N85-32437

SILICON RIBBON STRESS-STRAIN ACTIVITIES

JET PROPULSION LABORATORY

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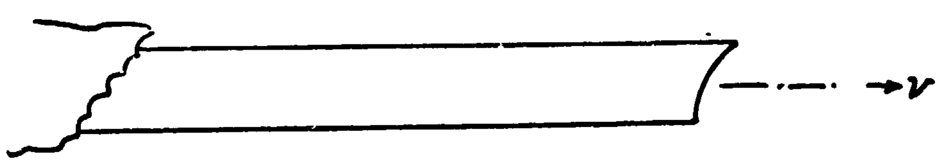
Objective

PRESENT PRELIMINARY RESULTS

- STRESS - STRAIN
- MATERIAL PROPERTIES

Ultimate Goal

- ULTIMATE GOAL-ANALYTICAL SIMULATION



INFLUENCE OF
- GEOMETRY, NONAGON, ...
- SPEED, VELOCITY, TRANSIENT
- TEMPERATURE PROFILE, TRANSIENT
- GROWTH METHOD
- FORCES, GRAVITY, SUR. TEN, ...
- PRODUCTION

ON ⇒

- RESIDUAL STRESS
- DEFORMATION
- EFFICIENCY

$= \int_A c_{ij} \, dA$

- VALUABLE FOR
  - LOWER COST, LOWER YIELD
  - HIGH EFFICIENT CELLS

JPL Stress-Strain Effort

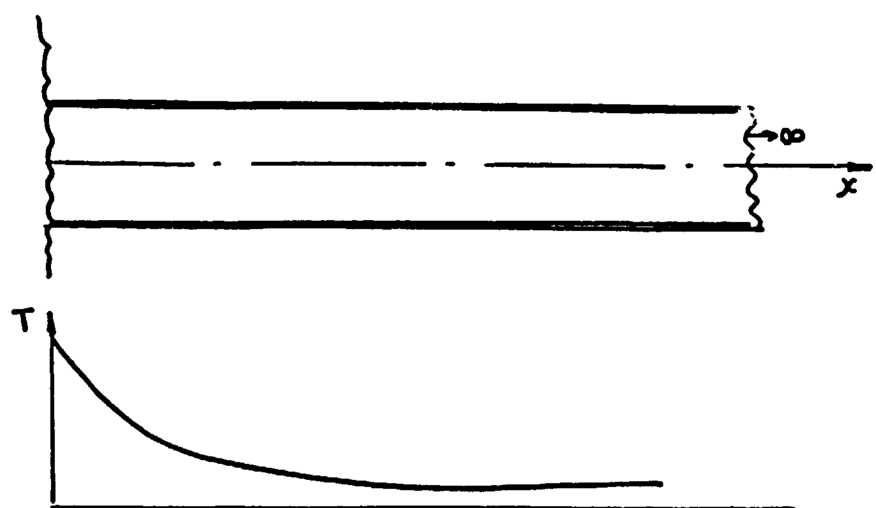
- USE EXISTING FINITE ELEMENT CODES
  - FLEXIBILITY IN GEOMETRY
- TWO APPROACHES

I. QUASI-STATIC NASTRAN DR. C-F SHIH	II. IN-PROCESS GROWTH ANSYS DR. C. P. KUO

- TOTAL PROBLEM
  - STRESS, BUCKLING, MATERIAL NON-LINEARITY, CREEP, IMPERFECTION -----> WHAT'S CRITICAL?
  - PARAMETRIC STUDY -----> VARY ENGINEERING PARAMETERS

    ------> SUPPORT PROJECT

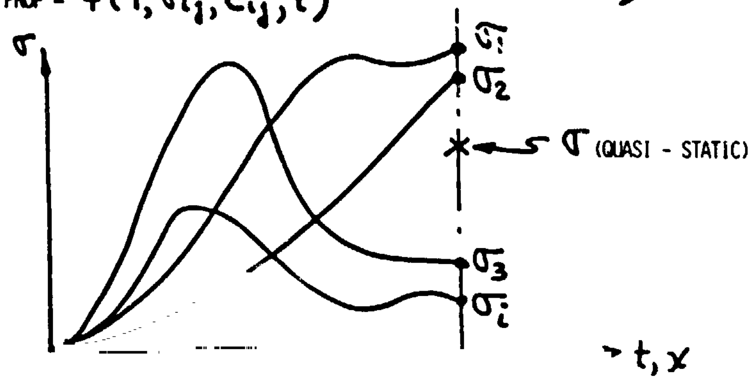
Quasi-Static



In-Process Growth

- (1) (2) .... (n)

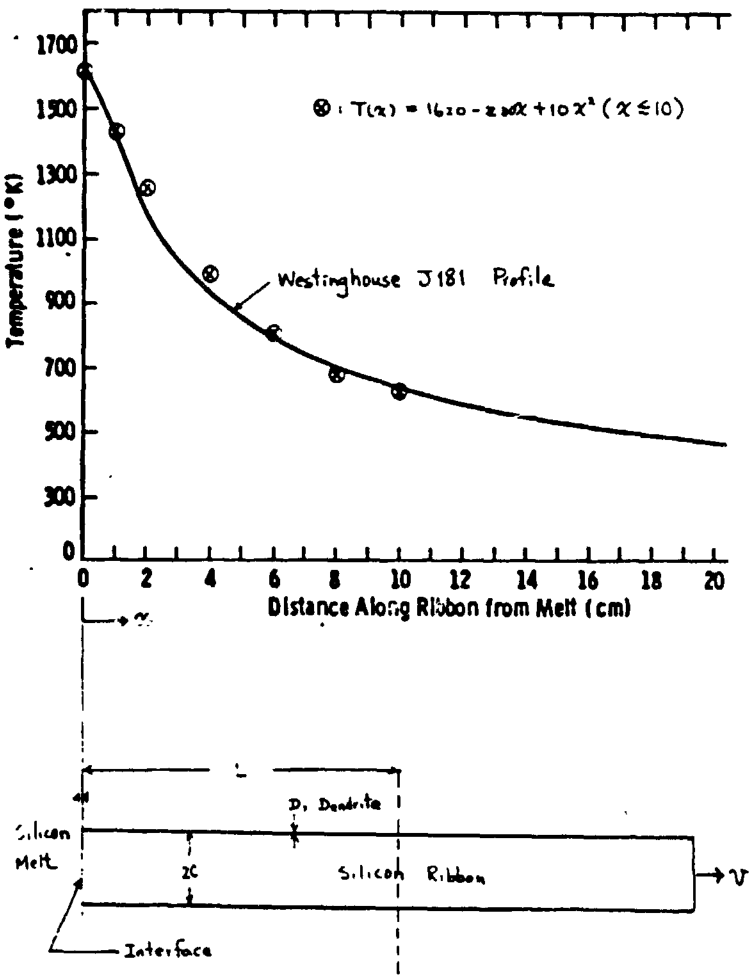
- MATERIAL PROP = $f(T, \sigma_{ij}, \epsilon_{ij}, t)$



