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AN EQUATION FOR BOLT CLAMPUP RELAXATION IN TRANSIENT ENVIRONMENTS

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The viscoelasticity of resin-based laminates allows bolt clampup relaxation and a corresponding degradation in joint strength. Clampup relaxation for steady temperature and moisture (T-M) conditions has been studied in Ref. 1. In typical applications, however, laminate temperature and moisture both vary with time. These transient conditions influence clampup in two ways. First, the laminate thermal expansion (or contraction) and moisture swelling (or shrinkage) cause elastic changes in the clampup. Second, the T-M conditions influence the rate of clampup relaxation.

This paper presents an equation for bolt clampup relaxation for transient T-M conditions. The equation was derived starting with a relaxation equation from Ref. 1 for steady-state conditions, and then using an incremental time approach that exploits the superposition principle for linear viscoelastic materials [2]. The resulting equation uses the initial T-M condition (at the time of clamping), the T-M history after clamping, and elastic clampup coefficients for temperature and moisture changes. For a given material and joint configuration, the clampup coefficients are constants that can be calculated by elastic analyses. The clampup equation was used to calculate the changes in clampup occurring in a T300/5208 graphite/epoxy joint exposed to a one-year history of temperature and moisture. Two cases were considered: one was a dry

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joint exposed to a relatively humid environment and the other was a nearly saturated joint exposed to an arid environment.

BACKGROUND

Fig. 1(a) shows the joint analyzed--three 32-ply (quasi-isotropic) graphite/epoxy laminates in a double-lap joint with a steel bolt. After this joint is clamped by tightening the bolt, the clampup force F_t relaxes. An equation for this relaxation was presented in Ref. 1 for a room-temperature-dry (RTD) environment.

$$F_t = \frac{F_{01}}{1 + F_R t^n} \qquad (1)$$

The t represents elapsed time in weeks. The F_{01} is the initial (elastic) clampup force calculated using the finite-element program VISCEL [3], as explained in Ref. 1. The F_R is a constant obtained in Ref. 1 by fitting Eq. (1) to finite-element viscoelastic results for the RTD case. F_R is 0.1126 for the present analysis, with time t expressed in weeks. The exponent n in Eq. (1) was taken from the "power-law" expression for the 5208 matrix compliance; $n = 0.20$ [4]. Results from Eq. (1) are shown as the upper curve in Fig. 1(b), where for convenience, F_t was normalized by its initial value F_{01}. After 52 weeks, F_t relaxed to about 80 percent of its initial value.

Ref. 1 also presented a more generalized form of Eq. (1) to account for the viscoelastic effects of temperature and moisture. Using the shift-factor concept [2], the time variable t was replaced by a "reduced-time" variable ξ, where $\xi = t/a_{TH}$. This a_{TH} is a shift factor corresponding to a specific steady-state temperature or moisture level. All a_{TH} values in this study were taken from Ref. 5. Eq. (1) was rewritten as

$$F_t = \frac{F_{01}}{1 + F_R \xi^n} \tag{2}$$

Figs. 1(b) and 1(c) show results from Eq. (2). As expected, both temperature and moisture accelerate the relaxation compared to the RTD case. In both figures, after 52 weeks the F_t relaxes to about 60 percent of its initial value. In typical service conditions, however, the joints rarely experience such steady-state temperature or moisture conditions. As a result, the objective of the present study was to extend the Ref. 1 analysis to transient T-M conditions.

TRANSIENT ANALYSIS

The incremental time approach used in this analysis can be introduced using Fig. 2. First, the temperature and moisture histories were divided into small time intervals. During each such interval, the T-M condition was assumed to be constant, as shown in Fig. 2(a) for transient temperature. Next, a clampup force increment was calculated for each time interval. These increments were then summed to calculate the total clampup force. This procedure will be explained and used for an elastic case and then extended to include viscoelasticity.

Elastic Analysis

The elastic clampup force due to bolt torquing was assumed to occur in the first time interval at $t = 0$. The temperature and moisture, T_1 and M_1, in the first interval were used as the initial values for subsequent

T-M histories. Accordingly, the force increment ΔF_{01} for the first time interval was caused solely by bolt torquing, and the subsequent force increments ΔF_{0i} were due solely to changes in temperature and moisture between successive time intervals. Following this incremental approach, shown schematically in Fig. 2(b), the elastic clampup force F_{0t} after N time intervals was expressed as

$$F_{0t} = \sum_{i=1}^{N} \Delta F_{0i} \tag{3}$$

The ΔF_{01} in this equation equals the F_{01} in Eq. (1).

