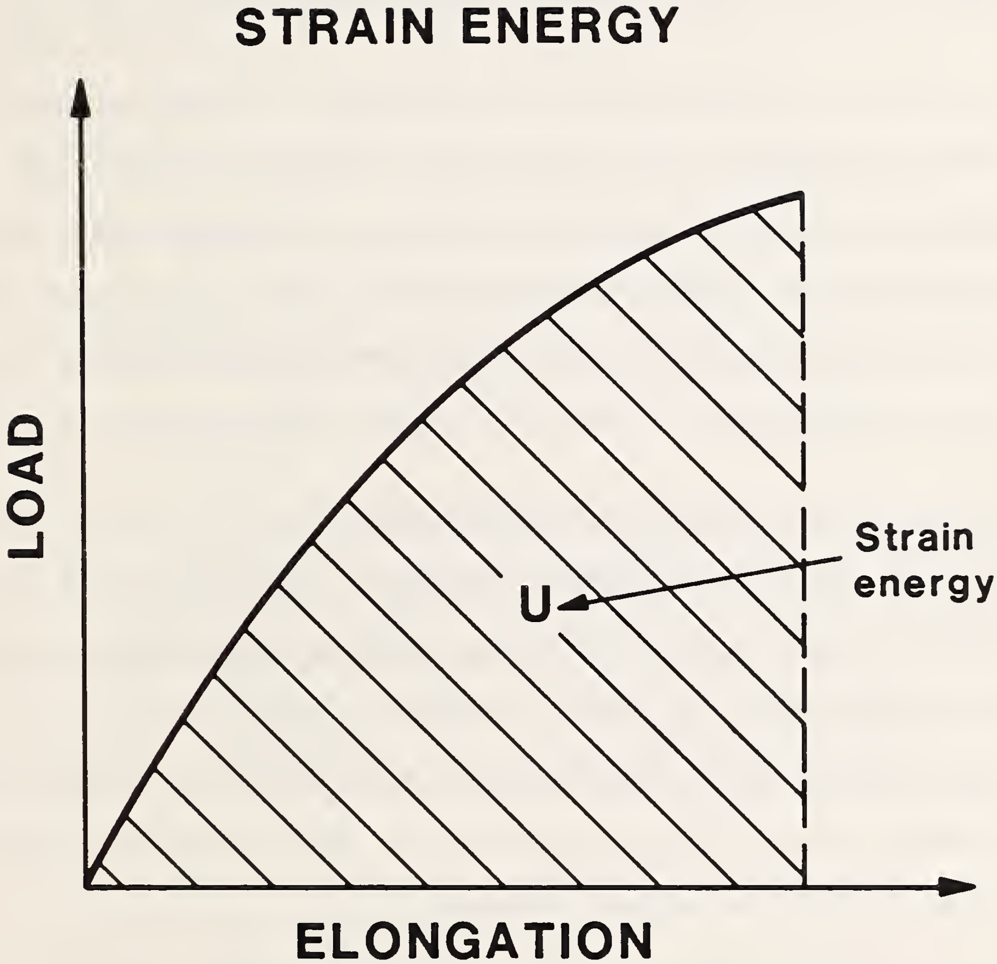

Figure 1. Strain energy: the area under the load-elongation curve

for a linear elastic solid of unit dimension, ℓ, subjected to a uniaxial stress, σ_3, the strain energy, U, is:

$$U = \frac{(\sigma_3 \ell^2)(\ell \varepsilon_3)}{2} = \frac{\sigma_3 \varepsilon_3 \ell^3}{2} \tag{10}$$

or strain energy per unit volume (strain energy density) becomes $1/2\ \sigma_3 \varepsilon_3$.

Roofing materials may exhibit anisotropy and nonlinear load-deformation response. For these reasons, it is desirable to examine the possibility of measuring the strain energy of specimens [29]. It is recognized that materials of high extensibility must remain waterproof even at large strains and, consequently, it may be necessary to specify that specimens which undergo these high extensions be impermeable to water when tested using appropriate techniques.

2.1.4.1 Possible Application of Strain Energy Theory

Strain energy concepts may be applied by continuous recording of load and deformation during tensile testing. The area under the resulting load deformation curve is the strain energy. For roofing membrane materials that fail at relatively small strains or deformations (<2-3 percent), higher strength may be required to achieve a given strain energy than for specimens which undergo relatively large deformations without rupture.

A criterion resulting from application of this approach may involve specifying a minimum value of strain energy for uniaxial specimens, tested in the weakest direction, under test temperatures and loading rates considered representative of those in service. The test specimen should remain watertight over the range of strain which a membrane might experience in service. A watertightness test should be run at the elongation where minimum strain energy is attained or higher if warranted by service conditions.

2.1.5 Finite Element Techniques

Finite element techniques are considered an indirect approach for categorizing bituminous membrane performance. Finite element techniques are used to compute the distribution of loads and deformations in the membrane as well as the other components of the roofing system. However, before the computation can be done, the materials properties of the membrane (as well as other system components) must be well characterized. Use of computers is required. If properties are well-defined, stresses imposed in service for the membrane system can be estimated.

