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NONLINEAR THERMOMECHANICAL RESPONSE OF COMPOSITE PANELS WITH CONTINUOUS AND TERMINATED STIFFENERS

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Abstract

A two-phase approach and a computational procedure are used for predicting the variability of the response of stiffened composite panels associated with variations in the geometric and material parameters of the structures. In the first phase, hierarchical sensitivity analysis is used to identify the major parameters that have the most effect on the response quantities of interest. In the second phase, the major parameters are taken to be fuzzy parameters, and a fuzzy set analysis is used to determine the range of variation of the response, associated with preselected variations in the major parameters. Numerical results are presented showing the variability of the response of panels with both continuous and terminated stiffeners associated with variations in the micro mechanical and geometric parameters. Both flat and curved panels are considered.

Introduction

A significant numerical simulation capability now exists for studying the various phenomena associated with the response, failure and performance of multilayered composite panels and shells. The phenomena involved cover a wide range of length scales from local to global structural response. The modeling approaches used for multilayered panels can micromechanical models, three-dimensional continuum models, quasi-three-dimensional models, and two-dimensional plate and shell models. Within each category a number of models with several levels of sophistication has evolved. The four categories are described in review papers [1,2] and monographs [3-5]. Despite the extensive literature cited in the aforementioned references, only a few studies have been reported on the effects of stiffness discontinuities, such as those associated with an abrupt stiffener termination or dropped plies, on the response of composite panels (see, for example, [6-8]). Stiffener termination is often necessary in composite aerospace structures to satisfy detailed design requirements and, therefore, an understanding and a prediction of its effect on the response and failure of composite panels are desirable. Such a prediction must take into account the fact that current measurement technology does not allow the accurate determination of the material parameters that are used in the analytical models.

The present paper is a step in that direction. The results of a finite element study of the effect of stiffener termination on the response of composite panels are presented. The objectives of the study are to: a) develop better understanding of the effects of the stiffness discontinuities and load path eccentricities associated with this structural detail; and b) assess the effects of variability of material and geometric parameters on the response of composite panels with continuous and terminated stiffeners.

The panels considered in the present study have a number of T-shaped continuous or terminated stiffeners (see Fig. 1). Both flat panels and panels having cylindrical geometry are analyzed. The panel skin, flange and rib of each stiffener consist of a number of perfectly bonded plies (layers). The individual plies are assumed to be homogeneous and anisotropic. The Aboudi cell method is used to evaluate the effective properties of the individual plies.[9] A plane of thermoelastic symmetry exists at each point of the skin and the stiffener sections parallel to the reference

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surface of the section, and the material properties are assumed to be independent of temperature.

Basic Idea of the Approach Used for Assessing the Variability of the Response

The approach used for assessing the variability of the response associated with variations in material and geometric parameters consists of two major phases. In the first phase, hierarchical sensitivity analysis is used to evaluate the sensitivity coefficients with respect to a hierarchy of parameters ranging from micro mechanical to component parameters, and to identify the major parameters that have the most effect on the response quantities of interest. In the second phase, the major parameters are taken to be fuzzy parameters, and a fuzzy set analysis is used to determine the range of variation of the response quantities of interest associated with preselected variations of the fuzzy parameters. The details of the approach are described in [10].

Numerical Studies

Panels and Loading Conditions Considered

Both flat and cylindrical composite panels with five and seven T-shaped continuous and terminated stiffeners are studied. The panel skin and stiffener blades were taken to be either eight or sixteen layers. The number of layers in the stiffener flanges was assumed to be half of that of the blades. The material properties and geometric characteristics for the panels are given in Figs. 1 and 2. The material properties, the fiber orientation and the stacking sequence selected for the panels and stiffeners are those typical of panels considered for cryogenic fuel tanks of space transportation vehicles. The loads on each panel consisted of a sequence of mechanical and thermal loads: a monotonically increasing edge extension q_e, followed by a uniform pressure load of 344.7×10^3 Pa, and then a uniform temperature change of -412.8 °C. The boundary conditions are shown in Fig. 1. The sign convention for the generalized displacements, stress resultants and transverse shear stresses is shown in Fig. 3. For each panel, the maximum value of q_e was selected in such a way that the magnitude of the maximum principal strains on the surfaces does not exceed 0.01.

Finite Element Models and Computational Strategy

The analytical formulation is based on a first-order shear-deformation Sanders-Budiansky type shell theory with the effects of large displacements, moderate rotations, average transverse shear deformation through the thickness, and laminated anisotropic material behavior included. A linear Duhamel-Neumann type constitutive model is used and the material properties are assumed to be independent of temperature. The constitutive relations for each of the skin, stiffener blades and flanges are given in [11]. A total Lagrangian formulation is used and the panel deformations, at different values of the applied loads, are referred to as the original undeformed configuration. Mixed finite element models were used for the discretization of the skin and the blade section of each stiffener. Each of the stiffener flanges is combined with the adjacent skin (below it) into a single finite element. Bi-quadratic shape functions were used for approximating each of the generalized displacements, and bilinear shape functions were used for approximating each of the stress resultants. The characteristics of the finite element model are given in [11].

For each load case, global and detailed response quantities were generated. In addition, the hierarchical sensitivity coefficients are evaluated. The hierarchical sensitivity coefficients are derivatives of the different response quantities with respect to sub-component parameters, laminate stiffnesses, material parameters and fiber angles of individual plies, and the micro mechanical parameters (see Fig. 4). The hierarchical sensitivity coefficients are used to identify the major parameters, at each level, for the response quantities of interest. The major parameters are taken to be fuzzy parameters and a fuzzy set analysis is used to determine the range of variation of the response quantities of interest, associated with pre-selected variations of the fuzzy parameters. The details of the approach are described in [10].

To reduce the computational effort, the multiple parameter reduction methods described in [12-14] were used in generating the response and evaluating the sensitivity coefficients. The global response results obtained by an in-house research program were validated by comparing them with those obtained by the STAGS general analysis code.[15] Typical results are presented in Figs. 5-9 for the response studies, in Figs. 10 and 11 for the sensitivity studies, and in Figs. 12 and 13 for the variability of the nonlinear response, and are described subsequently.

Response Studies

Some of the global and detailed response characteristics of the panels considered in the present study are shown in Figs. 6-9. Plots of the total axial force N_t and the total strain energy U versus the applied edge extension q_e, are shown in Figs. 5 and 6 for panels with continuous and terminated stiffeners, respectively. For each of the panels, the variations of the ratios of the strain energy in the skin, stiffener flanges (including adjacent skin) and blades to the total strain energy of the panel, with load, are shown in Fig. 7. For four of the panels, typical contour plots for the transverse displacement w in the skin and stiffener flanges, after each loading stage, are shown in Fig. 8. For the same four panels, through-the-thickness distributions of the transverse shear strain energy density (per unit volume) $\hat{U}_{sh}$, at the location of the maximum $\overline{U}_{sh}$ (transverse shear strain energy per unit surface area), are shown in Fig. 9. An examination of Figs. 5-9 reveals:

