OPTIMIZATION OF AN AXIALLY COMPRESSED RING AND STRINGER STIFFENED CYLINDRICAL SHELL WITH A GENERAL BUCKLING MODAL IMPERFECTION

AIAA Paper 2007-2216

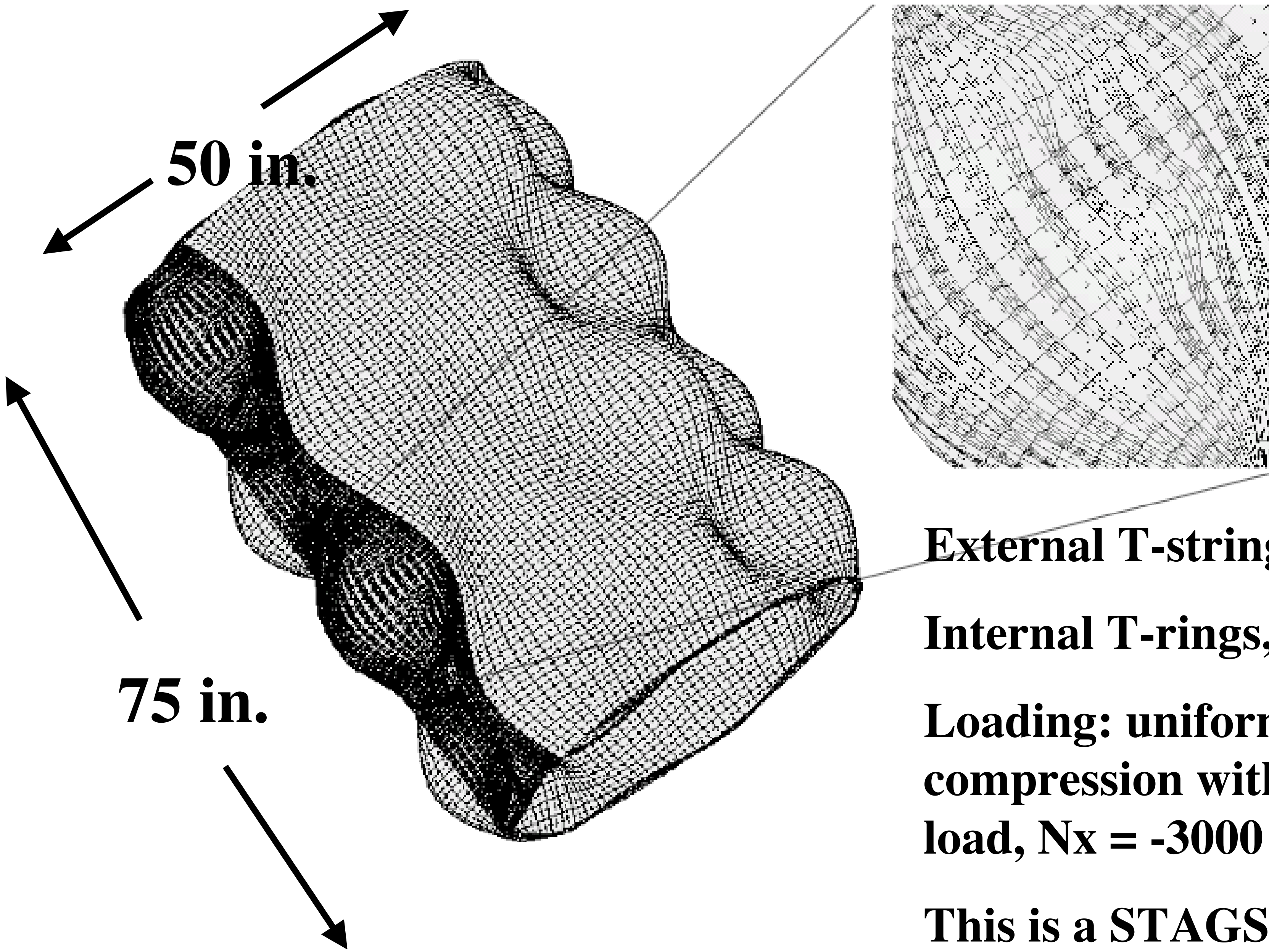
David Bushnell, Fellow, AIAA, retired

In memory of Frank Brogan, 1925 - 2006, co-developer of STAGS

Summary of talk

1. **The configuration studied here**
2. **Two effects of a general imperfection**
3. **PANDA2 and STAGS**
4. **PANDA2 philosophy**
5. **Seven cases studied here**
6. **The optimization problem**
7. **Buckling and stress constraints**
8. **Seven cases explained**
9. **How the shells fail**
10. **Imperfection sensitivity**

General buckling mode from STAGS



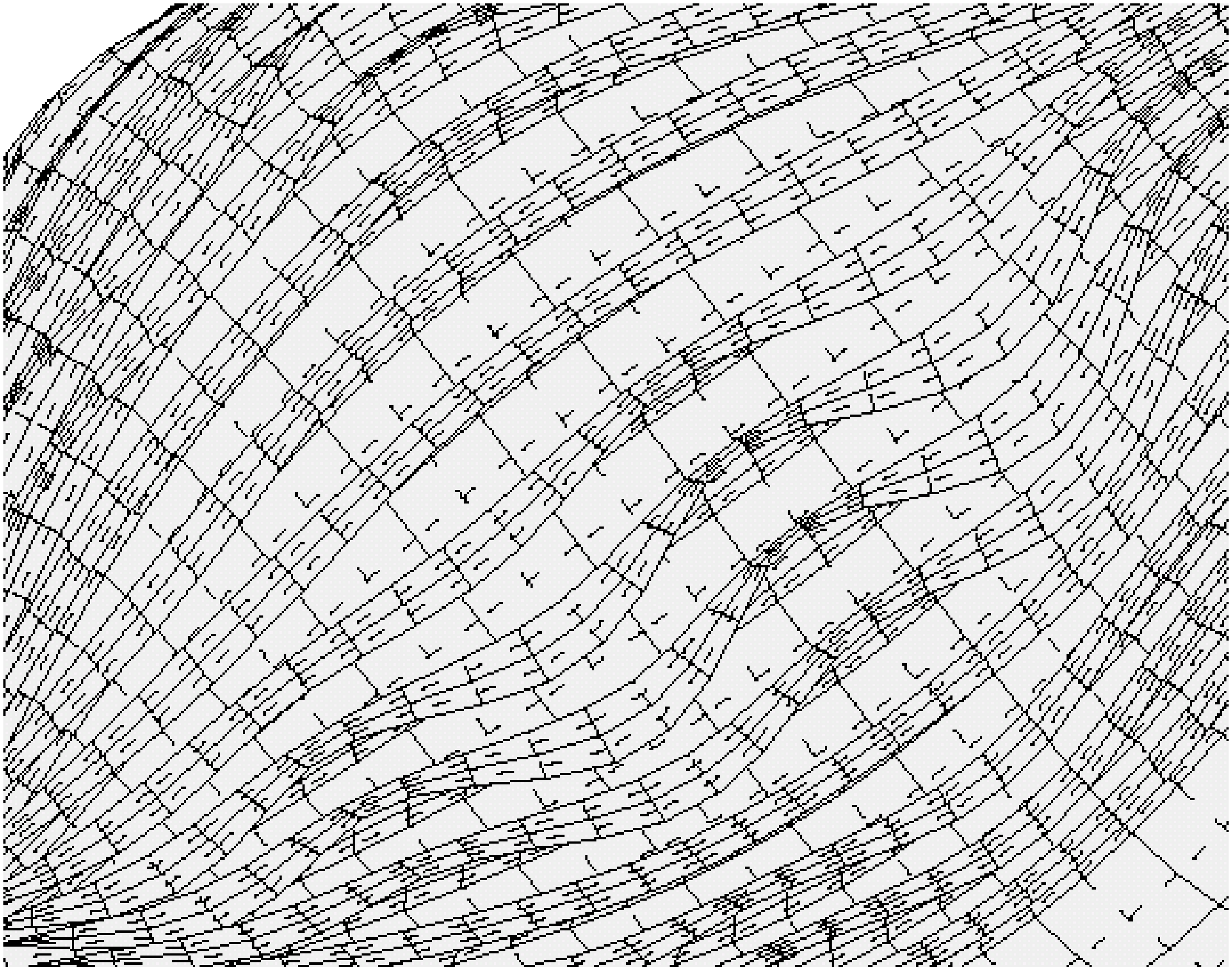
External T-stringers,

Internal T-rings,

Loading: uniform axial compression with axial load, Nx = -3000 lb/in

This is a STAGS model.

Expanded region of buckling mode



TWO MAJOR EFFECTS OF A GENERAL IMPERFECTION

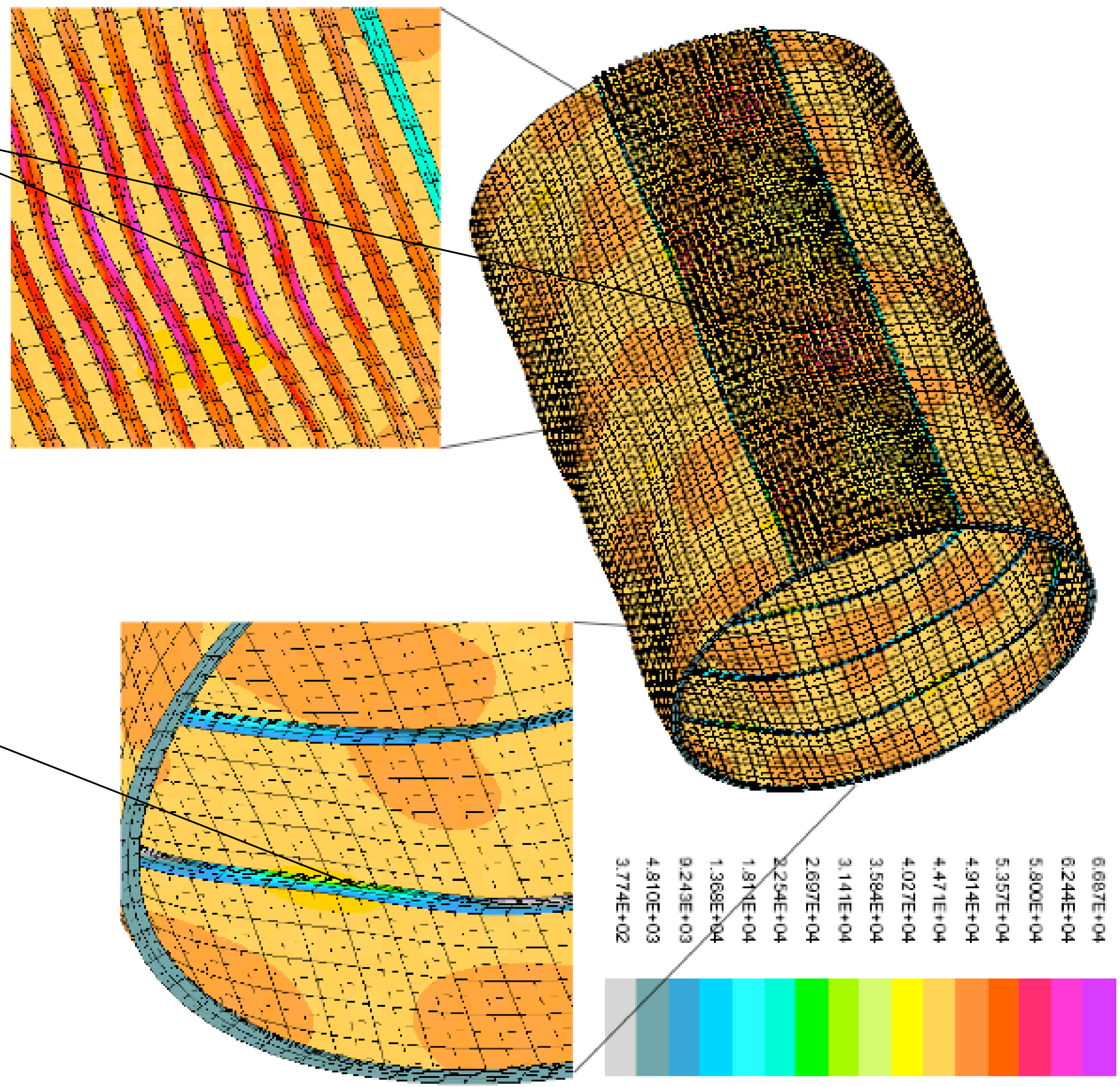
1. The imperfect shell bends when any loads are applied. This “prebuckling” bending causes **redistribution of stresses** between the panel skin and the various segments of the stringers and rings.

2. The **“effective” radius of curvature** of the imperfect and loaded shell is larger than the nominal radius: **“flat” regions develop**.