The finite-element program VISCEL was used to calculate the elastic clampup response due to temperature changes. First, the elastic clampup forces were calculated for two different temperatures. Then the difference in clampup force was divided by the corresponding temperature difference to get a thermal force coefficient α_F. A similar procedure provided β_F, the moisture force coefficient. The ΔF_{0i} needed for Eq. (3) was expressed as

$$\Delta F_{0i} = \alpha_F\left(T_i - T_{i-1}\right) + \beta_F\left(M_i - M_{i-1}\right) \qquad \text{for} \quad i \geq 2 \tag{4}$$

The first case analyzed involved a dry joint exposed to a relatively humid environment (Langley AFB, Hampton, Virginia). Fig. 3(a) shows the monthly average temperature history [6] for a one-year period, starting from July 1. Fig. 3(b) shows the moisture history for the 32-ply graphite/epoxy laminate, calculated using the finite-difference moisture analysis from Ref. 7 with the temperature history in Fig. 3(a) and the corresponding humidity data [6]. After these temperature and moisture histories were discretized as previously illustrated in Fig. 2, the corresponding elastic clampup history was calculated from Eq. (3). In addition to the material properties given for T300/5208 in Ref. 1, the following constants were used in this elastic analysis. The thermal expansion coefficients used for the lamina were -0.4 με/°C and 27 με/°C for the longitudinal and transverse directions, respectively. The corresponding moisture swelling coefficients for the lamina were 0 and 3000 με/percent moisture [5], based on laminate weight. A thermal expansion coefficient of 11.7 με/°C was used for the steel bolt. These material constants were used to calculate the clampup force coefficients α_F = 21N/°C and β_F = 4910 N/percent moisture.

The results from Eq. (3) are shown as the dashed curve in Fig. 3(c). This curve was calculated for an initial clampup force F_{01} = 5380 N (1210 lb), which corresponds to a 5.65 N·m (50 in·lb) clampup torque. These calculations show that the moisture increase was more significant than the temperature fluctuation. During the first 25 weeks, the force increased by about 50 percent as the moisture increased, despite the temperature decrease during this period.

Viscoelastic Analysis

The viscoelastic clampup forces were also calculated using an incremental time approach. The viscoelastic force F_t was found by summing the viscoelastic force components from the discretized T-M history.

$$F_t = \sum_{i=1}^{N} \Delta F_i \qquad (5)$$

The ΔF_i is the relaxed clampup force at the end of the Nth interval due to an incremental elastic force ΔF_{0i} occurring in the ith interval. The first term ΔF_1 corresponds to bolt torquing and other terms correspond to subsequent increments in temperature and moisture. This is illustrated schematically in Fig. 2(c). An expression for ΔF_i was obtained by generalizing the clampup relaxation equation (2) as

$$\Delta F_i = \frac{\Delta F_{0i}}{1 + F_R \xi_i^n} \tag{6}$$

The ΔF_{0i} is the elastic clampup increment for the ith time interval. The ξ_i was expressed as

$$\xi_i = \sum_{j=i}^{N} \frac{t_{j+1} - t_j}{\left(a_{TH}\right)_j} \tag{7}$$

and represents the elapsed "reduced time" following the occurrence of ΔF_{0i} in the ith time interval. The $\left(a_{TH}\right)_j$ is the shift factor for the T-M condition in the jth interval. Substituting Eqs. (6) and (7) into Eq. (5) produces the desired equation for clampup relaxation.

$$F_t = \sum_{i=1}^{N} \frac{\Delta F_{0i}}{1 + F_R \sum_{j=i}^{N} \left[\frac{t_{j+1} - t_j}{\left(a_{TH}\right)_j}\right]} \tag{8}$$

VISCOELASTIC RESULTS AND DISCUSSION

The clampup relaxation for case 1 was calculated using Eq. (8) with the previously discussed temperature and moisture histories from Figs. 3(a) and 3(b). The results are plotted in Fig. 4. The separate effects of temperature and moisture are shown in Figs. 4(a) and 4(b), respectively. For comparison, the elastic clampup forces from Eq. (3) are also shown, as dashed curves. Fig. 4(a) shows that the temperature history alone would have very little influence on clampup. But viscoelasticity relaxed the clampup by about 20 percent. Fig. 4(b) shows that moisture absorption alone could have increased clampup by more than 50 percent. But, again, relaxation limited the increase to about 20 percent. Fig. 4(c) shows the combined effects of temperature and moisture. The viscoelastic relaxation nearly canceled elastic increase in clampup due to temperature and moisture. Hence, the clampup force remained nearly unchanged.