1. For the given value of the maximum principal strain (0.01), the maximum values of the edge displacement q_e in panels with continuous stiffeners is much higher than the corresponding values for panels with terminated stiffeners. The same is true for the maximum values of the edge force N_t and total strain energy U. This is particularly true for flat panels.
2. For the case of edge extension, the total axial load, total strain energy and stiffness of each of the panels with continuous stiffeners, increases with increasing the number of plies in the skin, the number of plies in the stiffener (blades and flanges), and the number of stiffeners. The increase with increasing the number of stiffeners is less pronounced than that with the number of layers in the stiffener, which in turn is less pronounced than that with the number of stiffeners. By contrast, for flat panels with terminated stiffeners, the maximum edge extension and total strain energy increase with increasing the number of plies in the skin, but decrease with increasing either the number of plies in the stiffeners or the number of stiffeners. The decrease with increasing the number of stiffeners is less pronounced than that with increasing the number of plies.
3. For the case of edge extension, the stiffness of the curved panels is lower than that of the corresponding flat panels. Also, for a given maximum value of the principal strains, the maximum values of the edge extension and total axial force in curved panels with continuous stiffeners are lower than those for the corresponding flat panels.
4. The percentage of the strain energy carried by the skin in panels with terminated stiffeners is higher than that in panels with continuous stiffeners. By contrast, the percentage of the strain energy carried by the stiffener blades is lower than that in panels with continuous stiffeners.
5. The percentage of the strain energy carried by the skin increases significantly with the increase in the number of plies of the skin, as well as with the reduction in the number of stiffeners and the number of their plies. An increase in the percentage of energy carried by the skin is associated with a corresponding decrease in the energy carried by the stiffener blades.
6. For the edge extension case, the percentages of the strain energy carried by the skin and stiffener blades are insensitive to the panel curvature. For flat panels, the application of the pressure load results in decreasing the percentage of energy carried by the skin and increasing that carried by the stiffener blades. An opposite effect is observed after the application of temperature load, as well as for curved panels.
7. The changes in the percentages of energy carried by the skin and stiffener blades resulting from the application of pressure and temperature loads are significantly higher for panels with terminated stiffeners than those for the corresponding panels with continuous stiffeners.

<u>Sensitivity Studies</u>

Sensitivity studies were conducted to identify which of the subcomponent parameters, laminate parameters, effective ply properties, and micro mechanical parameters most affect the nonlinear response. Typical results showing the sensitivity of the total strain energy U with respect to the subcomponent parameters, for panels with five continuous and terminated stiffeners and eight plies in the skin and stiffener blades, are shown in Fig. 10. Sensitivity coefficients of U with respect to the fiber angles of the skin, stiffener flanges and blades, the effective material properties of the individual plies and the micro mechanical parameters are shown in Fig. 11. An examination of Figs. 10 and 11 reveals:

1. For the case of edge extension, the total strain energy in each panel is sensitive to the variations in the stiffener dimensions h_r and b. After application of the pressure load, U becomes sensitive to variations in the stiffener spacing ℓ. The same is true after application of the temperature load. Exception to that is the flat panel with terminated stiffeners, for which the magnitude of the sensitivity coefficient of U with respect to ℓ does not monotonically increase with the increase in the temperature load.
2. The total strain energy in each panel is considerably more sensitive to variations in the following parameters than to each of the other parameters in the same category: a) the fiber angles + 45° and –45 ° in the skin; b) the effective elastic modulus E_L, and for the temperature load, the elastic modulus E_T and the coefficient of thermal expansion α_T; c) the micro-mechanical parameters v_f and E_{1f}, and for the temperature load E_m, ν_m, α_m, E_{2f} and α_{2f}.

3. For curved panels, the magnitudes of the aforementioned sensitivity coefficients of U are lower than those of the corresponding flat panels. For panels with terminated stiffeners, the magnitudes of the stiffness coefficients are lower than those of the corresponding panels with continuous stiffeners.
4. The magnitudes of the sensitivity coefficients of U increase with the increase in the edge shortening q_e. For the pressure and temperature loads, the magnitudes of some of the sensitivity coefficients increase with the increase in load, others decrease.

Variability of the Response

Studies were conducted to assess the effect of variability of the two major micromechanical parameters, the fiber volume fraction v_f and the elastic modulus of the fibers in the longitudinal direction E_{1f}, on the total strain energy U and the transverse shear strain energy per unit volume $\hat{U}_{sh}$, at the location of the maximum $\overline{U}_{sh}$. Each of the two major micromechanical parameters, v_f and E_{1f}, was taken as a fuzzy parameter, and their nominal values were changed by 10% and 15%, respectively. The variations of the upper and lower bounds of U with load due to variations in each of the micromechanical parameters are shown in Fig. 12. The corresponding variations of the through-the-thickness distributions of the upper and lower bounds of $\hat{U}_{sh}$ (at the location of the maximum $\overline{U}_{sh}$) are shown in Fig. 13.

An examination of Figs. 12 and 13 reveals that the selected variations in v_f and E_{1f} result in higher percentage change in $\hat{U}_{sh}$, N_t, and lower percentage change in U for curved panels than for the corresponding flat panels. The changes in $\hat{U}_{sh}$ for the flat panel with terminated stiffeners is much more pronounced than that for the corresponding panel with continuous stiffeners. An opposite situation is observed for the curved panels.

Concluding Remarks

A study is made of the nonlinear response of flat and curved composite panels with continuous and terminated stiffeners. The panels have either five or seven T-shaped stiffeners with eight or sixteen perfectly bonded plies in the skin and the stiffener blades. The number of plies in the stiffener flanges are half those in the blades. Each of the panel skin, stiffener flanges and blades were modeled as two-dimensional shear flexible elements. The external loads applied to each panel consisted of an edge extension, uniform pressure load and uniform temperature change. The maximum value of the edge extension was selected to correspond to a maximum value of the principal strain in the panel of 0.01.

For each panel, both the geometrically nonlinear response, as well as the hierarchical sensitivity coefficients, are generated. The hierarchical sensitivity coefficients measure the sensitivity of the different response quantities to variations in the subcomponent parameters (stiffener dimensions and spacing), as well as to three sets of interrelated parameters; namely, laminate properties, effective ply properties, and micromechanical parameters.

The effect of variation of the major micromechanical parameters on the variability of the total strain energy, and the transverse shear strain energy per unit volume for the panel are studied.

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NASA Cooperative Agreement NCC-1-01-014 and NASA Grant NAG1-01-028 supported the work. The authors gratefully acknowledge the help of Dr. Charles C. Rankin and the staff of the Lockheed Martin Advanced Technology Center in Palo Alto, California, in using the STAGS General Shell Analysis Program.

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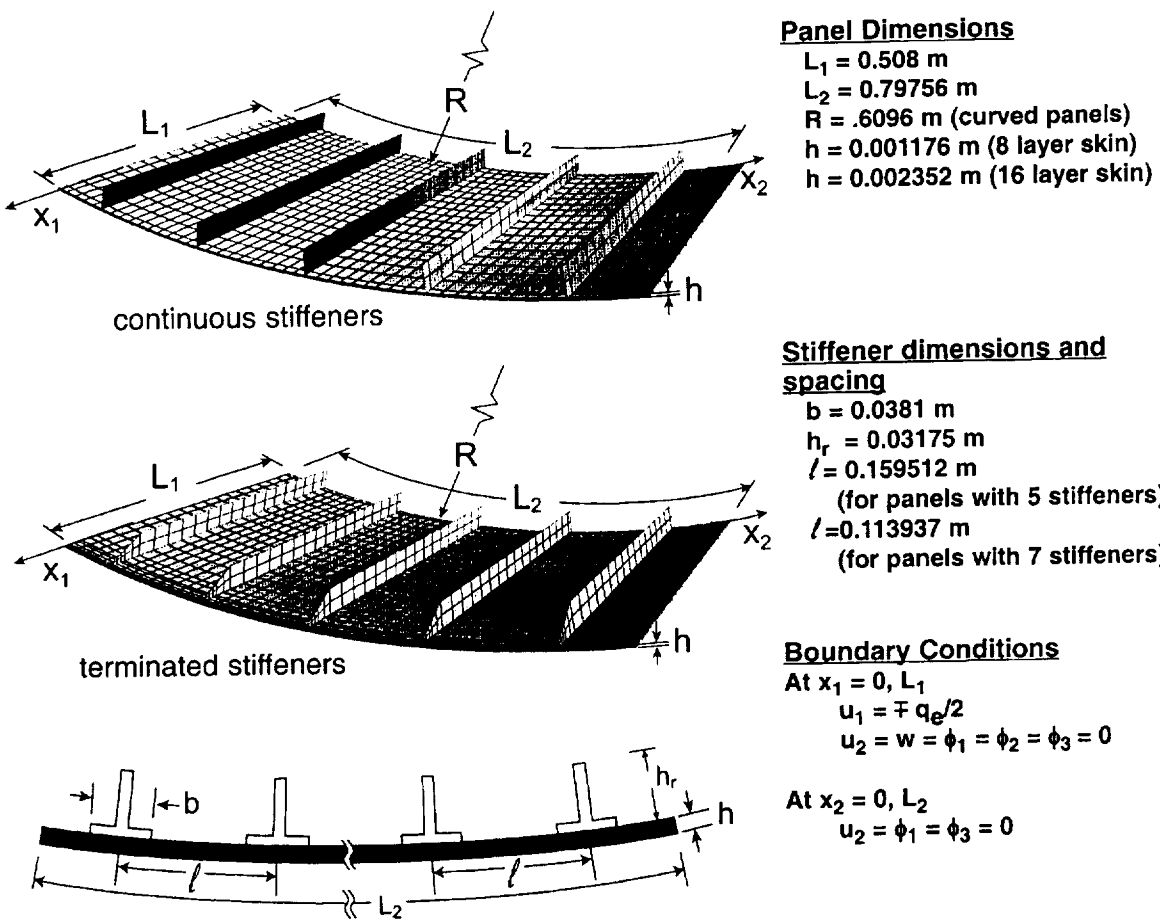