Finite element theory involves a general method of approximate solution of problems in engineering science and applied mathematics [30]. Technological advances in computers have stimulated application of finite element techniques. The basic scheme of the technique involves substituting a simplified problem for an actual one. In two-dimensional elasticity, for example, the following expressions are used:

$$\varepsilon_x = \frac{1}{E}(\sigma_x - \mu\sigma_y) + \varepsilon_o \qquad (11)$$

$$\varepsilon_y = \frac{1}{E}(\sigma_y - \mu\sigma_x) + \varepsilon_o$$

$$\gamma_{xy} = \frac{1}{G}\tau_{xy}$$

where ε_o is the initial strain.

Geometric elements are used to model the structure of interest. The accuracy of the computation is dependent upon the extent of discretization of the elements, especially in regions of large variations in stress. The solution procedure involves the following steps:

a. discretize the structural shape into elements joined at nodes,

b. express the displacements within each element as functions of the unknown displacement at the nodes,

c. set up equilibrium equations in terms of the unknown nodal displacements,

d. compute nodal displacements (or strains) by solving the incrementally linear system of equilibrium equations, and

e. determine stresses using the stress-strain law of the material.

Researchers [15,31-33] have used finite element analysis to compute stresses in roofing membranes having:

1. open joints between insulation panels,

2. sharp-cornered penetrations through the roof,

3. horizontal variation of thermal or drying shrinkage,

4. horizontal variation of the degree of insulation attachment, and

5. nails through the bottom ply of a membrane applied to a nailable substrate.

Heat loss through insulated built-up roofing systems has also been estimated using finite element techniques [31].

2.1.5.1 Possible Application of Finite Element Techniques

Properties of the materials of the membranes are first measured, perhaps by one of the methods already discussed (for example, by elasticity or viscoelasticity theory or by another measurement obtained from laboratory or in-service experiments). These properties are used in the finite element model and the stress-deformation performance of the entire membrane in a model roofing system is then predicted. Areas where stresses or deformations are likely to be critical, based on the finite element analysis, may be checked for adequacy of design strength in the membrane. A possible criterion may follow from development of a representative model of a severe case of membrane stress. The criterion might be stated that the membrane have adequate strength and extensibility under the service environment to withstand stresses and deformations predicted by finite element analysis.

To apply finite element techniques to the analysis of the ultimate behavior of the entire roof system, a complete, non-linear (i.e., large displacements and non-linear material properties) finite element analysis might be needed. On the other hand, areas of the roof system where stresses may concentrate might be analyzed and maximum stresses adequately approximated using simplified, linear finite element techniques. For this reason, the application of finite element techniques should consider a linear approach before a non-linear approach.

2.2 Tensile Strength Fatigue Criteria

Fatigue life of membranes has not been studied extensively, although some references are noted from the literature [2,8,34-37]. In general, at relatively low amplitudes of load or deformation, many cycles of loading or deformation are required to fail built-up membranes [2]. A limited number of load cycles may not cause the membrane to fail; however, it is generally recognized that as load or deformation amplitude increases, fewer cycles are required to cause failure. Bonafont [34] noted that both bitumen and traditional felt reinforcement suffer from the weakening effects of repeated loadings, and may be ruptured at comparatively small strains, if these are applied a sufficiently large number of times.

Membrane specimens cut from roofs which have experienced splitting failures in service have been found by NBS researchers to have lower values of tensile strengths than values typical of new membranes [38]. However, it could not be determined whether the membrane strength was low at the time of application or whether the strength decreased in service due to environmental exposure (e.g., moisture effects) or fatigue. In contrast, Fardis [15] has noted that conventional membrane materials are not susceptible to fatigue under cyclic mechanical loads. He indicated that membrane specimens cut from roofs that have split typically showed no strength deterioration. Beech [35], however, documents strong dependence of fatigue life upon amplitude of movement and temperature.

Nelson [36,37] and Sushinsky and Mathey [2] demonstrated experimentally that membranes did fail as a result of repeated loading. Nelson [37] noted that for the conventional membranes he tested, time under load was more important than number of load cycles in causing failure. Splitting failures for built-up membranes in service seem to be more prevalent when tensile loads are imposed as, for example, during cold weather especially when the low temperature is protracted.

Fatigue failure is used in engineering to describe structural failure caused by repeated stress where the single application of any one of these stresses will not result in failure. The higher the applied stress (often alternating stress), the lower the number of cycles a component will endure before rupture.

Fatigue behavior is often conveniently depicted by an S-N curve (Wohler curve). The total number of cycles to failure, N, is plotted against a cyclic stress parameter, S, which may include the stress amplitude or stress range. In general, the log-log plot of S and N fits most fatigue data and can be represented by the expression: log N log A - B log S, or $N = A/S^B$ [37,39]. For some materials, a fatigue limit stress is identified although most authorities agree that there is no true fatigue limit. An infinite number of cycles below this stress will not cause failure.