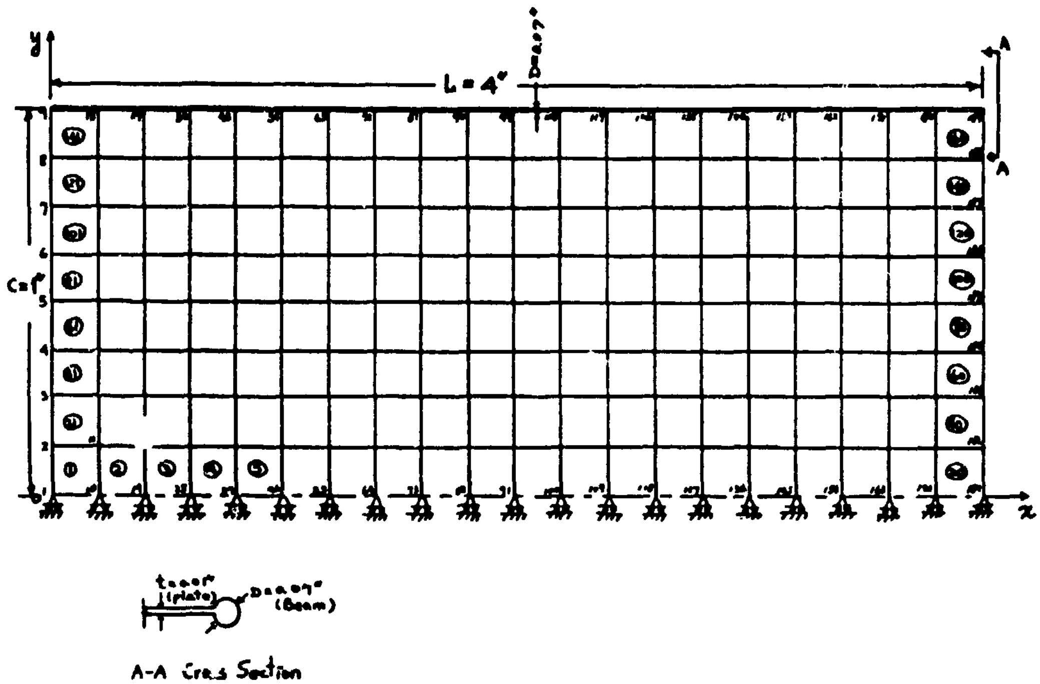
Failure Considerations

- HIGH FINAL RESIDUAL STRESS -------> HANDLING PROBLEMS
- HIGH IN-PROCESS RESIDUAL STRESS -------> DISLOCATIONS ------> LOW EFFICIENCIES
- BUCKLING -------> DEFORMED PRODUCTS -------> INSTALLATION -------> BREAKAGE

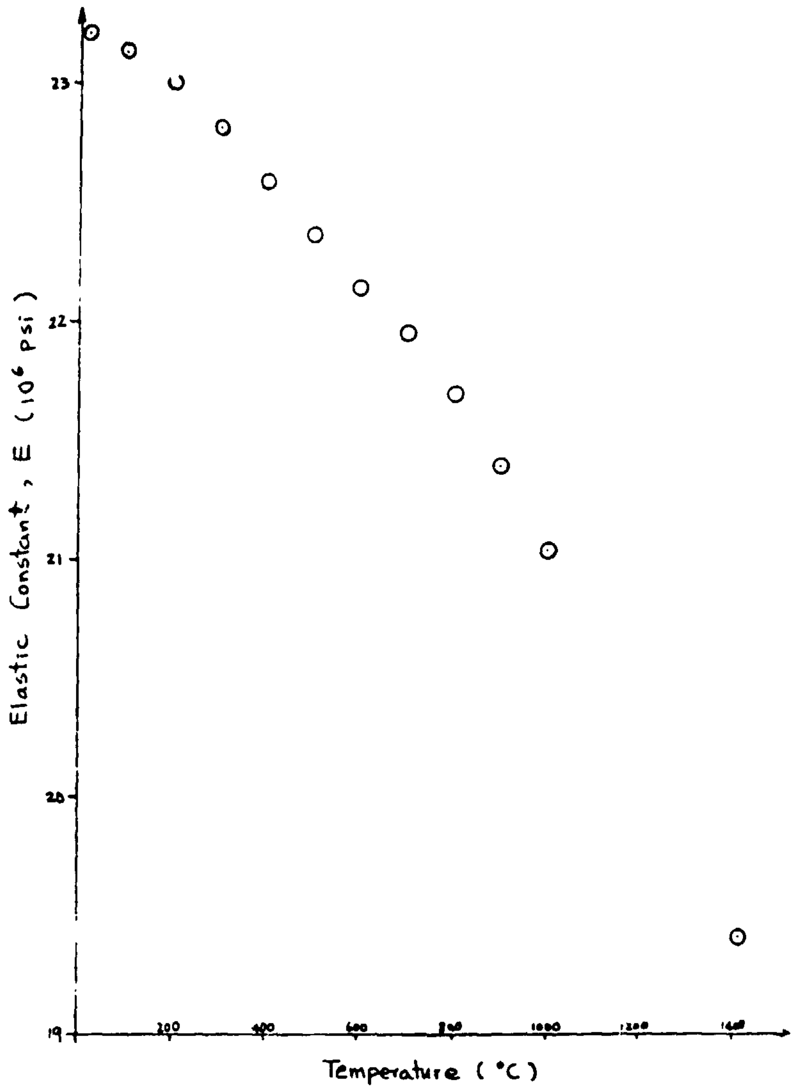
Temperature Profile



Finite Element Model of 4 × 2 in. Silicon Ribbon



Elastic Constant as a Function of Temperature (Burenkov)