Figs. 5(a) and 5(b) show temperature and moisture profiles for case 2. This case involves an initially moist laminate exposed to a dry environment, typical of Las Vegas, Nevada [6]. Fig. 5(c) shows the combined effects of temperature and moisture on the elastic clampup and the corresponding viscoelastic relaxation. Because moisture desorption dominated the elastic response, the elastic clampup decreased to about 45 percent after one year. Viscoelastic relaxation produced only a small contribution to the total clampup decrease. The relaxation was small because of the "viscoelastic recovery" that occurs when the elastic forces decrease with time.

In summary, the present analysis extended the clampup relaxation equation (2), for steady-state environments, to obtain the corresponding equation (8) for transient T-M conditions. Although Eq. (2) was experimentally verified for steady-state conditions in Ref. 1, the accuracy of Eq. (8) has not been evaluated. Such an evaluation was beyond the scope of the present study.

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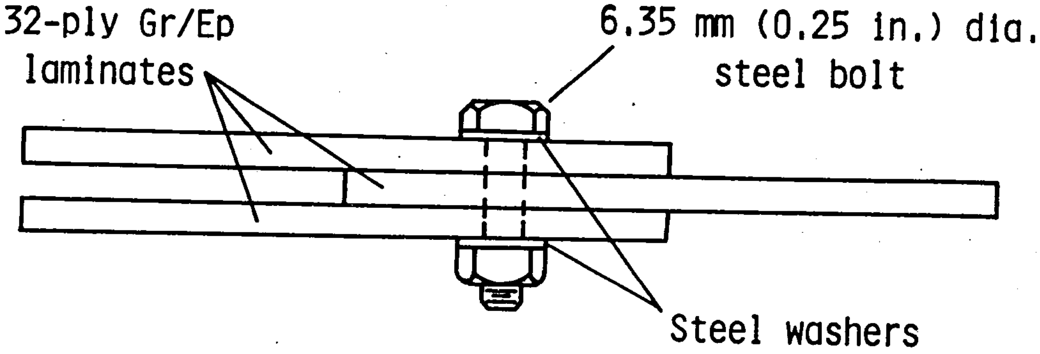
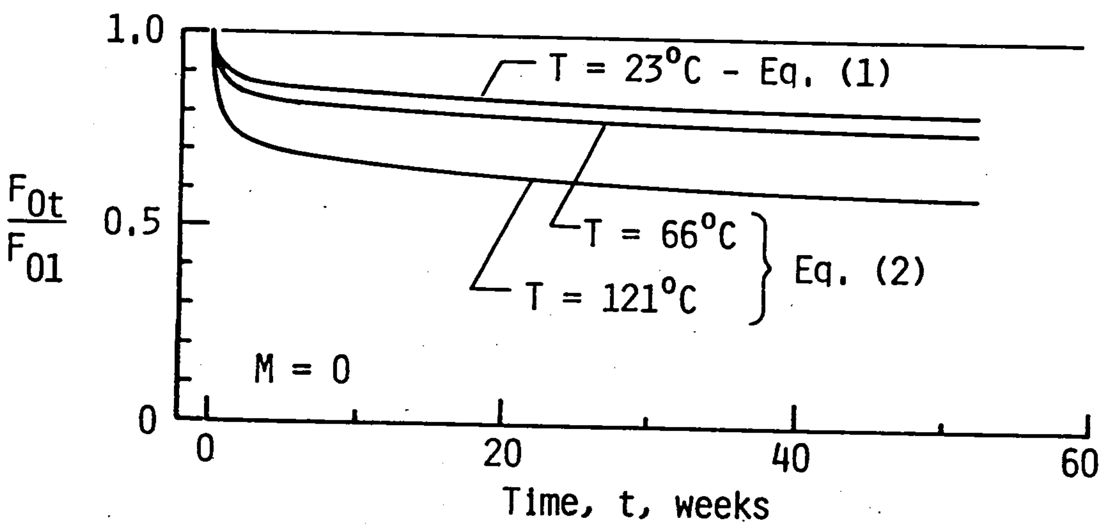
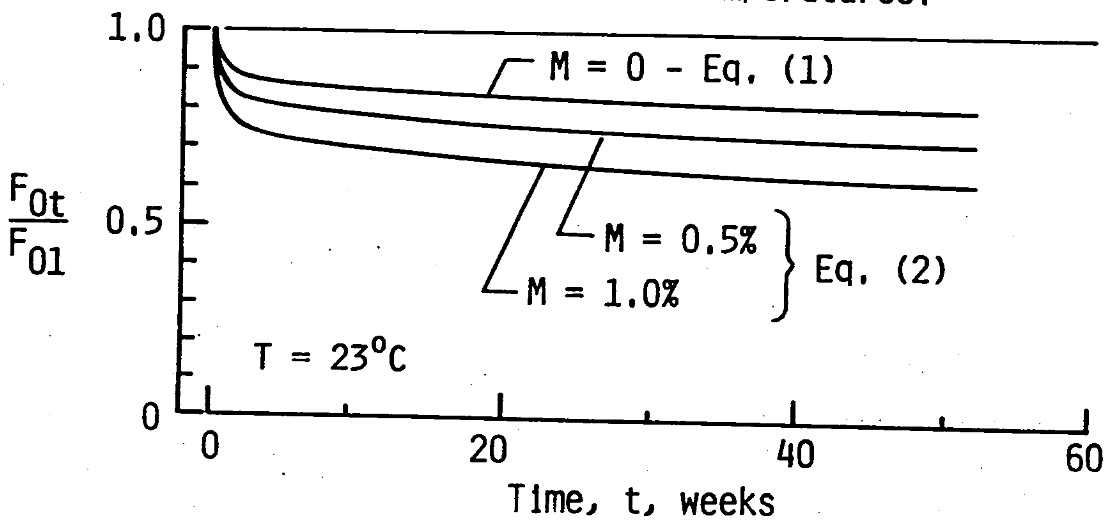