Because roofing materials are subjected to irregular fluctuating stresses in which the maximum and minimum stresses are constantly changing, it is necessary to account for the damage caused by different magnitudes of stress cycles. The Miner theory of cumulative fatigue damage [40] states that fatigue damage incurred at a stress level is proportional to the number of cycles, n_i, applied at that stress level divided by the total number of cycles, N_i, required to cause failure at the same level. This damage is referred to as the cycle ratio or cumulative damage ratio. It may be expressed:

$$n_1/N_1 + n_2/N_2 + n_3/N_3 + . . . = 1.0 \qquad (12)$$

Three parameters which may affect the magnitude of the summation of the cycle ratios include the order of load applications, continuous loading to the same level of load, and the presence of notches or defects.

The scatter in a series of fatigue tests performed on the same type of specimen under the same cyclic stresses can be represented by a statistical log-normal distribution (probability density) curve. The area under the distribution curve between any two values of $\log N - (\log N)_{mean}$ corresponds to the percentage of occurences within that interval.

Stress concentration caused by notches, holes, and other defects reduce fatigue strength by a factor K_f. This factor, the fatigue strength reduction factor, is analogous to the theoretical stress concentration factor, K_t.

It has been recognized [39] that the effect of a stress concentration on fatigue life depends on the material. The notch sensitivity index, q, is sometimes used to define this dependence. It is determined from (Eq. 13). Comprehensive

$$q = (K_f - 1)/(K_t - 1) \qquad (13)$$

investigation of these factors for roofing materials should be conducted.

Testing for tensile fatigue strength can be patterned after those tests described previously for tensile strength. These approaches included: theory of elasticity; brittle fracture (notch sensitivity); theory of viscoelasticity; and strain energy. In fatigue testing, the ultimate (rupture) load is not applied at once. The fatigue criterion might be developed in two ways. In the first case, selected levels of load or deformation may be applied repeatedly until rupture occurs. In the second case, in the event that rupture does not occur after repeated load applications, the specimen can be loaded or deformed to failure to assess the residual strength after the accumulated damage caused by application of repeated loads or deformations. One aspect of fatigue testing is that it may be time-consuming, expensive, and subject to wide scatter of results.

Possible applications described for tensile fatigue strength are discussed here except for finite element techniques. Finite element techniques are indirect approaches and require additional identification of mechanical properties. In all approaches, the preferred test orientation involves uniaxial loading in the weakest direction, because built-up bituminous membranes normally undergo splitting failures perpendicular to the weakest direction of the felts.

2.2.1 Tensile Fatigue Strength Criteria Approaches

For tensile fatigue strength testing, either the number of load cycles or the time under load may be specified. A cycle of load would include any initial load (deformation) and incremental loads (deformations) imposed during the duration of interest. The duration of a load cycle would have to be determined based upon testing parameters related to the test methods and equipment. For example, elastic materials may be tested using more rapid cycles than visco-elastic materials for which time dependent ("delayed") material response is significant.

If the membrane does not break after a large number of load cycles, residual strength can be measured. Strength or elongation of unfatigued membranes (control specimens) should be compared to similar properties of membrane specimens subjected to fatigue load cycles. Membranes whose fatigue life or residual strength is decreased significantly by application of repeated loads or deformations may not be as suitable for roofing as membranes which retain strength after application of representative loads.

2.2.1.1 Possible Application of Elasticity Theory

A specified level of stress (load) or strain may be applied repeatedly until failure occurs or until testing for residual strength occurs. For elastic materials, the fatigue tests may be applied as tests which involve two or more levels of tensile load or deformation. A sufficient number of load cycles should be imposed to simulate weather-induced cycles and to determine whether, after application of repeated load cycles, the membrane modulus (σ/ε) remains constant. After repeated application of loading, the membrane should remain waterproof.

2.2.1.2 Possible Application of Brittle Fracture Theory

Tension fatigue testing of built-up membranes would include application of a sufficient number of load cycles (tension-tension) to cause failure or to assess whether the number of load cycles which simulates expected environmental cycling weakens the membrane or has an effect on the strain energy release rate, G. The membrane should remain watertight after cycling.

2.2.1.3 Possible Application of Viscoelasticity Theory

Membranes could be tested for maximum values of creep deformation after application of repeated loading or for residual tensile strength (or relaxation modulus) following application of numbers of loads or specific magnitude.

2.2.1.4 Potential Application of Strain Energy Theory

Tensile fatigue tests would be conducted as described previously with repeated application of loads or deformation and measurement of strain energy. Various minimum levels of elongation, strength, or strain energy might be specified for a membrane subjected to specified numbers of repeated loads.

2.2.1.5 Potential Application of Tensile Fatigue Strength Approaches

Possible criteria for tensile fatigue strength may involve measurement of the number of load (deformation) cycles to failure or the cumulative time under which the specimen was loaded. Measurement of residual properties and specification of a minimum residual extensibility, or a minimum number of load (extension) cycles are possible criteria. Other criteria may include:

a) the membrane should not rupture during fatigue loading,

b) strain energy should not decrease below a minimum value, and

c) the membrane should remain watertight after fatigue cycling.

3. DISCUSSION OF APPROACHES

For each of the approaches considered, quantitative measurement of performance is possible and a theoretical framework and historical precedent (not necessarily in roofing technology) exists. While each of the methods could be considered satisfactory in limited circumstances (e.g., for research), not all approaches can be applied readily at this time and some approaches have little historical use in roofing technology. Therefore, some approaches may need more development through laboratory research prior to their application to roofing technology.