Stress Contours and Their Corresponding Stress Levels

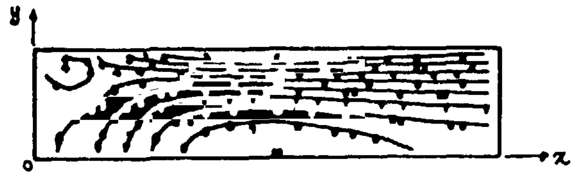


Fig. 3a X-X Normal Stresses

No.	σ_{xx} (Psi)
1	-3.017459E+03
2	-2.202389E+03
3	-1.387321E+03
4	-5.722522E+02
5	2.426163E+02
6	1.057685E+03
7	1.872953E+03
8	2.688322E+03
9	3.503099E+03
10	4.318159E+03

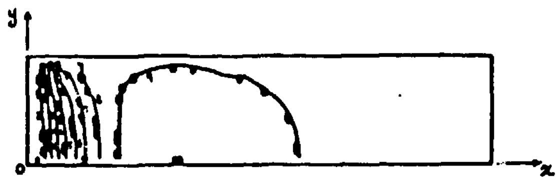


Fig. 3b Y-Y Normal Stresses

No.	σ_{yy} (Psi)
1	-1.064383E+04
2	-9.186611E+03
3	-7.729806E+03
4	-6.273180E+03
5	-4.816664E+03
6	-3.359749E+03
7	-1.903282E+03
8	-4.463157E+02
9	1.010403E+03
10	2.467187E+03

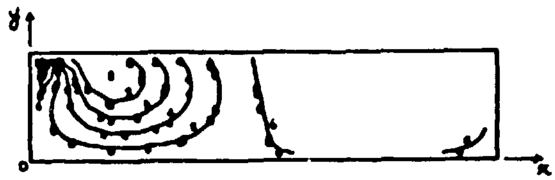


Fig. 3c X-Y Shear Stresses

No.	σ_{xy} (Psi)
1	-2.400780E+03
2	-1.914568E+03
3	-1.428297E+03
4	-9.420589E+02
5	-4.558147E+02
6	3.042651E+01
7	5.166677E+02
8	1.002929E+03
9	1.489152E+03
10	1.975391E+03

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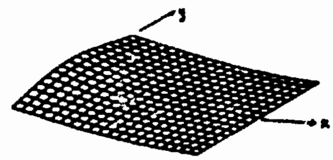
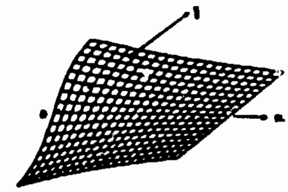
L = 4 in., c = 1 in., t = 0.01 in., D = 0.07 in.

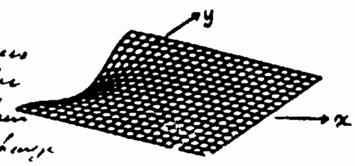


1st Mode
$\lambda_1 = 0.2126$

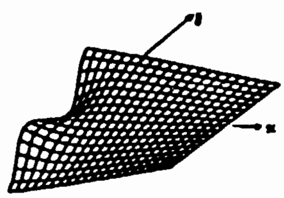


2nd Mode
$\lambda_2 = 0.2281$

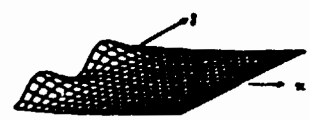
Multiplier times stress used for buckling. To obtain buckling stress, change f until $\lambda = 1.0$.



3rd Mode
$\lambda_3 = 0.3987$

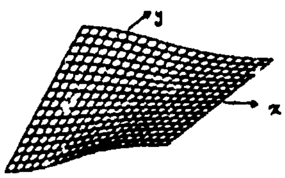


4th Mode
$\lambda_4 = 0.7289$

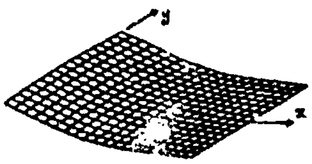


5th Mode
$\lambda_5 = 1.1649$

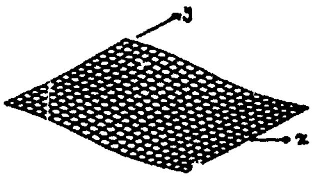
First Five Buckling Modes of EFG Ribbon (D = 0.0 in.)



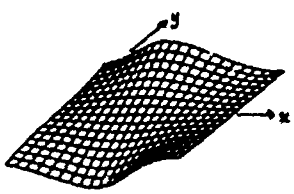
1st Mode
$\lambda_1 = 0.3632$



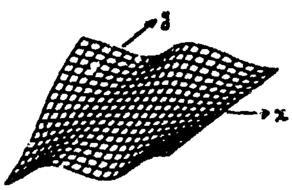
2nd Mode
$\lambda_2 = 0.3786$



3rd Mode
$\lambda_3 = 0.5142$

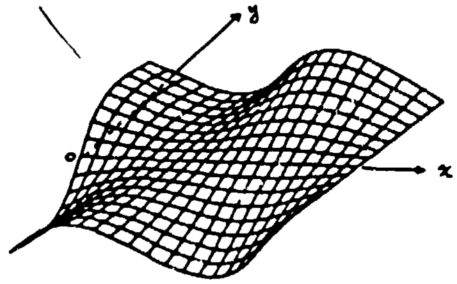


4th Mode
$\lambda_4 = 0.5479$

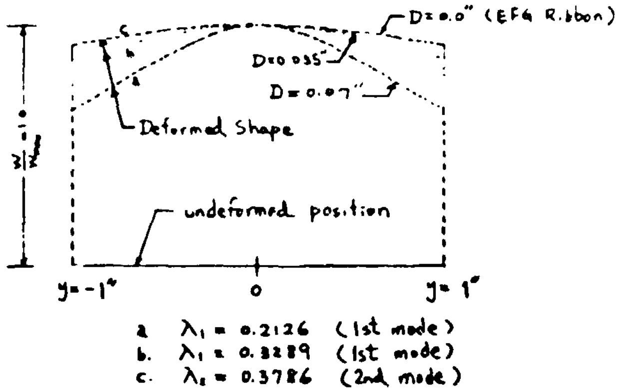


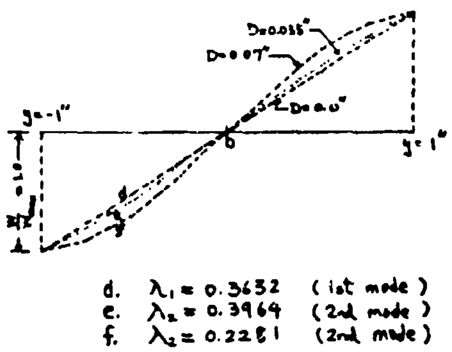
5th Mode
$\lambda_5 = 0.7762$

Buckling Mode (D = 0.035 in.)



