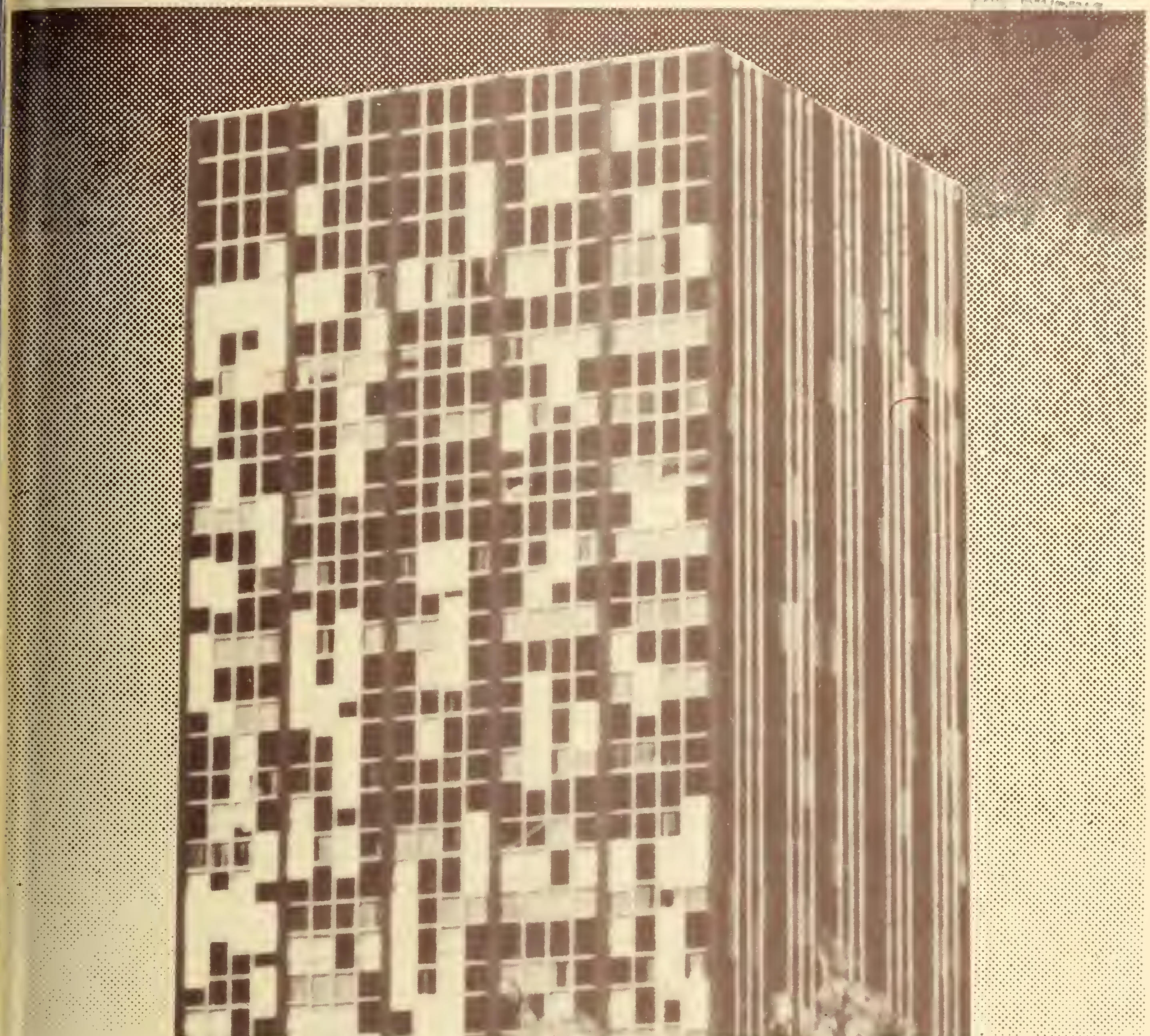

NBS BUILDING SCIENCE SERIES **154**

Wind Loading and Strength of Cladding Glass

U.S. DEPARTMENT OF COMMERCE • NATIONAL BUREAU OF STANDARDS

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NBS BUILDING SCIENCE SERIES 154

Wind Loading and Strength of Cladding Glass

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ABSTRACT

A procedure for investigating glass cladding behavior under arbitrary loads, including fluctuating wind loads, is presented. The procedure accounts for the fact that internal stresses are nonlinear functions of the external loads, that initial glass strengths are random functions of position and direction, and that glass strength undergoes degradation under the action of external loads in accordance with basic fracture mechanics laws. Numerical examples are presented, and corresponding probability distribution curves are calculated, indicating the probability of failure of a specified panel subjected to fluctuating wind loads and to 1-minute constant loads. These curves are used to illustrate a method for assessing current glass cladding design procedures. For the case considered in the paper, it was found that transformation of the peak wind load averaged over 1-2 seconds into an equivalent 1-minute load appears to underestimate the probability of failure of glass cladding. The work reported in the paper is part of an ongoing window cladding research program being conducted at the National Bureau of Standards.

Key words: aerodynamics; buildings; deformation; engineering mechanics; failure; glass; loads (forces); probability theory.

ACKNOWLEDGMENTS

Cover photo: Guaranty Bank Building, Corpus Christi, Texas, following Hurricane Celia, August 3, 1980. View is of the east face of the building. The photograph was graciously supplied by Dr. Joseph E. Minor, Director of the Institute for Disaster Research, Texas Tech University, Lubbock, Texas, 79409.

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1. INTRODUCTION

The improvement of design procedures for cladding glass subjected to wind loads has been the focus of a considerable amount of research in recent years. In 1979, Pittsburgh Plate Glass (PPG) published revised design charts [2] based upon nonlinear stress analyses used in conjunction with elementary statistical methods. In a number of instances, these charts differ from those issued by other manufacturers, notably LOF [8], and exhibit internal inconsistencies as well. For example, according to the PPG charts, a 3.67 ft x 18.33 ft (1.12 m x 5.60 m) glass panel with a thickness of 12.7 mm supported on four sides deflects 11.9 mm under a load of 100 psf (4790 Pa)); for a panel with a span of 1.12 m, with the same thickness and under the same load but supported on two sides, the deflection as obtained from the PPG charts is only 9.1 mm, rather than being equal to or in excess of 11.9 mm. Inconsistencies with respect to design loads exist as well. As an example, for a 1/8 in (3 mm) thick annealed float glass panel supported on four sides the PPG charts specify a 15 psf (719 Pa) one-minute load if the dimensions of the panel are 2.83 ft x 7.07 ft (0.865 m x 2.15 m), and the same - rather than a larger - one-minute load if the dimensions are 2.24 ft x 6.70 ft (0.68 m x 2.04 m). Inconsistencies such as these, and discrepancies with respect to other manufacturers' charts [8], suggest that the development of an improved theoretical framework for the design of glass cladding is a necessary task.

An important step toward such an improvement was proposed in 1980 by Beason [2]. Reference 2 combined nonlinear stress analysis with the classic Weibull theory to estimate the probability of failure of a glass panel subjected to a specified load, given the parameters of the Weibull distribution of the glass strength. Conversely, the procedure of reference 2 can be applied to estimate these parameters from information obtained by loading glass panels up to the failure point.

The procedure of reference 2 requires the transformation of the stresses induced by actual, time-dependent loads into nominal stresses corresponding to a 1-minute constant load. It is suggested in reference 2 that the transformation be carried out by using the following relationship:

$$\sigma_{60}(M) = \left[\frac{\int_0^{t_f} \sigma^n (M,t)dt}{60}\right]^{1/n} \qquad (1)$$

where $\sigma_{60}(M)$ = equivalent one-minute stress at point M, $\sigma(M,t)$ = stress induced by actual load at point M and time t, t_f = duration of loading or time to failure in seconds, whichever is smaller, and n = material constant. However, the time to failure t_f in equation 1 is unknown for panels that would fail under wind loads. To the extent that an arbitrary value for t_f is used in equation 1, and that this value could differ by as much as one or even two more orders of magnitude from actual values, significant errors would be introduced in estimating $\sigma_{60}(M)$. Note also that if equation 1 were used, it would be necessary to evaluate the integral at each point M, since the system is nonlinear (i.e., in general $\sigma(M,t)$ is not proportional to the wind loading at time t, p(t)).

On account of the difficulty--or impossibility--of specifying t_f, and of estimating the integrals in equation 1, to the writers' knowledge, no previous attempts have been made to study the behavior of glass cladding subjected to fluctuating wind loads. Instead, previous research has focused on the study of the behavior of glass cladding subjected to nominal 1-minute loads purported to be representative of fluctuating loads.

The purpose of this paper is to present a procedure for studying the behavior of glass under arbitrary time-dependent loads, including fluctuating wind loads. Like reference 2, the present procedure is based on a nonlinear analysis of stresses that develop under the action of the external loads, and on a Weibull probabilistic model for the strength of glass. However, unlike reference 2, the procedure presented here incorporates phenomenological models describing the fracture mechanisms of glass developed in the last decade by Wiederhorn and other workers (e.g., see references 5, 25, 26), as well as information on the fluctuating character of the wind loads. No *a priori* assumptions are needed with regard to the time to failure, t_f, which is one of the outputs of the procedure. As in reference 2, it is assumed that temperature and humidity effects can be neglected. Additional outputs include the location and direction of the failure initiation crack, and the amount of strength degradation due to the action of the fluctuating wind load.

To provide a background for the development of the proposed procedure, basic elements of the fracture mechanics of glass will be briefly summarized. A method for obtaining time-dependent stresses from time-dependent loads, which utilizes a computer program developed at Texas Tech University, will be described. A brief section will be devoted to the subject of time-dependent wind loading on cladding glass. The proposed procedure for investigating glass behavior under arbitrary loads will then be presented. The procedure will be applied to obtain estimates of probabilities of failure of a glass panel under fluctuating wind loads and under one-minute constant loads. Such estimates will then be used to illustrate a method for assessing current practices for the design of glass cladding subjected to wind loads.

2. FRACTURE MECHANICS OF GLASS

The basic criterion for fracture is derived from the Griffith equilibrium expression, which can be written as

$$K_I = K_{IC} \tag{2}$$

where K_I = stress intensity factor, and K_{IC} = critical value of K_I. If equation 2 holds, the system reaches the state of instability wherein the rate of crack growth becomes for practical purposes infinite [5, 7] and failure occurs. K_{IC} is a property of the material and is determined experimentally. The stress intensity factor, K_I, is proportional to the actual stresses in the material in the presence of cracks causing stress concentrations. K_I can be expressed as follows [5, 7]:

$$K_I(t) = Y\sigma(t)\sqrt{c(t)} \tag{3}$$

where

Y = geometric shape factor

σ = nominal stress (i.e., stress calculated by assuming the absence of cracks)

c = crack length

t = time

The geometric shape factor, Y, is assumed to be constant; this is equivalent to assuming that the crack geometry does not change and can be characterized by one dimension, c. According to experiments reported in references 5 and 22-26, the following relationship holds for the rate of subcritical crack growth (figure 1):

$$\frac{dc}{dt} = AK_I^n(t) \tag{4}$$

The parameters A and n depend upon ambient humidity and temperature and are obtained experimentally. Equation 4 expresses quantitatively the fact that the cracks of an element of glass subjected to stress for some length of time will grow - albeit not catastrophically - provided that the stress is contained within a certain range. This phenomenon is referred to as static or dynamic fatigue according to whether the stress is constant or time-dependent.

It follows from equations 2 and 3 that the strength of glass, S, i.e., the value of the nominal stress at which failure occurs, is:

$$S(t) = \frac{K_{IC}}{Y\sqrt{c(t)}} \tag{5}$$

If K_I and c are eliminated from equations 3, 4, and 5 and the notation $S(0) = S_i$ is used (S_i = initial strength), the following relationship is obtained:

$$S(t) = [S_i^{n-2} - \frac{1}{B}\int_0^t \sigma^n(\tau)\, d\tau]^{\frac{1}{n-2}} \qquad (6)$$

where $1/B = (n-2)\, AY^2\, K_{IC}^{n-2}/2$ [5]. It follows from the definition of S(t) that failure occurs if

$$\sigma(t) \geq S(t) \qquad (7)$$

In the calculations presented in this paper it is assumed that the variability of A and n in equation 4 is small and that its effect upon the results being sought can be neglected. As far as the variability of B is concerned, the following comment is in order. Because B is a function of Y, which in turn depends upon the flaw shape, its variability is difficult--if at all possible--to ascertain. If a deterministic value of B is assumed, based on a conventional value of Y, it is possible by using equation 6 to obtain values of S_i from experiments in which n, A, K_{Ic}, $\sigma(t)$ are known, and the time to failure, t_f, and the strength, $S(t_f)$, are measured. The empirical probability distributions of the initial strength estimated from the values S_i so obtained automatically reflect the actual shapes of the flaws.