Each of the different approaches for revision of tensile strength and tensile fatigue strength performance criteria has inherent advantages and limitations. Furthermore, each approach should be considered in the context of existing testing methods and equipment which may be used in obtaining numerical values of performance criteria. Principal advantages and limitations identified for each of the approaches are summarized in this section.

3.1 Tensile Strength Approaches

3.1.1 Elasticity Theory

Advantages

- the approach has broad applicability at low membrane temperatures where material behavior is linear
- the theory is widely used and is familiar
- the theory can be used with other test parameters (i.e., brittle fracture)
- for conditions where linear elasticity is valid, factors of safety can be computed
- experimental verification of material elasticity is accomplished readily

- the method can be applied to tension and bending test modes.

Limitations

- the approach is not applicable for general nonlinear response at moderate temperatures

- failure generally occurs in the inelastic region for all but a few materials

- the method does not detect when relatively extensible membranes become permeable; a watertightness test would be needed.

3.1.2 Brittle Fracture (Notch Sensitivity) Theory

Advantages

- the approach may be used at low temperatures where splitting is more likely to occur

- the method provides quantitative estimates of strength reduction due to discontinuities, shape, or cross-section changes

- the method may use existing (or modified) testing methods and equipment.

Limitations

- the approach is not applicable at higher temperatures or for wide temperature ranges or when bitumens flow at low temperatures

- the method is not now widely used in roof membrane testing; therefore, historical precedent is not common and the approach cannot be related to the current criteria for bituminous membrane roofing.

3.1.3 Viscoelasticity Theory

Advantages

- the approach can accommodate time- and temperature-dependent effects representative of service conditions

- it can use static or repeated test modes

- the tests may be more representative of material performance in service.

Limitations

- the theory has not been widely applied to roofing performance

- it has a narrow range of applicability for many materials

- the method involves mathematical complexities

- failure may occur at large deformations for which the theory is not applicable

- tests may be lengthy to allow for rate effects and stress/strain recovery

- it does not identify when the membrane becomes permeable to water.

3.1.4 Strain Energy

Advantages

- the approach involves a simple testing technique

- it uses readily available testing equipment

- the method is easy to implement and has historical precedent

- it may use data from previous testing and evaluations

- the method detects incremental changes

- the method can be used with other tests (e.g., brittle fracture)

- it can be combined with residual strength (energy) concepts and fatigue life evaluations.

Limitations

- the approach is empirical and it may be necessary to identify the minimum strain energy for satisfactory performance

- test method uses an arbitrary strain rate and may not detect rate sensitive anomalies

- the approach does not identify permeability to water.

3.1.5 Finite Element Techniques

Advantages

- the approach may be used with conventional test methods and laboratory equipment

- it can be used with a variety of different scales from component to whole roof modeling

- it may be used in simulation of environmental effects

- the method is potentially useful in identifying safety factors if complete material characterization and failure criteria are known.

Limitations

- the membrane material properties must be completely characterized and constitutive relationships determined before applying method

- the method has not been widely used in roofing and is generally unfamiliar to roofing technologists

- it needs further development for applicability to roofing

- the method requires sophisticated computational systems, expensive graphic input-output devices, and software; those conducting finite element analyses should be specially trained.

3.2 Tensile Fatigue Strength Approaches

Advantages and limitations of approaches for tensile fatigue strength are identical to those listed for tensile strength except that finite element techniques are not considered. Experimental work needs to be done to confirm the validity of these approaches to tensile fatigue testing and their resulting advantages and limitations.

4. SUMMARY AND RECOMMENDATIONS

A review of several approaches that were considered as candidates for use in revising the preliminary performance criteria for tensile strength and tensile fatigue strength was completed. Based on this review and considering the state of testing and development in the roofing materials and systems industry, the approach using strain energy for both tensile strength and for fatigue tensile strength is recommended to be most effective for current use. The ease of testing and use of available equipment were key advantages contributing to this recommendation.

Furthermore, existing research results and data could be used to assist with validating findings and integrating new criteria with original criteria in BSS 55 [1]. The existence of testing methods by which conventional built-up membrane materials have been tested strengthens the basis for using strain energy.

The use of strain energy criteria for other materials (such as geotextiles) indicates that it is becoming a familiar concept for evaluating materials. Use of strain energy concepts to define membranes of high, medium, and low extensibility [9] can be helpful in establishing more comprehensive performance criteria and in stimulating development of new materials with a wide range of properties. Tensile strength, by itself, is not useful for specifying low modulus, highly extensible membranes which may perform satisfactorily over local discontinuities such as uneven supports or joints over insulation panels, and under the impact of foot traffic.

High extensibility may cause unseen discontinuities in the membrane components with resulting loss of waterproofness. Consequently, the load and deformation testing (needed to compute strain energy) of bituminous roofing membranes should be complemented by permeability testing at some given extent of elongation. When membrane specimens are tested at low temperatures, the testing procedure should detect when one or more roofing plies or asphalt layers break. Either of these occurrences may result in loss of membrane watertightness. Wherever possible, the strain at which such fracture occurs should be recorded.