Buckling Mode Shapes at Melt Interface (x = 0) and Their Corresponding Eigenvalues





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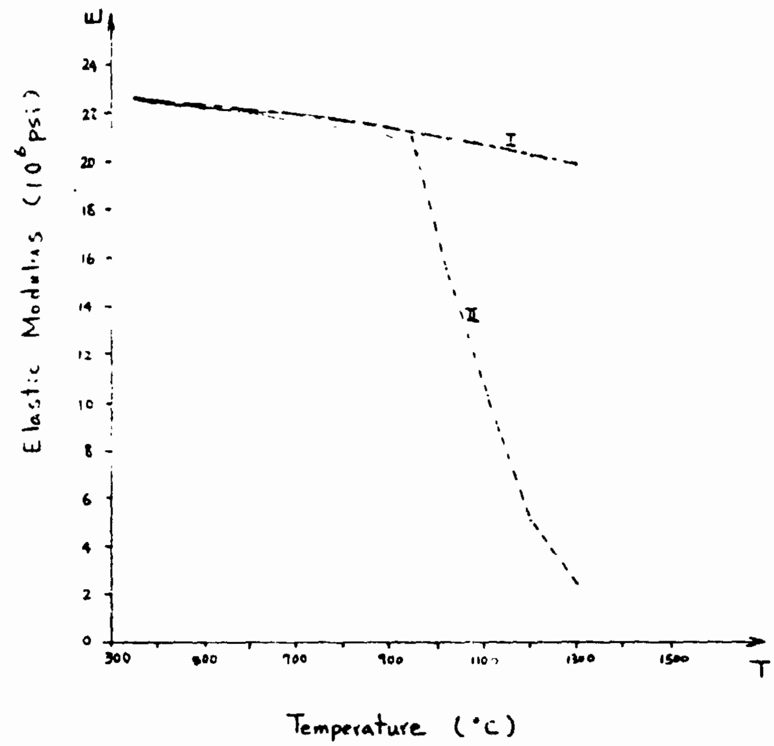
Dendrites Effect

	D = 0.07"	D = 0.035"	D = 0.0"
σ_x	-3017 psi +4318 psi	-5011 psi +3792 psi	-6043 psi +3396 psi
$\Delta\sigma_x$	7335 psi	8803 psi	9439 psi
σ_J	-10643 psi + 2467 psi	- 5990 psi + 1648 psi	- 4997 psi + 1450 psi
$\Delta\sigma_J$	13110 psi	7638 psi	6447 psi
λ_1 λ_2	0.213 0.228	0.329 0.396	0.363 0.379

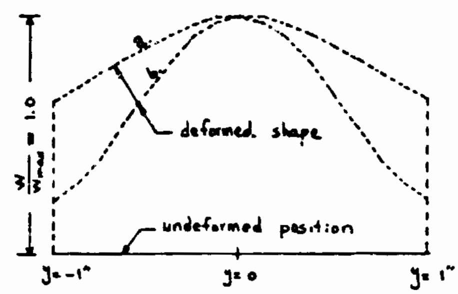
λ increases as σ_J (compression) decrease

Influence of Young's Modulus (Sylwestrowica)



	E_{I}	E_{II}
σ_{xx}	−3017 psi +4318 psi	−2666 psi +3805 psi
σ_{yy}	−10643 psi +2467 psi	−3828 psi +1818 psi
λ_1 λ_2	0.213 0.228	0.085 0.109

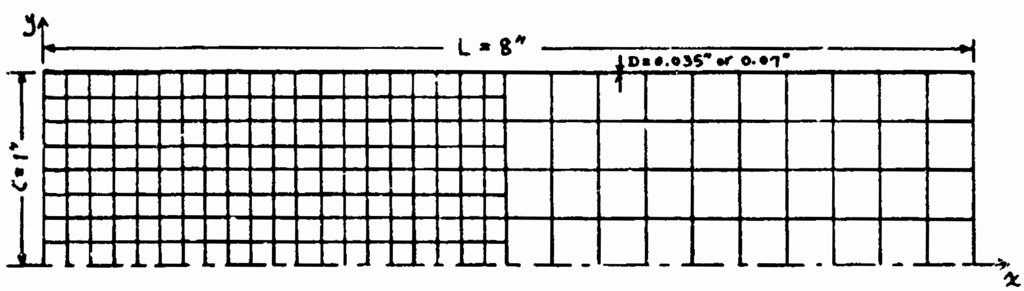
Buckling Mode Shapes at Melt interface (x = 0)
and Their Corresponding Eigenvalues



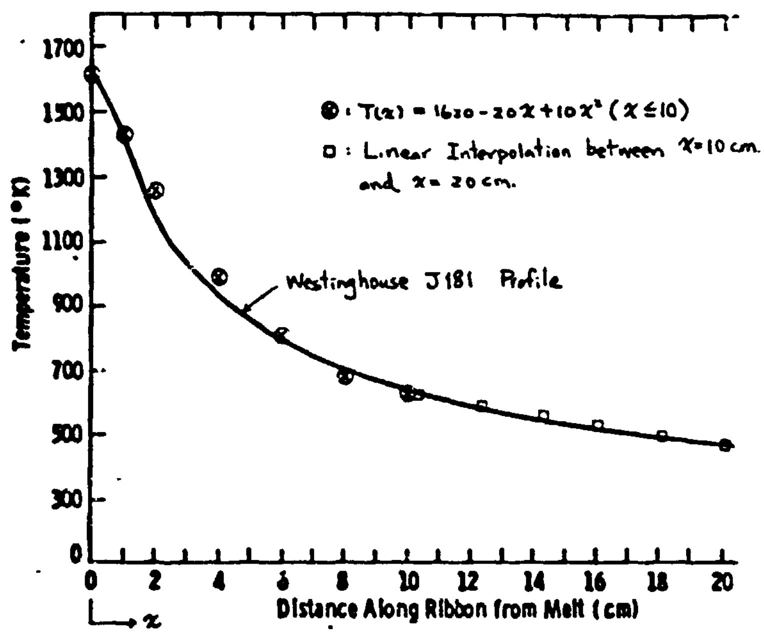
a. $\lambda_1 = 0.2126$ (model in ref. 1) E_I