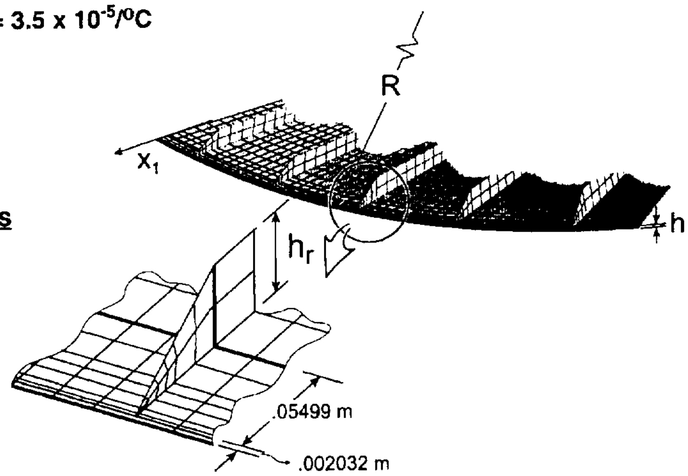
Figure 1 - Panels and boundary conditions considered in the present study.

Micromechanical Properties

Fiber
E_{1f} = 226.5 GPa
E_{2f} = 21.35 GPa
G_{12f} = 20.37 GPa
ν_{12f} = .303
ν_{23f} = .523
$\alpha_{1f} = -6.94 \times 10^{-7}/^{o}C$
$\alpha_{2f} = 17.2 \times 10^{-6}/^{o}C$
v_f = .60

Matrix
E_m = 3.3 GPa
ν_m = .35
$\alpha_m = 3.5 \times 10^{-5}/^{o}C$

Effective Ply Properties
E_L = 137.2 GPa
E_T = 8.62 GPa
G_{LT} = 3.76 GPa
G_{TT} = 2.89 GPa
ν_{LT} = .32
$\alpha_L = -3.42 \times 10^{-7}/^{o}C$



Fiber Orientation
Skin: NL=16 $[\pm 45/90_2/\mp 45/0_2]_s$
NL=8 $[\pm 45/0/90]_s$
Blade: NL=16 $[\pm 45/0/90]_{2s}$
NL=8 $[\pm 45/0/90]_s$
Flange: NL=8 $[\pm 45/0/90]_s$
NL=4 $[\pm 45/0/90]$
Thickness of individual layers = 1.397×10^{-4} m

Figure 2 - Material properties for the panels used in the present study.

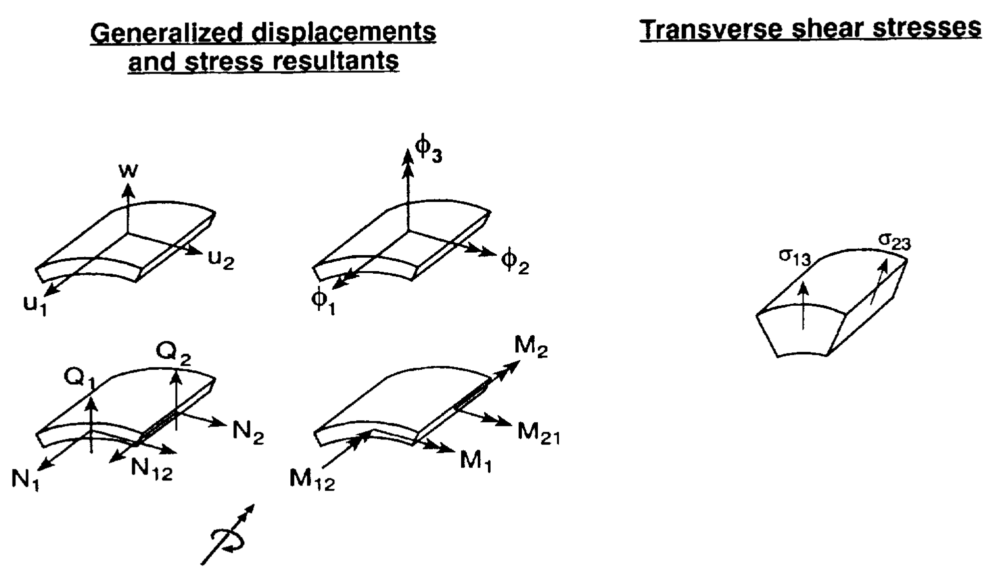


Figure 3 - Sign convention for generalized displacements, stress resultants and transverse shear stresses.

