La conception analytique des propriétés viscoélastiques optimales des materiaux pour les sandwichs et les composites

Analytical Formulation of Optimal Viscoelastic Designer Material Properties for Sandwich / Composites

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ABSTRACT

Viscoelastic materials are known for their ability to dissipate energy. This property has been successfully used by the author and his colleagues to produce effective passive structural control for column and plate creep buckling, various vibratory modes, and aero-viscoelastic phenomena, such as torsional divergence, lifting surface and panel flutter, and attenuation of aerodynamic noise in panels. In self-excited systems the application of increased dissipation may stabilize or destabilize such systems depending on the influence of damping and all other forces on phase relations. Conventional design and analysis formulations call for use of the best available "off the shelf" materials. On the other hand, the optimum designer material protocols based on calculus of variation principles developed in [1] are formulated to determine the global best elastic or viscoelastic properties for specified service conditions. It has been previously established in [2] that in isotropic and anisotropic viscoelastic materials the shape of the relaxation curve is a major contributor to the material ;s response performance. In particular, it has been shown that Region C and the ratio $E_0 \ / \ E_\infty$ of the relaxation modulus, as seen in Fig.1, are the most influential in dictating material dissipation rates. Consequently, such relaxation modulus functions are tailored through prescriptions of appropriate functionally graded viscoelastic materials to produce the desired designer material performance. Relaxation moduli are, of course, highly temperature sensitive and performances must be evaluated relative to operational demands. In this paper, an analytical study presents optimal sandwich combinations of high shear modulus auxetic [3] webs with composite faceplates of proper number of stacking sequences and fibers as well as their orientations, and their viscoelastic material properties. The constraints that can be imposed consist of one or more selected from weight, dimensions, cost, deformations, failure probabilities, survival / life-times, etc. Some preliminary results are presented. The delamination failure analyses are based on uniaxial viscoelastic experimental data found in [4] and the theoretical stochastic failure criteria developed in [5]. For the same structural weight, the optimized designer viscoelastic sandwich composite plate clearly shows substantial longer survival times and orders of magnitude smaller probabilities of delamination. Extensions of these analyses to multi-element structures, i. e. entire structures, are also presented.

Key Words : aero-servo-viscoelasticity, designer viscoelastic materials, functionally graded materials, failure probability, servo controls, structural control, survival times, torsional creep divergence, viscoelasticity

INTRODUCTION

Viscoelastic mechanical properties of existing materials, such as metals, concrete, polymers, cheeses and human and animal tissue, are extensively described in [6 – 10] while relations between their chemistry and such properties are only now starting to be understood [11]. Current conventional wisdom and practice in structural analysis of air, space, naval and land vehicles call for use of the best "off the shelf" available materials. Novel and unconventional analytical direct and inverse protocols have been previously successfully formulated [1], [12 – 14] through computer simulations in a number of pilot studies seeking to determine the best designer viscoelastic material properties and their spatial non-homogeneous distributions (viscoelastic functionally graded materials, i.e. VFGM) throughout structural members tailored and engineered to specific tasks, such as beam bending, column and plate buckling, thermal stresses, structural survival times, aero-viscoelastic flutter and aero-acoustics, to mention a few.

The term "composites" is generically used to denote any substance made of two or more materials with distinct properties. Notable examples are textiles, reinforced concrete, polymer or ceramic matrices with polymer or metal fibers [15 – 27]. Another example is a plasma sprayed five-layer functionally graded ZrO_2 / Ni Co Cr AlY thermal barrier coating of a μ–meter scale thickness described in [28] and shown in Fig. 2.

ANALYSIS

Viscoelastic Constitutive Relations

Consider an anisotropic, isothermal, composite, rectangular plate with dimensions $a \otimes b \otimes h$ in a Cartesian coordinate system $x = \{x_i\}$ with $i = 1, 2, 3$, with x_3 normal to the plane of the plate. All materials, i.e. fibers and matrix, obey linear viscoelastic constitutive relations of the type [29 – 31]

$$\sigma_{ij}(x,t) \;=\; \int_{-\infty}^{t} E_{ijkl} \left[\underbrace{t - t', \overbrace{x, \mathcal{F}(x)}^{=\,\Xi_1(x)}}_{=\,\Xi(x,t-t')} \right] \; \epsilon_{kl}(x,t') \; dt' \tag{1}$$

where $\mathcal{F}(x)$ represents the relation describing the distribution of fiber orientation $\theta_{or}(x)$, number of plies $N_{pl}(x)$, number of fibers per ply $N_{fp}(x)$, volume fractions $v_{fr}(x)$ and stacking sequences $st(x)$, or

$$\mathcal{F}(x) \;=\; \mathcal{F}\left[\theta_{or}(x), N_{pl}(x), N_{fp}(x), v_{fr}(x), st(x)\right] \tag{2}$$