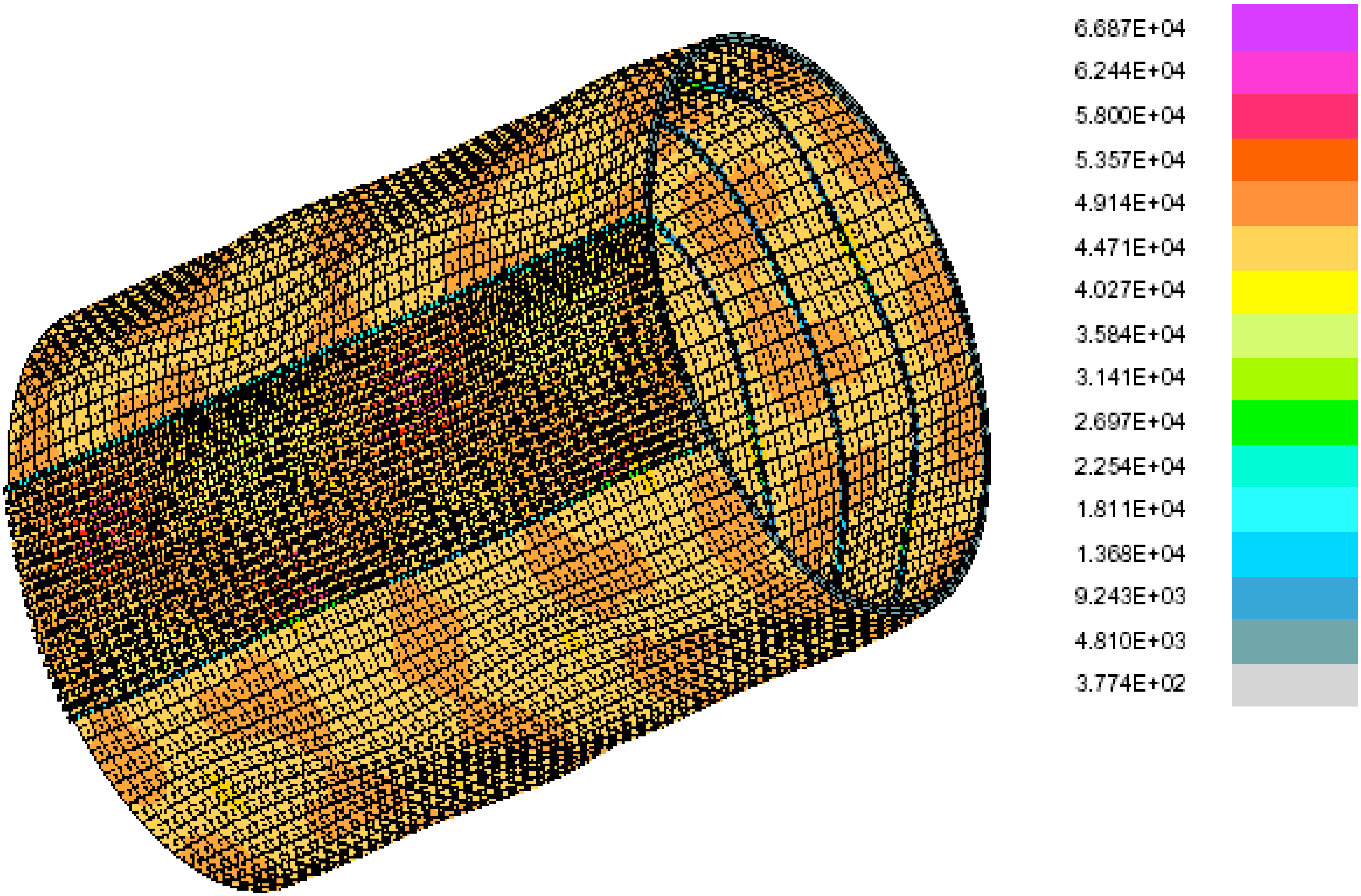
Loaded imperfect cylinder

Maximum stress, sbar(max) =66.87 ksi

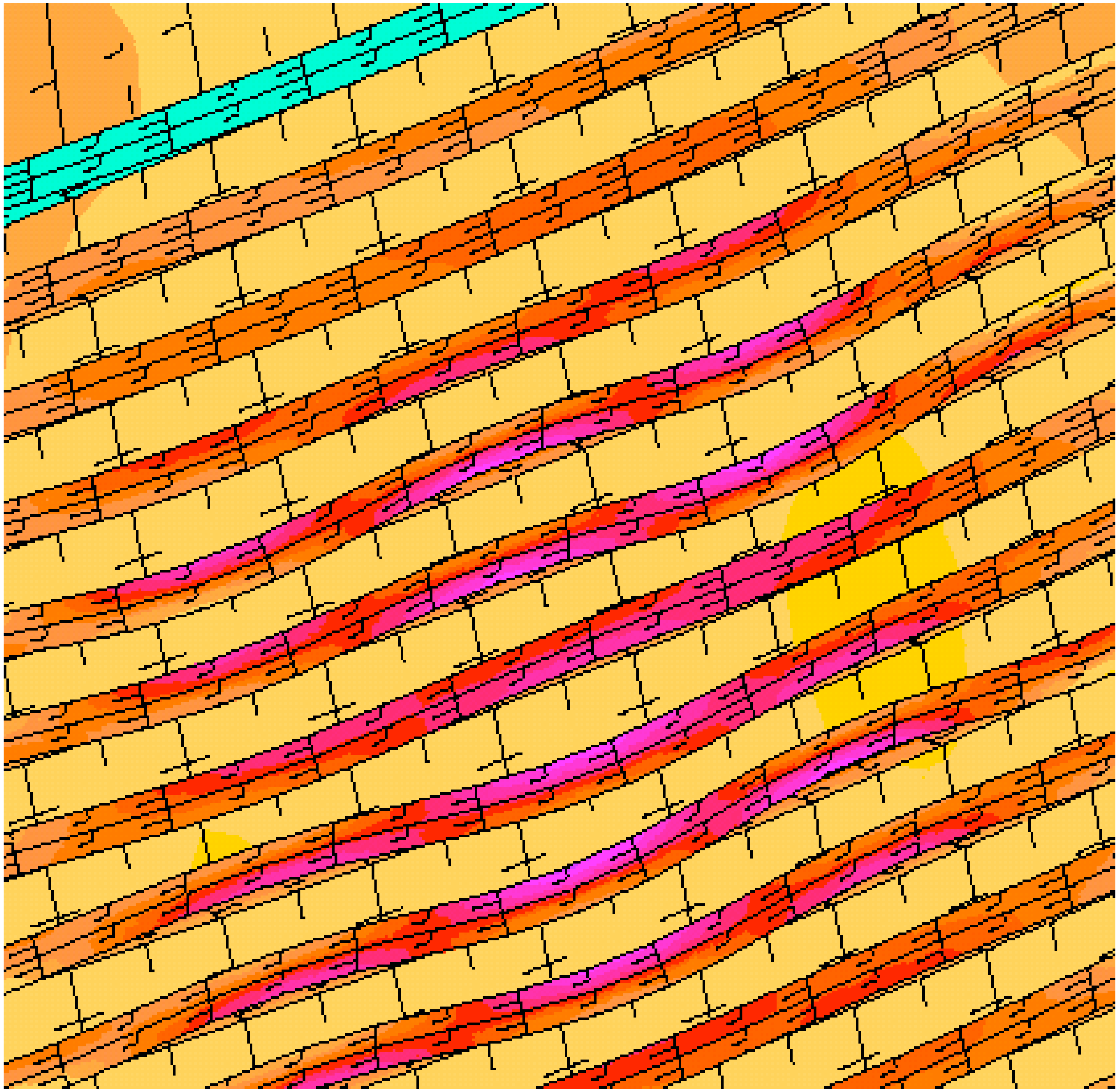
“Flat” region



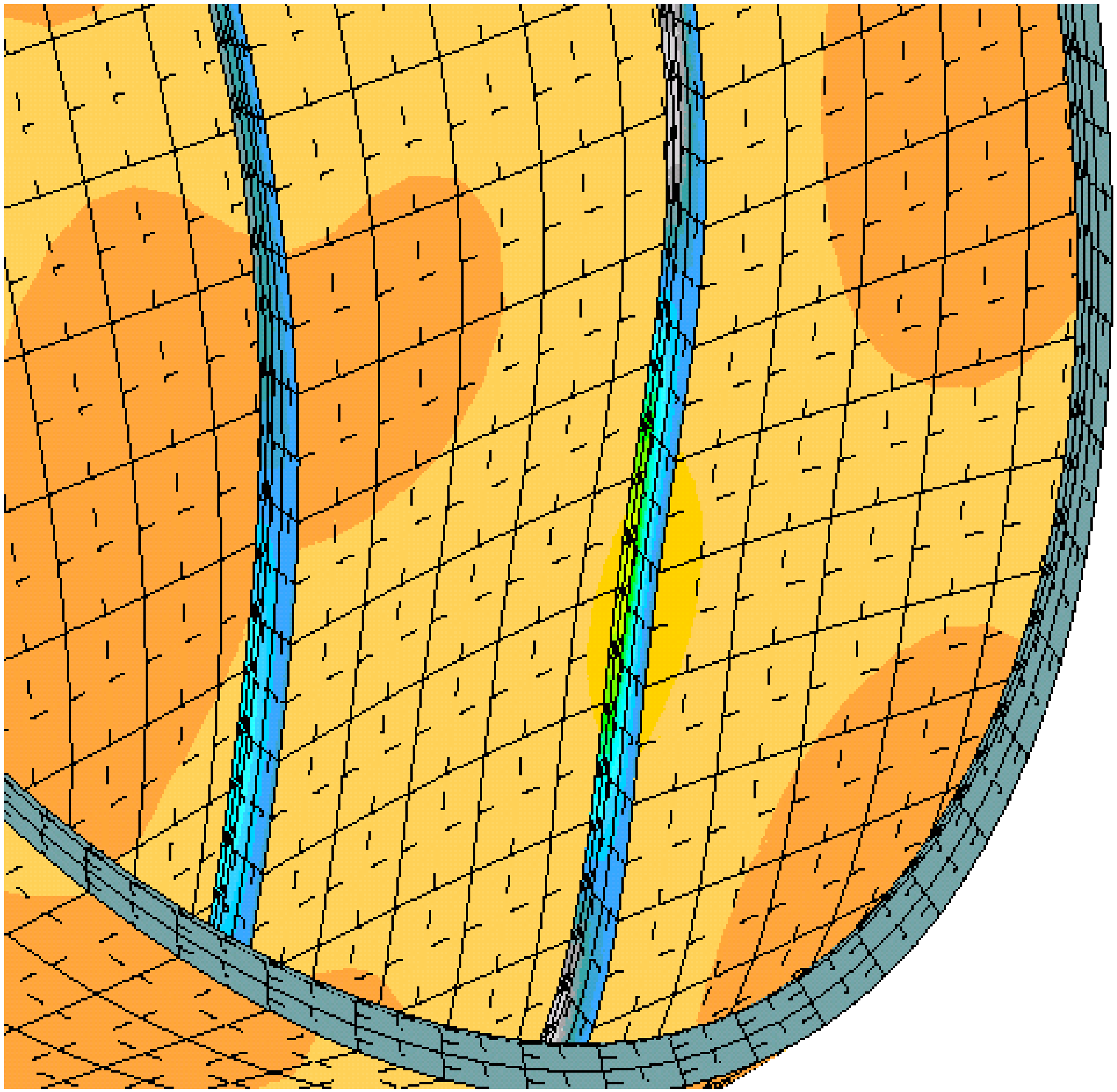
The entire deformed cylinder



The area of maximum stress



The “flattened” region



Computer programs **PANDA2** and **STAGS**

PANDA2 optimizes ring and stringer stiffened flat or cylindrical panels and shells made of laminated composite material or simple isotropic or orthotropic material. The shells can be perfect or **imperfect** and can be loaded by up to five combinations of **Nx, Ny Nxy**.