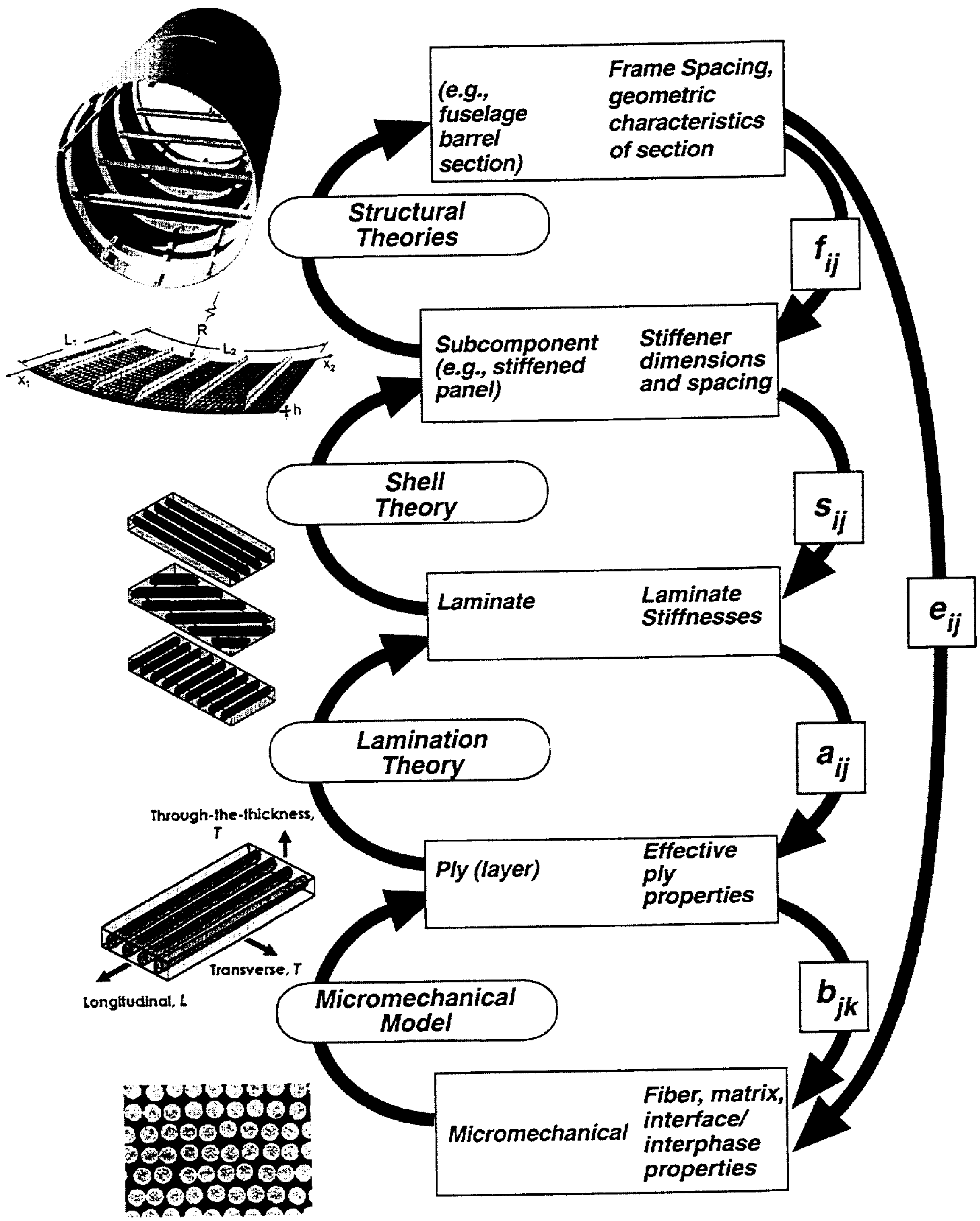
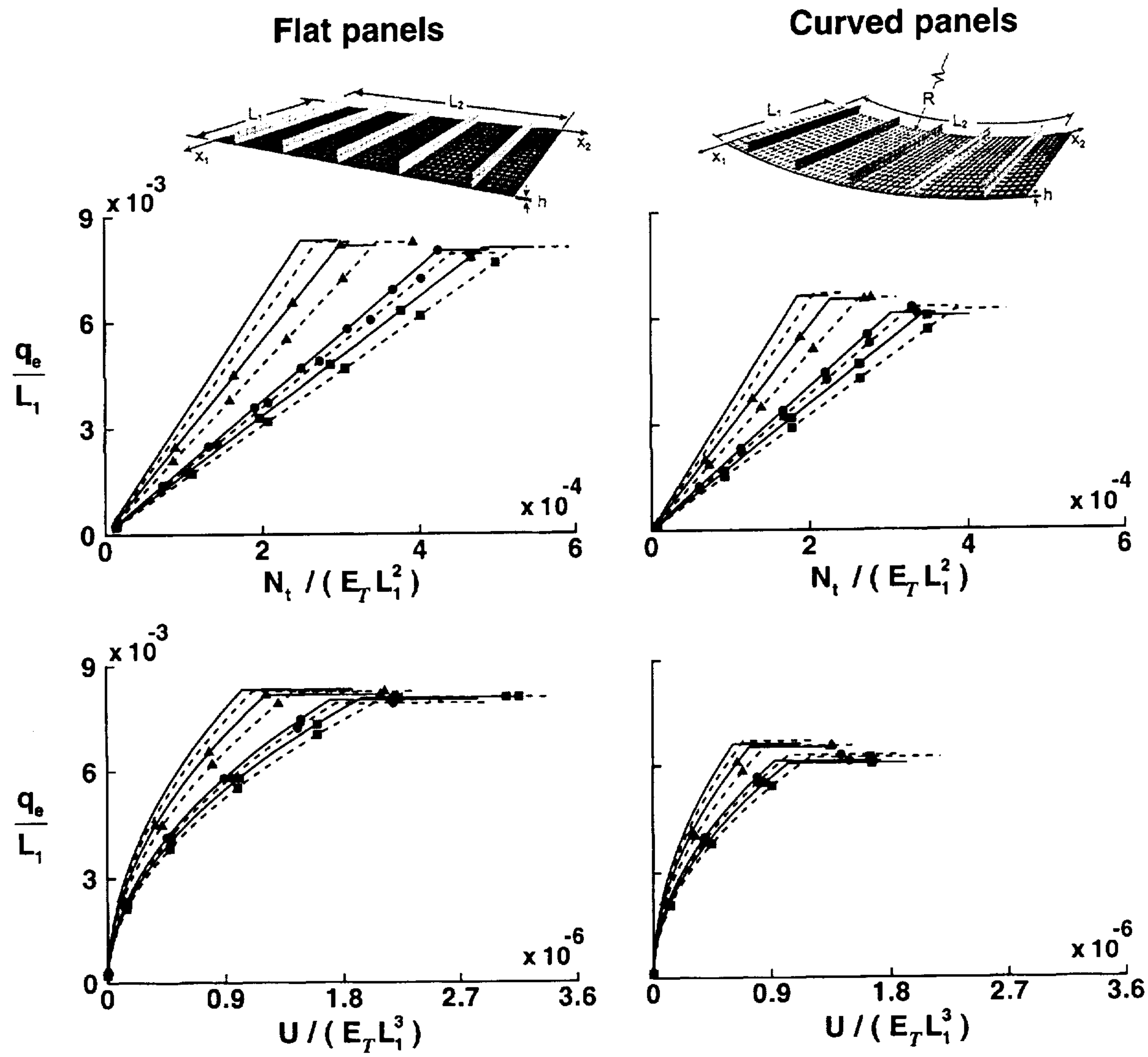
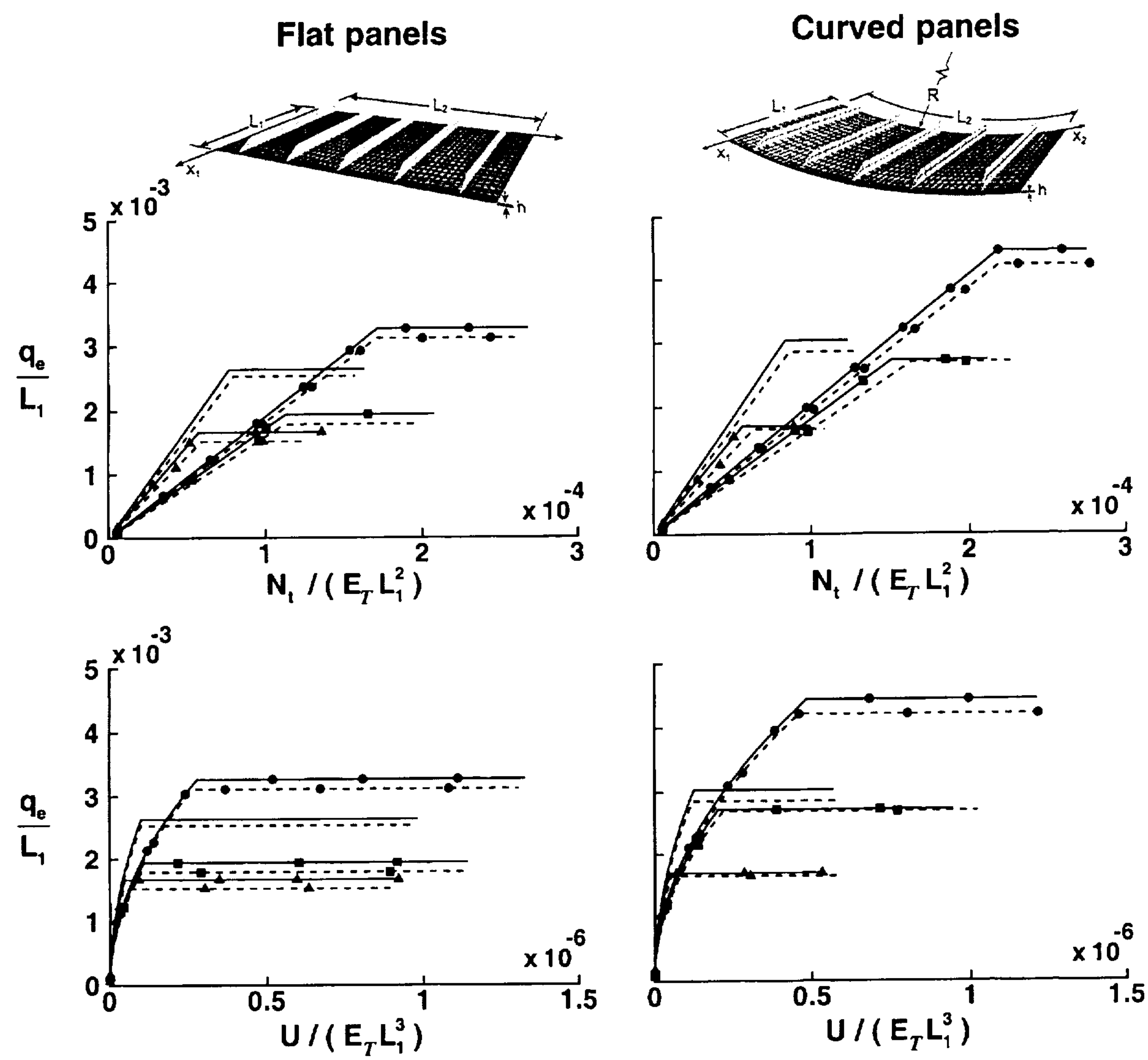