This function may also be thought of as defining functionally graded material (FGM) properties. The various roles of these functions in relation to optimum material performance (designer materials) will be analyzed in subsequent sections. Due to the complexity and number of variables some $a\ priori$ specifications of these functions may be necessary and practical. For instance, some variables may not be independent of each other. If the stacking sequence is to be optimized or prescribed because of manufacturing dictates, then only one of the θ_{or}s can be an independent variable. The N_{pl} and N_{fp} determine the v_{fr}. As a simple example one can consider a configuration where the the number of fibers is constant and the stacking sequence is repeated such that ply angles are $\theta_n = \theta_1 + (n-1)\Delta\theta$ for $n = 1, 2, \ldots, N_{pl}$ and

$$\mathcal{F}(x) \;=\; \mathcal{F}(\theta_1, \Delta\theta, N_{pl}, N_{fp}) \tag{3}$$

The integrals always reduce to convolution ones with $E = E(x, t - t')$ whenever the $\mathcal{F}$ is time independent and and no transient temperatures are present to modify viscoelastic material properties. The spatially non-homogeneous anisotropic relaxation modulus functions are definable in terms of Prony series [32], such that

$$E_{ijkl}(x,t) \;=\; E^{\infty}_{ijkl}\left[\Xi_1(x)\right] \;+\; \sum_{n=1}^{N_{ijkl}} E_{\underline{ijkl}n}\left[\Xi_1(x)\right] \;\exp\left(-\frac{t}{\tau_{\underline{ijkl}n}\left[\Xi_1(x)\right]}\right) \;= \tag{4}$$

where the instantaneous elastic modulus E^{0}_{ijkl} is given by

$$E^{0}_{ijkl}(x) \;=\; E_{ijkl}(x,0) \;=\; E^{\infty}_{ijkl}\left[\Xi_1(x)\right] \;+\; \sum_{n=1}^{N_{ijkl}} E_{\underline{ijkl}n}\left[\Xi_1(x)\right] \tag{5}$$

The underscored indices indicate no summations.

Governing Relations, Constraints and Designer Composite Materials

In general terms the problem can be stated in the following manner. The viscoelastic composite plate obeys depending on loading conditions (tractions, moments, etc.) one or up to $\mathcal{L}_{\mathcal{L}}$ number of differential-integral relations, which can be expressed in general terms as

$$\mathcal{L}_\ell\Big(x, t, \underbrace{\mathcal{F}(x), E_{ijkln}\left[\Xi_1(x)\right], \tau_{ijkln}\left[\Xi_1(x)\right]}_{=\ \Xi_{\mathcal{L}}(x)}\Big) \ = \ 0 \qquad \ell = 1, 2, \ldots, \mathcal{L}_{\mathcal{L}} \tag{6}$$

subject to $\mathcal{P}_\wp$ number of boundary conditions (BC)

$$\mathcal{BC}_\wp\Big(x, t, \Xi_{\mathcal{L}}(x)\Big) \ = \ 0 \qquad \wp = 1, 2, \ldots, \mathcal{P}_\wp \tag{7}$$

with a pre-determined constraint function $\mathcal{C}$ based on weight ρ, maximum deflections w_{max}, structural lifetime t_{LF}, failure probability P_F, cost $\mathcal{COST}$, etc., given by

$$\mathcal{C}\Big(x, t, \underbrace{\mathcal{F}(x), E_{ijkln}\left[\Xi_1(x)\right], \tau_{ijkln}\left[\Xi_1(x)\right], \rho, w_{max}, \mathcal{COST}, t_{LF}, P_F, \ldots}_{=\ \Xi_{\mathcal{C}}(x)}\Big) \ = \ 0 \tag{8}$$

A number of protocols for determining the various parameters are presented and analyzed in [1]. Let S_p be the general designation for each individual parameter in Eqs. (6) to (8) with a total number κ. Selecting, for instance, a Lagrangian multiplier (λ_ℓ) approach one obtains after applying Galerkin's method to eliminate all x-dependencies

$$\frac{\partial}{\partial S_p}\Big\{\mathcal{L}_\ell(t, \Xi^*_{\mathcal{L}}) \ + \ \lambda_\ell\, \mathcal{C}\left(t, \Xi^*_{\mathcal{C}}\right)\Big\} \ = \ 0 \tag{9}$$

$$\ell = 1, 2, \ldots, \mathcal{L}_{\mathcal{L}} \quad \text{and} \quad p = 1, 2, \ldots, \kappa + \mathcal{L}_{\mathcal{L}}$$

The time dependence in (9) is removed through the use of the least squares method with at least $25(\kappa + \mathcal{L}_{\mathcal{L}})$ time values.