The initial strength S_i of an element with area, a, experiencing a uniform, direction-independent state of tensile stress throughout one of its outer faces can be described probabilistically by a Weibull distribution [21], i.e.,

$$P(s_i,a) = 1 - \exp\left\{-\left(\frac{s_i}{S_o(a)}\right)^m\right\} \qquad \text{for } m \geqslant 1 \qquad (8)$$

where $P(s_i,a)$ = probability that the random variable $S_i < s_i$, $S_o(a)$ = scale parameter (characteristic strength), and m = shape (tail length) parameter.

The scale parameters, $S_o(a)$ and $S_o(a_1)$, of two elements with areas a and a_1, respectively, each experiencing uniform direction-independent states of tensile stress throughout one of its outer faces, can be written as [6]:

$$S_o(a) = S_o(a_1)\left(\frac{a_1}{a}\right)^{\frac{1}{m}} \qquad (9)$$

This relation reflects the dependence of strength distribution upon the distribution of flaw lengths. The larger the area of the panel, the larger will be the number of flaws and, therefore, the larger the probability that the area will contain a severe flaw to which, by virtue of equation 5, there corresponds a relatively low initial strength.

Consider now an element of glass with uniform but direction-dependent stresses throughout one of its outer faces. In this case, shear stresses are present, in addition to normal stresses. The effect of the normal stresses is by far the strongest, however, as far as crack propagation is concerned [7, p. 52]. Therefore it may be assumed to a first approximation--as is done in reference 2--that the effects of the shear stresses can be neglected. In the case of the element now being considered failure will not necessarily be initiated by a flaw normal to the maximum principal stress - indeed, it may well happen that all such flaws are relatively small. Neither will failure be necessarily initiated by the largest flaw within the element, since that flaw may well be perpendicular to a relatively low normal stress. Rather, failure will be initiated by the largest of the flaws oriented along some direction, α_f, such that

$$\sigma_n (t, \alpha_f) \geqslant \frac{K_{IC}}{Y\sqrt{c_{max}(t, \alpha_f)}} \qquad (10)$$

where $\sigma_n (t, \alpha_f)$ = normal stress perpendicular to direction α_f (equations 5 and 7) and $c_{max} (t, \alpha_f)$ = length of largest flaw oriented along direction α_f.

Under the assumption that the distribution of flaw orientation is uniform [2, p. 84], equation 9 can be applied to the case of an element subjected to uniform but direction-dependent state of stress as follows. The probability of occurrence within a certain area of flaws with crack length dimension less than c and having orientation angles $\alpha_1 < \alpha < \alpha_2$ is equal to $(\alpha_2 - \alpha_1)$ times the probability of occurrence within an area of flaws with dimension less than c and having any orientation $0 < \alpha < 2\pi$. The following relation is therefore consistent with equation 9 for any elemental circular area:

$$S_o(\alpha_1 < \alpha < \alpha_2) = S_o(0 < \alpha < 2\pi) \left(\frac{\pi}{\alpha_2 - \alpha_1}\right)^{\frac{1}{m}} \qquad (11)$$

3. STRESS ANALYSIS

Equations 6 and 7 clearly show that to investigate the behavior of glass, information is required on the time history of the stresses induced in the glass by the external loads.

The out-of-plane deflections of glass plates subjected to lateral loads can be large relative to the thickness of the plate. The plate develops substantial mid-plane membrane stresses in this condition, and the von Kármán equations [18, 20] must be used to account for this effect. Based on these equations, Vallabhan and Wang [19] have developed a program that uses the finite difference method to determine the deflections and stresses in uniformly loaded simply-supported thin glass plates having boundary conditions allowing for in-plane movement. With the permission of the Institute for Disaster Research, Texas Tech University, this program was employed in the present study to determine the stresses at various locations on the plate. The results from the program were non-dimensionalized as follows [9]

$$LF = pb^4/Dh \qquad (12)$$

$$SF = \sigma b^2 h/D \qquad (13)$$

where LF and SF = loading and stress factors, respectively, p = uniform pressure loading, σ = corresponding stress, b = smaller side of rectangular plate, D = flexural rigidity, defined by

$$D = \frac{Eh^3}{12(1-\nu^2)} \qquad (14)$$

E = modulus of elasticity, ν = Poisson's ratio, and h = thickness of plate.

For a square plate, the relationship between SF and LF for various locations is shown in figure 2. Note that the relationship is closer to being linear for the corner than for the center stresses.

Relationships for each location on the plate from the grid used for the finite difference analysis were determined and represented analytically in terms of piece-wise linear curves. On the basis of such relationships, given a time-dependent loading, the plate dimensions, and the material properties, the principal stresses and normal stresses corresponding to various directions can be calculated as functions of time.

4. WIND LOADING

Wind loading on cladding has a fluctuating character. Because the dimensions of cladding panels are relatively small (on the order of a few meters at most) it is acceptable to assume that the fluctuating loads acting over the area of the panel are uniformly distributed at any one instant and proportional to the pressures at the panel center.

The wind loads depend upon the local extreme wind climate [16, 17], the features of the oncoming air flow (which are in turn dependent upon the roughness of the surrounding terrain and the possible presence of neighboring buildings), and the aerodynamic characteristics of the building in question. These characteristics differ from point to point on the building facades and are, in addition, dependent upon wind direction.

Wind loading time histories are obtained principally from wind tunnel tests. Any given loading time history can be analyzed to determine its statistical characteristics; e.g., mean, standard deviation and peak. Models of the loading can be obtained in the frequency domain (using a spectral approach, for example, see reference 17), or in the time domain, e.g., using a Box-Jenkins approach [14]. Knowledge of these models in turn allows the numerical simulation of loading time histories that correspond to various reference wind speeds. In the particular case of a mean wind speed normal to a building face and in the absence of neighboring buildings which significantly alter the oncoming flow field, at a point Q near the center of the building face the pressures may be written approximately as

$$\bar{p}\,(Q) = \frac{1}{2}\,\rho\, C_p(Q)\, \bar{v}^2\,(z) \tag{14}$$

$$p'(Q,t) = \rho\, C_p(Q)\, \bar{v}(z) v'(z,t) \tag{15}$$

where $\bar{p}$ and p' = mean and fluctuating pressure, respectively, ρ = air density, $C_p(Q)$ = pressure coefficient at point Q, z = elevation of point Q, $\bar{v}(z)$ = mean wind speed, at elevation z and $v'(z,t)$ = longitudinal fluctuating component of wind speed. The fluctuating pressures can be simulated from spectral information or $v'(z,t)$ [17].

5. PROPOSED PROCEDURE FOR INVESTIGATING GLASS BEHAVIOR

Earlier in this paper it was noted that a glass panel will not necessarily fail at the point of maximum stress or of minimum strength. Rather, failure will occur where the relationship between stress and strength is such that equation 7 is satisfied, where $S(t)$ is given by equation 6, and S_i is described probabilistically by equation 8 (recall that the effects of area and of stress directionality are included in the procedure through equations 9 and 11).

With this background it is now possible to describe the proposed procedure for investigating glass behavior. The procedure entails the following steps:

1. For any given mean wind speed and direction generate the time history of the wind loading for the glass cladding panel of concern by Monte Carlo simulation as outlined in the section "Wind Loading."

2. Using the procedure outlined in the section "Stress Analysis" obtain from the time history of the wind loading the time histories of the stresses normal to the directions $\alpha_k = \frac{k\pi}{2r}$, $(k = 1, 2, \ldots r)$ at the center, M_j, of each of the elements into which the panel is divided for numerical computation purposes.

3. From equations 8 and 9 generate by Monte Carlo simulation initial strengths $S_i\ (M_j, \alpha_k)$, where $\alpha_k = k\Delta\alpha\ (k = 0, 1, 2, \ldots n)$ - see figure 3.

4. Evaluate numerically the expression

$$S(M_j, \alpha_k, t) = \left\{S_i^{n-2}(M_j, \alpha_k) - \frac{1}{B}\int_0^t [\sigma^n(M_j, \alpha_k, \tau)]\, d\tau\right\}^{\frac{1}{n-2}} \tag{16}$$

   for all j and k and $t = m\Delta t$, where Δt = incremental time used in numerical computations, and $m = 1, 2, \ldots$.

5. Computation is stopped if for at any set j, k,

$$\sigma(M_j, \alpha_k, m\Delta t) \geq S(M_j, \alpha_k, m\Delta t). \tag{17}$$

   At that point, failure of the general panel has occurred.

6. INPUT DATA FOR NUMERICAL CALCULATIONS

Numerical examples were carried out for the case of annealed float glass panels simply supported on four sides with dimensions 4 ft x 4 ft x 1/8 in (1.2 m x 1.2 m x 3 mm). The following parameters were used: $S_o(a_1 = 1\ m^2) = 35.2$ MPa [4], m = 6 [4], $A = 1.08\ (MPa)^{-n}\ m^{1-\frac{n}{2}}\ sec^{-1}$ [23], n = 19.69 [23], $K_{I_C} = 0.75$ MPa [23], $\nu = 0.22$ [2], E = 0.0689 MPa [2]. The values A and n correspond to 50 percent humidity and 20°C temperature (see figure 1). It was assumed that the geometric shape factor Y = 1.12 [see reference 10 for details]. It was further assumed that the glass panel is located near the center of a building facade at an elevation of z = 150 ft (46 m), that it is subjected to winds normal to the building face, that the building is located in open terrain, and that $C_p = 1.0$ in equations 14 and 15.

For any given mean wind speed, $\bar{v}$, the corresponding mean wind pressure was obtained by using equation 14. The fluctuating wind pressures were generated by numerical simulation using equation 15 and the following expression for the spectrum of the longitudinal velocity fluctuations v', [17]:

$$\frac{\tilde{n}\, S_v(\tilde{n})}{u_*^2} = \frac{200f}{(1 + 50f)^{5/3}} \tag{18}$$

where $u_* = \overline{v(z)}/[2.5\ \ell n(z/z_o)]$, $\tilde{n}$ = frequency, $f = \tilde{n}z/\overline{v(z)}$, z = elevation of panel in meters, and the roughness length corresponding to open terrain z_o = 0.07 m [17].

7. PROBABILITIES OF GLASS FAILURE

Failure of Glass Cladding Under Fluctuating Wind Loads. Consider the wind load, $p_i(t)$, corresponding to a mean wind speed, $v(z)$. The subscript, i, indicates that $p_i(t)$ is the i-th realization of the specified stochastic process. Let x_p, y_p be the coordinates of the centers of the elements into which the glass panel is divided. The size of these elements is sufficiently small so that the variation of the stresses over each element is insignificant for practical purposes. Let α_r be the directions, perpendicular to the normal stresses, being considered at each point. Obtain the stresses $\sigma_i(x_p, y_q, \alpha_r, t)$ corresponding to $p_i(t)$ for all values p, q, r. Assume that the number of panels (the sample size) is L. Simulate initial strengths $S_{o\ell}(x_p, y_q, \alpha_r)$ for one given set of values p, q, r for all the panels of the sample (ℓ = 1, 2, ... L). Rank order these strengths beginning with the smallest. Denote this smallest value by $S_{o1}(x_p, y_q, \alpha_r)$. Compare $\sigma_i(x_p, y_q, \alpha_r, t)$ to $S_1(t)$ by using equation 6. If $\sigma_i < S_1$ for every t, then no panel will break at point x_p, y_q in the direction of α_r. However, if $\sigma_i \geq S_1$ for some t, the panel for which the initial strength at x_p, y_q, α_r is S_{o1} will break. One breakage is recorded, and the panel concerned is eliminated from further consideration. If $\sigma_i \geq S_2$, where S_2 is derived from the second smallest initial strength for the given p, q, r, then breakage initiated at x_p, y_q, α_r will occur. Repeat the comparison until $\sigma_i \leq S_N$. The number of failures initiated at x_p, y_q, α_r will then be $\tilde{N}=N-1$, and the corresponding panels are eliminated from further consideration. Repeat the procedure for all values, p, q, r. The probability of failure under load $p_i(t)$ is $P[\text{failure} \mid p_i(t)] = \Sigma(\tilde{N}/L)_i$. Repeat the the procedure for different realizations of the pressure. The probability of failure under load p(t) is $P[\text{failure} \mid p(t)] = \sum_i^G \text{Prob. } [\text{failure} \mid p_i(t)]/G$, where the summation is over the number of realizations, G, being considered.