b. $\lambda_1 = 0.0849$ (Current Model) E_{II}

Finite Element Model of 8 in. × 2 in. Silicon Ribbon



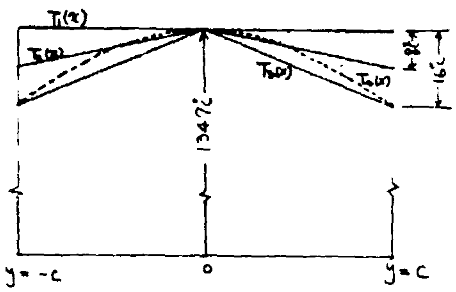
Temperature Profile



	D = 0.07"	D = 0.035"	D = 0.0"
σ_x	−3017 psi (−2967 psi) +4318 psi (+4245 psi)	−5011 psi (−5015 psi) +3792 psi (+3787 psi)	−6043 psi +3396 psi
$\Delta\sigma_x$	7335 psi	8803 psi	9439 psi
σ_y	−10643 psi (−10644 psi) +2467 psi (+2505 psi)	−5990 psi (−5994 psi) +1648 psi (+1650 psi)	−4997 psi +1450 psi
$\Delta\sigma_y$	13110 psi	7638 psi	6447 psi
λ_1	0.213 (0.147)	0.329 (0.311)	0.363
λ_2	0.228 (0.249)	0.396 (0.393)	0.379
λ_3	0.399 (0.420)	0.730 (0.707)	

λ increases as σ_y (compression) decrease

Temperature Profiles Across the Ribbon Width



Eigenvalues for Corresponding Temperature Profile Acting on a Dendritic Web (D = 0.07 in)

Mode No.	$T_1(x)$	$T_2(x,y)$	$T_3(x,y)$	$T_4(x,y)$
1st	0.2126	0.2150	0.2174	
2nd	0.2281	0.2644	0.2695	0.2705
3rd	0.3987	0.4645	0.4751	0.4751
4th	0.7289	0.7685	0.7853	

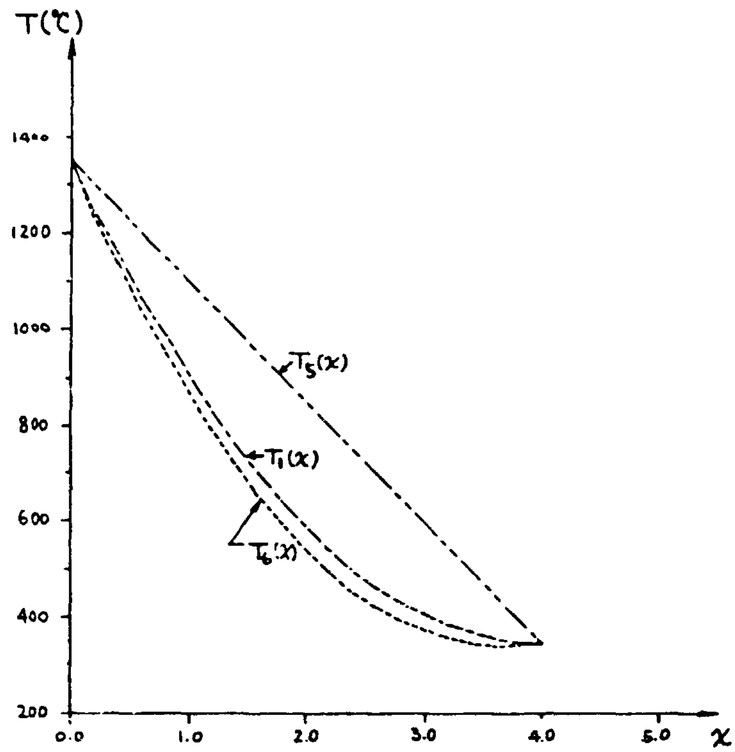
Eigenvalues of EFG Ribbon (D = 0.0 in.) Subjected to Two Temperature Profiles

Mode No.	$T_1(x)$	$T_3(x,y)$
1st	0.3632	0.4116
2nd	0.3786	
3rd	0.5142	0.5868

Eigenvalues of EFG Ribbon With Constant Material Properties

Mode No.	$T_1(x)$	$T_2(x,y)$	$T_3(x,y)$
1st	0.632	0.714	0.821
2nd	0.664	0.759	1.112

Temperature Profiles Along the Ribbon Length



Eigenvalues of a Dendritic Web (D = 0.07 in.) Subjected to Two 1-D Temperature Profiles

Mode No.	$T_1(x)$	$T_5(x)$	$T_6(x)$
1st	0.2126	0.295	0.204
2nd	0.2281	0.466	0.244
3rd	0.3987	0.929	0.429
4th	0.7289		

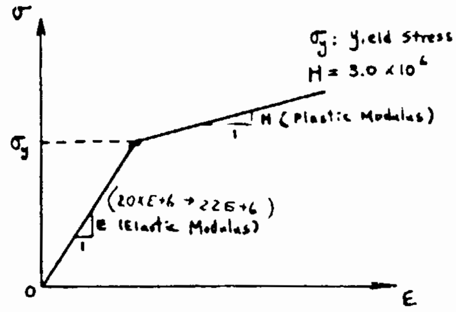
Eigenvalues of Ribbons Subjected to Linear Temperature Profile

Mode No.	Dendritic Web ($D \neq 0$) $D=0.07$; $\alpha(T)$; $E(T)$	Dendritic Web α, E are uniform ($\neq f(T)$)	EFG Ribbon $D=0.0$; $\alpha(T)$, $E(T)$
1	0.295	0.406	0.566
2	0.466	0.753	0.581
3	0.929		1.087