STAGS is a general-purpose program for the nonlinear elastic or elastic-plastic static and dynamic analyses. **I used STAGS to check the optimum designs obtained by PANDA2.**

PHILOSOPHY OF PANDA2

1. **PANDA2** obtains optimum designs through the use of **many relatively simple models**, each of which yields **approximate** buckling load factors (eigenvalues) and stresses.
2. Details about these models are **given in previous papers**. Therefore, they are **not repeated here**.
3. **"Global" optimum designs** can be obtained reasonably quickly and are not overly unconservative or conservative.
4. Because of the approximate nature of PANDA2 models, optimum designs obtained by **PANDA2** should be **checked** by the use of a general-purpose finite element computer program.
5. **STAGS** is a good choice because PANDA2 automatically generates input data for STAGS, and **STAGS has excellent reliable nonlinear capabilities.**

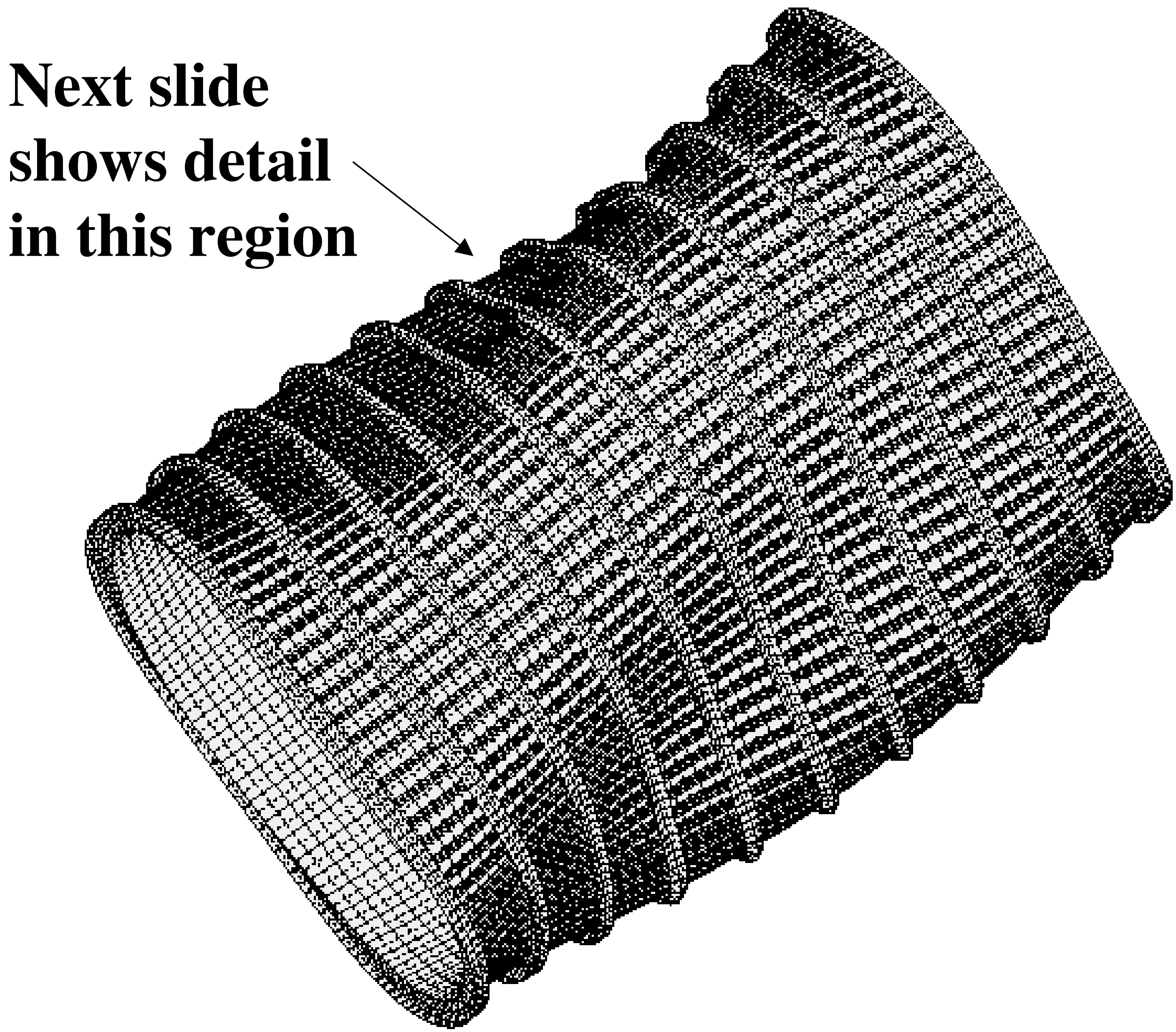
Example of PANDA2 philosophy

PANDA2 computes general buckling **from a simple closed-form model in which the stringers and rings are "smeared out"** as prescribed by Baruch and Singer (1963). [Bushnell (1987)]

Correction factors (knockdown factors) are computed to compensate for the inherent unconservativeness of this "smeared" model: one knockdown factor for "smearing" the stringers and another knockdown factor for "smearing" the rings.

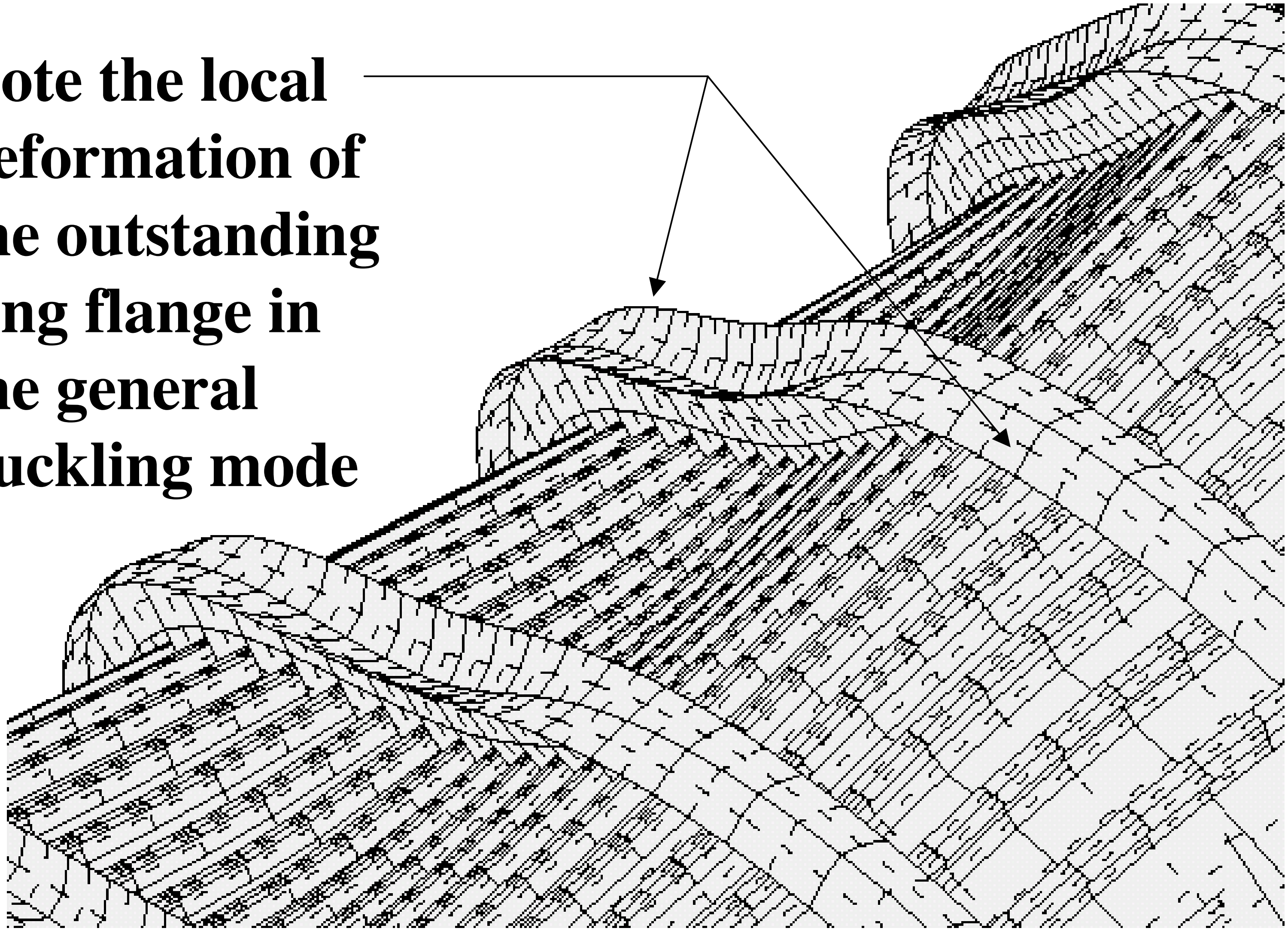
The next several slides demonstrate **why a knockdown factor is needed** to compensate for the inherent unconservativeness of "smearing" the rings and **how this knockdown factor is computed**.