The strain energy approach provides information that may be useful in studying the effects of aging, environmental exposure including UV degradation, treatment with coatings, and effects of other degradation factors which may occur over the life of the membrane. The potential combination of strain energy testing with performance in notch sensitivity and brittle fracture testing at low temperatures appears to be useful. The strain energy approach can also be used in measuring tensile fatigue strength. The reduction of strain energy as the number of load cycles increases is a potential approach for determining a fatigue criterion.

The following summary recommendations are based on the considerations and the evaluation of approaches noted in this report:

1. Tensile strength and tensile fatigue strength performance criteria should include the strain energy approach. This approach is simple, works with currently available equipment, and can be used for both strength-elongation testing and for fatigue testing.

2. Brittle fracture and notch sensitivity may be included with the recommended strain energy approach. This approach has promise but has not been used in roofing technology.

3. Elasticity theory may not be applicable for newer roofing materials which exhibit nonlinear load-deformation response, especially at large deformations.

4. Viscoelasticity theory has potential in research applications, but little historical precedent in roofing technology. Considerable research would be needed before implementation of the approach.

5. Finite element computational techniques are premature at this time. Considerable testing to characterize the mechanical properties of roofing materials would be needed. More importantly, proper training of roofing technologists to carry out this approach would also be essential.

It is recommended that a laboratory testing program be undertaken to investigate the performance of a wide variety of new roof membranes to determine what level of strain energy is appropriate to separate acceptable membrane materials from others. In addition, data from previous tests for preliminary performance criteria should be analyzed to determine the value of strain energy inherent in the traditional built-up membrane described in BSS 55 [1]. The application of the strain energy approach will be undertaken in a second phase of this study.

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APPENDIX A. MAJOR TYPES OF FAILURE OF BITUMINOUS BUILT-UP ROOFING MEMBRANES

A conservative estimate of the total amount of low-sloped roofing in the United States is 25 billion ft^2 (2.3 billion m^2). The area of low-sloped roofing is applied each year in this country would cover about 3 billion ft^2 (0.3 billion m^2). Currently about two thirds of this area of applied low-sloped roofing built-up bituminous roofing. Prior to the late 1970s, almost all low-sloped roofing in the United States was built-up bituminous roofing. While built-up roofing in general performs satisfactorily, premature failures cause unneeded complications and inordinate expenses for owners, roofing contractors, and material manufacturers. It was reported in 1975 that roofing contractors and roofing manufacturers indicated that a probable premature failure rate of 4 - 5 percent may be accurate; however, others quote higher figures [A1]. Regardless of the precise percentage of premature failures, they constitute a major problem. It is also noted that bituminous built-up membranes that are properly applied and well maintained may perform satisfactorily 15 to 20 years or more.

Premature roofing failures are generally attributed to some type of physical failure within the built-up membrane. They are caused by both economic and technical factors. Griffin [A2] has discussed many of these factors. He ranks fieldwork as accounting for most roof failures and design errors as next in rank, with material-related failures being further down the list. The technical factors contributing to premature roof failures as noted by Griffin [A2] are: the extraordinary rigors of roof-performance requirements, proliferation of new materials, complexity of roof system design, expanding roof dimensions, field application problems, and the modern trend toward more flexible buildings.

Griffin [A2] lists the three major modes of built-up membrane failure as: blistering, splitting, and ridging. In addition, he lists as less widespread, but still potentially destructive types of failures, slippage, delamination. alligatoring, and surface erosion. According to Baker [A3] the most common problems associated with low-sloped built-up bituminous membranes are: surface oxidation, surface blistering, surface erosion, thermal shrinkage, slippage, interface blistering, ridging, splitting, flashing failures, and blow offs.

Results of the 1974 and 1978 National Roofing Contractors Association's Project Pinpoint Program indicated from 3,500 baseline jobs that the most common roof problem was blistering and the second most common problem was splitting [A4, A5]. Their combined total accounted for over 60 percent of all types of problems reported. The remainder of the defects were attributed to ridging, buckling, ply separation, slippage, and blow-offs. The causes of roofing problems may in many cases be attributed to the types of materials used and to the design of the roofing system. As an example, the use of two-ply coated bituminous systems in the mid 1970s led to a relatively large number of blistering problems. Changes in materials and their use have contributed to an increase in roofing problems. Some examples include new insulations (plastic foams), thicker layers of insulation, increased use of Type III asphalt for interply moppings, and thin steel decking as the roof support [A5]. According to the survey data, most contractors can expect to see the majority of their problem roofing jobs developed within a few years after installation. Nearly 50 percent of the problem jobs reported in the 1978 Project Pinpoint Program occurred within the first two years of the initial installation of the roofing system [A5].

In the 1983 Project Pinpoint survey conducted by the National Roofing Contractors Association, information was obtained from 1,300 roofing jobs [A6]. In this more recent survey, membrane splitting was the most frequently reported problem. It occurred on 17 percent of the problem jobs. Blistering and interply separation were reported to be the second most common problem. The other types of problems reported in the 1983 survey included ridging, buckling, fishmouths, leaks, wind blow-off, flashing defects, and slippage. Slope was found to play an important role in roofing systems performance. The information appeared to confirm that roofs with small slope perform better than roofs with no slope. Problems were less apparent on roofing employing mechanically attached insulation. Another observation from data obtained in the 1983 NRCA survey was that metal decks may be more susceptible to roofing problems than other decks such as wood and concrete.