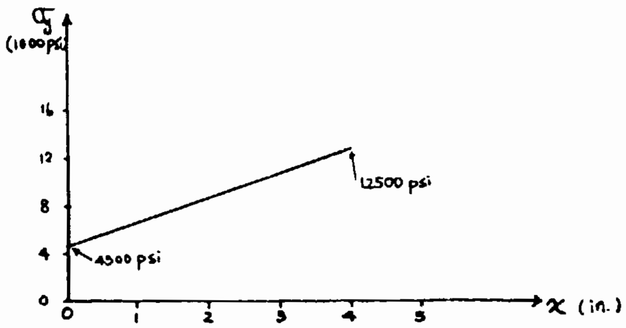
Summary: Linear Buckling Analysis

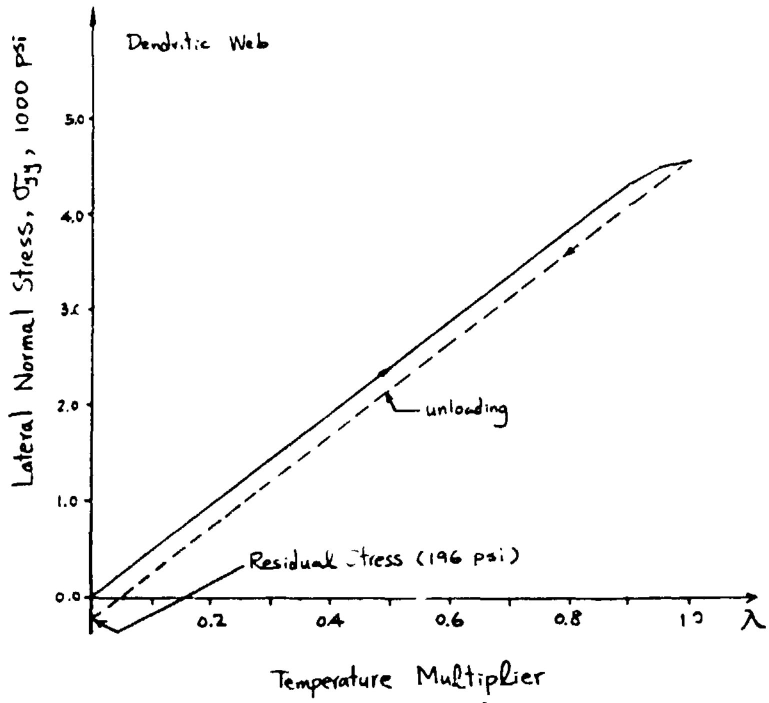
1. σ_y PLAY AN IMPORTANT PART IN THE RIBBON BUCKLING PROBLEM.
2. $\Delta\sigma_x$ IS NOT AN ADEQUATE DESIGN PARAMETER.
3. BUCKLING MODE INCLUDES BOTH BEAM TYPE AND PLATE TYPE.
4. DENDRITES AFFECT THE THERMAL STRESSES AS WELL AS THE BUCKLING ANALYSIS.
5. L = 4" MODEL PROVIDES SUFFICIENTLY GOOD RESULTS.
6. NEED MORE RELIABLE DATA OF E(T) FOR 1000°C < T < 1400°C.
7. EFFECT OF TEMPERATURE VARIATION ACROSS THE RIBBON WIDTH IS MORE SIGNIFICANT IN THE EFG RIBBON.
8. LINEAR TEMPERATURE PROFILE PROVIDES A SLIGHTLY HIGHER CRITICAL TEMPERATURE MULTIPLIER. A BETTER TEMPERATURE PROFILE SHOULD BE INVESTIGATED TO ACHIEVE ZERO STRESS (IF POSSIBLE).

Elastic-Plastic Stress-Strain Relationship

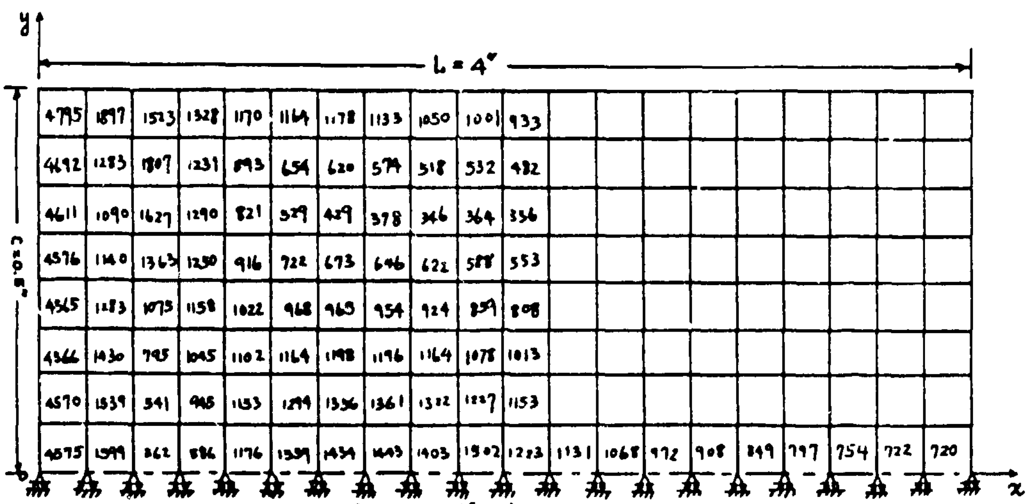


Yield Stress vs Distance From Interface





Effective Stresses of a Dendritic Web at T(x)



$\lambda_{min} = 1.02$ (Elastic Buckling)

$\lambda = 0.8$ $\quad \sigma_{e\,max} = 4244$ psi $\quad$ No Yield

$\lambda = 0.85$ $\quad \sigma_{e(141)} = 4502$ psi $\quad$ Yield on element # 141

$\lambda = 0.90$ $\quad \left\{ \begin{array}{l} \sigma_{e(121)} = 4514 \text{ psi} \\ \sigma_{e(141)} = 4590 \text{ psi} \end{array} \right.$ $\quad$ Yield on elements # 121, # 141

$\lambda = 0.95$ $\quad \sigma_{e(1)} = 4516$ psi ; $\quad \sigma_{e(121)} = 4605$ psi

$\sigma_{e(21)} = 4511$ psi ; $\quad \underset{\text{element no.}}{\sigma_{e(141)}} = 4697$ psi