Specifically, a plate under aerodynamic loading has a governing relation for the mid-plane deflection $w(x,t)$ which reads

$$\mathcal{L}_1\Big\{w(x_1, x_2, t)\Big\} \ = \ \underbrace{\int_{-\infty}^{t} \frac{\partial^2}{\partial x_1^2}\left(D_1(x, t-t')\ \frac{\partial^2 w(x,t')}{\partial x_1^2}\right)\ dt'}_{\text{viscoelastic bending resistance } (\mathrm{T}_1)}$$

$$+ \underbrace{\int_{-\infty}^{t}\left[2\,\frac{\partial^2}{\partial x_1 \partial x_2}\left(D_2(x, t-t')\,\frac{\partial^2 w(x,t')}{\partial x_1 \partial x_2}\right) + \frac{\partial^2}{\partial x_2^2}\left(D_3(x, t-t')\ \frac{\partial^2 w(x,t')}{\partial x_2^2}\right)\right]\ dt'}_{\text{viscoelastic bending resistance } (\mathrm{T}_1)}$$

$$- \left[\underbrace{\int_{-\infty}^{t}\int_0^a D_4(\overline{x}_1, x_2, t-t')\left(\frac{\partial w(\overline{x}_1, x_2, t')}{\partial \overline{x}_1}\right)^2 d\overline{x}_1\, dt'}_{\text{in plane force due to length change in } \mathrm{x}_1 \text{ direction } (\mathrm{T}_2)} + \underbrace{\mathcal{N}^{\mathbf{EX}}_{11}(x_2, t)}_{\substack{\text{external force}\\ (\mathrm{T}_3)}}\right]\frac{\partial^2 w}{\partial x_1^2} \ + \ \underbrace{m_p\,\frac{\partial^2 w(x,t)}{\partial t^2}}_{\substack{\text{inertia effects}\\ (\mathrm{T}_4)}}$$

$$+ \left[\underbrace{\int_{-\infty}^{t}\int_0^b D_5(x_1, \overline{x}_2, t-t')\left(\frac{\partial w(x_1, \overline{x}_2, t')}{\partial \overline{x}_2}\right)^2 d\overline{x}_2\, dt'}_{\text{in plane force due to length change in } \mathrm{x}_2 \text{ direction } (\mathrm{T}_5)} \ + \ \underbrace{\mathcal{N}^{\mathbf{EX}}_{22}(x_1, t)}_{\substack{\text{external force}\\ (\mathrm{T}_6)}}\right]\frac{\partial^2 w}{\partial x_2^2}$$

$$
- \left[\underbrace{\int_{-\infty}^{t} \int_0^a D_6(\overline{x}_1, x_2, t-t') \, \frac{\partial w(\overline{x}_1, x_2, t')}{\partial \overline{x}_1} \frac{\partial w(\overline{x}_1, x_2, t')}{\partial x_2} \, d\overline{x}_1 \, dt'}_{\text{in plane force due to angle change between } x_1 \text{ \& } x_2 \text{ directions } (T_7)} + \underbrace{\mathcal{N}_{12}^{\mathbf{EX}}(t)}_{\substack{\text{external force} \\ (T_8)}} \right] \frac{\partial^2 w}{\partial x_1 \partial x_2}
$$

$$
- \left[\underbrace{\int_{-\infty}^{t} \int_0^a D_7(x_1, \overline{x}_2, t-t') \, \frac{\partial w(x_1, \overline{x}_2, t')}{\partial x_1} \frac{\partial w(x_1, \overline{x}_2, t')}{\partial \overline{x}_2} \, d\overline{x}_2 \, dt'}_{\text{in plane force due to angle change between } x_1 \text{ \& } x_2 \text{ directions } (T_9)} + \underbrace{\mathcal{N}_{12}^{\mathbf{EX}}(t)}_{\substack{\text{external force} \\ (T_{10})}} \right] \frac{\partial^2 w}{\partial x_1 \partial x_2}
$$

$$
+ \underbrace{a_0 \, q \, \sin \left\{ \frac{\pi}{2\,\alpha_{ST}} \left[\underbrace{\overbrace{\mathcal{A}_W(\alpha, \theta, W)}^{\substack{\text{wing contribution} \\ \text{Eq. (11)}}} + \overbrace{\arctan\left(\frac{1}{U_\infty} \frac{\partial w(x,t)}{\partial t} + \frac{\partial w(x,t)}{\partial x_1} \right)}^{\text{panel contribution}}}_{\text{combined angle due to attack of deformed wing and panel}} \right] \right\}}_{\text{lift forces } (T_{11})}
$$

$$
+ \underbrace{\mathcal{N}_{11}^{\mathbf{P}}(x,t) \frac{\partial^2 w}{\partial x_1^2}}_{x_1 \text{ piezo force } (T_{12})} + \underbrace{\mathcal{N}_{22}^{\mathbf{P}}(x,t) \frac{\partial^2 w}{\partial x_2^2}}_{x_2 \text{ piezo force } (T_{13})} + \underbrace{\mathcal{N}_{11}^{\mathbf{T}}(x,t) \frac{\partial^2 w}{\partial x_1^2}}_{x_1 \text{ thermal force } (T_{14})} + \underbrace{\mathcal{N}_{22}^{\mathbf{T}}(x,t) \frac{\partial^2 w}{\partial x_1 \partial x_2}}_{x_2 \text{ thermal force } (T_{15})}
$$