(a) Edge view of bolted joint.

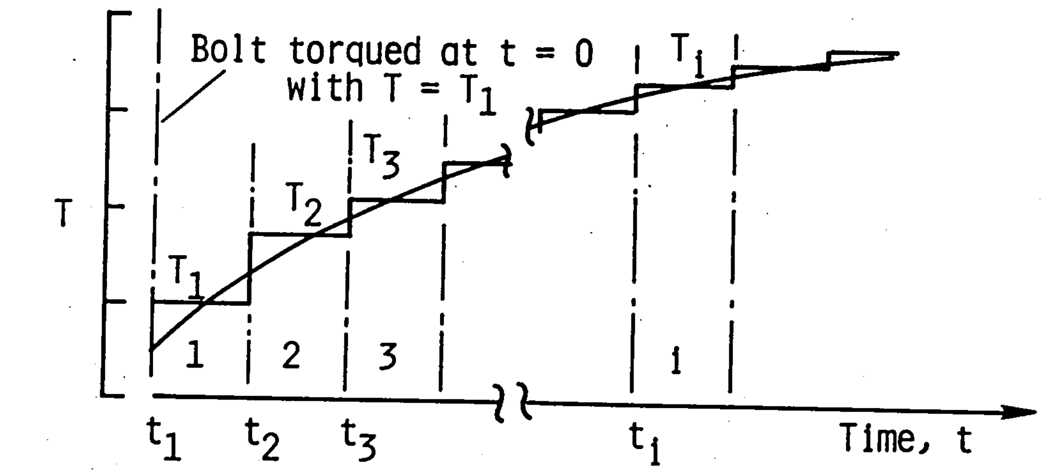


(b) Relaxation for various temperatures.

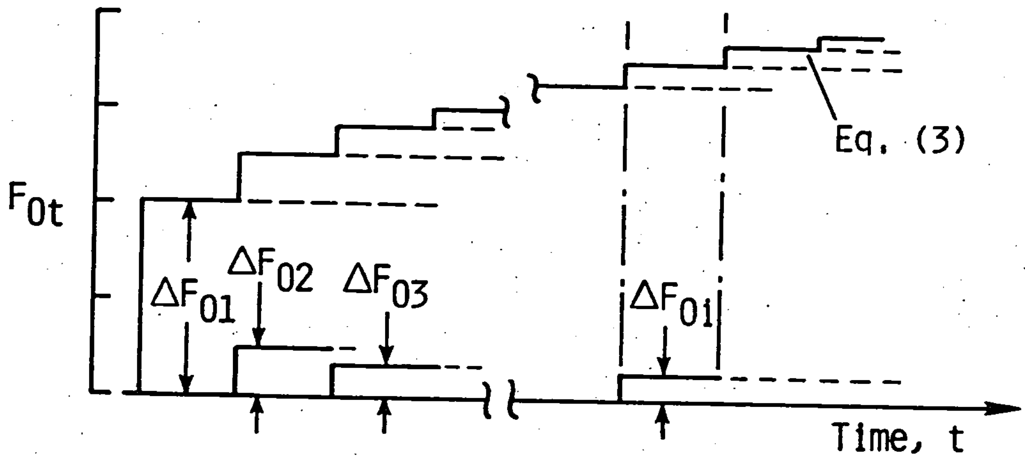


(c) Relaxation for various moisture levels.