A general buckling mode from STAGS

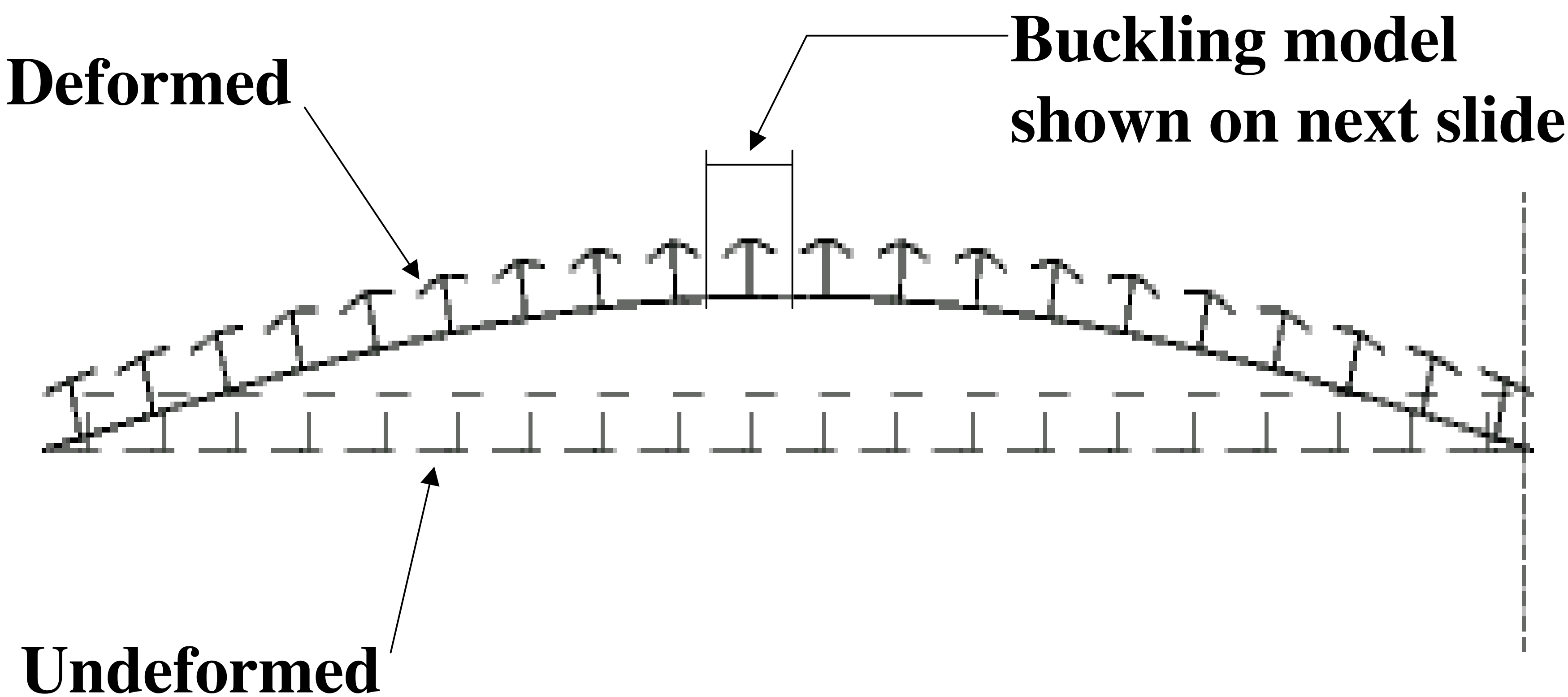


Detail showing local/global deformation in STAGS model

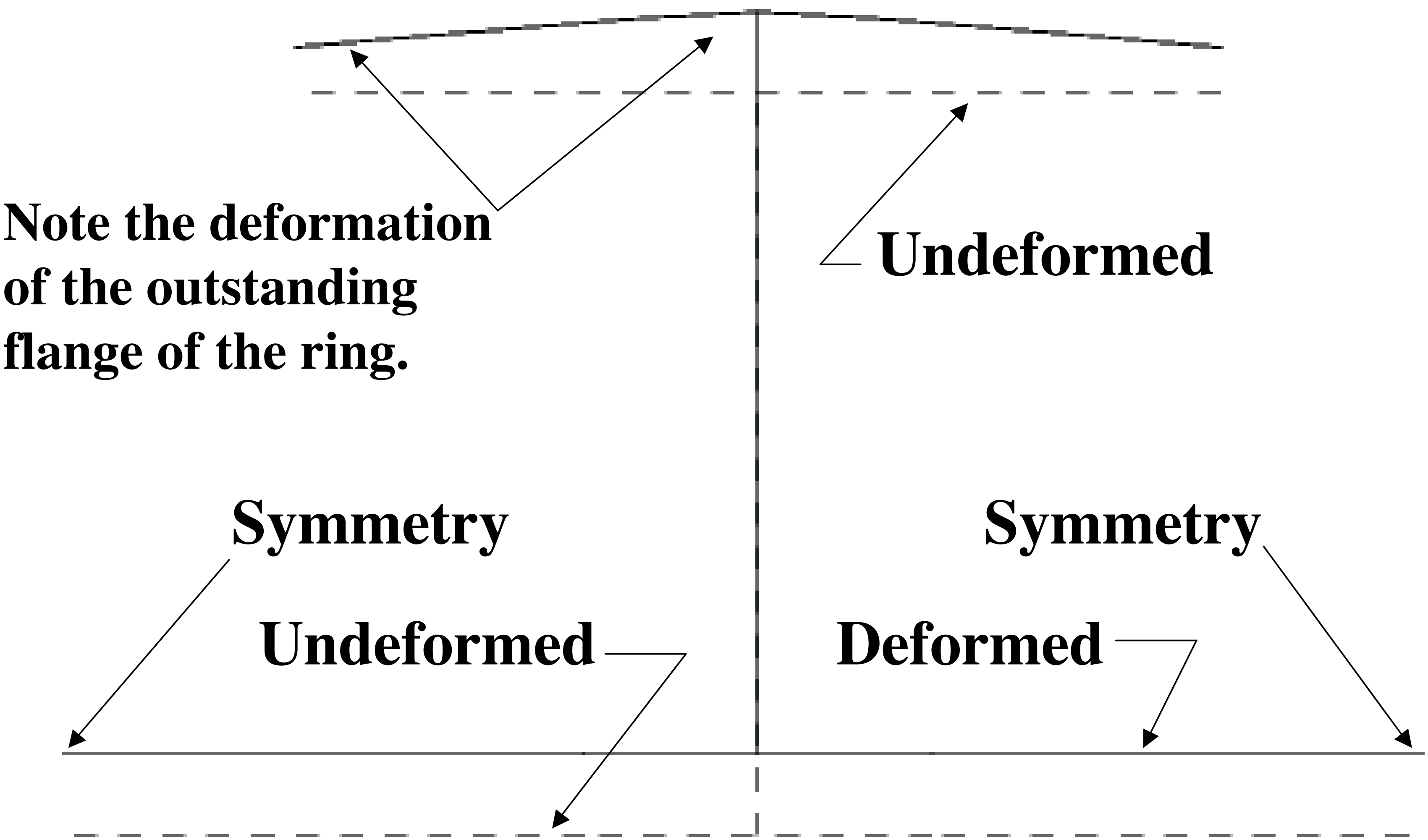
Note the local deformation of the outstanding ring flange in the general buckling mode



The same general buckling mode from BIGBOSOR4 (Bushnell, 1999). n = 3 circumferential waves



Approximate BIGBOSOR4 model of general buckling, n = 3



Knockdown factor to compensate for inherent unconservativeness of "smearing" rings

Ring knockdown factor =

(Buckling load from the BIGBOSOR4 model)/

("Classical" ring buckling formula)

"Classical" ring buckling formula= $(n^2 - 1)\ EI/r^3$

SEVEN PANDA2 CASES IN TABLE 4 OF THE PAPER

Case 1: perfect shell, “no Koiter”, ICONSV=1

Case 2: imperfect, “no Koiter”, yes change imperf., ICONSV=-1

Case 3: imperfect, “no Koiter”, yes change imperf., ICONSV= 0

Case 4: imperfect, “no Koiter”, yes change imperf., ICONSV =1

Case 5: imperfect, “yes Koiter”, yes change imperf., ICONSV=1

Case 6: as if perfect, “no Koiter”, Nx=-6000 lb/in, ICONSV= 1

Case 7: imperfect, “no Koiter”, no change imperf., ICONSV= 1

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4. **PANDA2 philosophy**
5. **Seven cases studied here**
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7. **Buckling and stress constraints**
8. **Seven cases explained**
9. **How the shells fail**
10. **Imperfection sensitivity**

Decision variables for PANDA2 optimization

Stringer spacing **B(STR),** Ring spacing **B(RNG),** Shell skin thickness **T1(SKIN)**

T-stringer web height **H(STR)** and outstanding flange width **W(STR)**

T-stringer web thickness **T2(STR)** and outstanding flange thickness **T3(STR)**

T-ring web height **H(RNG)** and outstanding flange width **W(RNG)**

T-ring web thickness **T4(RNG)** and outstanding flange thickness **T5(RNG)**

OBJECTIVE = MINIMUM WEIGHT

Global optimization: PANDA2

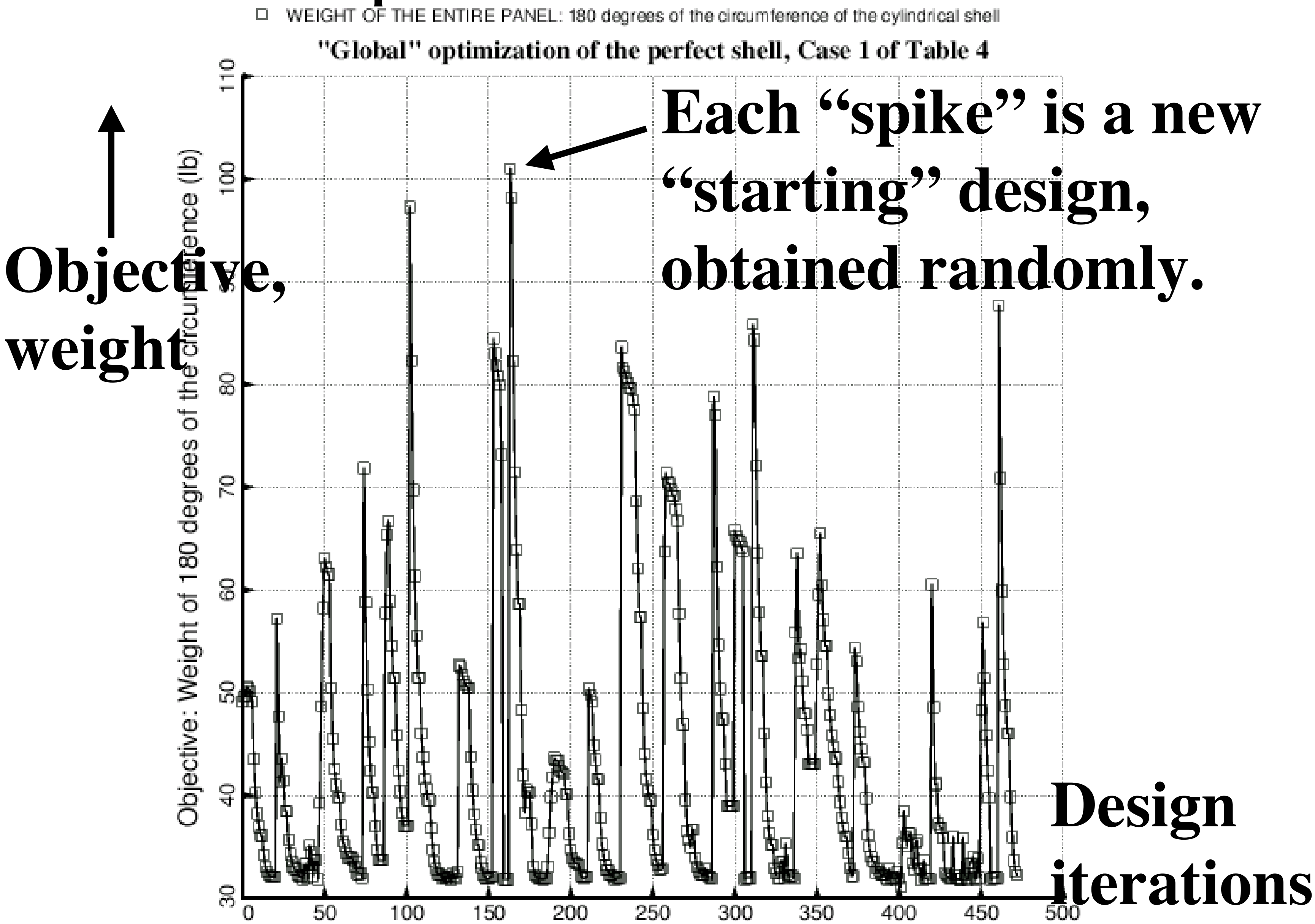


FIG. 3 Design iterations during the first SUPEROPT: Case 1, Table 4

CONSTRAINT CONDITIONS

Five classes of constraint conditions:

1. Upper and lower bounds of decision variables

2. Linking conditions

3. Inequality constraints

4. Stress constraints

5. Buckling constraints

DEFINITIONS OF MARGINS

Buckling margin= (buckling constraint) -1

(buckling constraint) =

(buckling load factor)/(factor of safety)

Stress margin = (stress constraint) - 1.0

(stress constraint) = (allowable stress)/

[(actual stress)x(factor of safety)]

TYPICAL BUCKLING MARGINS

1. Local buckling from discrete model

2. Long-axial-wave bending-torsion buckling

3. Inter-ring buckling from discrete model

4. Buckling margin, stringer segment 3

5. Buckling margin, stringer segment 4

6. Buckling margin, stringer segments 3 & 4 together

7. Same as 4, 5, and 6 for ring segments

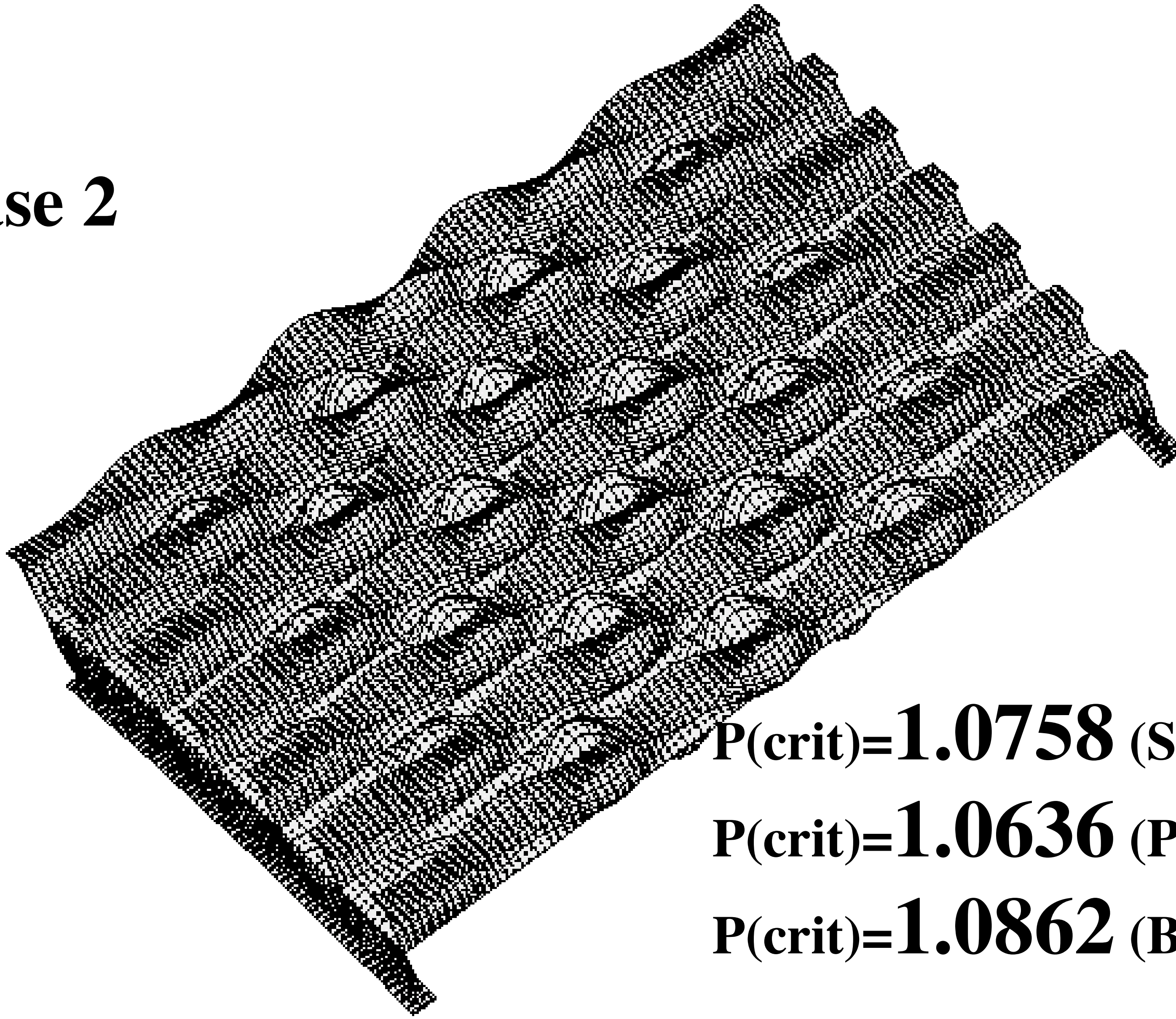
8. General buckling from PANDA-type model