$$
+ \underbrace{2 \, \mathcal{N}_{12}^{\mathbf{T}}(x,t) \frac{\partial^2 w}{\partial x_1 \partial x_2}}_{\substack{\text{thermal shear} \\ \text{force } (T_{16})}} + \underbrace{\frac{\partial M_{11}^{\mathbf{T}}}{\partial x_2^2}}_{\substack{x_3 \text{load due} \\ to\ M_{11}^{\mathbf{T}}(T_{17})}} + \underbrace{\frac{\partial M_{22}^{\mathbf{T}}}{\partial x_1^2}}_{\substack{x_3 \text{load due} \\ to\ M_{22}^{\mathbf{T}}(T_{18})}} + 2 \underbrace{\frac{\partial M_{12}^{\mathbf{T}}}{\partial x_1 \partial x_2}}_{\substack{x_3 \text{load due} \\ to\ M_{12}^{\mathbf{T}}(T_{19})}} =
$$

$$
\underbrace{\Delta p \left(x, t, \alpha, w, \overbrace{\frac{\partial w}{\partial x}, \frac{\partial w}{\partial t}, \frac{\partial^2 w}{\partial t^2}}^{\text{panel contributions}}, \overbrace{\theta, W, \frac{\partial W}{\partial t}, \frac{\partial^2 W}{\partial t^2}}^{\text{wing contributions}} \right)}_{\text{aerodynamic noise pressure } (T_{20})} \tag{10}
$$

where the plate $w = w(x,t) = w(x_1, x_2, t)$ and the wing $W = W(x_2, t)$ unless otherwise indicated. In the absence of chordwise bending the panel effective angle of attack due to wing contributions is

$$
\mathcal{A}_W(\alpha, \theta, W) = \overbrace{\alpha_r(x_2) - \alpha_0(x_2)}^{\substack{f_\alpha(x_2)=\text{built in} \\ \text{rigid angles}}} + \overbrace{\alpha(x_2)}^{\substack{\text{angle of} \\ \text{attack}}} + \underbrace{\overbrace{\theta(x_2,t)}^{\substack{\text{wing angle} \\ \text{of twist}}} + \overbrace{\arctan\left(\frac{1}{U_\infty} \frac{\partial W(x_2,t)}{\partial t} \right)}^{\text{wing bending velocity}}}_{\text{wing aero}-\text{viscoelastic contributions}} \tag{11}
$$

For elastic plates based on Eqs. (10) similar relations can be derived without the time integrals and with

$$
D_m^E(x) \equiv D_m(x, t, t') \tag{12}
$$

If the elastic or viscoelastic material is isotropic then in terms T_1, the bending rigidities become

$$
D_1 = D_2 = D_3 \equiv D \tag{13}
$$

and the T_1 terms reduce to

$$
\text{Term } T_1 \text{ viscoelastic} \implies \int_{-\infty}^{t} D(x, t-t') \, \nabla \, w(x,t') \, dt' \quad \text{or} \quad \int_{-\infty}^{t} D(x, t, t') \, \nabla \, w(x,t') \, dt' \tag{14}
$$

$$
\text{Term } T_1 \text{ elastic} \implies D^E(x) \, \nabla \, w^E(x,t) \tag{15}
$$

with

$$\nabla \;=\; \frac{\partial^4}{\partial x_1^4} + 2\,\frac{\partial^4}{\partial x_1^2\,\partial x_2^2} + \frac{\partial^4}{\partial x_2^4} \tag{16}$$

It is to be noted that in corresponding elastic isotropic cases, the modulus D^E is defined as

$$D^E \;=\; \frac{E^E\;h^3}{12\;[1-(\nu^E)^2]} \tag{17}$$

whereas for equivalent isotropic viscoelastic materials the use of Poisson's ratio is inappropriate and counter-indicated [33, 34], since there is no viscoelastic counterpart for the elastic expression (17), except under severely restricted conditions. In all other more general cases, viscoelastic Poisson ratios are time, loading history and stress dependent [33], [34]. For viscoelastic materials, therefore, only relaxation moduli or functions can be used to define bending rigidities, i. e.

$$D_{ijkl}(t) \;=\; \frac{E_{ijkl}(t)\,h^3}{12} \tag{18}$$

The linearity or nonlinearity of terms in the governing relation of Eq. (10) is independently influenced by geometry (size of deflections), material property characterizations. boundary conditions and failure conditions. It should be noted that if a single term of the governing relations exhibits nonlinear properties, then integral transforms, such as Laplace and Fourier, are inapplicable and solutions to the governing DEs or integral-differential relations must be obtained by other means.

For nonhomogeneous materials Eqs. (18) must be returned to their fundamental roots and become

$$D_{ijkl}(x_1,x_2,t) \;=\; \int_{-h/2}^{h/2} E_{ijkl}(x_1,x_2,x_3,t)\;x_3^2\;dx_3 \tag{19}$$

rather than the simple moment and product of inertia expressions associated with homogeneous elastic and/or viscoelastic material plates. For auxetic materials, quantities associated with shear, such as $D_2, D_6.D_7$, can be orders of magnitude larger than the corresponding bending stiffnesses, i.e. $D_2 \gg D_1 \simeq D_3$, etc., [1], [3].

Stability and Failure Considerations

Viscoelastic plates are subject to two separate and unrelated failure modes : (1) creep buckling - stability criteria in bending and/or twisting and (2) failures due to de-bonding and/or internal core cracks - material property induced failures due to combined bending, compressive and shear stresses. In addition if they are subjected to aerodynamic loading such as lift and/or aerodynamic noise they will subject to further modes of instability, such as panel flutter.