An overview of the most common types of premature built-up roofing membrane failures is given in this appendix. As noted previously, the causes of membrane failures may be attributed to workmanship, design, and material-related factors. Some of the materials that were extensively used in the mid-1970s and resulted in a relatively high number of premature failures are used little today [A5, A6]. Included among these materials were 2-ply bituminous coated systems and asbestos felts [A5].

A.1. Blistering

A mechanism for blister formation in built-up roofing membranes was proposed by Warden [A7] in 1960. Recent reviews of the subject have been prepared by Griffin [A2] and Baker [A3]. The key element in blister formation is a void within the plies of the membrane (or between the membrane and insulation board substrate), and the expansion of air, moisture, or other gases trapped within the void. The diurnal temperature cycle to which the roof is exposed also plays a role. Early in the day, the sun warms the membrane causing the bitumen to soften and be more susceptible to flow. In addition, the gas entrapped in the void increases in pressure as the membrane warms. Since the membrane has low permeability, the gas cannot readily escape from the void. If the gas pressure is greater than the bond strength between the membrane plies, the void will increase in size and a blister will begin to grow. Later in the day, the bitumen stiffens and with the decrease in temperature the pressure in the enlarged void is reduced. However, since the bitumen has stiffened, the enlarged void does not return to its original size but remains expanded. The cooled gas develops a negative pressure which may draw air and moisture into the void throughout the nighttime until equilibrium is reached with the ambient pressure. Subsequently, the cycle repeats itself and the blister continues to grow.

Two factors should be noted concerning this mechanism of blister formation. First, moisture need not be entrapped in the system for a blister to grow. It is only necessary to have a void with air in the system. Secondly, the system with the void must not be completely closed so that air can leak into the void during nighttime cooling.

A.2 Splitting

Splitting is failure of the membrane in tension and generally occurs during cold winter weather. The brittle, glasslike nature of bituminous materials at low temperature and the corresponding high coefficient of thermal expansion make built-up bituminous membranes vulnerable to splitting. Membrane splitting is considered to be the most serious failure mode and generally occurs over continuous insulation joints and perpendicular to the weakest direction of the felts in the membrane. The tensile strength of asphalt-impregnated organic felt membranes in the longitudinal direction is usually more than twice that in the transverse direction when tested in the temperature range of +30 to −30°F (1 to −34°C) [A8]. Many of the glass fiber felts are almost isotropic.

Stress concentrations in the membranes at insulation joints can cause splitting at these locations compared to locations where the membrane is reinforced by being bonded to the insulation. Lack of bond between insulation layers or between the insulation and other components increases the possibility of membrane splitting. This type of failure has many causes and may occur from a single factor or a combination of factors. Stress concentrations in membranes may be caused by contraction, insulation movement, drying shrinkage or wet felts, shrinkage cracking of cast-in-place decks, and deck deflection or movement. In addition, membranes may become weakened or exhibit a decrease in tensile strength because of flexing due to insulation joint movements and from water absorption into the felts from below. The locations where membranes become weaker are more susceptible to splitting than other areas.

A.3 Ridging

Ridging of bituminous built-up roofing membranes is sometimes referred to as wrinkling or buckling. It is more common in membranes with organic or asbestos felts than those with glass-fiber because wet organic and asbestos felts expand and contract more than glass-fiber felts. Ridging can be described as narrow, upward ripples in the membrane that frequently extend over continuous joints between insulation boards, deck joints, and base sheet edges. There does not appear to be any clear agreement as to their cause [A3]. The cause and mechanism of ridging differ from those involved with blistering. A blister is formed from the expansion of air, moisture, or other gases trapped within a void, whereas a ridge may form by expansion of the felts at insulation joints by moisture absorption from below. In addition to moisture absorption, other contributing factors to ridging include movement from cyclic temperature change and slippage between felt layers. Examination of membranes at ridges indicates that membrane length at the ridge is often very much in excess of that normally attributed to moisture absorption alone.

During membrane application, hot asphalt on insulation boards may flow between the joints resulting in little if any asphalt on the bottom of the membrane along the insulation joints. Water vapor from the building interior may enter the membrane at these locations and condense within the lower ply of felt. With moisture absorption, organic and asbestos felts swell and buckle causing ridges to form along the insulation joints. In order to reduce the incidence of ridging, a widespread practice of the roofing industry has been to use a bitumen-coated felt (a base sheet) as the first ply of the membrane. Other practices or preventive measures have included staggering joints in insulation boards, covering insulation joints with tape, and orienting the felts perpendicular to the longitudinal insulation board joints.

Ridging usually begins early in the life of a membrane and may continue to grow to a height of 2 in. (25 mm) or more. Loss of bitumen top coating and protective surfacing from the raised portion of the membrane leads to deterioration of the felts. With time, cracking may occur along the top of the ridges and allow water to penetrate the membrane. Stresses in the membrane due to temperature changes, drying shrinkage, and foot traffic may cause the membrane to split open and allow water to enter the roofing system.