Figure 4 - Hierarchical sensitivity coefficients for composite structures.



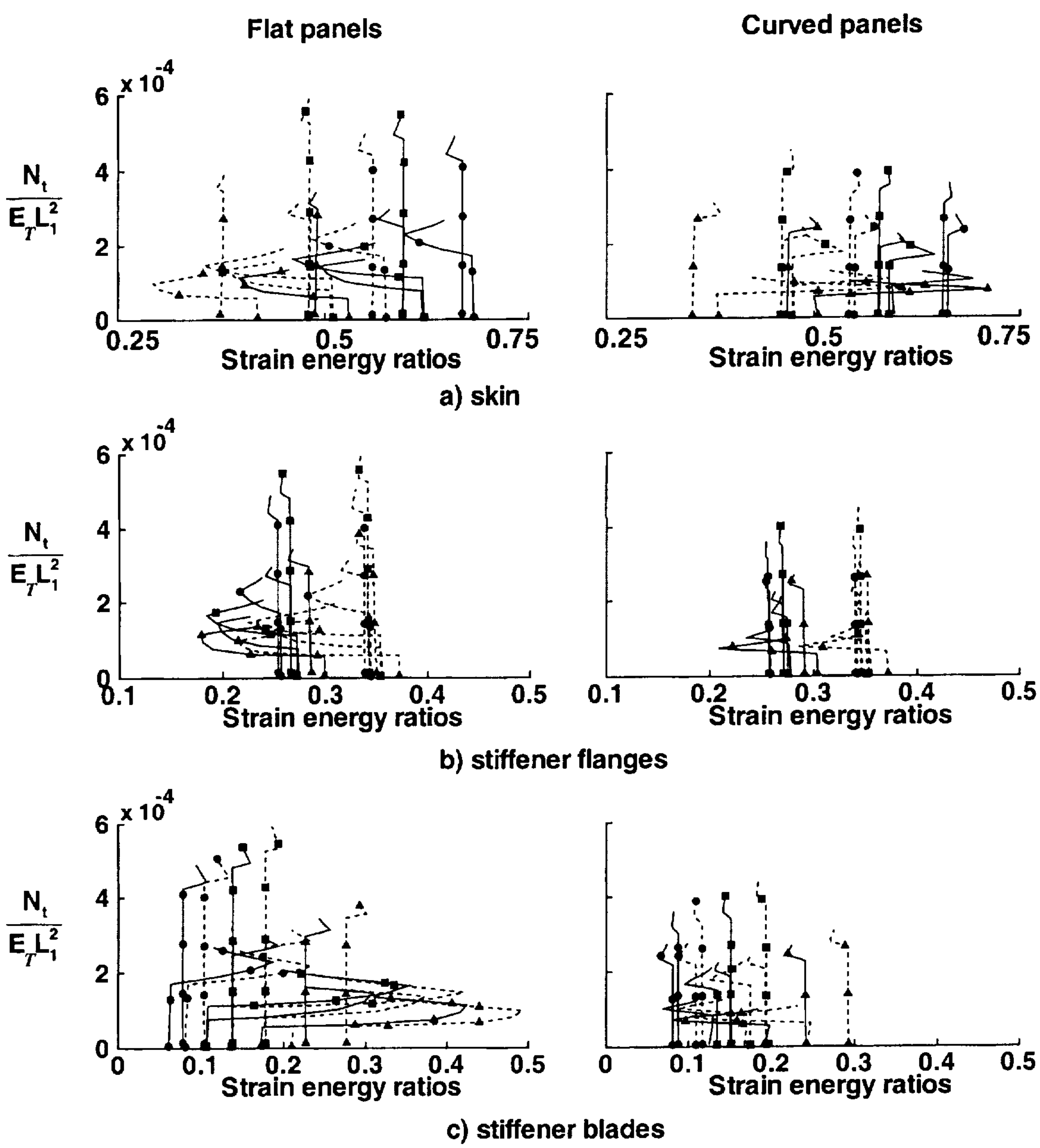
Number of stiffeners	Number of plies			Designation
	skin	Stiffener blades	Stiffener flanges	
5 7	8	8	4	——— - - - - -
5 7	8	16	8	——▲—— - - -▲- - -
5 7	16	8	4	——●—— - - -●- - -
5 7	16	16	8	——■—— - - -■- - -

Figure 5 - Global response characteristics of stiffened panels with continuous stiffeners subjected to combined edge extension, pressure load and temperature change.



Number of stiffeners	Number of plies			Designation
	skin	Stiffener blades	Stiffener flanges	
5 7	8	8	4	—— - - - - -
5 7	8	16	8	—▲— - - -▲- - -
5 7	16	8	4	—●— - - -●- - -
5 7	16	16	8	—■— - - -■- - -

Figure 6 - Global response characteristics of stiffened panels with terminated stiffeners subjected to combined edge extension, pressure load and temperature change.



Number of stiffeners	Number of plies: skin	Stiffener blades	Stiffener flanges	Designation
5 7	8	8	4	
5 7	8	16	8	
5 7	16	8	4	
5 7	16	16	8	

Figure 7 - Effect of loading condition on the strain energy ratios in the skin, stiffener flanges and stiffener blades. Stiffened panels with continuous and terminated stiffeners subjected to combined edge extension, pressure load and temperature change. Lower values are for panels with terminated stiffeners.