$\sigma_{e(41)} = 4506$ psi

$\sigma_{e(61)} = 4503$ psi

$\sigma_{e(81)} = 4509$ psi

$\sigma_{e(101)} = 4536$ psi

SILICON SHEET

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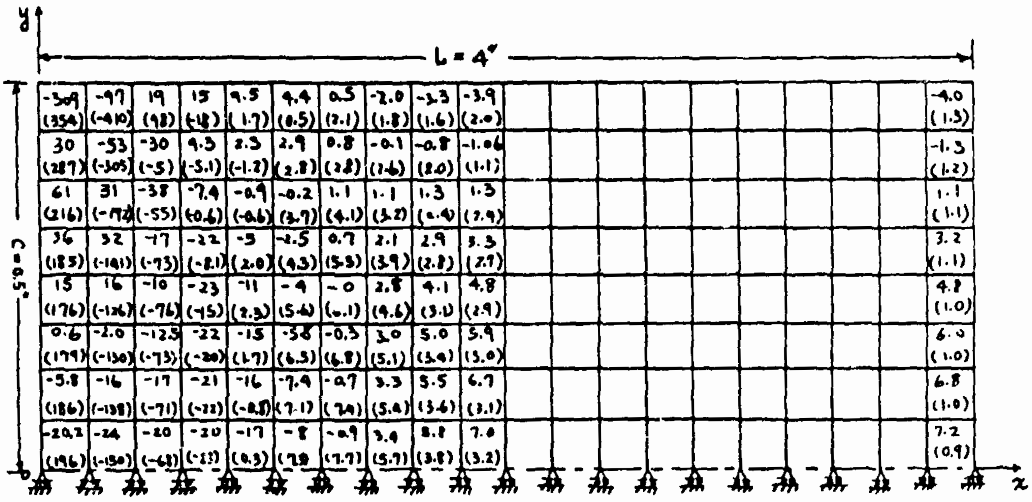
Residual Stresses on a Dendritic Web at Room Temperature (20°C)



σ_{xR}: Residual Stresses of σ_{xx} (x-x Normal Stress)

(σ_{yR}): Residual Stresses of σ_{yy} (Y-Y Normal Stress)

$D = 0.07"$
$t = 0.015"$
$C = 0.5"$
$\lambda_{min} = 1.02$

Geometrical Nonlinearity and Imperfection (5.0×10^{-4} in.)

TABLE 1. Thermal Stresses (PSI) at Each Increment ($\varepsilon = 5.0 \times 10^{-4}$ in.)

λ	Case I $\Delta\lambda = 0.05$ "SEMIQN" Method	Case II $\Delta\lambda = 0.025$ "SEMIQN" Method	Case III $\Delta\lambda = 0.025$ "ITER" Method
0.10	-515.5 -483.7	-515.5 -483.7	-515.0 -484.2
0.125		-644.5 -604.5	-644.2 -604.9
0.15	-773.6 -725.0	Numerical Unstable	-773.2 -725.5
0.175			Diverging
0.20	~~Negative Diagonal~~ Numerical Unstable		
0.225			