A.4 Slippage

Slippage occurs on sloped roofs as a relative movement between plies of felts. In most cases, a membrane which has undergone slippage has a randomly wrinkled appearance. Because of the slippage between plies there may be areas of the roof where the membrane has fewer plies than specified. Although slippage failures are relatively uncommon, they are costly and difficult to correct.

The factors to consider that affect slippage include the viscosity of the interply bitumen at service temperatures, interply bitumen thickness, surface loading from mineral aggregate or other top cover, roof surface temperature, heat capacity of the substrate, membrane installation (i.e., phase construction of the felts), and roof slope [A9].

Slippage failures usually occur during the first year or two after membrane application. Bitumen hardens with time, thus reducing the possibility of slippage failure. Slippage has occurred on roofs having slopes of 1/4 in./ft (20 mm/m). Slopes of 1/4 to 1/2 in./ft (20 to 40 mm/m) are more vulnerable to slippage than is generally suspected [A9]. Membranes with slopes over 1 in./ft (80 mm/m) seldom slip because mechanical fastening or other techniques for positive anchorage are employed.

A.5 Delamination

Delamination is the separation of felt plies in a built-up membrane. This type of failure may produce wrinkling or ridging and then cracking, much like a wrinkled or ridged membrane. Delamination is a less common type of membrane failure and according to Griffin [A2] is promoted by the following: insufficient bitumen between felts; improper imbedment of felts because of inadequate brooming of underweight mopping; application of inadequately heated bitumen; use of coal-tar-saturated felts with asphalt, or asphalt-saturated felts with coal tar; water absorption during winter followed by evaporation in spring or summer; and freeze-thaw cycling of water entrapped between plies.

A.6 Alligatoring

Alligatoring consists of deep shrinkage cracks in exposed bitumen. The cracks progress from the surface downward as a result of oxidation, aging, and embrittlement. As the exposed bitumen ages, it becomes progressively harder. After exposure of the bitumen for some time, a pattern of random cracks appears on the surface. The cracks enlarge and become deeper with time so that islands of bitumen are formed which continue to shrink until in many cases the cracks extend through the bitumen coating layer to the felts in the membrane. Water can be retained in the alligator cracks and, by wicking, can wet the membrane resulting in reduced membrane strength and accelerated deterioration of both felts and bitumen. In advanced stages of alligatoring, curled segments of asphalt or the islands of bitumen peel away and expose the felt in the membrane.

A.7 Surface Erosion

Surface erosion is the displacement of the protective aggregate surfacing along with some of the bitumen flood coat. Wind and water can blow away and wash away the protective surfacing to expose the bitumen which will deteriorate due to oxidation and further erosion. The eroded membrane surface may allow water to infiltrate into the membrane or the insulation. This may result in alligatoring, blistering, felt deterioration, or other failures of the membrane and roofing system.

The movement or displacement of aggregate protective surfacing on roofs occurs on areas exposed to high wind speeds where the air flow is turbulent. The predominant areas are at windward corners of buildings and along the eaves extending away from the windward corners. Scouring of gravel generally occurs at corners, but it can occur for a considerable distance downwind from the corner, or at any area subjected to high wind speed and suction. Underweight flood coat has been attributed as the major reason for aggregate surfaced membranes being vulnerable to erosion. The size, mass, and grading of the aggregate surfacing also influence the extent of scouring.

A.8 References for Appendix A

A1. Busching, H. W., Mathey, R. G., Rossiter, W. J., Jr., and Cullen W. C., "Effects of Moisture in Built-Up Roofing -- A State-of-the-Art Literature Survey," Technical Note 965, National Bureau of Standards, Washington D.C., July 1978.

A2. Griffin, C. W., Manual of Built-Up Roof Systems, 2nd Edition, McGraw-Hill, New York, 1982.

A3. Baker, M. C., Roofs, Multiscience Publications Ltd., Montreal, Canada, 1980.

A4. Roofing Spec, National Roofing Contractors Association, Chicago, IL., p. 38, November 1979.

A5. Roofing Spec, National Roofing Contractors Association, Chicago, IL., p. 28, May 1980.

A6. Roofing Spec, National Roofing Contractors Association, Chicago, IL., p. 37, October 1984.

A7. Warden, W. B., "A Theory of the Mechanism of Blistering," in "A Study to Improve Bituminous Built-Up Roofs," Monograph No. 1, Building Research Institute, National Academy of Sciences, Washington, D.C., pp. 14-26, 1960.

A8. Mathey R. G. and Cullen W. C., "Preliminary Performance Criteria for Bituminous Membrane Roofing," Building Science Series 55, National Bureau of Standards, Washington D.C., November 1974.

A9. Cramp, A. P., Cullen W. C., and Tryon, M., "Slippage of Built-Up Roof Membranes -- Causes and Prevention," Report 10950, National Bureau of Standards, November 1972.