9. General buckling from double trig. series expansion

10. Rolling only of stringers; of rings

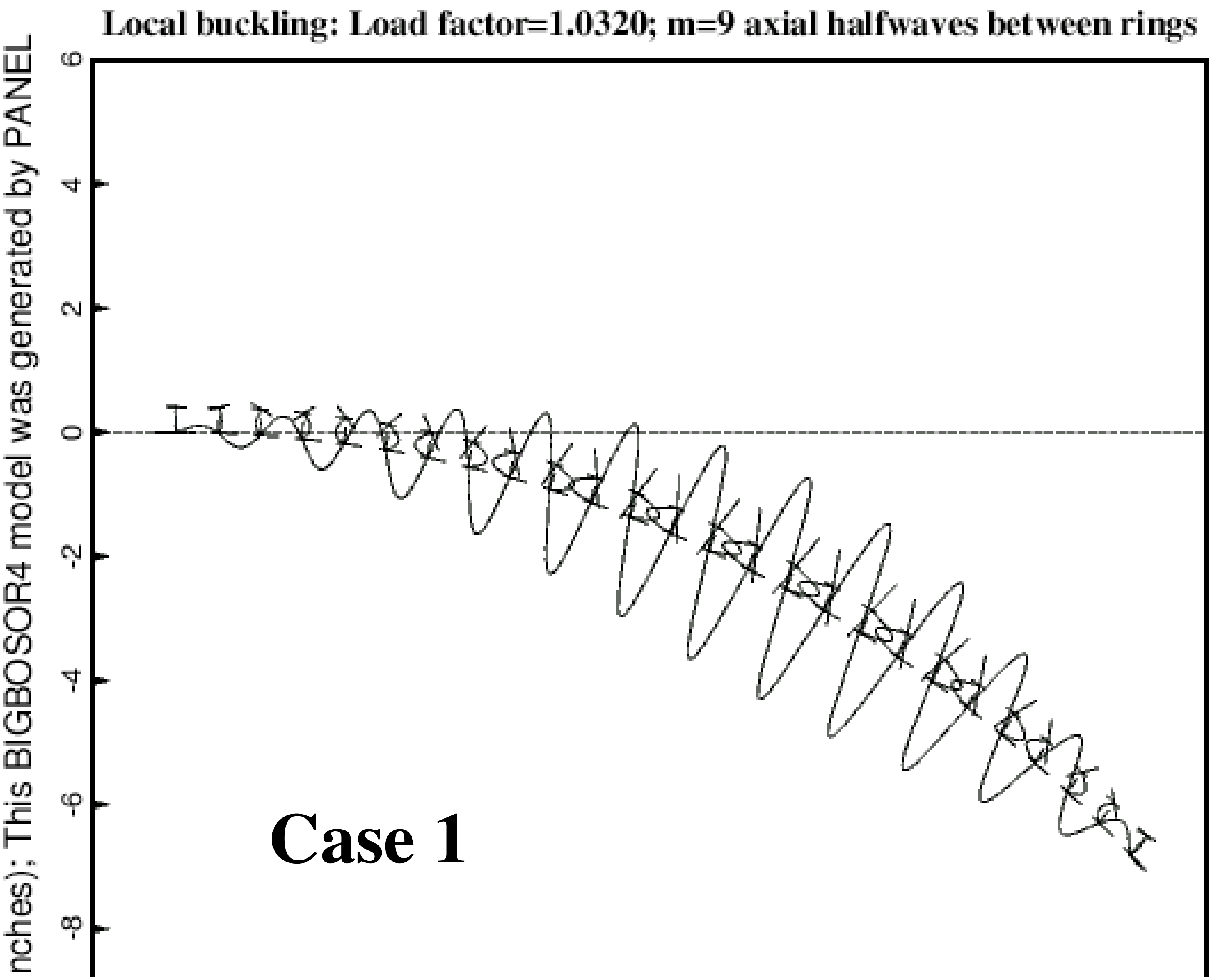
Example of local buckling: STAGS

Case 2



P(crit)=1.0758 (STAGS)
P(crit)=1.0636 (PANDA2)
P(crit)=1.0862 (BOSOR4)

Example of local buckling: BIGBOSOR4

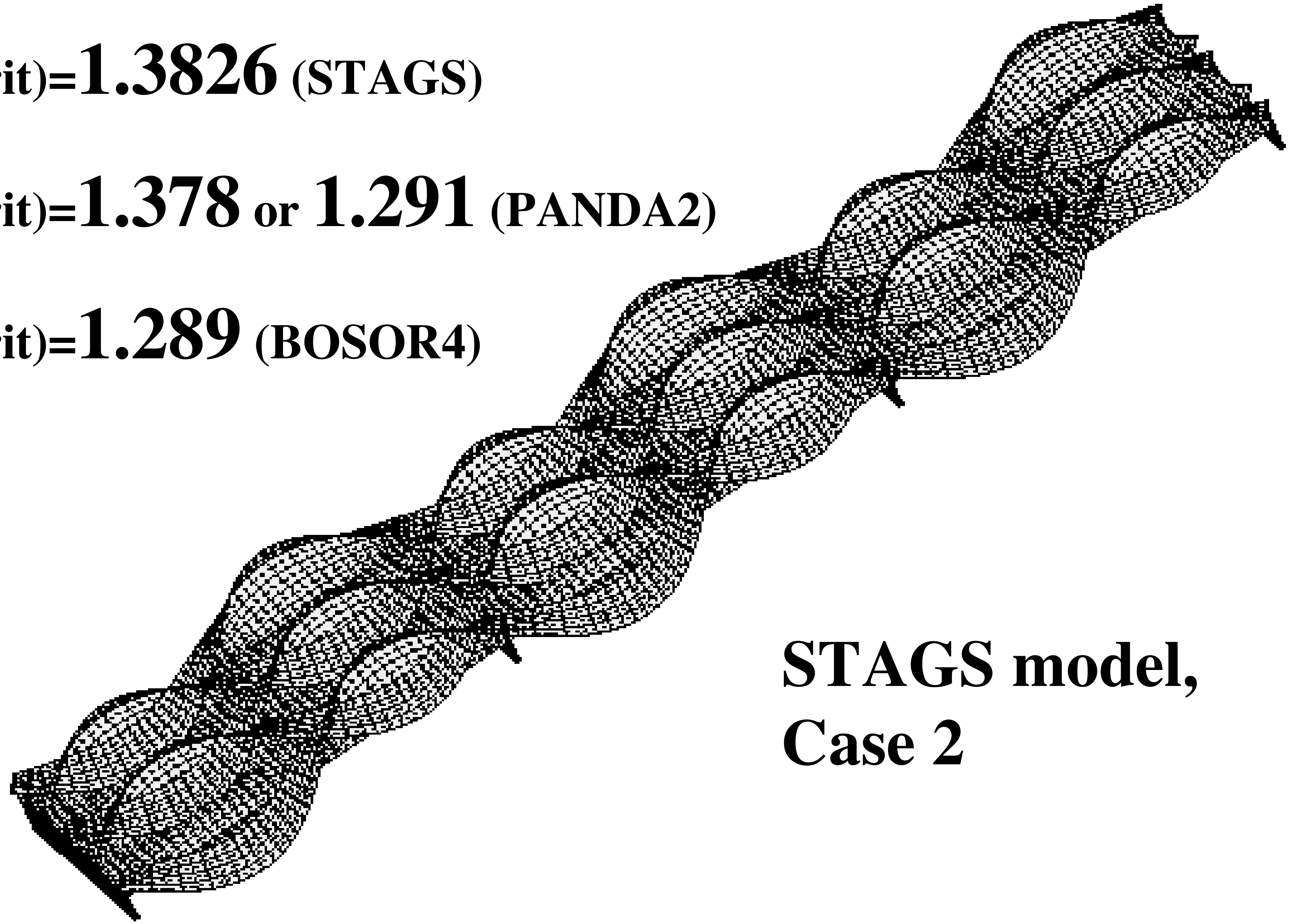


Example of bending-torsion buckling

P(crit)=1.3826 (STAGS)

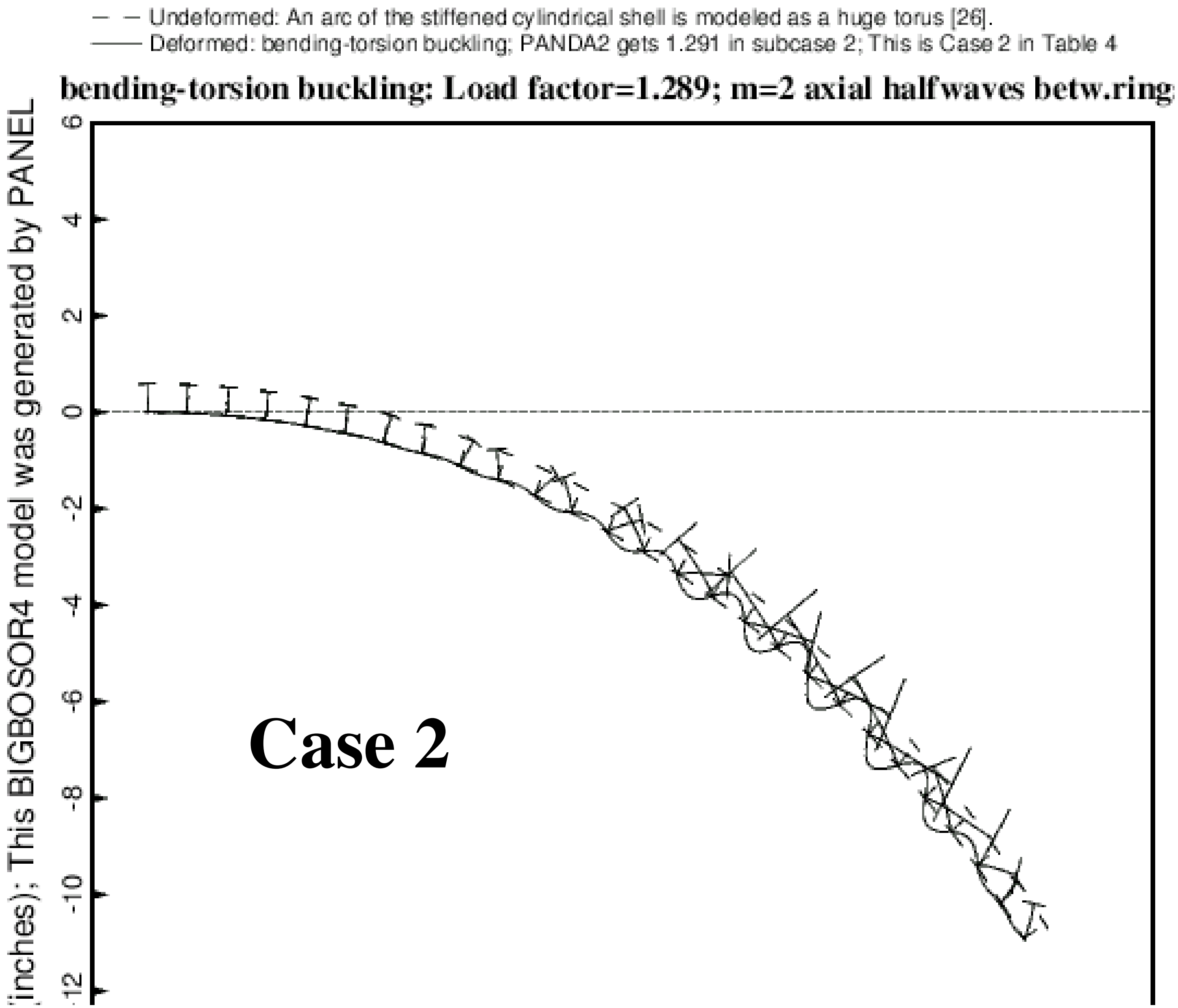
P(crit)=1.378 or 1.291 (PANDA2)

P(crit)=1.289 (BOSOR4)