A cumulative distribution function $P[\text{failure} \mid p(t)]$ is derived indicating that the strength of the plate is less than required to withstand the load p(t) in 100 x $P[\text{failure} \mid p(t)]$ percent of the cases. Note that $P[\text{failure} \mid p(t)]$ embodies both the characteristics of the material and the aerodynamic characteristics of the loading under consideration. These two types of characteristics are inseparable owing to the dependence of glass strength upon load time history.

For convenience, the load p(t) may be indexed by its mean value $\bar{p}$, so that the notation $P[\text{failure} \mid \bar{p}]$, or simply $P_f(\bar{p})$ may be substituted for $P[\text{failure} \mid p(t)]$. Estimates of points of the cumulative distribution function $P_f(\bar{p})$ estimated for the conditions described in the section "Input Data for Numerical Calculations" are shown in figure 4. These points were obtained for simulated failure tests carried out on two sets of 1,000 panels, each set being subjected to different realizations of the fluctuating pressure, p(t).

Typical time histories of pressure, stress, and strength at panel points where failure was found to occur are shown in figure 5. Note the continuous strength degradation under load. In certain instances a storm can cause significant strength degradation without causing failure. The weakened panel could then break under the action of subsequent, less intense storms, should such storms occur during its lifetime.

Failure of Glass Cladding Under 1-Minute Constant Load. Let the normal stress induced by the 1-minute load, p_{60}, and the initial strength be denoted by $\sigma_{60}(M, \alpha)$ and $S_i(M, \alpha)$, respectively, where M and α are the point and the direction under consideration. It is assumed that the 60-second action of $\sigma_{60}(M, \alpha)$ causes failure. It follows from equation 6 that, with negligible error, the following relation holds:

$$\sigma_{60}(M, \alpha) \simeq \left(\frac{S_i^{n-2}(M, \alpha)}{60/B}\right)^{1/n} \tag{19}$$

The procedure for obtaining p_{60} is as follows: Generate initial strengths, $S_{o\ell}$ (x_p, y_q, α_r) for $\ell = 1, 2, \ldots$ L panels. Use equation 19 to solve for $\sigma_{60}(M, \alpha)$ at each x_p, y_q, α_r for panel ℓ. Calculate the value of p_{60} corresponding to each $\sigma_{60}(M, \alpha)$. Find the minimum p_{60} for panel ℓ; it represents the lowest 60-second pressure loading for which failure of panel ℓ will occur. Repeat the procedure for $\ell = 1, 2, \ldots$ L panels. The results obtained can be plotted in the form of a cumulative distribution function P[failure | p_{60}], denoted as $P_f(p_{60})$. Figure 6 shows a cumulative distribution $P_f(p_{60})$ for the conditions described in the section "Input Data for Numerical Calculations," based results of obtained for a set of 4,000 panels.

Note that according to the PPG charts [2] the 1-minute load, p_{60}, corresponding to a probability of failure of 8 in 1,000 is 23 psf. The corresponding value of p_{60} indicated by figure 6 is about 19 psf.

8. ASSESSMENT OF CURRENT PROCEDURES FOR DESIGNING GLASS CLADDING

The purpose of this section is to compare the current design loadings with the present procedure.

Procedure Used in Refs. 12-13. This procedure is based on the assumption that the effect of wind loading is determined solely by the peak load averaged over 1 or 2 seconds that occurs during the storm. It is assumed that the loading on the cladding which is subjected to a fluctuating wind pressure is equivalent to a 1-minute constant pressure, p_{60}^{C}, defined as

$$p_{60}^{C} = p_{pk} \left(\frac{t_{pk}}{60}\right)^{\frac{1}{n}} \tag{20}$$

where p_{pk} = peak pressure averaged over the time, t_{pk}, that occurs during the storm being considered, and t_{pk} = 1-2 seconds. According to this assumption, then, provided that p_{pk} is the same, it does not matter whether the mean loading is large and the fluctuations are small or vice-versa. The probability of failure of a panel subjected to a load, p(t), implicit in reference 12 is thus equal to the probability of failure of that panel under the action of a 1-minute load, p_{60}, obtained from p(t) by using the above equation.

Procedure Proposed in Ref. 3. This procedure assumes that the equivalent 1-minute pressure loading is given by

$$p_{60}^{D} = \left\{\frac{\int_{o}^{t_s} p^n (t)\, dt}{60}\right\}^{1/n} \tag{21}$$

where t_s = duration of storm.

Comparison of Design Loadings Based on Various Procedures. The purpose of this section is to compare the loads p(t), p_{60}^{C}, and p_{60}^{D} corresponding to various probabilities of failure. These loads are obtained from the cumulative distribution functions of figs. 4 and 6.

To the storm with mean speed $\bar{v}$ these corresponds a mean pressure $\bar{p}$, a 1-minute load obtained in accordance with reference 12, p_{60}^{C}, and a 1-minute load obtained in accordance with reference 3, p_{60}^{D}. For the conditions described in the section "Input Data for Numerical Calculations," the ratios $p_{60}^{C}/\bar{p}$ and $p_{60}^{D}/\bar{p}$ were found to be approximately 1.08 and 1.26, respectively. Values of p_{60}^{C} and p_{60}^{D} corresponding to various values $\bar{p}$, and the probabilities of failure

$P_f(p) \equiv P[\text{failure} \mid p(t)]$, $P_f\,(p_{60}^{C} = p_{60})$, and $P_f\,(p_{60}^{D} = p_{60})$, obtained from figs. 4 and 6, are listed in table 1. It is seen that, in this instance, the estimates based on the procedure of reference 12 appear to be overly optimistic, i.e., they appear to underestimate the probability of failure of the panel under any given storm and, therefore, the probability of failure of the panel during its lifetime. The probability estimates based on the procedure of reference 3 are somewhat closer to those based on the time history of the stresses. Note that for storms causing rates of failure of about 8 in a 1,000 the probability estimates based on the stress time history and on the nominal 1-minute loads p_{60}^{C} and p_{60}^{D} happen in this case to be relatively close. The respective discrepancies increase considerably in the case of stronger storms.

9. CONCLUSIONS

A procedure for investigating glass cladding behavior under arbitrary loads, including fluctuating wind loads, was presented. The procedure accounts for the fact that internal stresses are nonlinear functions of the external loads, that initial glass strengths are random functions of position and direction, and that the glass strength undergoes degradation under the action of external loads in accordance with basic fracture mechanics laws that reflect subcritical crack growth. Numerical examples were presented, and corresponding probability distributions were calculated, indicating the probability of failure of a specified panel subjected to fluctuating wind loads and to 1-minute constant loads. These curves are used to illustrate a method for assessing current glass cladding design procedures. For the case considered in the paper it was found that procedures based on the transformation of the wind load averaged over 1-2 seconds into an equivalent 1-minute load appear to result in overly optimistic assessments of the probability of failure of glass cladding under wind loads. The work reported in the paper is part of an ongoing window cladding research program being conducted at the National Bureau of Standards. Future work will consider the effect of fluctuating loads on corner and eave panels, and the effect upon fracture load predictions of the variability of the parameters that control glass behavior under load.

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APPENDIX I. NOTATION

a, a_1 = area under uniform tension

A = material constant relating rate of crack propagation to the stress intensity factor K_I