The classical elastic and creep buckling definitions are

$$\text{elastic} \quad\Longrightarrow\quad \lim_{\sigma_{11}\to\sigma_{11}^{cr}} \left\{ w^E(x,q) \right\} \;\to\; \infty \quad \text{or} \quad \lim_{\sigma_{11}\to\sigma_{11}^{cr}} \left\{ \frac{\partial w^E(x,q)}{\partial \sigma_{11}} \right\} \;\to\; \infty$$

$$\sigma_{11}^{cr} \;=\; \frac{\pi^2\,k_c\,E^0}{12(1-\nu_E^2)} \left(\frac{h}{b}\right)^2 \tag{20}$$

$$\text{viscoelastic} \quad\Longrightarrow\quad \lim_{t\to t_{cr}} \{w(x,t)\} \;\to\; \infty \quad \text{or} \quad \lim_{t\to t_{cr}^*} \left\{ \frac{\partial w(x,t)}{\partial t} \right\} \;\to\; \infty$$

$$\sigma_{11} < \sigma_{11}^{cr} \tag{21}$$

However, in [35 – 37] it has been shown that small deflection linear viscoelastic analysis without any twisting results in finite deflections for $0 < t_{cr}$ and $t_{cr}^* < \infty$. This proof can be readily extended to the present coupled deformations. Consequently, alternate creep buckling definitions must be formulated. Two distinct types based on (1) strain reversal in time and on (2) time dependent material failure criteria have been offered.

In [38] it has been proposed and successfully experimentally demonstrated that for elastic plates the buckling load can be established by analyzing graphs of outer plate fiber strains where compressive strains due loads and tensile strains due to bending take place. The elastic in-plane buckling load N_{cr} is then defined as

$$\lim_{N \to N_{cr}} \frac{\partial \left[\epsilon_c^E(N) + \epsilon_t^E(N)\right]}{\partial N} \to 0 \qquad t = 0 \tag{22}$$

This definition has been modified in [40] for creep buckling of columns and can now be applied to plates in the form

$$\lim_{t \to t_{cr}^{\#}} \frac{\partial \left[\epsilon_c(t) + \epsilon_t(t)\right]}{\partial t} \to 0 \qquad 0 \leq N_{11} < N_{11}^{cr} \quad \text{and} \quad 0 < t_{cr}^{\#} < \infty \tag{23}$$

If thermal loads are present, then one needs to change the domain to $0 \leq N_{11}(t) + N_{11}^T(t) < N_{11}^{cr}$ in order to incorporate in-plane thermal load $N_{\alpha\beta}^T$ effects.

Viscoelastic failure criteria, such as ultimate stresses, degrade in time independently of relaxation moduli and failures may occur before or after any creep buckling instabilities manifest themselves. These are material failures which are independent of creep buckling and define the life time of the structure designated as t_{LF}. Consequently, t_{cr} or t_{cr}^* or $t_{cr}^{\#}$ may be greater, smaller or equal than t_{LF} [39], [40]. Indeed, in Refs. [35], [41] and [42] the Shanley & Ryder [43] interaction or stress ratio curve approach has been used to estimate plate failures under combined inelastic deterministic stresses.

Some failure mechanisms observed in composites are substantially different from those seen in metals as for example delamination which is a phenomenon unique to composites [4], [44] [45]. From an aerospace design analysis point of view, one needs only to consider delamination onset because at that stage a structure has for all practical purposes failed, particularly if it is a light weight flight structure. In [4] an expression has been formulated for the temperature, moisture and time dependency of uniaxial composite failure stresses. An extensive review of available experimental composite failure data is presented in [45] where such data is used to formulated deterministic and stochastic delamination failure analyses. Experimental results indicate that uniaxial deterministic delamination onset stresses in tension and shear obey laws of the type

$$\sigma_{ij}^{\boldsymbol{F}}(t) = \begin{cases} \sigma_{ij0}^{\boldsymbol{F}} & -\infty \leq t \leq t_2^{\boldsymbol{F}} \\ \sigma_{ij0}^{\boldsymbol{F}} \left[1 - \left| \dfrac{\log\left(t/t_4^{\boldsymbol{F}}\right)}{\log\left(t_3^{\boldsymbol{F}}/t_4^{\boldsymbol{F}}\right)} \right| \right] & 0 < t_2^{\boldsymbol{F}} \leq t \leq t_3^{\boldsymbol{F}} \\ 0 & t \geq t_3^{\boldsymbol{F}} \end{cases} \tag{24}$$

where all parameters are material, temperature, moisture and uni-axial load (compression, shear, bending, etc.) dependent (Fig. 3).

DISCUSSION and CONCLUSIONS

In Eq. (10) the input forces are Terms T_{11} (lift) and T_{20} (aerodynamic noise). Each force in its own right creates a self-excited system and can result in time dependent viscoelastic panel instabilities, such as creep buckling and creep flutter. Additionally and independently failures due to delamination, aging, cracks, etc., can take place. These failure modes are illustrated in Figs. 4 and 5. The first plots indicate the importance of aerodynamic noise at lower flight velocities, while flutter generally predominates at higher values. Fig. 5 shows the relative contributions to maximum panel deflections due to aerodynamic noise, creep buckling and creep flutter. Each instability mode in turn provides limits on panel lifetimes or survival times, unless preceded by delamination or other material failures, which have their own survival times.