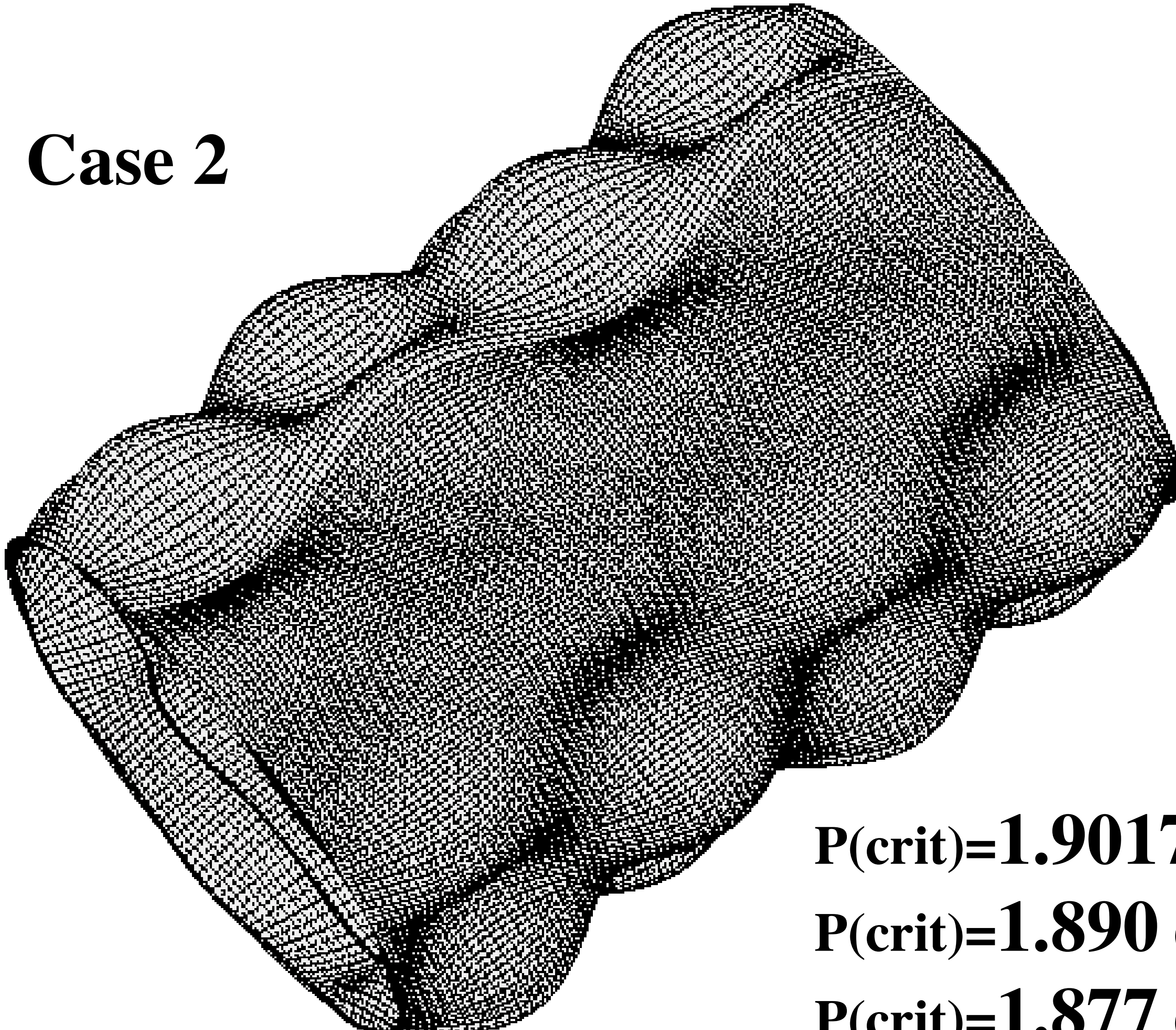
STAGS model, Case 2

Bending-torsion buckling: BIGBOSOR4



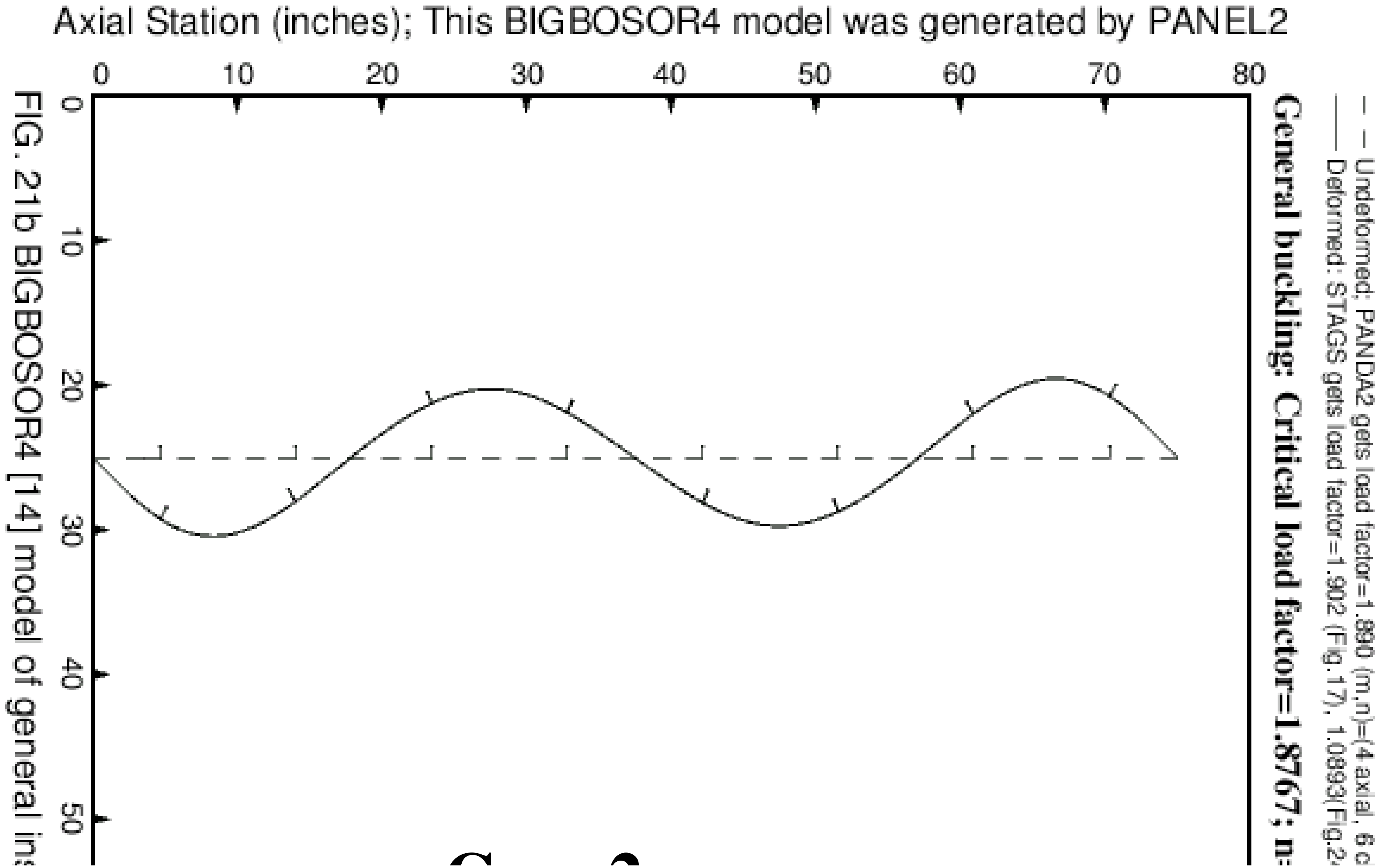
Example of general buckling: STAGS

Case 2

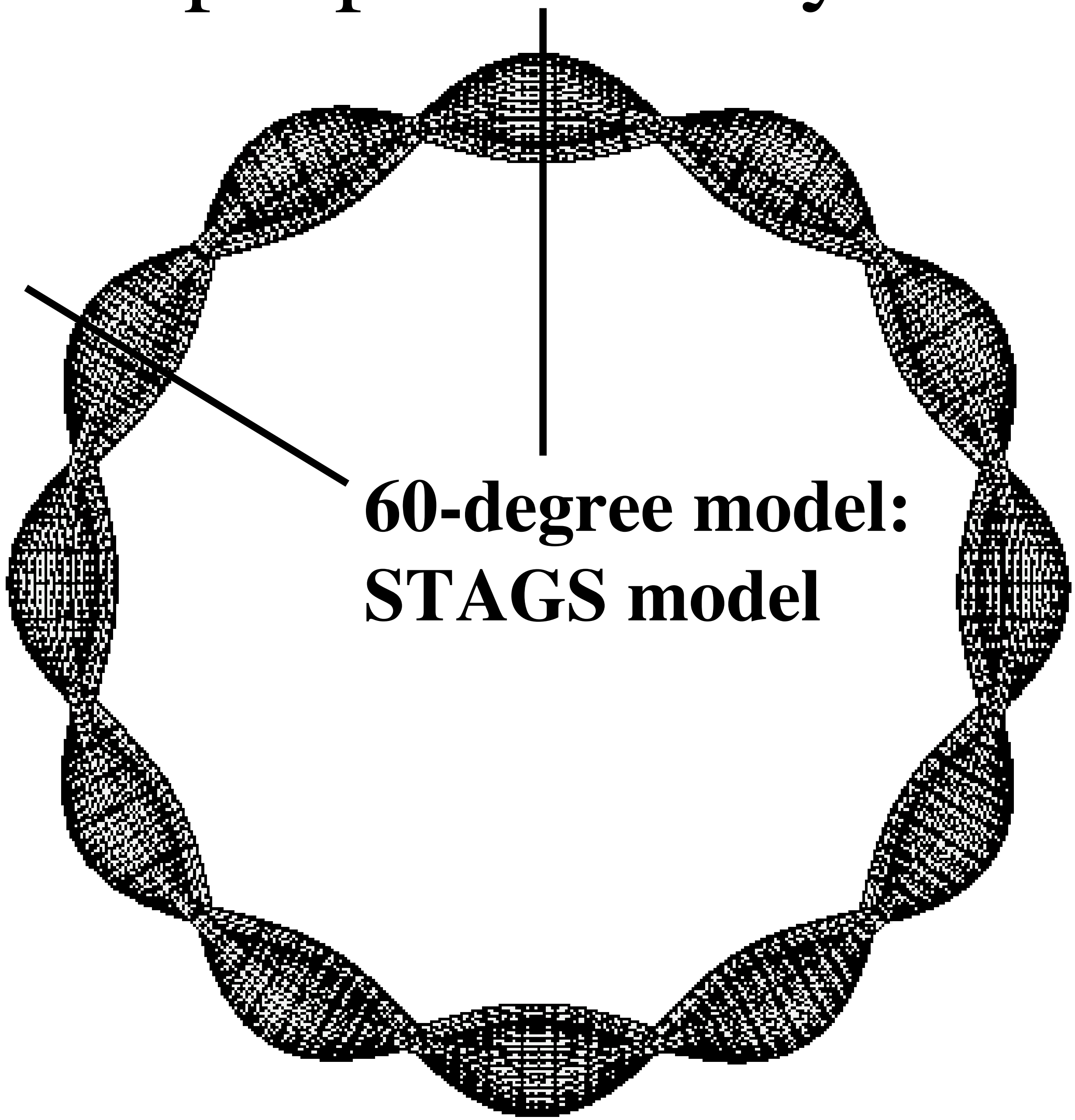


P(crit)=1.9017 (STAGS)
P(crit)=1.890 (PANDA2)
P(crit)=1.877 (BOSOR4)