B = material constant used in fracture mechanics analysis

b = length of side

c = flaw (crack) length

D = flexural rigidity

E = modulus of elasticity

f = Monin or similarity coordinate

G = total number of storm realizations

h = plate thickness

K_I = stress intensity factor

K_{I_c} = critical value of K_I

LF = load factor

m = Weibull parameter

n = material constant

$\tilde{n}$ = frequency in Hz

$\tilde{N}$ = total number of panel failures/storm realization

$p(t)$ = wind pressure loading at time t

$\bar{p}(Q)$ = mean component of the quasi-static pressure at point Q

$p(Q,t)$ = fluctuating component of the quasi-static pressure at point Q

$P60$ = one minute effective loading

$P60^C$ = one minute effective loading defined by equation 20

$P60^D$ = one minute effective loading defined by equation 21

p_{pk} = peak pressure

q_m = internal velocity pressure

q_p = effective velocity pressure for parts and portions

s = sample standard deviation

S(t) = strength at time t

Si = initial strength

So = Weibull location parameter

SF = stress factor

t = time

tpk = time duration of peak pressure

$\overline{V}_f$ = fastest mile wind speed

$\overline{X}$ = sample mean

Y = proportionality constant

y = parameter calculated in Type I distribution

z = elevation

α_f = direction

ν = Poisson's ratio

ρ = density of air

$\sigma(M,t)$ = nominal stress induced by a pressure load at point M and time t

$\sigma_n(t, \alpha_f)$ = normal stress perpendicular to direction α_f at time t

$\sigma_{60}(M)$ = equivalent one-minute stress at point M

APPENDIX II. COMPUTER LISTING

```
C
C              GLASS ANALYSIS PROGRAM
C
C
C        THIS PROGRAM ESTIMATES THE PROBABILITY OF FAILURE
C        OF SQUARE GLASS PANELS SUBJECTED TO ARBITRARY
C        PRESSURE LOADINGS.  THE PROGRAM CAN BE EASILY
C        MODIFIED TO ACCOMODATE RECTANGULAR PANELS.
C        THE LOADINGS CAN BE CONSTANT ONE-MINUTE LOADS,
C        DETERMINISTIC TIME DEPENDENT LOADS, OR
C        FLUCTUATING LOADS.  THE LATTER ARE SIMULATED
C        USING QUASI-STATIC THEORY AND AUTOREGRESSIVE MODELS,
C        OR CAN BE READ IN AS FLUCTUATING OR CONSTANT.
C        THE INITIAL STRENGTH VALUES FOR EACH LOCATION
C        ON THE PANEL ARE GENERATED FROM INPUT WEIBULL
C        PARAMETERS, OR CAN BE READ IN, OR SIMPLY INPUT
C        AS CONSTANT.  STRENGTH DEGRADATION IS DETERMINED
C        AND IF DESIRED, THE STRESS AND STRENGTH TIME
C        HISTORIES OF THOSE PANELS WITH DEGRADATION
C        OF A CERTAIN PERCENTAGE CAN BE WRITTEN ONTO A
C        FILE.
C
C
C        THE SIXTY-SECOND LOADINGS GIVEN BY EQNS. 20 AND 21 ARE
C        CALCULATED FOR EACH P(T) (FLUCTUATING LOADING).
C
C
C
C        TO OBTAIN FAILURE STATISTICS, NUMERICAL EXPERIMENTS
C        ARE CONDUCTED ...
C        UP TO 1000 PANELS CAN BE SUBJECTED TO AS MANY
C        AS 10 STORMS, EACH HAVING THE SAME MEAN BUT
C        WITH FLUCTUATINF TIME HISTORIES THAT ARE
C        DIFFERENT ON ACCOUNT OF THE RANDOM NATURE OF
C        THE FLUCTUATIONS.  EACH STORM CAN BE OF DURATION
C        900 SECONDS OR LESS.  TO SUMMARIZE...
C        TEN STORMS CAN BE TESTED.
C        1000 PANELS/STORM CAN BE TESTED.
C        STORM DURATION CAN BE 900 SECONDS OR LESS.
C        THESE PARAMETERS CAN BE CHANGED BY INCREASING
C        OR DECREASING THE DIMENSION STATEMENTS BELOW...
C        INPUT PARAMETERS ARE DEFINED BELOW.....
C
C
C      THE STATEMENTS CONCERNING THE PRESSURE TIME
C      HISTORY IN THIS PROGRAM CORRESPOND TO THE
C      CASE WHERE (1) THE VELOCITY IS PERPENDICULAR
C      TO THE PLANE OF THE FACADE AND (2) THE PANEL
C      IS SUFFICIENTLY FAR FROM THE EAVE OF THE
C      GROUND (SEE EQNS 14 AND 15 IN THE REPORT).
C      FOR ANY OTHER POSITION OF THE PANEL, THE PRESSURES
C      ARE DETERMINED IN ACCORDANCE WITH THE RELATION:
C
C       P(Y,Z,T) = 0.5 RHO (U(H)**2 ) CP(Y,Z,T)
C
C      WHERE P(Y,Z,T) = TIME DEPENDENT PRESSURE AT ELEVATION Z
C                       AT DISTANCE Y FROM THE CENTERLINE OF
C                       THE FACADE AT TIME T
C            RHO      = AIR DENSITY
C            U(H)     = MEAN WIND SPEED AT THE TOP OF THE
C                       BUILDING
```

```
C           CP(Y,Z,T)= PRESSURE COEFFICIENT CORRESPONDING TO
C                      THE WIND TUNNEL OR FULL SCALE REFERENCED
C                      WITH RESPECT TO U(H)
C
C
C
C
C
C PARAMETER DEFINITIONS IN ORDER OF  INPUT...
C
C
C NSTORM          NUMBER OF STORMS
C NPANEL          NUMBER OF PANELS
C NDUR            STORM DURATION ( SECONDS )
C DT              TIME STEP ( SECONDS )
C SIDEA           LENGTH OF PANEL SIDE (INCHES)
C TH              THICKNESS (INCHES)
C E               MODULUS OF ELASTICITY (PSI)
C PR              POISSONS RATIO
C KIC             STRESS INTENSITY FACTOR (COMPATIBLE W/ MPA UNITS)
C A               FRACTURE MECHANICS PARAMETER(SAME AS WITH KIC)
C RY              GEOMETRIC SHAPE PARAMETER
C RN              POWER USED IN EQN. 6
C SO              UNITS = MPA, WEIBULL DISTRIBUTION PARAMETER
C CO              M=1/CO IN WEIBULL DISTRIBUTION, EQN. 8  IN
C                        THE REPORT
C SCONT           CONSTANT STRENGTH VALUE ,UNITS=MPA
C STCONT          CONSTANT STRESS VALUE, UNITS = MPA
C DAF(1)          NAME OF FILE WHICH CONTAINS INITIAL
C                 STRENGTH VALUES, IF THIS OPTION IS
C                 CHOSEN
C ILOAD           LOAD TYPE
C                  = 1 , SIMULATE FROM AR(2) MODEL
C                  = 2 , CONSTANT, READ IN FROM LOGICAL UNIT 5
C                  = 3 , READ IN FROM LOGICAL UNIT 10
C ISTREN          INITIAL STRENGTH TYPE
C                  = 1 , WEIBULL DISTRIBUTION
C                  = 2 , CONSTANT, INPUT VALUE
C                  = 3 , READ IN FROM LOGICAL UNIT 11
C ISTRES          STRESS TIME HISTORY TYPE
C                  = 1 , CALCULATE FROM P(T)
C                  = 2 , CONSTANT, INPUT VALUE
C IWRIT           PRINTING OPTION
C                  = 1 ,PRINT ONLY FINAL TABLE
C                  = 2 ,PRINT OUT FAILURE TIME & INITIAL STRENGTH
C                       AT LOCATIONS WHERE FAILURE OCCURS
C                       & THE FINAL TABLE
C                  = 3 ,PRINT OUT FAILURE TIME & INITIAL STRENGTH
C                       AT LOCATIONS WHERE FAILURE OCCURS,
C                       AS WELL AS THE STRENGTH & STRESS TIME
C                       HISTORIES, & THE FINAL TABLE
C IRAT            RATIO CHECK
C                 = 1 , CHECK FOR % DEGRADATION
C                       & PRINT OUT % AT LOCATION & DIRECTION
C                 = 2 ,DO NOT CHECK
C                 = 3 ,CHECK AND PRINT OUT THE STRENGTH
C                      & STRESS TIME HISTORIES
C                 = 1 OR 3, INPUT RAT1,RAT2 %S BELOW
C                   NOTE RAT1 MUST BE .GE. RAT2
C
C
C
C
      DOUBLE PRECISION DSEED,TERM1,TERM2,RDIFF,RDIR,RATIO,SLOPE
      DOUBLE PRECISION A1(1000),A2(6),S(900),AI(6,1000),RSIG(36,6)
      REAL IT,PV(10),F(1000),PMEAN,PM(10),NFAIL2(216),FMAX,
```

```
     *UMEAN(10),PF(10),PCER(10),PDAG(10),RAT1,RAT2
      DOUBLE PRECISION P(900),SIGMA(36,900)
      EQUIVALENCE( P(1),S(1) )
      DOUBLE PRECISION M,COEF,D,SO,BP,A,KIC,TH,PR,E,ROOT,RNM,RN
      DOUBLE PRECISION P60(10),SCALE,FLEX,SCONT,STCON,SIGG2,
     *SINT(1000),SU,RY
      INTEGER MRI,ISTREN,NCOUNT,NPANEL,NDUR,I1,
     *ISEED,TIME(1000),IWRIT,IRAT,K7,K6(36)
      CHARACTER*16 DAF(4)
C
C ENTER PARAMETERS
C
C
C
      READ(5,*)NSTORM,NPANEL,NDUR,DT
      READ(5,*)SIDEA,TH
      READ(5,*)E
      READ(5,*)PR,KIC
      READ(5,*)A,RN,RY
      READ(5,*)ILOAD,ISTREN,ISTRES,IWRIT,IRAT
      IF( ISTREN .EQ. 1)READ(5,*)SU,SO,CO
      IF( ISTREN .EQ. 2)READ(5,*)SCONT
      IF( ISTRES .EQ. 2)READ(5,*)STCON
      IF( ISTREN .EQ. 3 )READ(5,8)DAF(1)
      IF( IRAT .NE. 2 )READ(5,*)RAT1,RAT2
C
      CALL TWRITE(ILOAD,ISTRES,ISTREN,NDUR)
C
C    DEFINE POWERS FOR EQUATIONS
C
      RNN=RN+1.
      RNM=RN-2.
      ROOT=1./RNM
      ROOT2=1./RN
C
C     CALCULATIONS
C
      BP=(RNM*A*RY*RY*(KIC**RNM))/2.
      FLEX=(E*TH*TH*TH)/(12.*(1-PR*PR))
      COEF=DT*BP/RNN
      SCALE=(SIDEA**4.)/(FLEX*TH)
C
C
C
      CALL GWRITE(SIDEA,TH,E,PR,A,KIC,NPANEL,RN,BP)
C
      DO 5555KK=1,NSTORM
      IF( IWRIT .NE. 1 )WRITE(6,7)KK
      IF( IRAT .NE. 2 )WRITE(9,7)KK
      IF ( ILOAD .EQ. 2 ) GO TO 1111
      IF ( ILOAD .EQ. 3 ) GO TO 1112
      IF( ISTRES .EQ. 2 ) GO TO 2222
      IF( ISTREN .GT. 4 )WRITE(6,9000)
      IF( ISTRES .GT. 4 )WRITE(6,9000)
C
C
C
C PARAMETER DEFINITIONS FOR P(T) SIMULATION
C
C CP                  STATIC PRESSURE COEFFICIENT
C Z                   ELEVATION
C ZO                  FRICTION LENGTH
C UMEAN               MEAN WIND VELOCITY
C MRI                 MEAN RECURRENCE INTERVAL
C
C
```

```
      READ(5,*)CP,Z,Z0,IT,MRI
      DATA XMIN,XMAX,NDIV/0,100,1000/
      UMEAN(KK)=IT
      IT=IT*1.47
C
C  ICLOCK IS A FUNCTION WHICH RETURNS THE NUMBER OF SECONDS
C  SINCE MIDNIGHT ....
C
C
        CALL ICLOCK(2,ISEED)
        DSEED=DFLOAT(ISEED)
C
C
C     GENERATE LOAD AND  NON-DIMENSIONALIZE
C
C
      CALL PRES(XMIN,XMAX,NDIV,DSEED,DT,NDUR,Z,Z0,IT,CP,PMEAN,PVA,P)
      PV(KK)=144.*PVA
      PM(KK)=144.*PMEAN
      CALL PWRITE(IT,MRI,DT,CP,PMEAN,P,NDUR)
C
C
C
      GO TO 444
1111  CONTINUE
      READ(5,*)P60(KK)