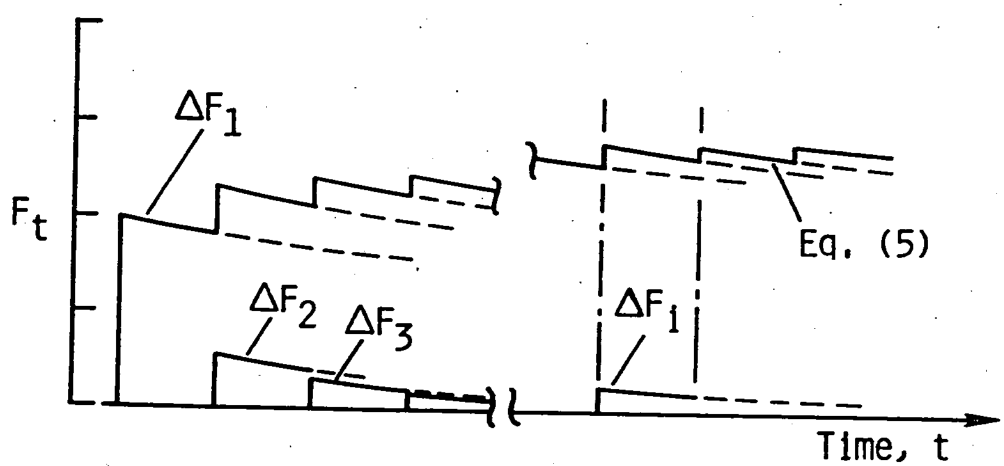
Fig. 1--Bolted joint clampup relaxation for constant temperature and moisture conditions.



(a) Temperature history.

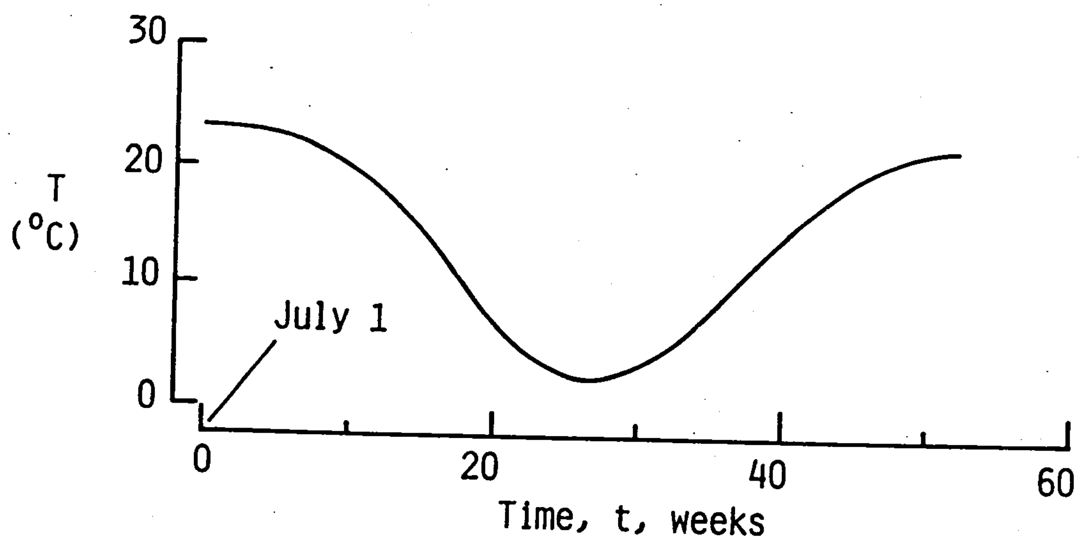


(b) Elastic clampup force.