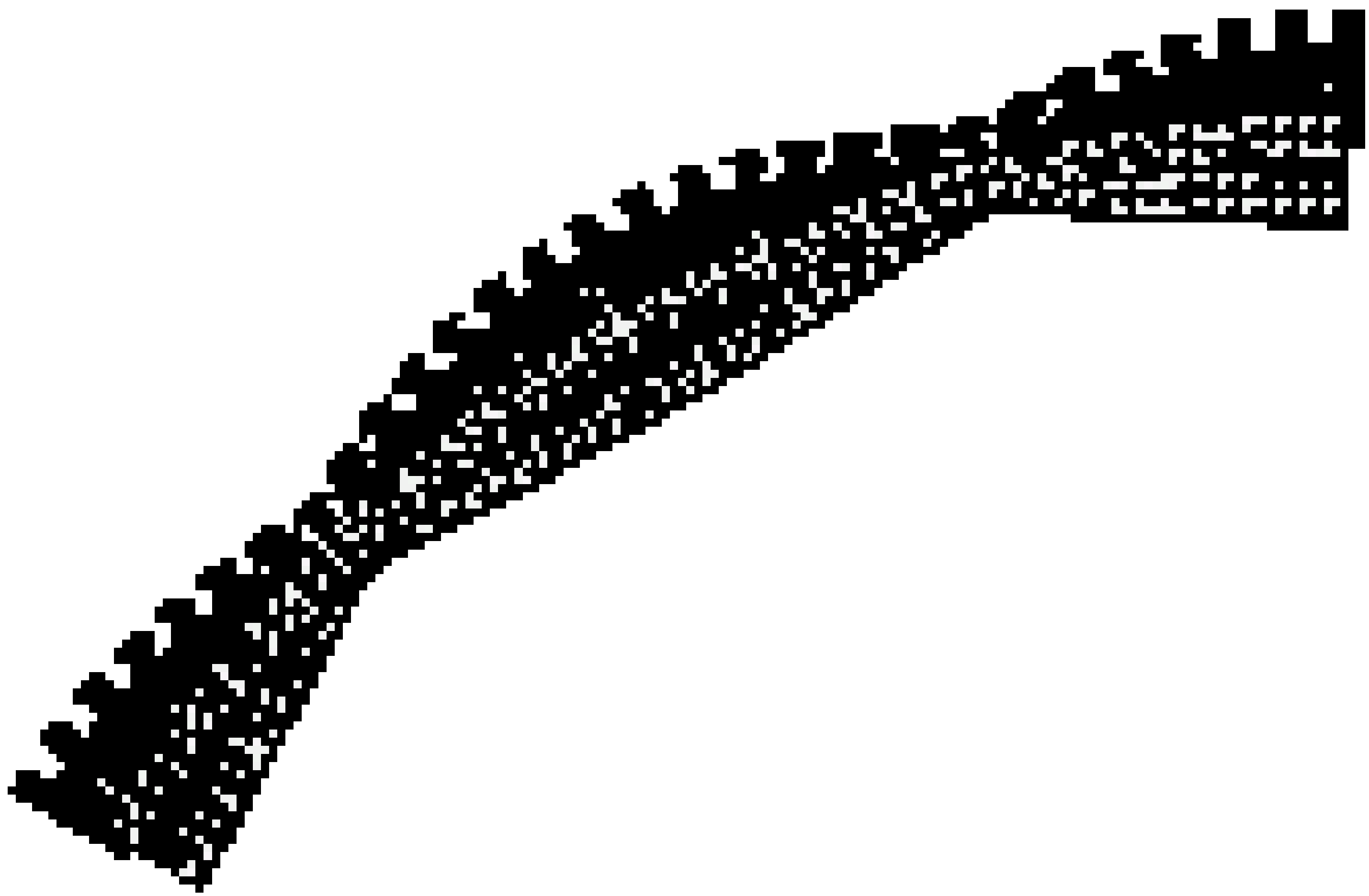
Example of general buckling: BIGBOSOR4



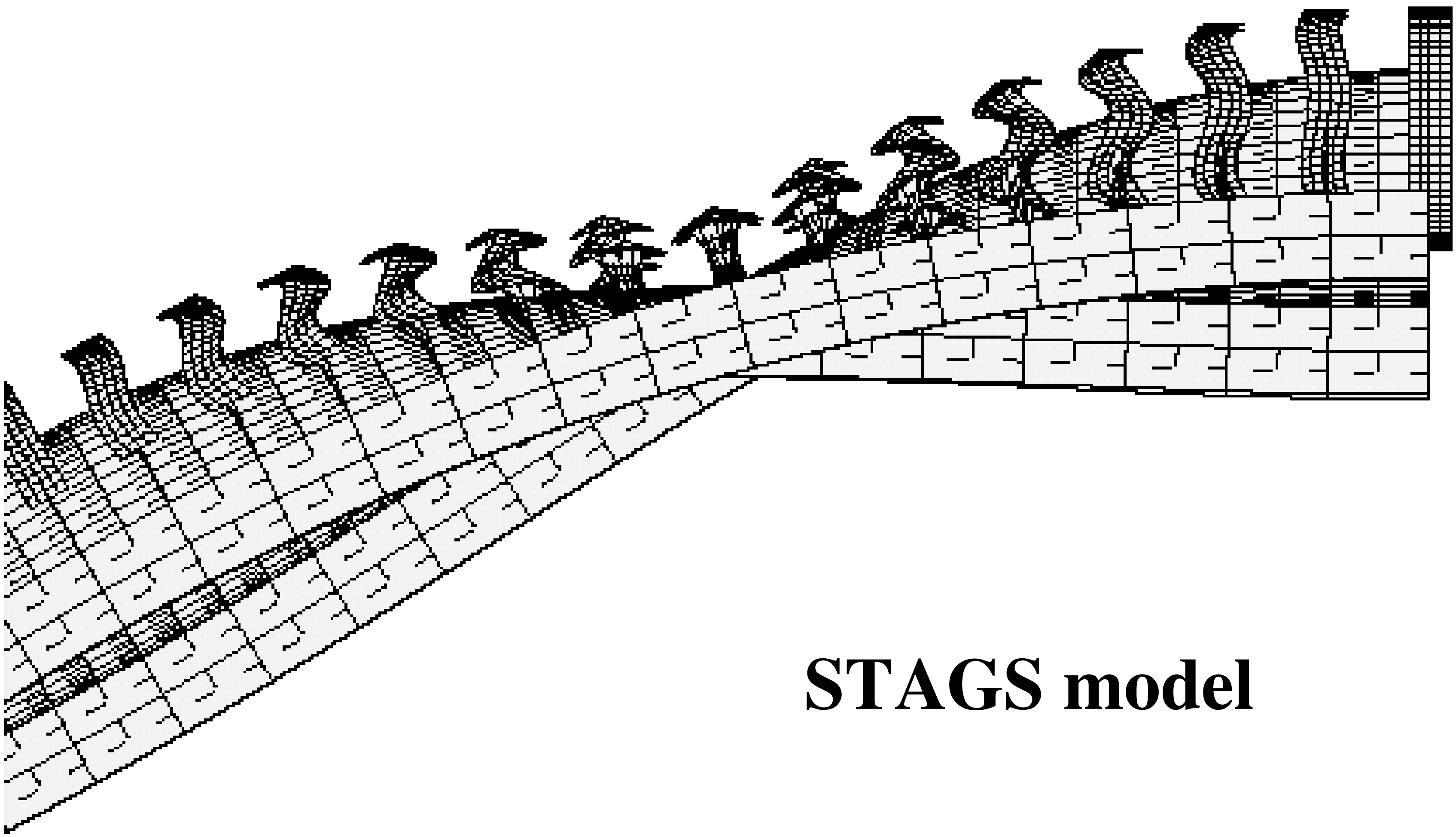
Multiple planes of symmetry



60-degree STAGS model: End view



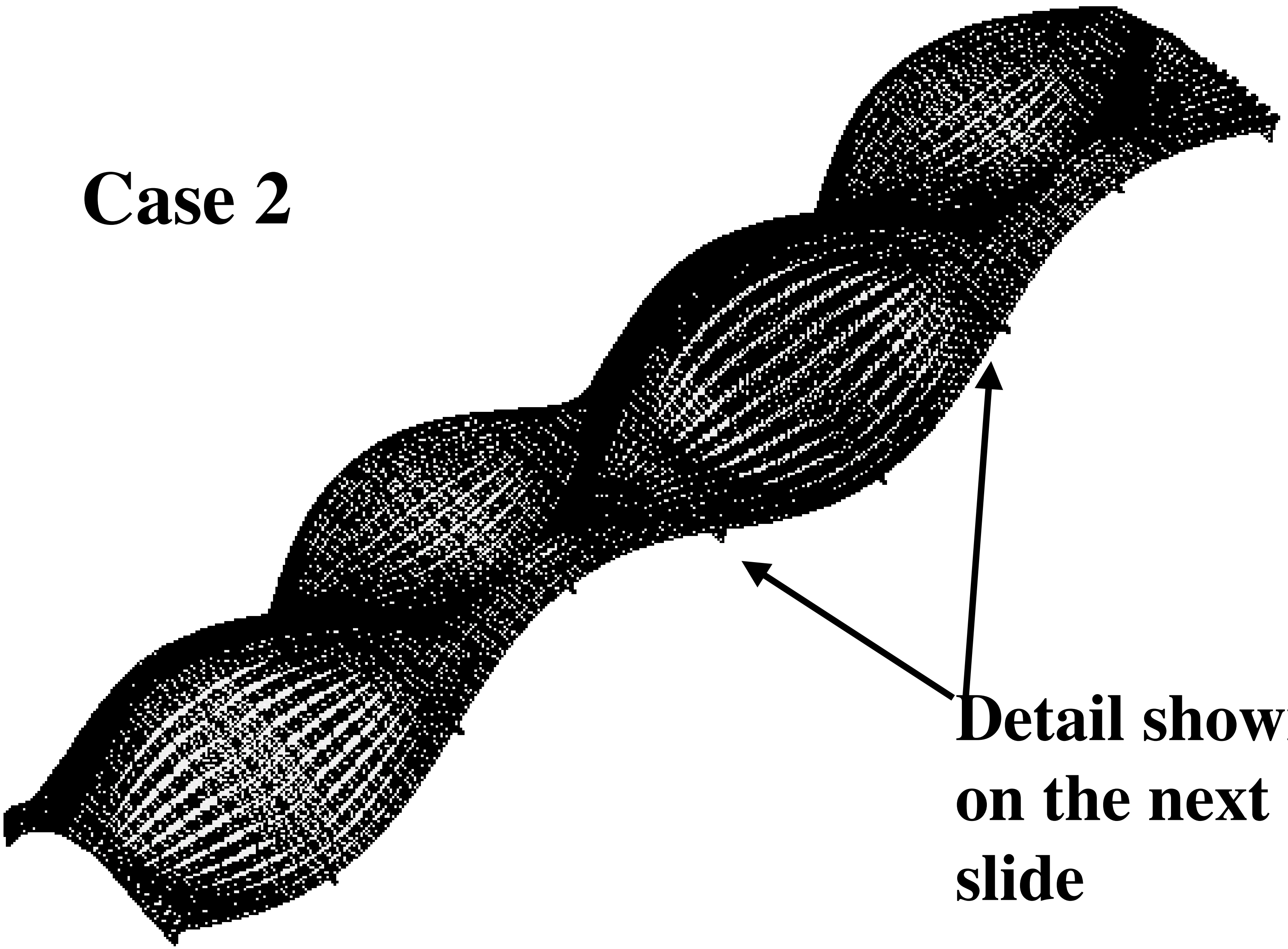
Close-up view of part of 60-deg. model



STAGS model

60-degree STAGS model

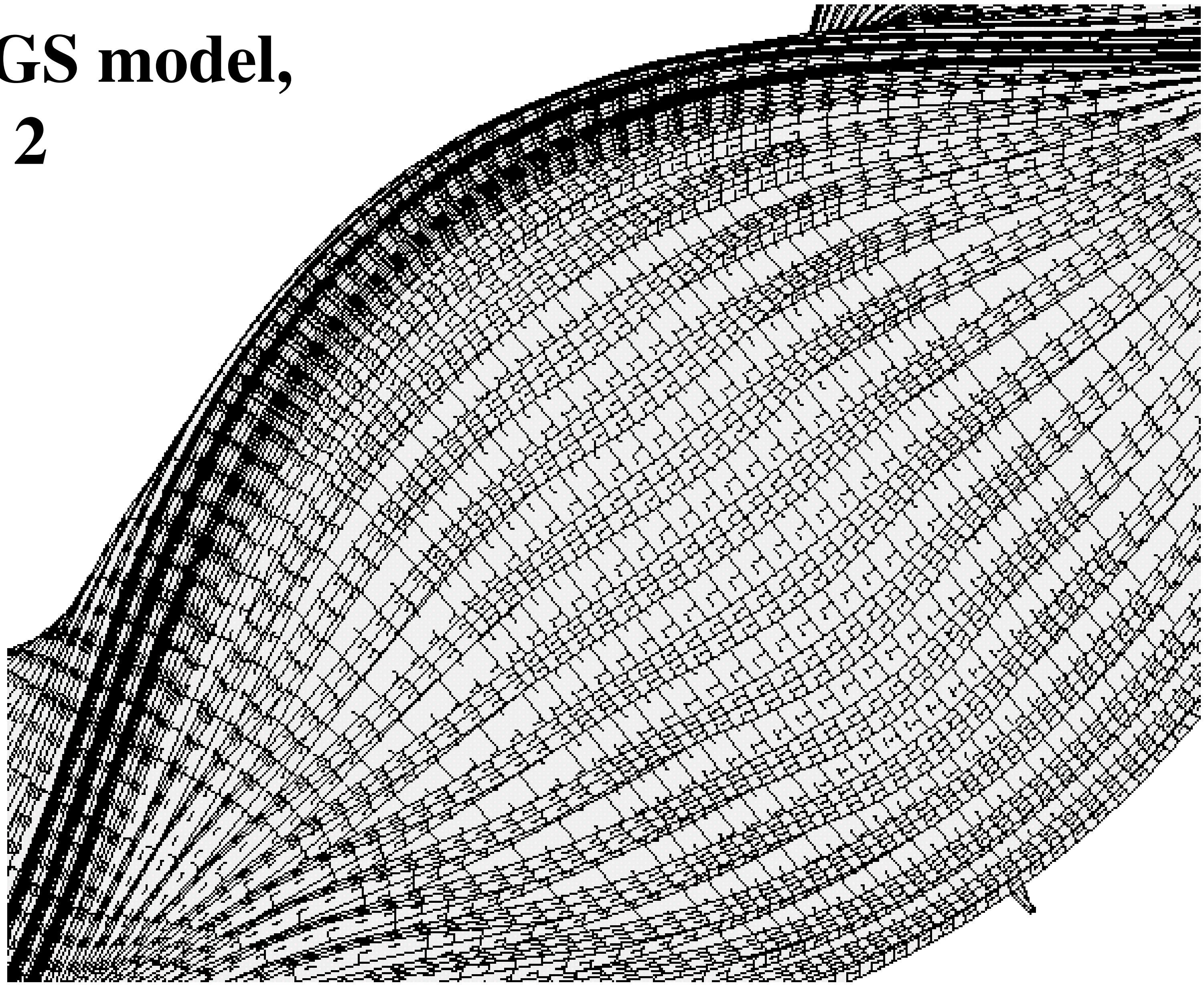
Case 2



Detail shown on the next slide

Detail of general buckling mode

STAGS model, Case 2



TYPICAL STRESS MARGINS

1. Effective stress, material x, location y, computed from SUBROUTINE STRTHK **(locally post-buckled skin/stringer discretized module)**

2. Effective stress, material x, location y, computed from SUBROUTINE STRCON **(No local buckling. Stresses in rings are computed)**