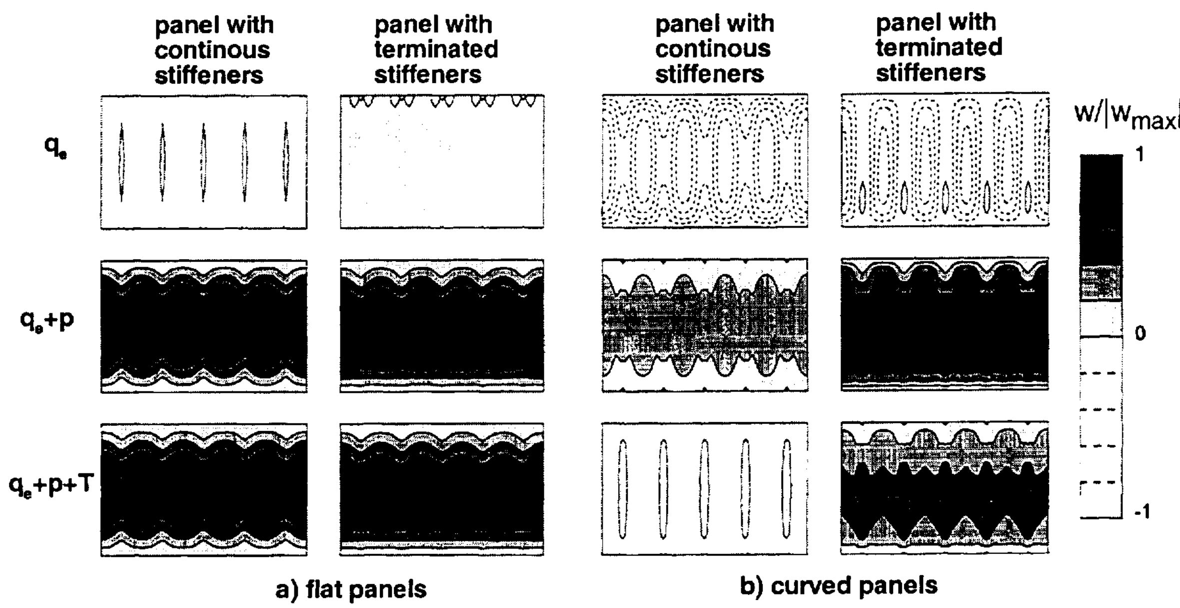


Figure 8 - Normalized contour plots depicting the effect of loading condition on the normalized transverse displacement $w/|w_{max}|$ in the skin and stiffener flanges. Stiffened panels with five continuous and terminated stiffeners, eight plies in the skin and stiffener blades, subjected to combined edge extension, pressure load and temperature change.

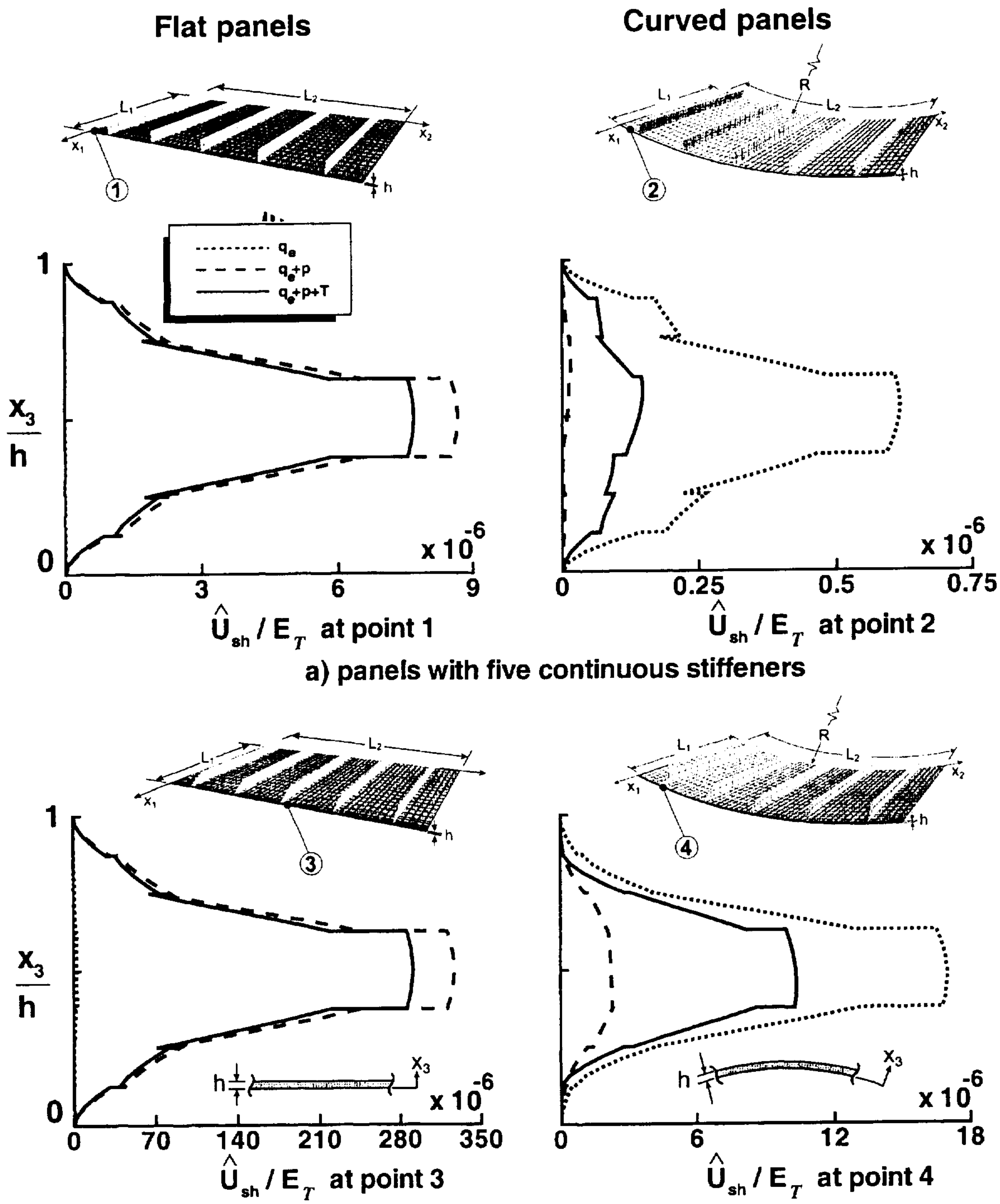


Figure 9 - Effect of loading condition on the through-the-thickness distributions of the transverse shear strain energy density (per unit volume) $\hat{U}_{sh}$ at the location of the maximum $\overline{U}_{sh}$ (transverse shear strain energy per unit surface area). Stiffened panels with five continuous and terminated stiffeners, eight plies in the skin and stiffener blades, subjected to combined edge extension, pressure load and temperature change.