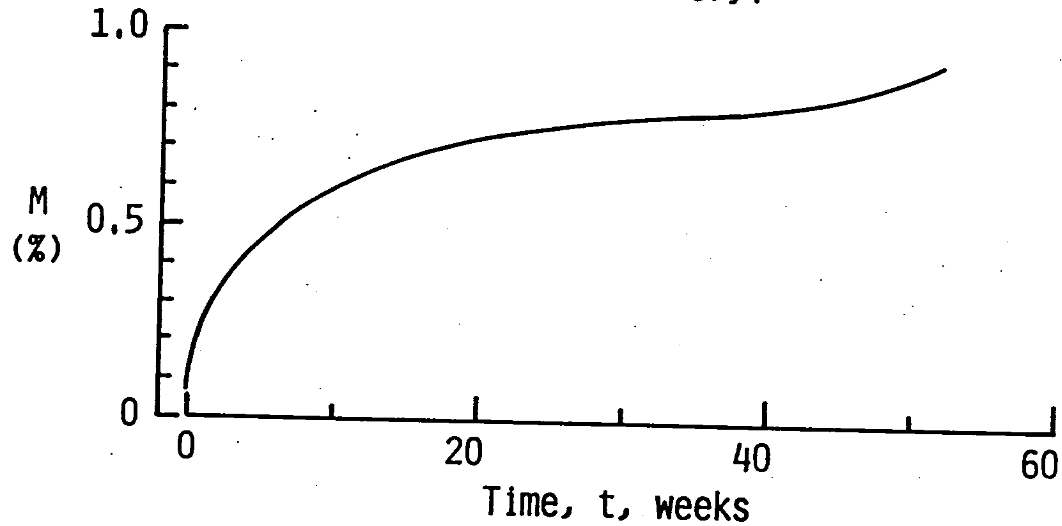


(c) Viscoelastic clampup force.

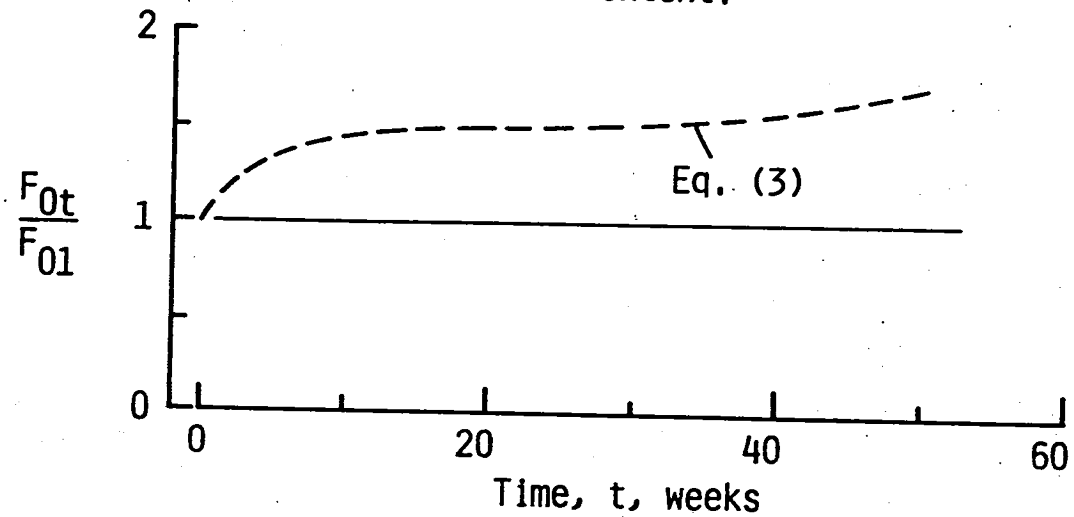
Fig. 2--Schematic temperature and force discretizations.



(a) Temperature history.

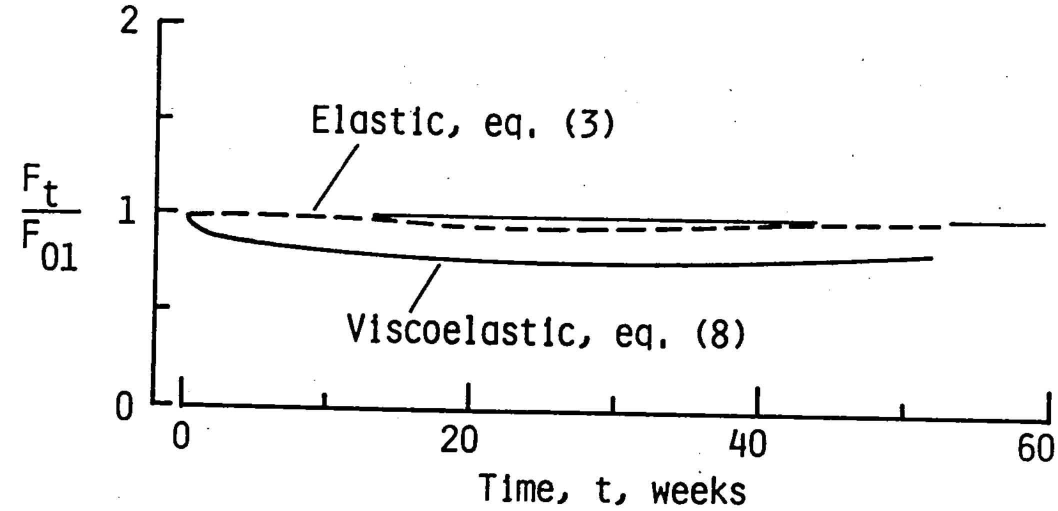


(b) Moisture content.