      DO 333I=1,NDUR
333   P(I)=P60(KK)
      GO TO 444
1112  READ(10,*)( P(I), I=1 ,NDUR )
C
C
C FIND THE EQUIVALENT SIXTY-SECOND LOADINGS FOR P(T)
C
C
444   CONTINUE
      CALL PEQ(NDUR,DT,RN,P,P1,P2)
      PCER(KK)=144.*P1
      PDAG(KK)=144.*P2
C
C
C CALCULATE THE LOAD FACTOR FROM P(T)...
C
C
      DO 3011I=1,NDUR
3011  P(I)=P(I)*SCALE
C
C FIND DIRECTIONAL MULTIPLIERS AND CALCULATE THE STRESS FACTORS...
C
      CALL DIR(RSIG)
      CALL STRESS(FLEX,SIDEA,TH,NDUR,P,SIGMA)
C
C
C
C INITIAL STRENGTH DISTRIBUTION
C       WEIBULL DISTRIBUTION ASSUMED.....
C
2222  CONTINUE
      IF ( ISTRES .NE. 2 .AND. ISTREN .NE. 2 )GO TO 2223
      J=1
      JK=0
      II1=0
      GO TO 60
2223  IF( ILOAD .NE. 2 .AND. IWRIT .NE. 1 )WRITE(6,3)
      IF( ISTREN .EQ. 3 )OPEN(11,IOSTAT=ISTAT,FILE=DAF(1))
C
```

```
C
C
      DO 111J=1,36
111   K6(J)=0
      DO 10J=1,36
      IF(ISTREN .EQ. 2) GO TO 50
      IF(ISTREN .EQ. 3) GO TO 40
      M=1./CO
C
C
      CALL ICLOCK(2,ISEED)
      DSEED=DFLOAT(ISEED)
      CALL GGUBS(DSEED,NPANEL,F)
C
C
      DO 22K=1,6
      DO 30I1=1,NPANEL
30    A1(I1)=SU + SO*((-ALOG(F(I1)))**M)
C
C RANK THE INITIAL STRENGTH VALUES ...
C
C ELIMINATE THOSE WHICH ARE TOO LARGE FOR FAILURE TO
C OCCUR...
C
C
      CALL VSRTAD(A1,NPANEL)
C
C
      DO 31I1=1,NPANEL
31    AI(K,I1)=A1(I1)
22    CONTINUE
      DO 23K=1,6
      A2(K)=AI(K,1)
23    CONTINUE
C
C VSRTAD IS AN IMSL SUPPLIED ROUTINE WHICH
C  RANKS THE VALUES OF THE INPUT VECTOR FROM SMALLEST
C  TO LARGEST....
C
C
C RANK THE INITIAL STRENGTH VALUES ACCORDING TO DIRECTION...
C
      CALL VSRTAD(A2,6)
C
C
C CHECK TO SEE HOW MANY DIRECTIONS CAN BE ELIMINATED FROM
C COMPARISON BELOW...
C
C
      DO 24K=1,6
      IF( A2(1) .EQ. AI(K,1) )K5=K
      K6(J)=K5
24    CONTINUE
      GO TO 10
C
C READ IN INITIAL STRENGTH VALUES AND RANK AS ABOVE FOR
C GENERATED VALUES .....
C
C
C
40    CONTINUE
      DO 26K=1,6
      READ(11,44) ( A1(I1), I1=1,NPANEL )
C
C RANK THE INPUT INITIAL STRENGTH VALUES ...
C
```

```
C
      CALL VSRTAD(A1,NPANEL)
C
C
C
      DO 27I1=1,NPANEL
      AI(K,I1)=A1(I1)
27    CONTINUE
26    CONTINUE
      DO 28K=1,6
      A2(K)=AI(K,1)
28    CONTINUE
C
C
C RANK ACCORDING TO DIRECTION.....
C
C
      CALL VSRTAD(A2,6)
C
C CHECK TO SEE HOW MANY DIRECTIONS MAY BE CRITICAL...
C
C
C
      DO 29K=1,6
      IF(A2(1) .EQ. AI(K,1)) K5=K
      K6(J)=K5
29    CONTINUE
10    CONTINUE
50    CONTINUE
C
C
C THE 100 LOOP IS FOR EACH NPANEL CHECK
C
C
      JK=0
      NPOS=36
      DO 110J=1,NPOS
      K7=K6(J)
      NCOUNT=0
      DO 20K=1,K7
      NCOUNT2=0
      JK=JK+1
      DO 100 I1=1,NPANEL
      IF(ISTREN .EQ. 2) GO TO 60
      S(1)=A1(I1)
      GO TO 70
60    S(1)=SCONT
      NCOUNT=0
      JK=JK+1
      II1=II1+1
70    CONTINUE
C
C  EQUATION 6 IN REPORT
C
C
      DO 200I=2,NDUR
      IF( ISTRES .EQ. 2 ) D=1.0
      IF( ISTRES .EQ. 2 )GO TO 700
      SLOPE=SIGMA(J,I)-SIGMA(J,I-1)
      IF( SLOPE .EQ. 0 ) GO TO 700
      IF( RSIG(J,K) .LT. 0 )GO TO 20
      RDIR= (RSIG(J,K))**RN
      D=RDIR*((SIGMA(J,I)**RNN) -(SIGMA(J,I-1)**RNN) )/SLOPE
      SIGG2=SIGMA(J,I)*RSIG(J,K)
      GO TO 800
700   IF( ISTRES .EQ. 2 )SIGG2=STCON
```

```
      IF( ISTRES .NE. 2 )SIGG2=SIGMA(J,I)*RSIG(J,K)
      IF( ILOAD .EQ. 2 )D=1.0
      IF( SIGG2 .LE. 0 ) SIGG2=0
      IF( SIGG2 .EQ. 0 )D=0
      IF( D .EQ. 0 ) GO TO 800
      D=RNN*( SIGG2**RN )
800   TERM1=S(I-1)**RNM
      TERM2=COEF*D
C     WRITE(6,*)' TERM1 ',TERM1
C     WRITE(6,*)' TERM2 ',TERM2
      RDIFF=TERM1 -TERM2
      IF( RDIFF .LT. 0 ) GO TO 900
      S(I)=RDIFF**ROOT
200   IF(  SIGG2  .GE. S(I) ) GO TO 900
C
C
C FAILURE DOES NOT OCCUR IN THE GIVEN TIME PERIOD
C CHECK FOR DEGRADATION ......
C
      IF( IRAT .EQ. 2 )GO TO 102
      RATIO = (S(NDUR)/S(1))*100.
      IF( RATIO .LT. RAT1 ) GO TO 901
102   CONTINUE
      IF( ISTRES .EQ. 2 .AND. ISTREN .EQ. 2 ) GO TO 5555
      IF( ISTREN .EQ. 2 ) GO TO 10
      GO TO 902
900     NCOUNT = NCOUNT + 1
        NCOUNT2=NCOUNT2+1
        TIME(NCOUNT)= I
        SINT(NCOUNT)= S(1)
      IF( IWRIT .EQ. 1 .OR. IWRIT .EQ. 2 ) GO TO 3334
      NEND=I
      IF( ISTRES .NE. 2) WRITE(6,6000)( SIGMA(J,I),I=1,NEND)
      WRITE(6,6000)( S(I), I=1,NEND )
      IF(I1 .LT. NPANEL)GO TO 100
      IF(ISTREN .NE. 2) GO TO 3334
      DO 4443I=1,NEND
4443  SIGMA(1,I)= SIGG2
      WRITE(6,6000)( SIGMA(J,I), I=1,NEND )
3334  DO 9999I=1,NEND
9999  S(I)=0.0
      GO TO 100
901   WRITE(9,*)'  RATIO OF FINAL TO INITIAL S =  ',RATIO,' %  '
      WRITE(9,*)' AT POSITION ',J,' AND DIRECTION ',K
      IF( ISTRES .EQ. 2 .AND. ISTREN .EQ. 2 )WRITE(9,*)' PANEL # ',II1
      IF(ISTRES.NE.2 .AND. ISTREN.NE.2)WRITE(9,*)' PANEL # ',I1
      WRITE(9,*)' % CHECK VALUES ARE ',RAT1,' AND ',RAT2
      IF ( RATIO .GE. RAT2 )GO TO 101
      IF( IRAT .EQ. 1 .OR. IRAT .EQ. 2 )GO TO 101
      IF( RATIO .LT. RAT2 )WRITE(9,6000)( S(I),I=1,NDUR )
      DO 8876I=1,NDUR
8876  SIGMA(J,I)=SIGMA(J,I)*RSIG(J,K)
      IF( RATIO .LT. RAT1 )WRITE(9,6000)( SIGMA(J,I),I=1,NDUR)
        DO 6788I=1,NDUR
6788    SIGMA(J,I)=SIGMA(J,I)/RSIG(J,K)
101   CONTINUE
      DO 9998I=1,NDUR
9998  S(I)=0.
C
C
C FINISH OF 100 LOOP
C
C
100   CONTINUE
C
C
```

```
902   DO 9988I=1,NDUR
9988  S(I)=0.
       NFAIL2(JK)=REAL(NCOUNT2)
       IF( NCOUNT .EQ. 0 ) GO TO 20
       IF( IWRIT .EQ. 1) GO TO 20
      WRITE(6,3)
        DO 7001I=1,NCOUNT
7001    WRITE(6,2)I,J,K,TIME(I),SINT(I)
      IF( ISTRES .EQ. 2 .AND. ISTREN .EQ. 2) GO TO 5555
C
C FINISH THE DIRECTION LOOP
C
20    CONTINUE
C
C FINISH THE LOCATION / POSITION LOOP
110   CONTINUE
C
C
C CALCULATE THE NUMBER OF FAILURES PER STORM AND
C WRITE TO AN OUTPUT DEVICE .....
C
       FMAX=0.0
       II=JK
       DO 7002I=1,II
7002   FMAX=AMAX1(FMAX,NFAIL2(I))
       PF(KK)=FMAX/NPANEL
      IF( ILOAD .EQ. 2 ) GO TO 5555
C
C
C GO TO NEXT STORM...
C
C
      CLOSE(11)
5555  CONTINUE
C
      IF( ISTREN .EQ. 2 .AND. ISTRES .EQ. 2 ) GO TO 5561
      IF( ILOAD .EQ. 2 )GO TO 5558
       WRITE(6,6)
C
C     PRINT THE FINAL PROBABILITY ESTIMATES
C     DEFINITIONS...
C     UMEAN(K)   MEAN WIND SPEEDS
C     PM(K)      MEAN PRESSURES
C     PV(K)      STANDARD DEVIATION OF P(T)
C     PCER(K)    60-SECOND LOADING OF EQN. 20
C     PDAG(K)    60-SECOND LOADING OF EQN. 21
C     PF(K)      # OF FAILURES FOR P(T)/# OF PANELS TESTED
C     UNITS OF PRESSURE VALUES = PSF
C     VELOCITY IN FT/SEC
C
C
       DO 5556KK=1,NSTORM
 5556  WRITE(6,5)UMEAN(KK),PM(KK),PV(KK),PCER(KK),PDAG(KK),PF(KK)
      GO TO 5559
5558  WRITE(6,9)
      DO 5560I=1,NSTORM
      P60(I)=144.*P60(I)
5560  WRITE(6,112)P60(I),PCER(I),PDAG(I),PF(I)
5561  CONTINUE
C
6000     FORMAT(1X,5F10.4)
9000  FORMAT(1X,' THE VALUE OF ILOAD, ISTREN, OR ISTRES IS WRONG')
2     FORMAT(1X,I5,6X,I5,7X,I5,5X,I5,2X,F12.4)
3     FORMAT(1X,' FAILURE # ',1X,' POSITION ',1X,' DIRECTION ',
     *1X,' TIME  ',1X,'S INITIAL ')
5     FORMAT(1X,6F10.5)
```

```
6     FORMAT(3X,' MEAN U ',3X,' MEAN P ',1X,' STAN P',1X,
     *'  P1   ',1X,' P2  ',1X,'PF(PMEAN) ')
7     FORMAT(1X,' STORM NUMBER ',I10)
8     FORMAT(16C)
9     FORMAT(3X,' PRESSURE ',5X,' P1  ',1X,' P2  ',7X,
     *' PF ')
112    FORMAT(1X,F10.2,5X,F10.2,5X,F10.5,5X,F10.5)
44    FORMAT(1X,6F10.4)
C
C
5559  CONTINUE
      STOP
      END
C
      SUBROUTINE DIR(RSIG)
C     FIND DIRECTIONAL MULTIPLIERS FOR STRESSES AT VARIOUS
C      ANGLES...
C
C
      DOUBLE PRECISION PH,RSIG(36,6),C(6),SII(6),S2S1(36)
      DATA S2S1/1.0,.98,.94,.89,.79,.68,.52,.12,.97,.93,
     *.86,.77,.65,.47,.05,.89,.82,.71,.57,.36,-.09,.73,.61,
     *.45,.21,-.24,.47,.28,.02,-.38,.83,-.17,-.52,-.39,-.66,
     *-.81/
      DO 5K=1,6
      PH=(K-1)*3.14159/10.
      C(K)=DCOS(PH)*DCOS(PH)
5      SII(K)=DSIN(PH)*DSIN(PH)
      DO 10J=1,36
       DO 11K=1,6
11      RSIG(J,K)=C(K) + S2S1(J)*SII(K)
10      CONTINUE
      RETURN
      END
C
      SUBROUTINE PEQ(NDUR,DT,RN,P,P1,P2)
C
C
C THIS ROUTINE CALCULATES THE 60- SECOND LOADINGS OF
C EQNS. 20 AND 21
C
C
C
      DOUBLE PRECISION RN,ROOT2,PEFF(2),PMAX,P(*)
     *,AREA,P1,P2,PD(900)
      ROOT2=1./RN
      PMAX=0.0
      II=NDUR
      DO 1000I=1,II
      PMAX=DMAX1(PMAX,P(I))
1000  CONTINUE
      DO 2000K=1,2
      PEFF(1)=((DT/60.)**ROOT2)*PMAX
      IF(K .EQ. 1) GO TO 3000
      DO 2500I=1,NDUR
2500  PD(I)=P(I)**RN
C
C
C INT IS AN INTEGRATION ROUTINE
C
C
      CALL INT(PD,NDUR,1.0,AREA)
C
C
      PEFF(2)=(AREA/60.)**ROOT2
      P2=PEFF(2)
```

```
3000  P1=PEFF(1)
2000  CONTINUE
      RETURN
      END
C
C
      SUBROUTINE INT(P,NDUR,H,AREA)
C
C
C TRAPEZOIDAL RULE
C
      DOUBLE PRECISION  AREA,P(900)
      N=NDUR-1
      SUM=0.0
      DO 50I=2,N
50    SUM=SUM+P(I)
      AREA=0.5*H*( P(1) + 2.0*SUM + P(NDUR) )
      RETURN
      END
C
C
      SUBROUTINE PWRITE(IT,MRI,DT,CP,PMEAN,P,NDUR)
C
C
C SUBROUTINE TO PRINT INPUT PRESSURE SIMULATION PARAMETERS
C
C
      DOUBLE PRECISION P(900)
      REAL IT
      WRITE(6,1)
      WRITE(6,2)IT,MRI,DT,CP
      WRITE(6,3)NDUR
      WRITE(6,30)PMEAN
      WRITE(6,4)( P(I), I=1,NDUR )
      WRITE(6,1)
1     FORMAT(1H1)
2     FORMAT(//,1X,' *** LOADING SIMULATION *** ',/,
     *5X,' INPUT MEAN VELOCITY (FT/SEC)      =',F10.4,/,
     *5X,' MEAN RECURRENCE INTERVAL (YEARS)  =',I10,/,
     *5X,' TIME STEP IN SECONDS              =',F10.4,/,