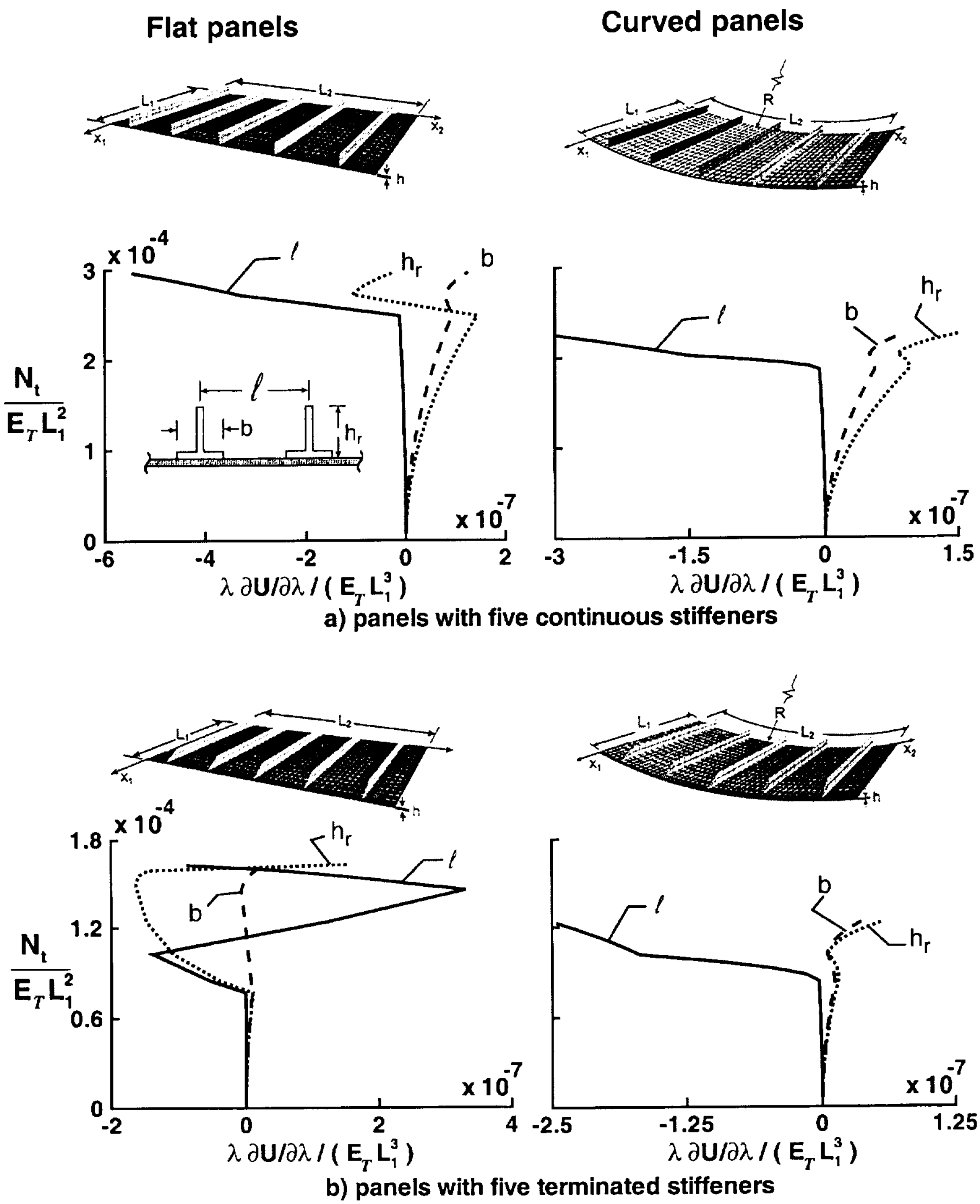


Figure 10 - Effect of loading condition on the normalized sensitivity coefficients of the total strain energy U with respect to subcomponent parameters. Stiffened panels with five continuous and terminated stiffeners, eight plies in the skin and stiffener blades, subjected to combined edge extension, pressure load and temperature change.

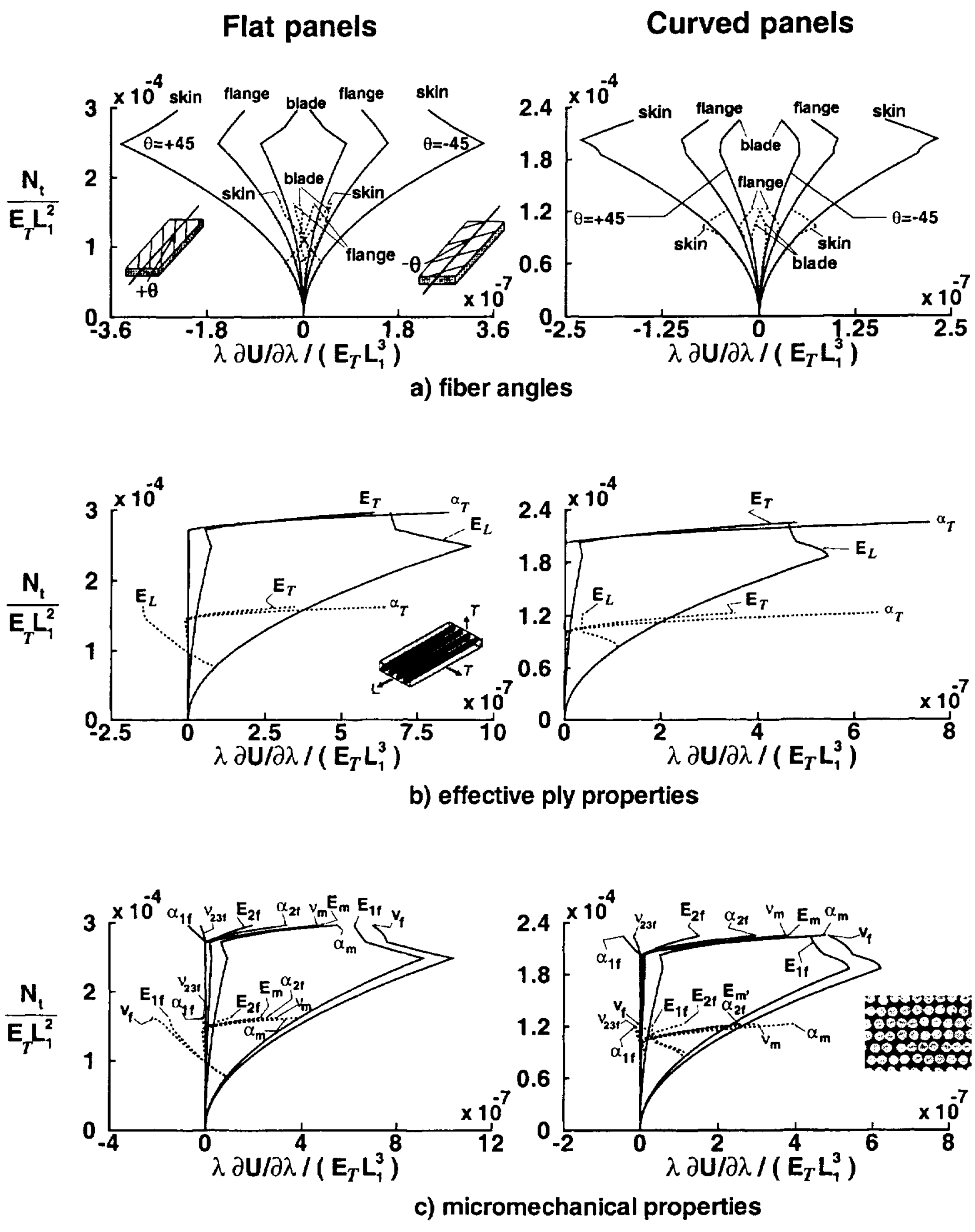


Figure 11 - Effect of loading condition on the normalized sensitivity coefficients with respect to fiber angles, effective ply and micro-mechanical parameters. Stiffened panels with five continuous and terminated stiffeners, eight plies in the skin and stiffener blades, subjected to combined edge extension, pressure load and temperature change.