Creep Analysis

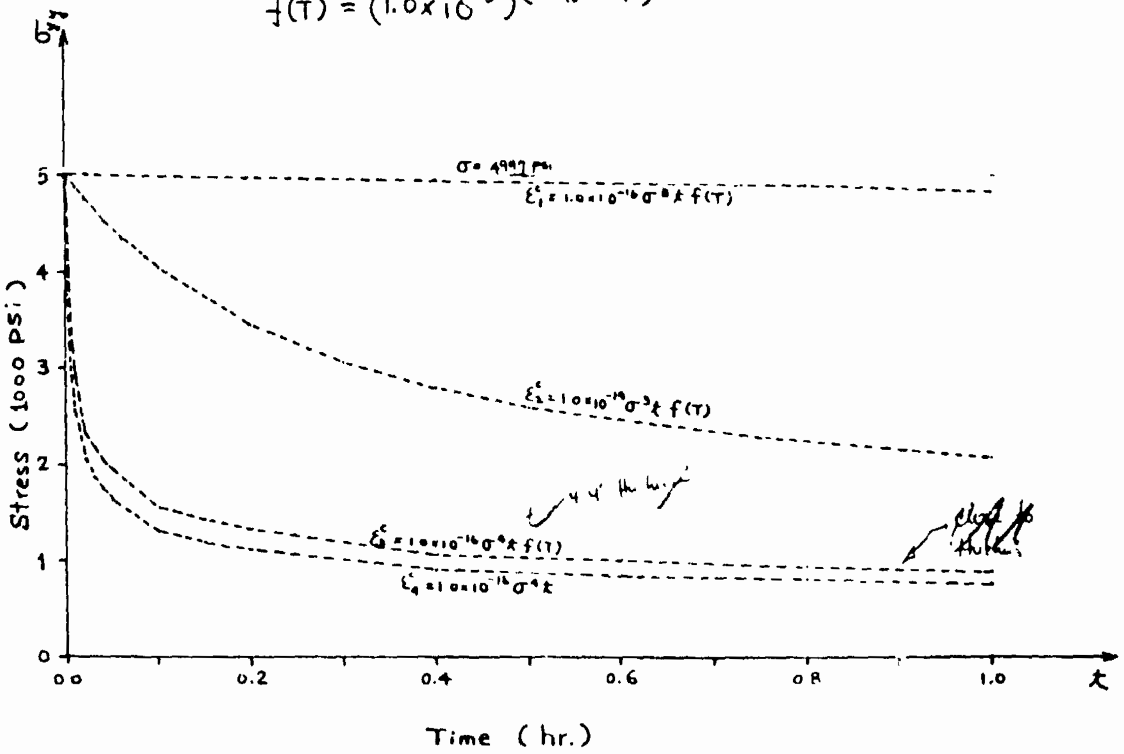
- CREEP LAW

$$\varepsilon^c = a\,\sigma^b\,c^{(T_0/T-1)}\,t$$

- RESULTS

$$\varepsilon^c = a\sigma^b C^{(\gamma_0 - 1)}$$

$$f(T) = (1.0 \times 10^{-5})^{(T/T_0 - 1)}$$



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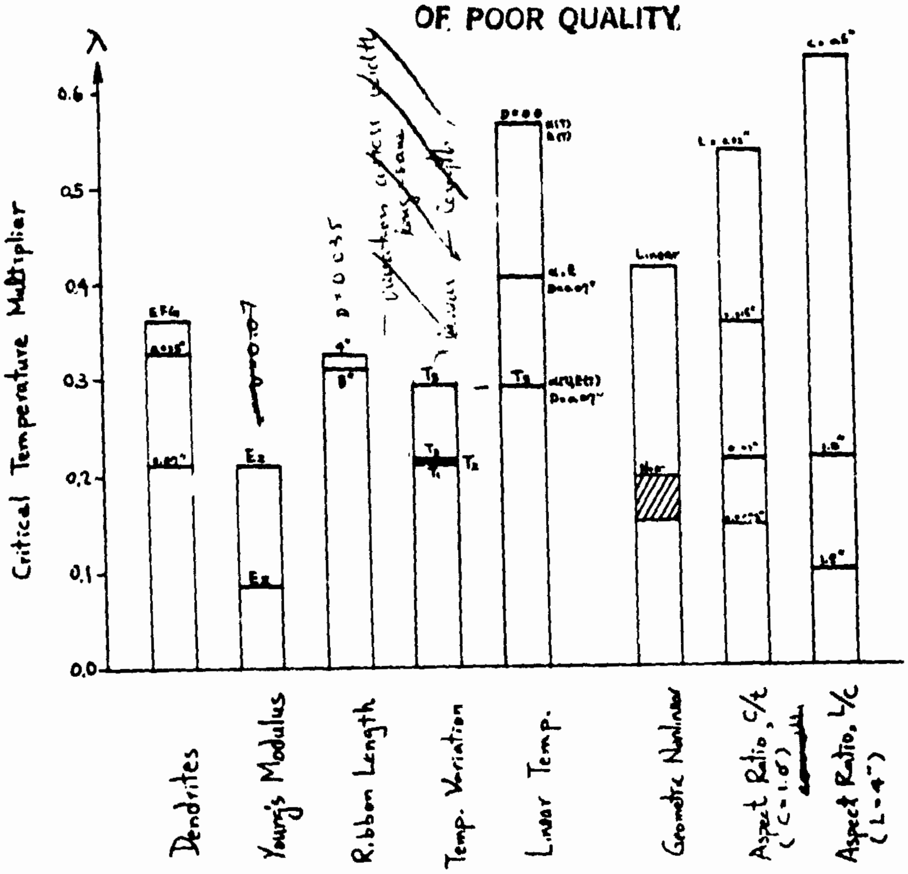
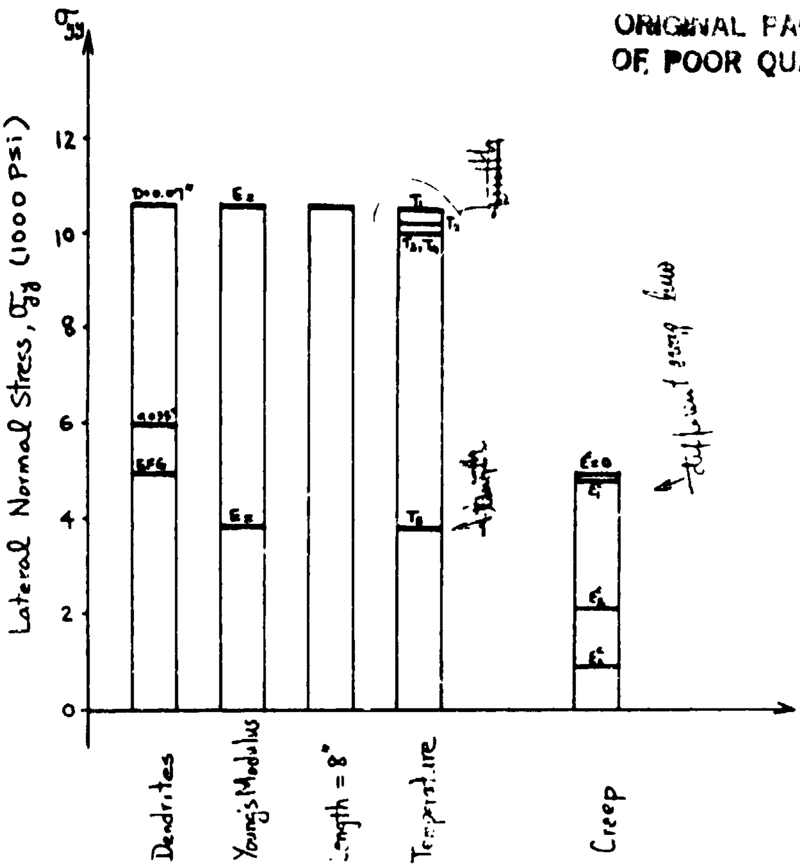
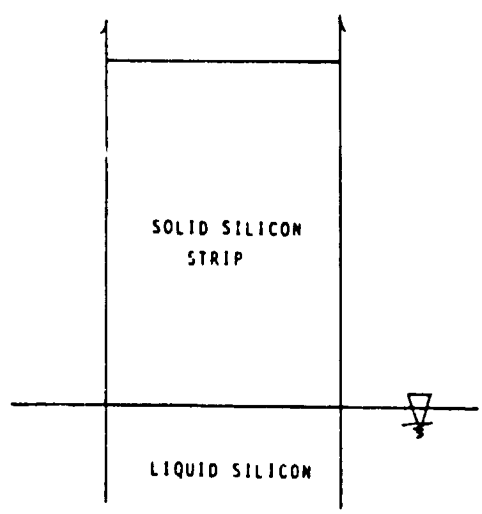




What Is the Pull-Up Process?



MATERIAL PROPERTIES ARE:

(1) HOMOGENEOUS AND ISOTROPIC (NO CRACKING, DISLOCATIONS, ETC.)

(2) MECHANICAL PROPERTIES OF SILICON BEING A FUNCTION OF TEMPERATURE ONLY (NOT A FUNCTION OF STRESS OR STRAIN)

(3) HAVING A BI-LINEAR STRESS-STRAIN CURVE (TRUE STRESS-STRAIN CAN BE USED)

(4) HAVING A PRIMARY AND A SECONDARY CREEP FUNCTION

$$\frac{d\varepsilon_{cr}}{dt} = C_1 \sigma^{C_2} \varepsilon^{C_3} e^{-\frac{C_4}{T}} + C_7 \sigma^{C_8} e^{-\frac{C_{10}}{T}}$$

$C_1, C_2, C_3, C_4, C_7, C_8, C_{10}$ = CONSTANTS
ε = EQUIVALENT STRAIN
σ = EQUIVALENT STRESS
T = TEMPERATURE (ABSOLUTE)

Methods, Criteria and Model Used in the Analysis

(1) FINITE ELEMENT METHOD

(2) ANSYS (GENERAL PURPOSE STRUCTURAL ANALYSIS PROGRAM)
2-DIMENSIONAL ISOPARAMETRIC PLANE STRESS ELEMENT
3-DIMENSIONAL ELEMENT
CAPABILITIES: PLASTICITY, CREEP, LARGE DEFORMATION, STRESS STIFFNESS, ETC.

(3) MODEL:
2" WIDE AND 4" LONG STRIP
294 D.O.F., 100 2-D PLANE STRESS QUADRALTERAL ELEMENTS
20 3-D BEAM ELEMENTS (FOR DENDRITE)

(4) CRITERIA:
TEMPERATURE IS CONSTANT LATERALLY (ACROSS THE WIDTH)