     *5X,' PRESSURE COEFFICIENT, CP          =',F10.4)
3     FORMAT(5X,' P(T), T=1, ',I5,' SECONDS ....')
30    FORMAT(6X,' MEAN PRESSURE IN PSI = ',F10.4)
4     FORMAT(5F10.4)
      RETURN
      END
C
      SUBROUTINE GWRITE(SIDEA,TH,E,PR,A,KIC,NPANEL,RN,BP)
C
C
C SUBROUTINE TO PRINT INPUT PLATE PARAMETERS...
C
C
      DOUBLE PRECISION  KIC,A,PR,E,RN,BP,SIDEA
      WRITE(6,1)
      WRITE(6,2)NPANEL
      WRITE(6,3)SIDEA,TH,E,PR,A,KIC,RN,BP
1     FORMAT(1H1)
2     FORMAT(1X,' ** GLASS PANEL CHARACTERISTICS ** ',//,
     *2X,I5,' PANELS ARE TO BE TESTED ',/)
3     FORMAT(/,5X,' LENGTH OF EACH SIDE              =',F10.4,/,
     *         5X,' THICKNESS                        =',F10.4,/,
     *         5X,' MODULUS OF ELASTICITY            =',E10.4,/,
     *         5X,' POISSONS RATIO                   =',F10.4,/,
     *         5X,' VALUE OF A                       =',F10.4,/,
     *         5X,' STRESS INTENSITY FACTOR          =',F10.4,/,
```

```
     *          5X,' POWER N IN EQUATION             =',F10.4,/,
     *          5X,' 1/B  IS CALCULATED TO BE        =',F10.4,///)
      RETURN
      END
C
      SUBROUTINE TWRITE(ILOAD,ISTRES,ISTREN,NDUR)
C
C
C
C PROGRAM TO WRITE TEST PARAMETERS
C
C
C
      WRITE(6,1)
      IF ( ILOAD .EQ. 1 )WRITE(6,2)
      IF ( ILOAD .EQ. 2 )WRITE(6,4)
      IF ( ILOAD .GT. 3 )WRITE(6,31)
      IF ( ILOAD .EQ. 3 )WRITE(6,32)
      WRITE(6,3)NDUR
      WRITE(6,5)
      IF ( ISTREN .EQ. 1 )WRITE(6,6)
      IF( ISTREN .EQ. 2 )WRITE(6,7)
      WRITE(6,8)
      IF( ISTRES .EQ. 1 )WRITE(6,9)
      IF ( ISTRES .EQ. 2 )WRITE(6,10)
      WRITE(6,3)NDUR
1     FORMAT(1X,' *** TEST PARAMETERS ***',//,
     *2X,' #1 ',' PRESSURE LOADING ',/)
2     FORMAT(7X,' SIMULATED P(T) ')
3     FORMAT(7X,' FOR ',I5,' SECONDS ',/)
31    FORMAT(7X,' NOT CONSIDERED ')
32    FORMAT(7X,' READ IN FROM FILE ')
4     FORMAT(7X,' CONSTANT PRESSURE ')
5     FORMAT(2X,' #2 ',' INITIAL STRENGTH DESCRIPTION',/)
6     FORMAT(7X,' TO BE GENERATED FROM A WEIBULL DISTRIBUTION ')
7     FORMAT(7X,' CONSTANT VALUE ')
8     FORMAT(2X,' #3 ',' STRESS TIME HISTORY ',/)
9     FORMAT(7X,' GENERATED FROM THE PRESSURE LOADING ')
10    FORMAT(7X,' CONSTANT SIGMA VALUE ')
      RETURN
      END
C
      SUBROUTINE PRES(R1,R2,NDIV,DS,DT,NDUR,Z,ZO,IT,CP,PM,PVAR,P)
C
C
C THIS SUBROUTINE COMPUTES THE QUASI-STATIC LOADING
C AT THE STAGNATION POINT USING THE ARIMA-COMBINED
C TECHNIQUE AND THE  SPECTRAL EXPRESSION IN EQN. 18
C
C
C
C
C
C
      REAL AO,JT,DENSTY,PI,Z,SUM,K1,C,UF
      DOUBLE PRECISION P(900),DS
      REAL U(900),NORM(900)
      REAL UFS,DT,PHI1,PHI2,ACOV(3),ACF(3),VARU,VARAU
      PI=3.14159
      DENSTY=.00258
        XMAX=R2
        XMIN=R1
        POWER=5./3.
        DX=(XMAX-XMIN)/NDIV
C
C
```

```
C
C DEFINITIONS
C
C
C         IT= MEAN VELOCITY
C         Z=ELEVATION
C         ZO=FRICTION PARAMETER
C         UF=FRICTION VELOCITY
C         ACOV=AUTOCOVARIANCE,  ACF=AUTOCORRELATION
C         VARU,VARAU= SCALING VARIANCES FOR VELOCITY
C         U=GENERATED VELOCITY, P=GENERATED PRESSURES
C
C
C GGNML IS A PSEUDO-RANDOM # GENERATOR FROM IMSL
C
C
C FOR AN EXPLANATION OF THE METHOD, SEE "AUTOREGRESSIVE
C MODELING OF LONGITUDINAL TURBULENCE SPECTRA", J. OF
C INDUSTRIAL AERODYNAMICS AND WIND ENGINEERING, 1982,
C BY REED AND SCANLAN.
C
C
C
      AO=50.*Z/IT
      UF=(0.4*IT)/(ALOG(12.*Z/ZO))
      UFS=UF*UF
      C=(200.*UFS*Z)/IT
C
        DO 10J=1,3
        I=1
        X=0.0
        SUM=1.0
        TAU=(2.*J)-2.
        TAU=PI*TAU
2       X=X+DX
        FREQ=TAU*X
        FX=COS(FREQ)/((1.+AO*X)**POWER)
        G=2.*FX
        SUM=SUM+G
        I=I+1
        IF(I .LT. NDIV)GO TO 2
        FB=COS(FREQ)/((1.+AO*XMAX)**POWER)
        SUM=SUM+FB
        AREA=SUM*(DX/2.)
10      ACOV(J)=(C/2.)*AREA
        DO 20J=1,2
20      ACF(J)=ACOV(J+1)/ACOV(1)
C
        D=1.-(ACF(1)**2.)
        PHI1=(ACF(1)*(1.-ACF(2)))/D
        PHI2=(ACF(2)-(ACF(1)**2.))/D
        WRITE(6,*)' AUTOREGRESSIVE MODEL PARAMETERS ARE ',PHI1,PHI2
        VARU=ACOV(1)
        VARAU=(((1.+PHI2)*((1.-PHI2)**2.-(PHI1**2.)))/(1.-PHI2))
     1  *VARU
        SDEVA=SQRT(VARAU)
          DO 30J=1,2
   30       U(J)=0.
C
C
C
      CALL GGNML(DS,NDUR,NORM)
C

C
C SET UP GENERATION EQUATION FOR FLUCTUATING VELOCITY
```

```
C DEFINE PMEAN
       PMEAN=(1./144.)*0.5*IT*IT*CP*DENSTY
       RCON=PMEAN/IT
C
           DO 50J=3,NDUR
50        U(J)=PHI1*U(J-1) + PHI2*U(J-2) + SDEVA*NORM(J)
            DO 60J=1,NDUR
60         P(J)=PMEAN + RCON*U(J)
C
C
C
C THIS P REPRESENTS THE TOTAL LOAD, MEAN + FLUCTUATING COMPONENT
C UNITS OF P = PSI
C
C
C
      SUM=0.0
      DO 5J=1,NDUR
5     SUM=SUM+P(J)
      PM=SUM/NDUR
      SUM=0.0
      DO 6J=1,NDUR
6     SUM=SUM + (( P(J) - PM )**2 )
      PVAR=SQRT( SUM/(NDUR-1) )
C
C      WRITE(8,70)(P(I),I=1,NDUR)
C70      FORMAT(5F10.4)
C
      RETURN
      END
C
      SUBROUTINE STRESS(FLEX,SIDEA,TH,NDUR,P,SIGMA)
C
C
C THIS PROGRAM CALCULATES THE STRESS FACTORS FOR A SQUARE
C PLATE , GIVEN A PRESSURE TIME HISTORY
C
C
      DOUBLE PRECISION  TH,FLEX,SIDEA,
     *R1(36),R2(36),R3(36),R4(36),S1(36),S2(36),S3(36),S4(36)
      DOUBLE PRECISION   P(900),SIGMA(36,900)
      COEF=(.00689*FLEX)/(SIDEA*SIDEA*TH)
C
C
C INPUT INTERCEPT AND SLOPE PARAMETERS FOR STRESS-PRESSURE
C LINEAR RELATIONSHIPS
C
C
      DATA R1/149.,151.,157.,163.,165.,157.,130.,78.,150.,155.,
     *162.,165.,157.,131.,79.,151.,157.,162.,156.,132.,82.,127.,
     *127.,122.,104.,70.,180.,181.,165.,120.,151.,144.,144.,
     *144.,143.,157./
      DATA S1/.058,.060,.066,.077,.092,.100,.094,.061,.059,.066,
     *.078,.092,.103,.096,.063,.065,.080,.096,.109,.103,.066,
     *.086,.106,.119,.113,.071,.070,.084,.085,.056,.089,.086,
     *.063,.086,.080,.118/
C
      DATA R2/ 207.,211.,223.,240.,257.,257.,224.,139.,209.,
     *221.,239.,258.,258.,227.,142.,216.,237.,258.,265.,
     *235.,148.,213.,233.,241.,217.,141.,250.,265.,250.,176.,
     *238.,230.,186.,237.,223.,246./
      DATA S2/.034,.036,.036,.043,.054,.067,.067,.047,
     *.037,.039,.045,.055,.068,.069,.048,.044,.048,.059,
     *.072,.075,.053,.059,.071,.089,.095,.068,.062,.087,
     *.099,.073,.100,.118,.090,.123,.105,.114/
C
```

```
      DATA R3/310.,319.,333.,370.,420.,457.,426.,279.,320.,
     *337.,374.,425.,463.,435.,286.,349.,381.,436.,482.,
     *460.,307.,392.,445.,507.,502.,345.,436.,525.,549.,
     *396.,539.,583.,457.,607.,607.,587./
      DATA S3/.019,.018,.019,.023,.032,.045,.053,.038,.022,
     *.023,.025,.034,.047,.053,.039,.028,.031,.037,.049,.055,
     *.041,.038,.042,.052,.060,.046,.050,.057,.070,.058,.058,
     *.083,.077,.096,.082,.105/
C
      DATA R4/407.,410.,430.,484.,581.,687.,689.,471.,428.,
     *454.,500.,593.,697.,700.,480.,490.,538.,620.,725.,735.,
     *511.,584.,656.,769.,803.,576.,688.,812.,901.,688.,827.,
     *998.,843.,1086.,1016.,1114./
      DATA S4/.029,.029,.027,.026,.032,.042,.049,.036,.030,.031,
     *.029,.032,.041,.048,.037,.033,.034,.034,.042,.049,.037,
     *.037,.038,.043,.050,.039,.044,.046,.056,.048,.038,.064,
     *.064,.072,.085,.110/
C
C
C
      DO 200I=1,NDUR
      IF(P(I).LE.1000)GO TO 3
      IF(P(I) .GT. 1000 .AND. P(I) .LE. 2000) GO TO 4
      IF( P(I)  .GT. 2000 .AND. P(I) .LE. 5000) GO TO 5
      IF(P(I)  .GT. 5000 .AND. P(I) .LE. 10000) GO TO 6
      IF(P(I)  .GT. 10000) GO TO 7
C
C
C
    3 CONTINUE
       SIGMA(1,I)= COEF*(202 - DLOG(P(I))*( 99.6 - 13.3*DLOG(P(I))))
       SIGMA(9,I)=SIGMA(1,I)
       SIGMA(16,I)=SIGMA(1,I)
       SIGMA(22,I)=SIGMA(1,I)
       SIGMA(2,I)=SIGMA(1,I)
       SIGMA(3,I)=SIGMA(2,I)
       SIGMA(10,I)=SIGMA(2,I)
       SIGMA(4,I)=COEF*(267 - DLOG(P(I))*(131 -16.9*DLOG(P(I))) )
       SIGMA(11,I)=SIGMA(4,I)
       SIGMA(17,I)=SIGMA(4,I)
       SIGMA(5,I) = COEF*(441 - DLOG(P(I))*( 201 - 23.5*DLOG(P(I))))
       SIGMA(12,I)=SIGMA(5,I)
       SIGMA(18,I)=SIGMA(5,I)
       SIGMA(23,I)=SIGMA(5,I)
       SIGMA(6,I)= COEF*( 676- DLOG(P(I))*(292-31.6*DLOG(P(I))))
       SIGMA(13,I)=SIGMA(6,I)
       SIGMA(19,I)=SIGMA(6,I)
       SIGMA(24,I)=SIGMA(6,I)
       SIGMA(28,I)=SIGMA(6,I)
       SIGMA(7,I)=COEF*( 4.96 + .130*P(I) )
       SIGMA(14,I)=SIGMA(7,I)
       SIGMA(20,I)=SIGMA(7,I)
       SIGMA(25,I)= COEF*(27.4 + .0790*P(I)  )
       SIGMA(29,I)=COEF*( 30.2 + .0885*P(I)  )
       SIGMA(32,I)= COEF*( 36.1 + .0969*P(I)  )
       SIGMA(8,I)= COEF*( 1.93 + .0785*P(I))
       SIGMA(15,I)=SIGMA(8,I)
       SIGMA(21,I)=SIGMA(8,I)
       SIGMA(26,I)= COEF*( 2.70 + .0384*P(I))
       SIGMA(30,I)= COEF*( 6.52 + 0.109*P(I))
       SIGMA(33,I)= COEF*( 8.37 + .120*P(I))
       SIGMA(35,I)= COEF*( 7.93 + .142*P(I))
       SIGMA(36,I)= COEF*( 7.07 + 0.156*P(I))
       SIGMA(27,I)=SIGMA(36,I)
       SIGMA(31,I)=SIGMA(36,I)
       SIGMA(34,I)=SIGMA(36,I)
```

```
C
C
      GO TO 200
C
C
    4 CONTINUE
      DO 42J=1,36
42    SIGMA(J,I)= COEF*( R1(J) + S1(J)*P(I) )
C
C
      GO TO 200
C
C
    5 CONTINUE
      DO 52J=1,36
52     SIGMA(J,I)=COEF*( R2(J) + S2(J)*P(I) )
      GO TO 200
C
    6 CONTINUE
      DO 62J=1,36
62    SIGMA(J,I)= COEF*(R3(J) + S3(J)*P(I) )
C
C
      GO TO 200
C
C
    7 CONTINUE
      DO 72J=1,36
72    SIGMA(J,I)= COEF*(R4(J) + S4(J)*P(I) )
C
200   CONTINUE
C
        RETURN
        END
$BEND
```