As can be seen from the results displayed in the above Analysis Section, the number of candidate optimization variables defining the designer material can be large. In Ref. [11], protocols for manufacturing polymers to order, i.e. to produce prescribed relaxation moduli, failure conditions, weight, cost, etc., are presented and it is shown that they still are in their early development phase. Consequently, at this stage designer material properties serve as a guide for manufacturers to plan for what material properties are needed to be engineered now and in the near future. In the meantime, results obtained for designer materials serve to improve the design selection by helping to identify, based on their properties, the "best" currently available materials to be used for particular service conditions.

Fig. 6 presents a typical example of the merits of the viscoelastic composite designer material protocols by selecting proper values for the variables that produce lower delamination probabilities and longer life times than conventional procedures based on catalogue available materials. Similar charts can be generated for optimal designer lifetimes governing creep buckling and flutter conditions. Weibull failure probability distribution functions [46] were used in the analysis.

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REFERENCES

1. H. H. Hilton, D. H. Lee, A. R. A. El Fouly, ≪ General analysis of viscoelastic designer functionally graded auxetic materials engineered/tailored for specific task performances ≫. Mechanics of Time-Dependent Materials, Vol. 12, pp.151-178, 2008.
2. H. H. Hilton, S. Yi, ≪ Analytical formulation of optimum material properties for viscoelastic damping ≫. Journal of Smart Materials and Structures, Vol. 1, pp. 113-122, 1992.
3. H. H. Hilton, A. R. A. El Fouly, ≪ Designer auxetic viscoelastic sandwich columns tailored to minimize creep buckling failure probabilities and prolong survival times ≫. Proceedings 48thAIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference, AIAA Paper 2007-2400, 2007.
4. D. A. Dillard, H. F. Brinson, ≪ A numerical procedure for predicting creep and delayed failures in laminated composites ≫. Long Term Behavior of Composites, T. M. O'Brien, ed., ASTM STP 813, pp. 23-37, 1983.
5. H. H. Hilton and S. T. Ariaratnam, ≪ Invariant anisotropic large deformation deterministic and stochastic combined load failure criteria ≫. International Journal of Solids and Structures, Vol. 31, pp. 3285-3293, 1994.
6. B. J. Lazan, ≪ Damping of Materials and Members in Structural Mechanics ≫. Pergamon Press, Oxford, 1968.
7. A. D. Nashif, D. I. G. Jones and J. P. Henderson, ≪ Vibration Damping ≫. John Wiley & Sons, New York, 1985.
8. D. I. G. Jones, ≪ Handbook of Viscoelastic Vibration Damping ≫. John Wiley & Sons, New York, 2001.
9. S. Gunasekaran and M. M. Ak, ≪ Cheese Rheology and Texture ≫. CRC Press, Boca Raton, 2003.
10. H. Kanai, ≪ Noninvasive measurement of myocardial viscoelasticity ≫. Proceeding of 8th Sendai Symposium on Ultrasonic Tissue Characterization, pp. 17–21, Institute of Development, Aging and Cancer, Tohoku University, 2005.
11. D. W. Van Krevelen, ≪ Properties of Polymers – Their Correlation with Chemical Structure ; Their Numerical Estimation and Prediction from Additive Group Contributions ≫. 3rd Ed. Elsevier, Amsterdam, 1990.
12. K. Ricker, ≪ The shape of things to come ≫. www.trecc.org/features/USS Ashville/, 2006.
13. E. Strebel, L1 NCSA researcher calculates ideal materials ≫. www.ncsa.uiuc.edu/News/09/0129NCSAresearcher.html, 2009.
14. H. H. Hilton, ≪ Optimum linear and nonlinear viscoelastic designer functionally graded materials Ð characterization and analysis, ≫. Composites Part A : Applied Science and Manufacturing, Vol. 36, pp. 1329–1334, 2005.