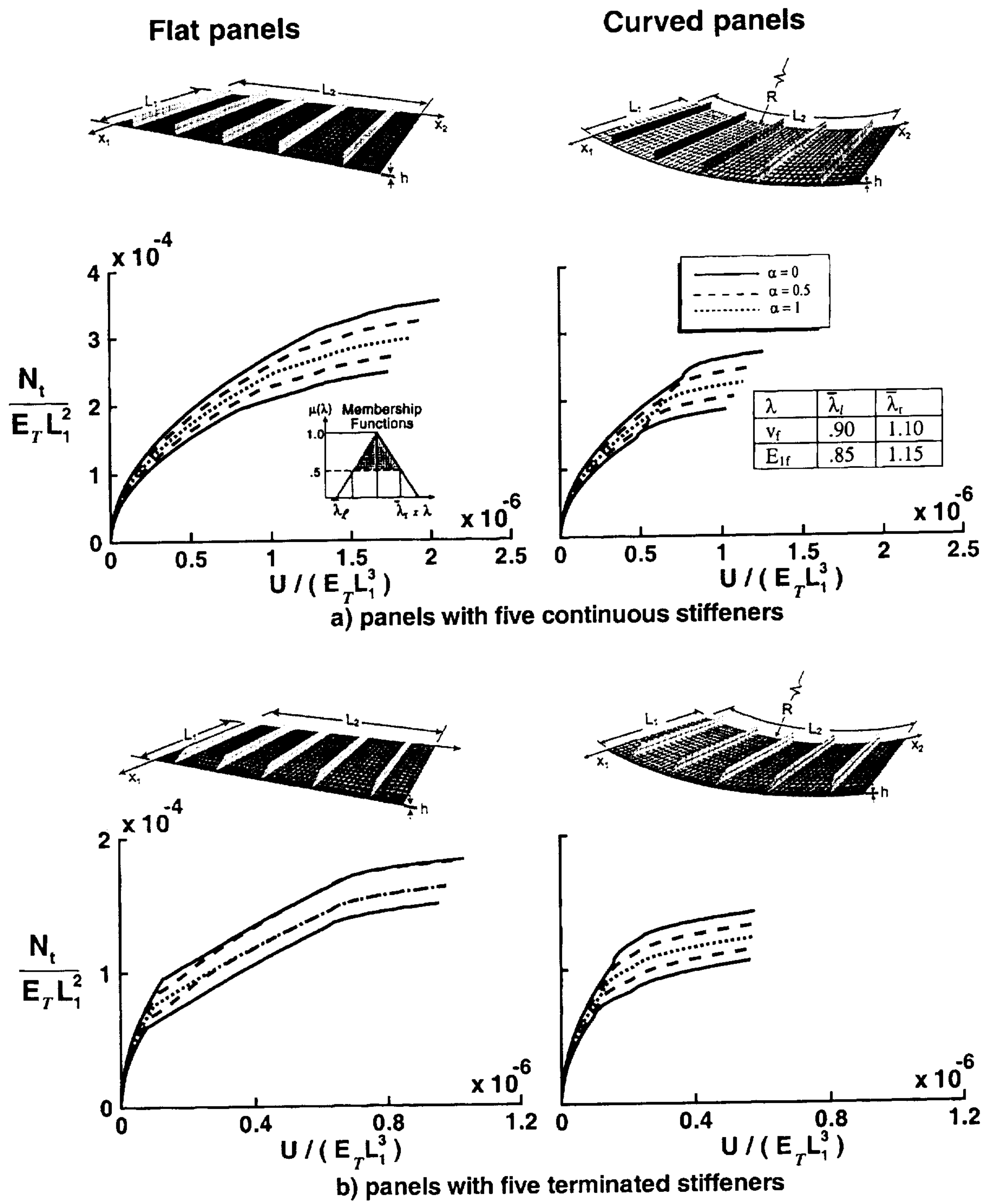


Figure 12 - Effect of variability in the micro-mechanical parameters on the total strain energy U. Stiffened panels with five continuous and terminated stiffeners, eight plies in the skin and stiffener blades, subjected to combined edge extension, pressure load and temperature change.

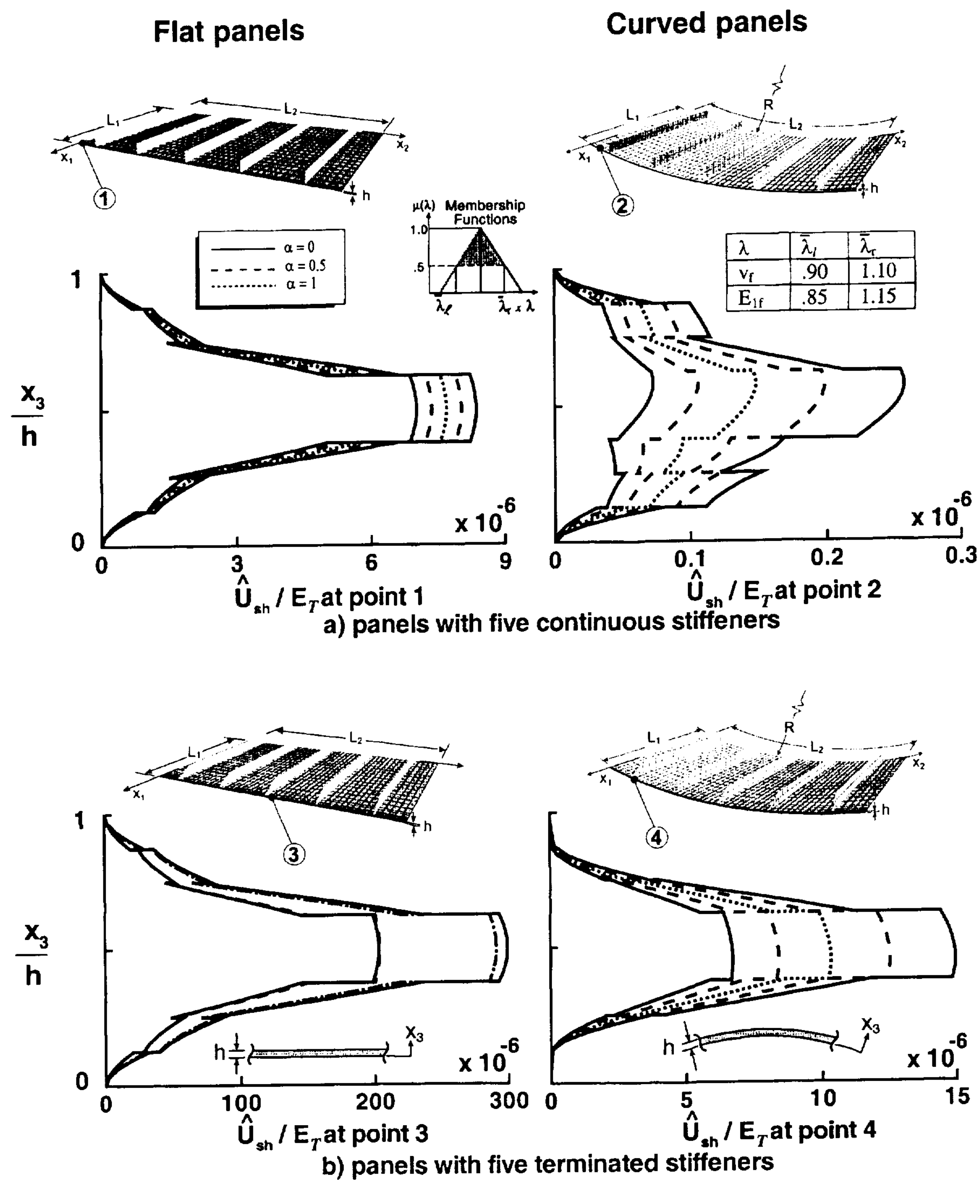


Figure 13 - Effect of variability in the micromechanical parameters on the through-the-thickness distribution of transverse shear strain energy density (per unit volume) of $\hat{U}_{sh}$ at the location of the maximum $\overline{U}_{sh}$ (transverse shear strain energy per unit surface area). Stiffened panels with five continuous and terminated stiffeners, eight plies in the skin and stiffener blades, subjected to combined edge extension, pressure load and temperature change.