Table 1. Estimated Probabilities of Failure Based on Stress Time History, and on 1-Minute Loads Estimated in Accordance with References 12 and 3. Units of pressure = psf.

$\bar{p}$	p_{60}^{C}	p_{60}^{D}	$P_f(\bar{p})$	$P_f(p_{60} = p_{60}^{C})$	$P_f(p_{60} = p_{60}^{D})$
10	10.8	12.6	0.001	0.002	0.003
15	16.2	18.9	0.015	0.004	0.008
20	21.6	25.2	0.050	0.012	0.022
25	27.0	31.5	0.150	0.035	0.069
30	32.4	37.8	0.400	0.084	0.160

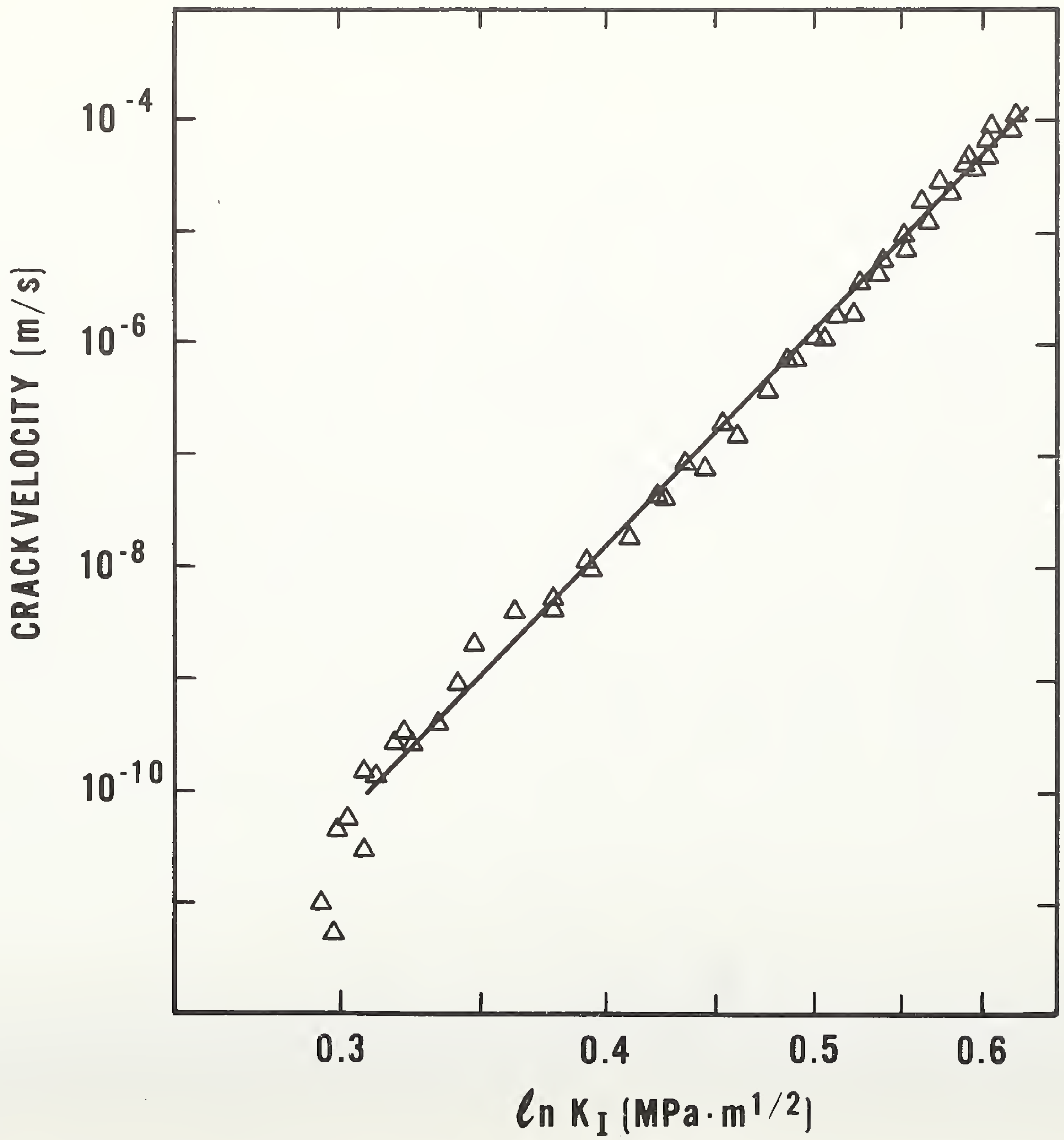

Figure 1. Crack velocity vs. ℓn (K_I) for soda-lime silica glass [23]