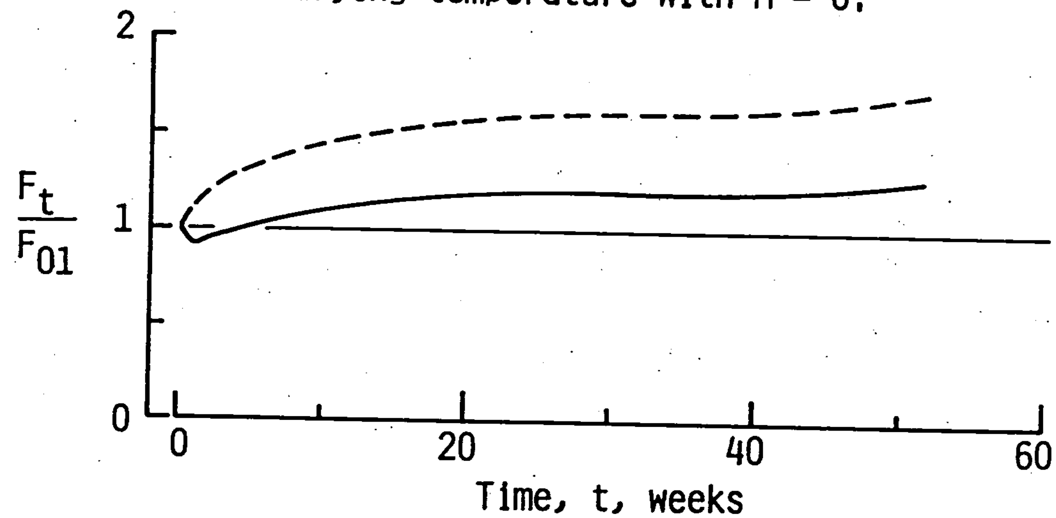


(c) Elastic clampup force.

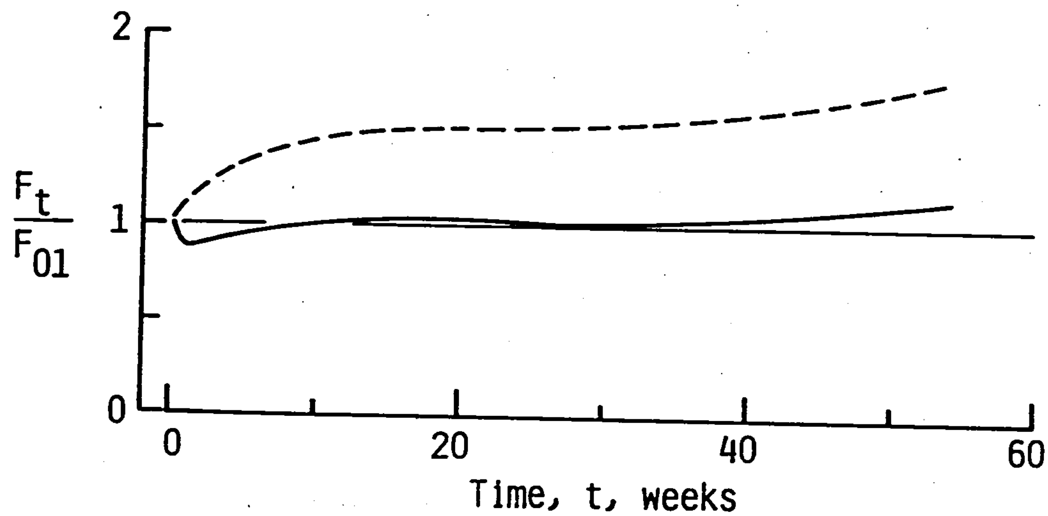
Fig. 3--Elastic clampup forces for varying temperature and moisture levels (case 1).



(a) Varying temperature with M = 0.



(b) Varying moisture with T = 23°C (RT).



(c) Varying temperature and moisture levels.

Fig. 4--Clampup relaxation for varying temperature and moisture levels (case 1).