15. H. Lederman, ≪ Elastic and Creep Properties of Filamentous Materials and other Higher Polymers ≫. Textile Foundation, Washington, DC, 1943.
16. J. E. Ashton, and J. M. Whitney, ≪ Theory of Laminated Plates ≫. Technomic Publishing Co., Stamford, CT, 1970.
17. J. M. Whitney, ≪ Structural Analysis of Laminated Anisotropic Plates ≫. Technomic Publishing Co., Lancaster, PA, 1987.
18. I. M, Daniel and O. Ishai, ≪ Engineering Mechanics of Composite Materials ≫. Oxford University Press, New York, 1994.
19. R. M. Jones, ≪ Mechanics of Composite Materials ≫. Scripte Boo Co., Washington, DC, 1975.
20. V. V. Vasiliev and R. M. Jones, ≪ Mechanics of Composite Structures ≫. Taylor and Francis, Hants, UK, 1993.
21. J. R. Vinson and T-W Chou, ≪ Composite Materials and Their Use in Structures ≫. John Wiley & Sons, New York, 1974.
22. J. R. Vinson, ≪ Structural Mechanics : the Behavior of Plates and Shells ≫. John Wiley & Sons, New York, 1974.
23. J. R. Vinson and R. L. Sierakowski, ≪ The Behavior of Structures Composed of Composite Materials ≫. Kluwer Academic Publ., Hingham, MA, 1987.
24. J. R. Vinson, ≪ Structural Analysis of Laminated Composites ≫. Technomic Publ. Co., Lancaster, PA, 1988.
25. J. R. Vinson, ≪ The Behavior of Thin Walled Structures : Beams, Plates, and Shells ≫. Kluwer Academic Publishers, Boston, 1993.
26. J. R. Vinson, ≪ The Behavior of Shells Composed of Isotropic and Composite Materials ≫. Kluwer Academic Publishers, Boston, 1993.
27. J. R. Vinson, ≪ Plate and Panel Structures of Isotropic, Composite and Piezoelectric Materials, Including Sandwich Construction ≫. Springer, New York, 2005.
28. K. K. Aik, ≪ Plasma sprayed functionally graded ZrO_2/NiCoCrAlY thermal barrier coating ≫. www.ntu.edu.sg/mae/research/programmes/adv_materials/FGM.htm, 2003.
29. R. M. Christensen, ≪ Theory of Viscoelasticity - An Introduction, 2^{nd} ed. ≫. Academic Press, New York, 1982.
30. H. H. Hilton, ≪ An introduction to viscoelastic analysis ≫. Engineering Design for Plastics (E. Baer, ed.), pp. 199–276, Reinhold Publishing Corp., New York, 1964.
31. H. H. Hilton and S. B. Dong, ≪ An analogy for anisotropic, nonhomogeneous linear viscoelasticity including thermal stresses ≫. Development in Mechanics, pp. 58–73. Pergamon Press, New York, 1964.
32. G. C. F. M. R. Baron de Prony, ≪ Essai experimental et analytique ≫. Journal de l'École Polytechnique de Paris, pp. 24–76, 1795.
33. H. H. Hilton and S. Yi, ≪ The significance of anisotropic viscoelastic Poisson ratio stress and time dependencies ≫. International Journal of Solids and Structures, Vol. 35, pp. 3081–3095, 1998.
34. H. H. Hilton, ≪ Implications and constraints of time independent Poisson ratios in linear isotropic and anisotropic viscoelasticity ≫. Journal of Elasticity, Vol. 63, pp.221–251, 2001
35. H. H. Hilton, ≪ Creep collapse of viscoelastic columns with initial curvature ≫. Journal of the Aeronautical Sciences, Vol. 19, pp. 844–846, 1952.
36. H. H. Hilton, ≪ On the nonexistence of finite critical times for generalized linear viscoelastic columns with arbitrary initial curvatures ≫. Journal of the Aero/Space Sciences, Vol. 28, pp. 655–656, 1961.
37. J. Kempner and F. V. Pohle, ≪ On the non-existence of a finite critical time for linear viscoelastic columns ≫. Journal of the Aeronautical Sciences, Vol. 20, pp. 572–573, 1953.
38. N. J. Hoff, B. A. Boley and J. A. Coan, ≪ The development of a technique for testing stiff panels in edgewise compression ≫. Proceedings of the Society for Experimental Stress Analysis, Vol. 5, pp. 14–24, 1948.
39. H. H. Hilton, ≪ Dynamic creep buckling of linear viscoelastic columns including failure probabilities and survival times ≫. University of Illinois UIUC, Technical Report UILU ENG 02-0503, 2002. Accepted for publication in Mechanics of Time-Dependent Materials, 2009.

40. H. H. Hilton, ≪ Viscoelastic column dynamic creep buckling – failure probabilities and survival times ≫. Proceedings International Conference on Nonlinear Problems in Aviation and Aerospace, p. 18, Melbourne, FL, 2002.
41. G. Gerard, ≪ Introduction to Structural Stability Theory ≫. McGraw-Hill Book Co., New York, 1962.
42. F. R. Steinbacker and G. Gerard, ≪ Aircraft Structural Mechanics ≫. Pitman Publishing Co., New York, 1952.
43. F. R. Shanley and E. I. Ryder, ≪ Stress ratios : The answer to the combined loading problem ≫. Aviation, Vol. 36, pp. 28–29, 43, 66, 69–70, 1937.
44. C. C. Hiel, M. Sumich and D. P. Chappell, ≪ A curved beam test specimen for determining the interlaminar tensile strength of a laminated composite ≫. Journal of Composite Materials, Vol. 25, pp. 854–868, 1991.
45. H. H. Hilton and S. Yi, ≪ Stochastic viscoelastic delamination onset failure analysis of composites ≫. Journal of Composite Materials, Vol. 27, pp. 1097–1113, 1994.
46. W. Weibull, ≪ A statistical distribution function of wide applicability ≫. ASME Journal of Applied Mechanics, Vol. 18, pp. 293–297, 1951.