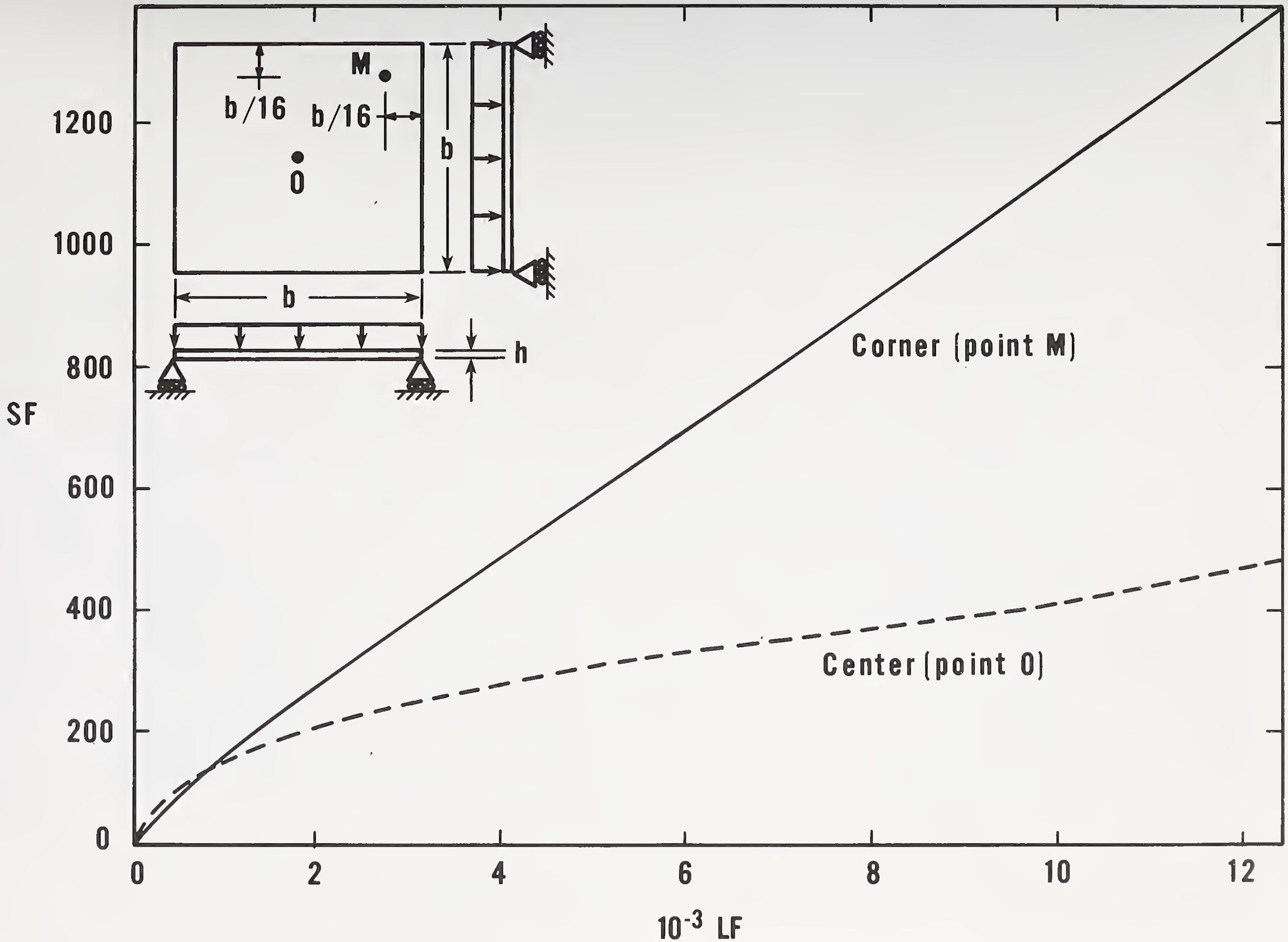

Figure 2. Center and corner maximum principal stresses for a square plate

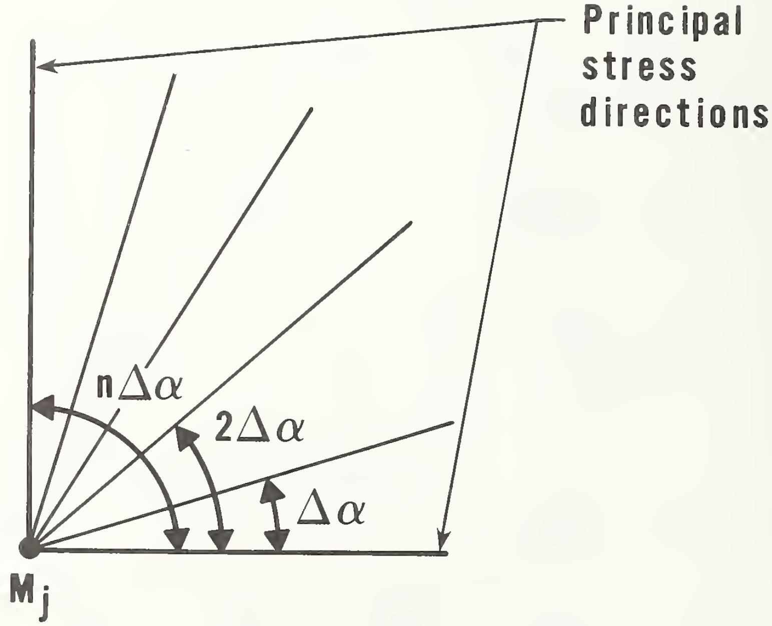

Figure 3. Schematic representation of angles $\alpha_k = k\Delta\alpha$

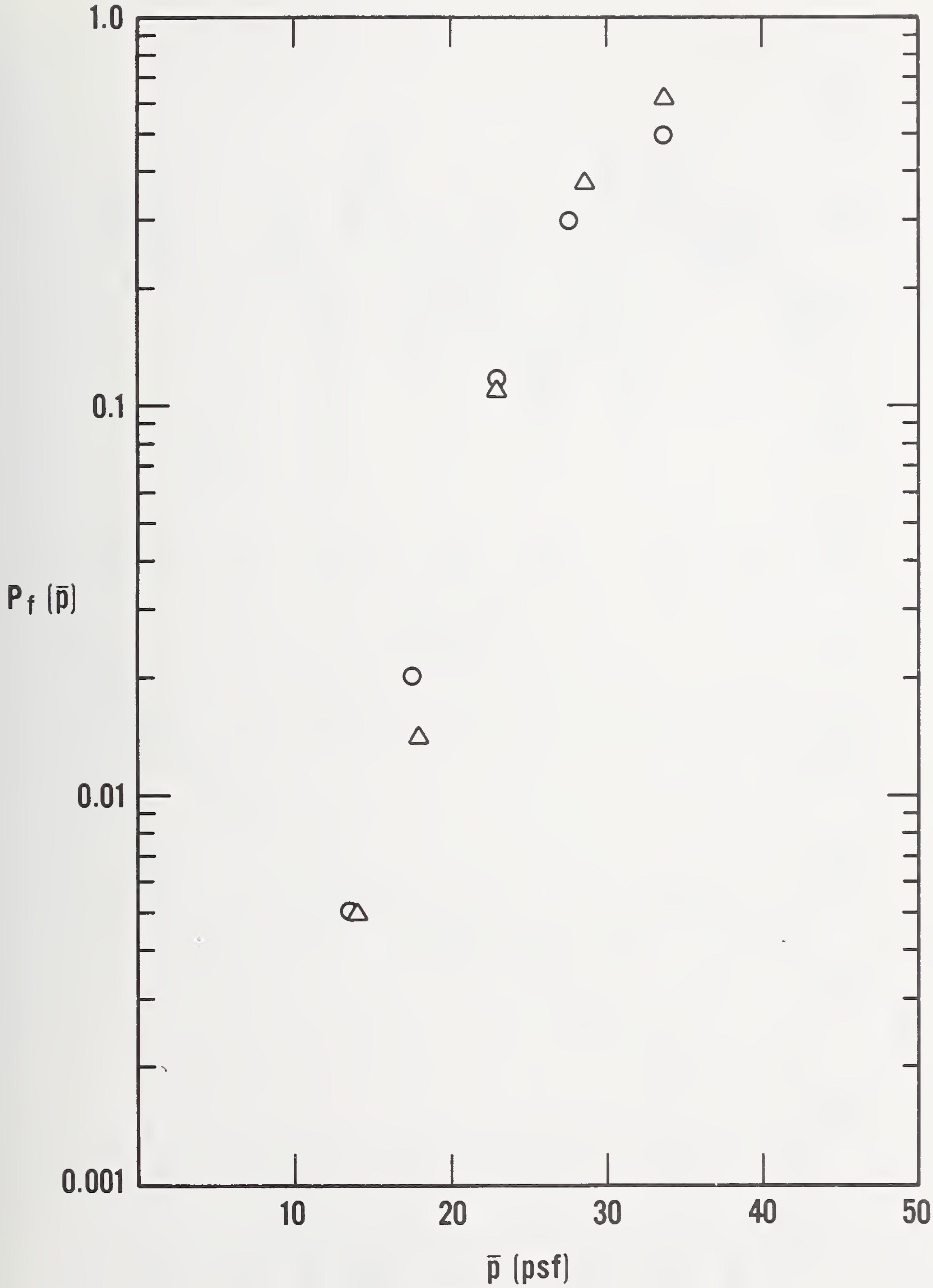

Figure 4. Cumulative distribution function for p(t)

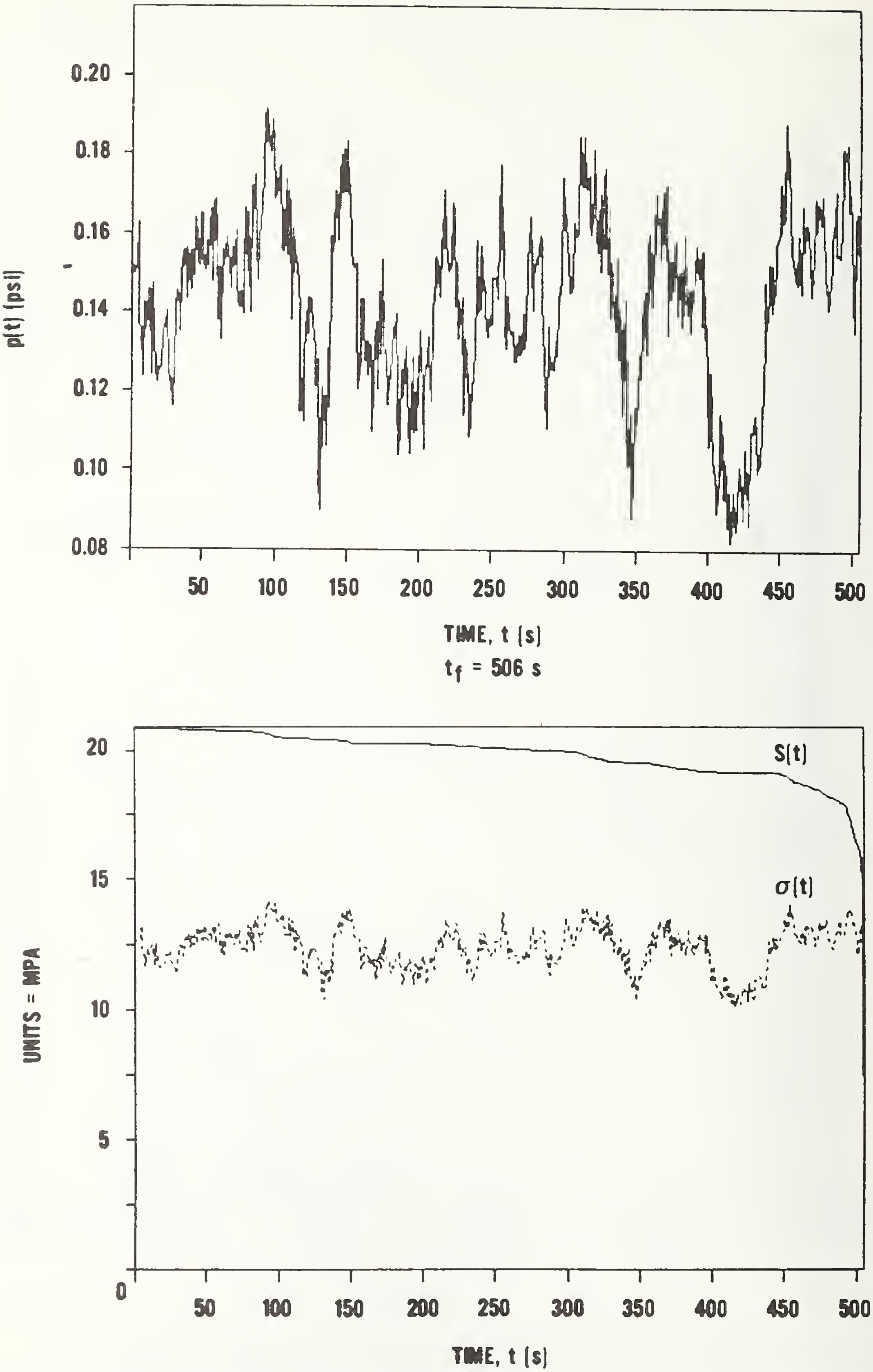

Figure 5. Evolution of strength and stresses with time for breaking panel

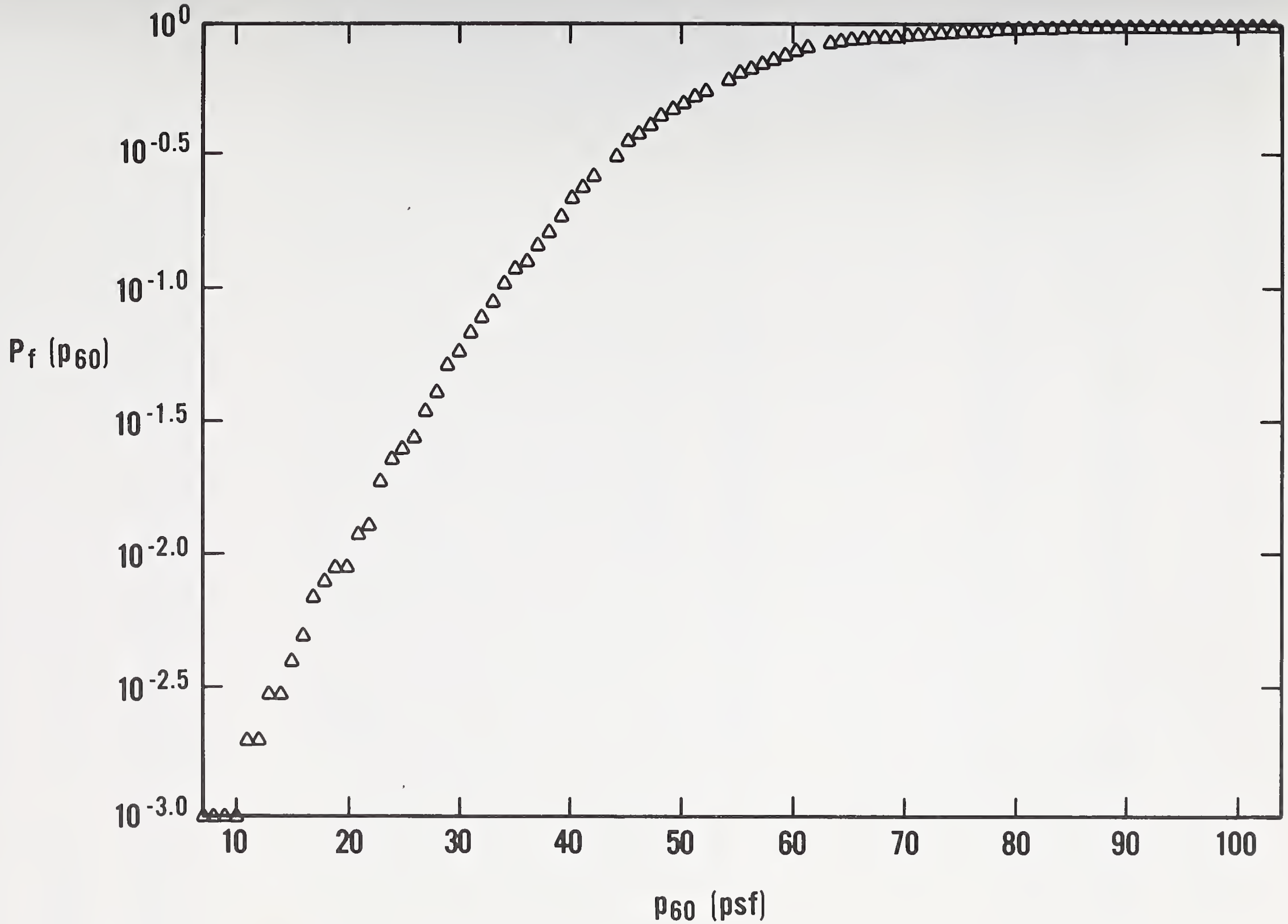

Figure 6. Cumulative distribution function for p_{60}

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

A procedure for investigating glass cladding behavior under arbitrary loads, including fluctuating wind loads, is presented. The procedure accounts for the fact that internal stresses are nonlinear functions of the external loads, that initial glass strengths are random functions of position and direction, and that glass strength undergoes degradation under the action of external loads in accordance with basic fracture mechanics laws. Numerical examples are presented, and corresponding probability distribution curves are calculated, indicating the probability of failure of a specified panel subjected to fluctuating wind loads and to 1-minute constant loads. These curves are used to illustrate a method for assessing current glass cladding design procedures. For the case considered in the paper, it was found that transformation of the peak wind load averaged over 1-2 seconds into an equivalent 1-minute load appears to underestimate the probability of failure of glass cladding. The work reported in the paper is part of an ongoing window cladding research program being conducted at the National Bureau of Standards.

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

aerodynamics; buildings; deformation; engineering mechanics; failure; glass; loads (forces); probability theory.

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