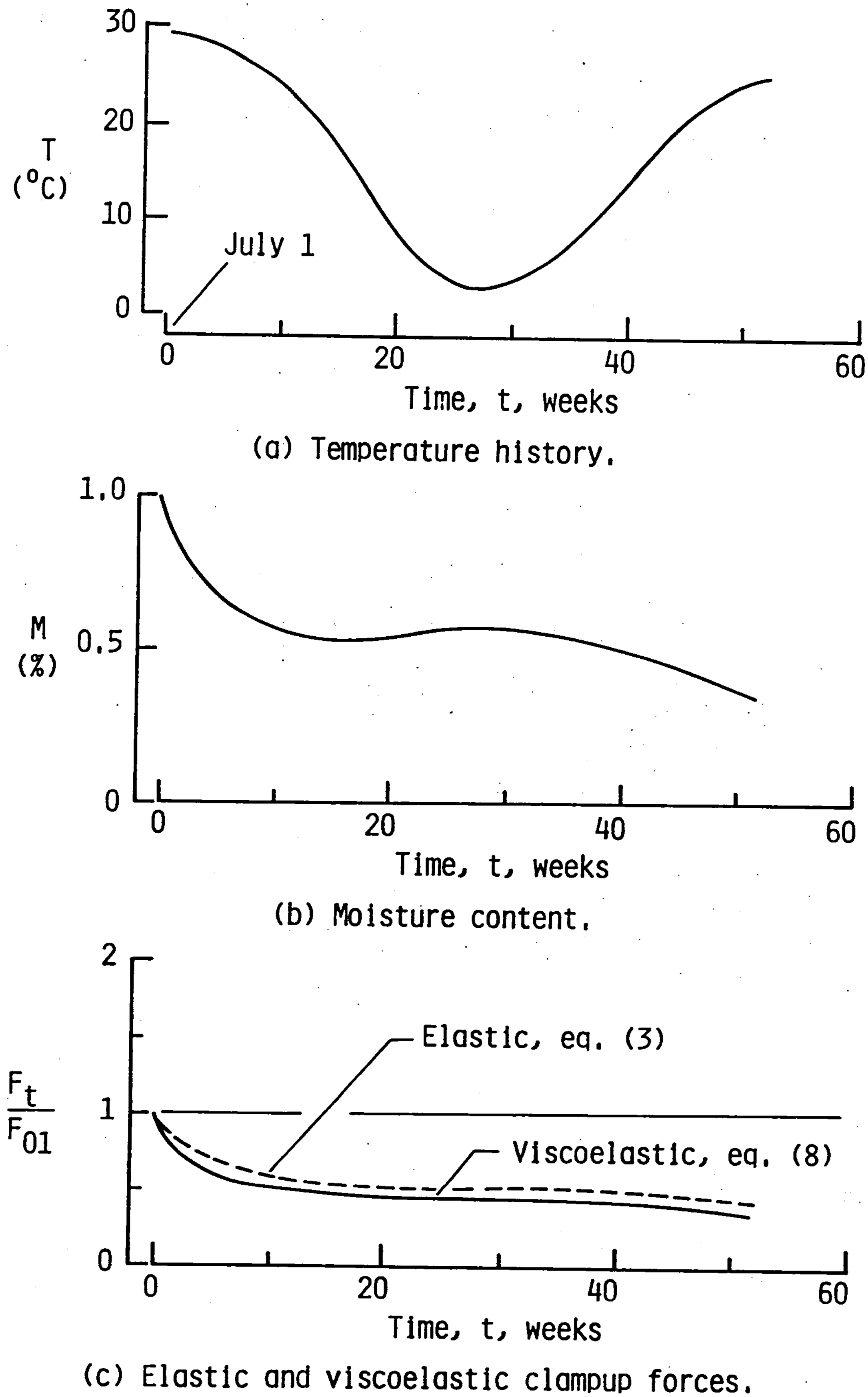


Fig. 5--Clampup relaxation for varying temperature and moisture levels (case 2).

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15. Supplementary Notes

16. Abstract

An equation is presented for bolt clampup relaxation for transient temperature-moisture (T-M) conditions. The equation was derived starting with a relaxation equation for steady-state conditions, and then using an incremental time approach that exploits the superposition principle for linear viscoelasticity. The resulting equation uses the initial T-M condition (at the time of clamping), the T-M history after clamping, and elastic clampup coefficients for temperature and moisture changes. For a given material and joint configuration, the clampup coefficients are constants that can be calculated by elastic analyses. The clampup equation was used to calculate the changes in clampup occurring in a T300/5208 graphite/epoxy joint exposed to a one-year history of temperature and moisture. Two cases were considered: one was a dry joint exposed to a relatively humid environment and the other was a nearly saturated joint exposed to an arid environment.

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