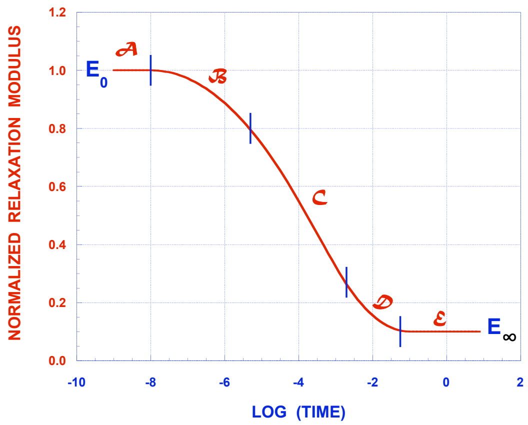

Fig. 1. Master relaxation curve

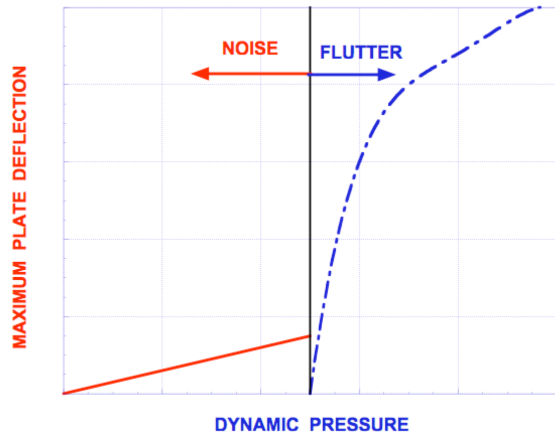

Fig. 4. Aerodynamic noise and flutter boundaries

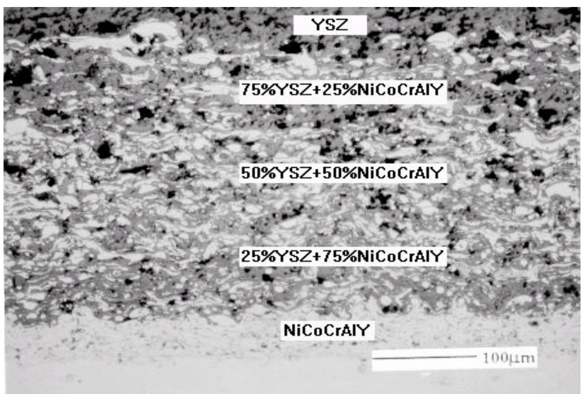

Fig. 2. Five-layer functionally graded ZrO_2/Ni Co Cr AlY coating [28]

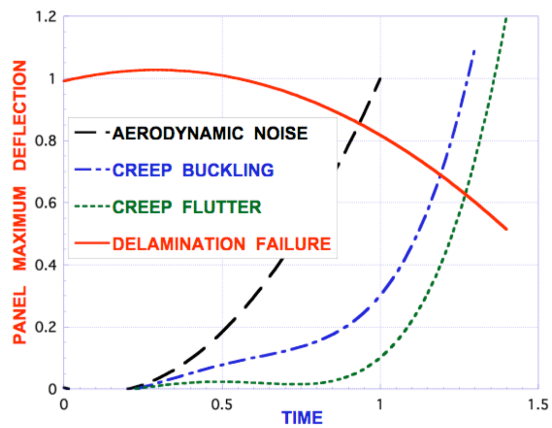

Fig. 5. Aerodynamic noise, panel flutter and buckling

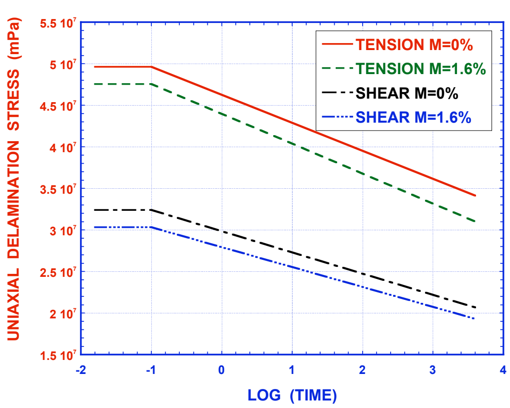

Fig. 3. Delamination stresses [4]

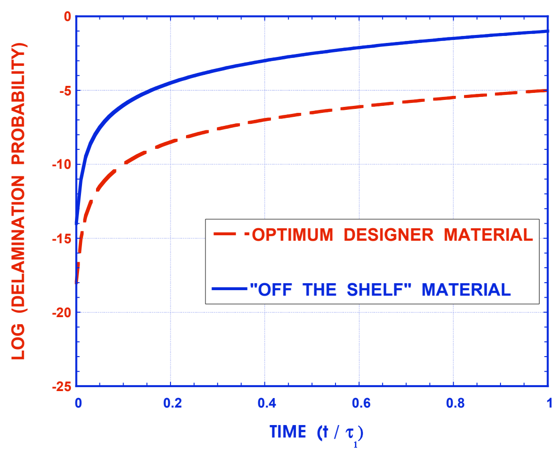

Fig. 6. Probability of delamination