APPENDIX B. TENSILE STRENGTH REQUIREMENTS GIVEN IN STANDARDS-RELATED DOCUMENTS

This appendix presents tensile strength tests and requirements given in the following documents:

1. CGSB Standard 37-GP-56M [B1].
2. MRCA Technical Document MB-20 [B2].
3. UEAtc Special Directives M.O.A.T. No. 30:1984 [B3], UEAtc Special Directives M.O.A.T. No. 31:1984 [B4].

These 4 documents were developed for polymer modified bituminous membrane materials and not conventional built-up bituminous membranes.

B.1 CGSB Standard

B.1.1 Test

Specimens are tested in tension in both the machine and cross machine direction at 73°F (23°C). The test specimens are 2 in. (50 mm) wide and 6 in. (150 mm) long. The rate of extension is 20 in./min. (500 mm/min.).

B.1.2 Tensile Strength

The tensile strength requirement has two classifications:

1. For grade 1 membranes (standard service), the minimum strength is 66 lbf (294 N).
2. For grade 2 membranes (heavy duty service), the minimum strength is 176 lbf (785 N).

B.1.3 Elongation at Break

The minimum elongation at break of the membrane is 4 percent for grade 1 membranes and 8 percent for grade 2 membranes.

B.1.4 Load-Strain Product

The minimum load strain product (which is specified as the product of the breaking strength in Newtons and the elongation at break (in percent)) is 2,940 for grade 1 membranes and 14,700 for grade 2 membranes. (If the tensile strength requirement of grade 1 membrane is not met, the load-strain product for this type material should be 19,400 minimum.)

B.2 MRCA Criteria

The MRCA criteria consider three classes of material which differ by their load-elongation properties. For each individual class, 3 requirements are given: tensile strength, elongation, and strain energy. The MRCA criteria require that modified bituminous membrane materials should meet two of the three requirements.

B.2.1 Test

The test specimen is a strip having a 1 in. (25 mm) width and a 7 in. (178 mm) gage length. The tension test is conducted at 0°F (-18°C) at a rate of extension of 0.08 in./min (2 mm/min).

B.2.2 Requirements for Low Elongation/High Strength Materials

These membrane materials should have a minimum of 2.5 percent elongation, 200 lbf/in. (35 kN/m) tensile and/or a minimum 20 lb•in. (2.3 N•m) strain energy in the weakest direction.

B.2.3 Requirements for Medium Elongation/Low-to-High Strength Materials

These membrane materials should have a minimum of 10 percent elongation, exhibit a strength from 50-200 lbf/in. (0.8 - 35 kN/m) and/or a minimum 150 lb•in. (17 N•m) strain energy in the weakest direction.

B.2.4 Requirements for High Elongation/Low-to-Medium Strength Materials

These membrane materials should exhibit a minimum of 20 percent elongation, a tensile strength range from 50-100 lbf/in. (8.8 - 17.5 kN/m) and/or have minimum 300 lb•in (34 N•m) strain energy in the weakest direction.

B.3 UEAtc Directives

The test method and requirements for polymer modified bitumens are similar in the document for APP products and SBS products.

B.3.1 Test

Tests for tensile strength and elongation at break are conducted using specimens which are 2 in. (50 mm) wide and have an 8 in. (200 mm) gage length. The rate of extension is 4 in./min (100 mm/min). The temperature is not specified (and may be assumed to be room or ambient laboratory temperature).

B.3.2 Tensile Strength

This test is used only to characterize the materials. Thus, the requirement is that the tensile strength at break must be a given percentage of that specified by the manufacturer. The allowable variation depends upon the type of reinforcement.

B.3.3 Elongation at Break

The elongation at break must also be a given percentage of that specified by the manufacturer. The allowable variation depends also upon the type of reinforcement.

B.4 References for Appendix B

B1. Canadian General Standards Board (CGSB), "Standard for: Membrane, Modified, Bituminous, Prefabricated and Reinforced for Roofing," CGSB 37-GP-56M, July 1980, Ottawa, Canada.

B2. Midwest Roofing Contractors Association, "Recommended Performance Criteria for Modified Bitumen Roof Membrane Systems," Technical Document MB-30, Kansas City, MO., November 1983.

B3. European Union of Agrément, "Special Directives for the Assessment of Reinforced Waterproof Coverings of Atactic Polyproplene (APP) Polymer Bitumen," M.O.A.T. No. 30: 1984, August 1984, Paris.

B4. European Union of Agrément, "Special Directives for the Assessment of Reinforced Homogenious Waterproof Coverings of Styrene-Butadiene-Styrene (SBS) Elastomer Bitumen," M.O.A.T. No. 30: 1984, August 1984, Paris.

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Alternative approaches are reviewed for revision of the original NBS preliminary performance criteria for tensile strength and tensile fatigue strength for bituminous membrane roofing. Reviews of five approaches - elasticity theory, brittle fracture, viscoelasticity theory, strain energy and finite element techniques - were completed. Advantages and limitations of these approaches were identified and use of the strain energy approach for both tensile strength and tensile fatigue strength preliminary performance criteria was recommended.

12. KEY WORDS (*Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons*)

bituminous roofing; built-up roofing; membranes; performance criteria; strain energy; tensile strength; tensile fatigue strength

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