Buckling and stress margins in PANDA2 design sensitivity study

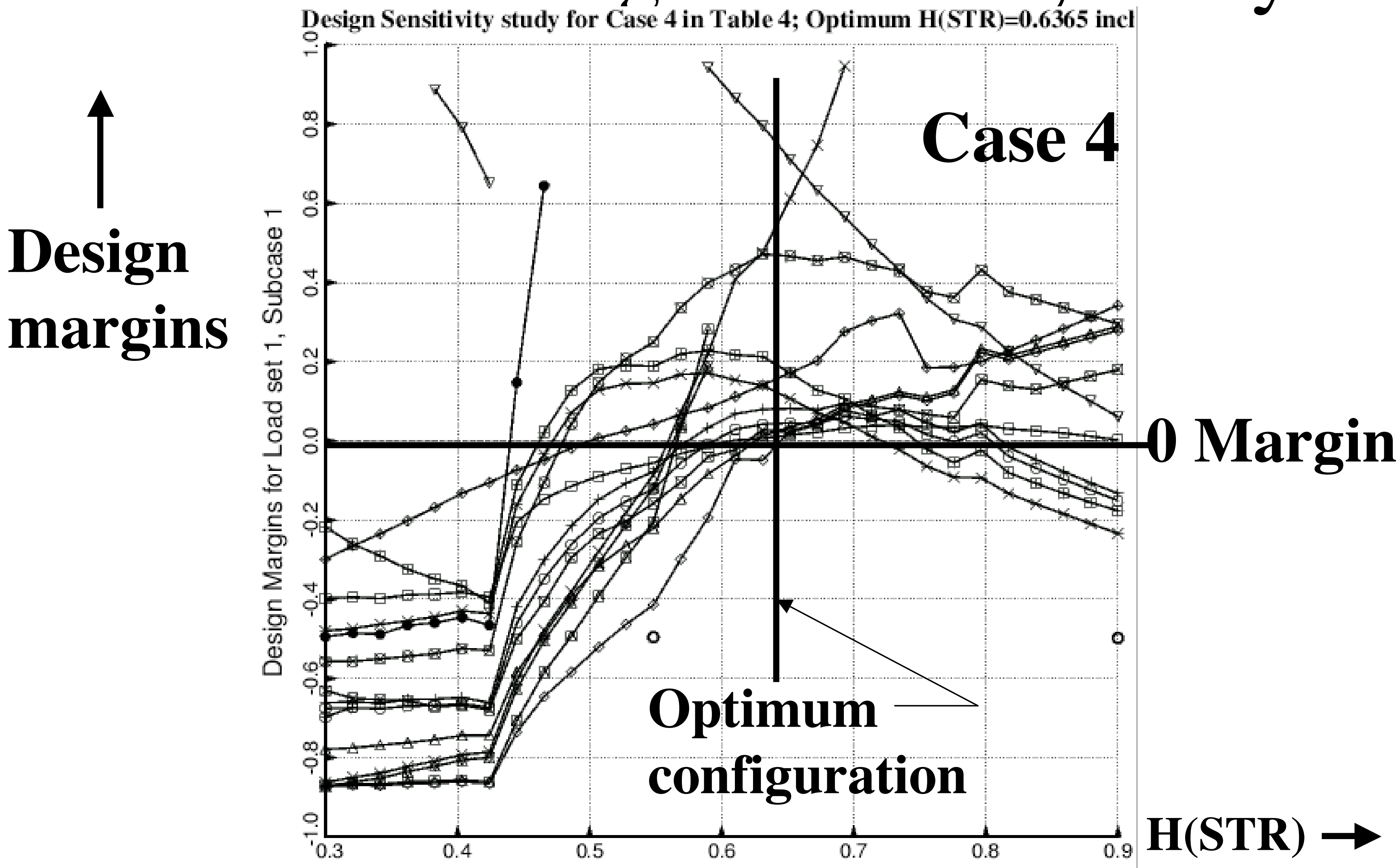


FIG. 44 PANDA2 design sensitivity study: Design Parameter, H(STR), inche

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SEVEN PANDA2 CASES

Case 1: perfect shell, “no Koiter”, ICONSV=1

Case 2: imperfect, “no Koiter”, yes change imperf., ICONSV=-1

Case 3: imperfect, “no Koiter”, yes change imperf., ICONSV= 0

Case 4: imperfect, “no Koiter”, yes change imperf., ICONSV =1

Case 5: imperfect, “yes Koiter”, yes change imperf., ICONSV=1

Case 6: as if perfect, “no Koiter”, Nx=-6000 lb/in, ICONSV= 1

Case 7: imperfect, “no Koiter”, no change imperf., ICONSV= 1

THE MEANING OF "ICONSV"

ICONSV = 1 (the recommended value):

1. Include the Arbocz theory for imperfection sensitivity.

2. Use a conservative knockdown for smearing stringers.

3. Use the computed knockdown factor for smearing rings.

ICONSV = 0:

1. Do not include the Arbocz theory.

2. Use a less conservative knockdown for smearing stringers.

3. Use the computed knockdown factor for smearing rings.

ICONSV = -1:

Same as ICONSV=0 except the knockdown factor for smearing rings is 1.0 and 0.95 is used instead of 0.85 for ALTSOL.

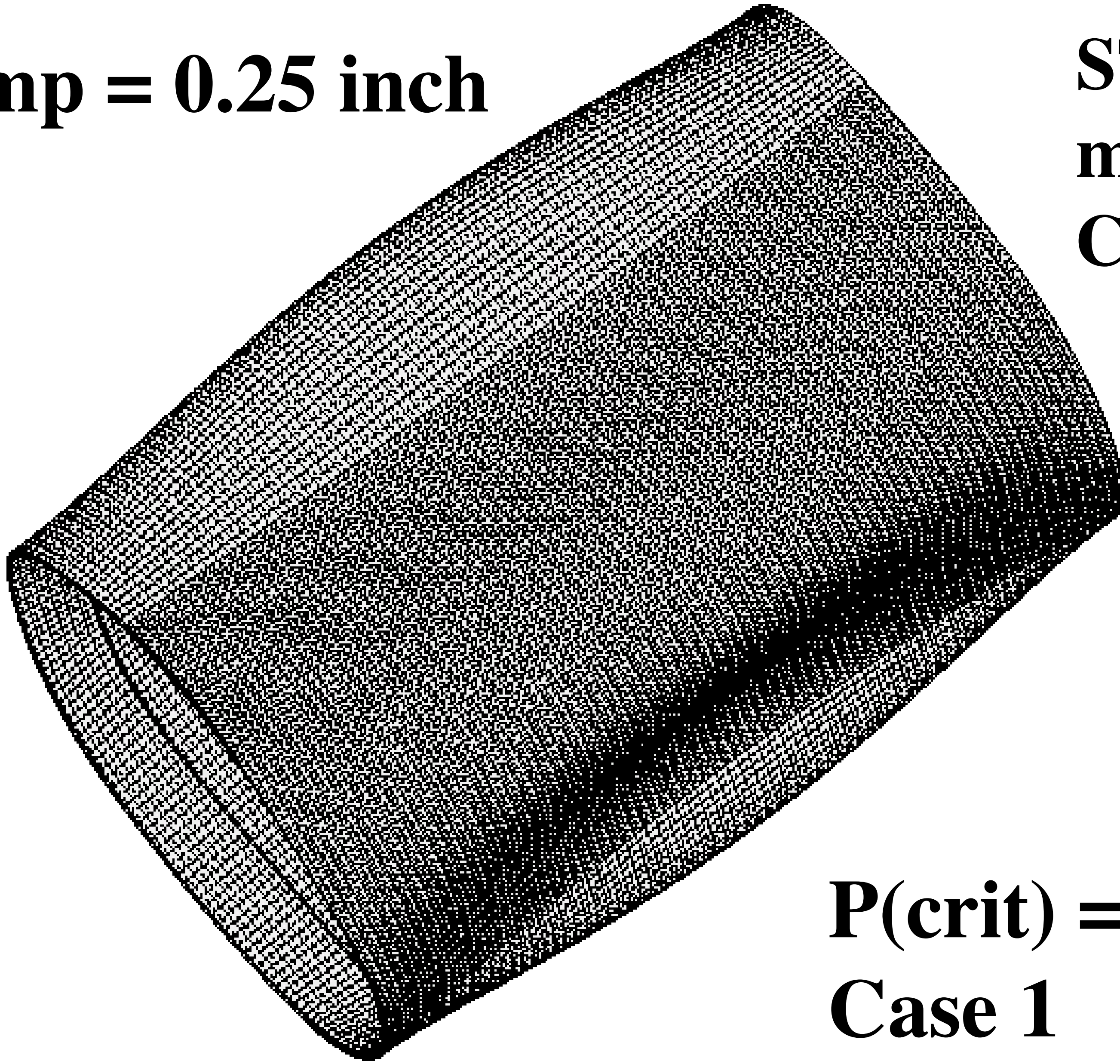
THE MEANING OF "YES CHANGE IMPERFECTION"

The general buckling modal imperfection **amplitude** is made **proportional to the axial wavelength of the critical general buckling mode shape.**

A simple general buckling modal imperfection

Wimp = 0.25 inch

STAGS model: Case 1

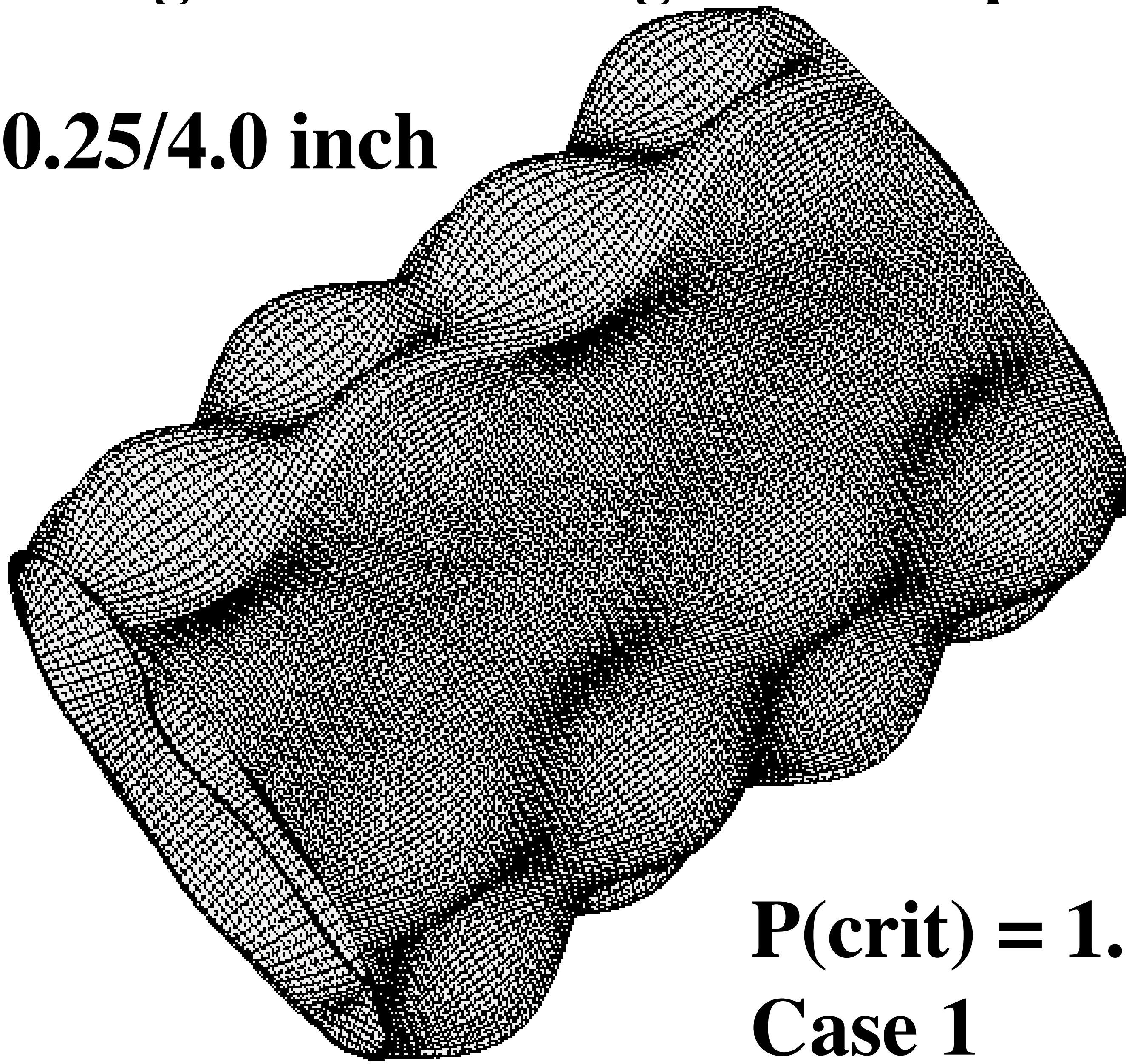


P(crit) = 1.090, Case 1

A “complex” general buckling modal imperfection

Wimp =0.25/4.0 inch

Case 1



P(crit) = 1.075, Case 1

“Oscillation” of margins with “no change imperfection” option

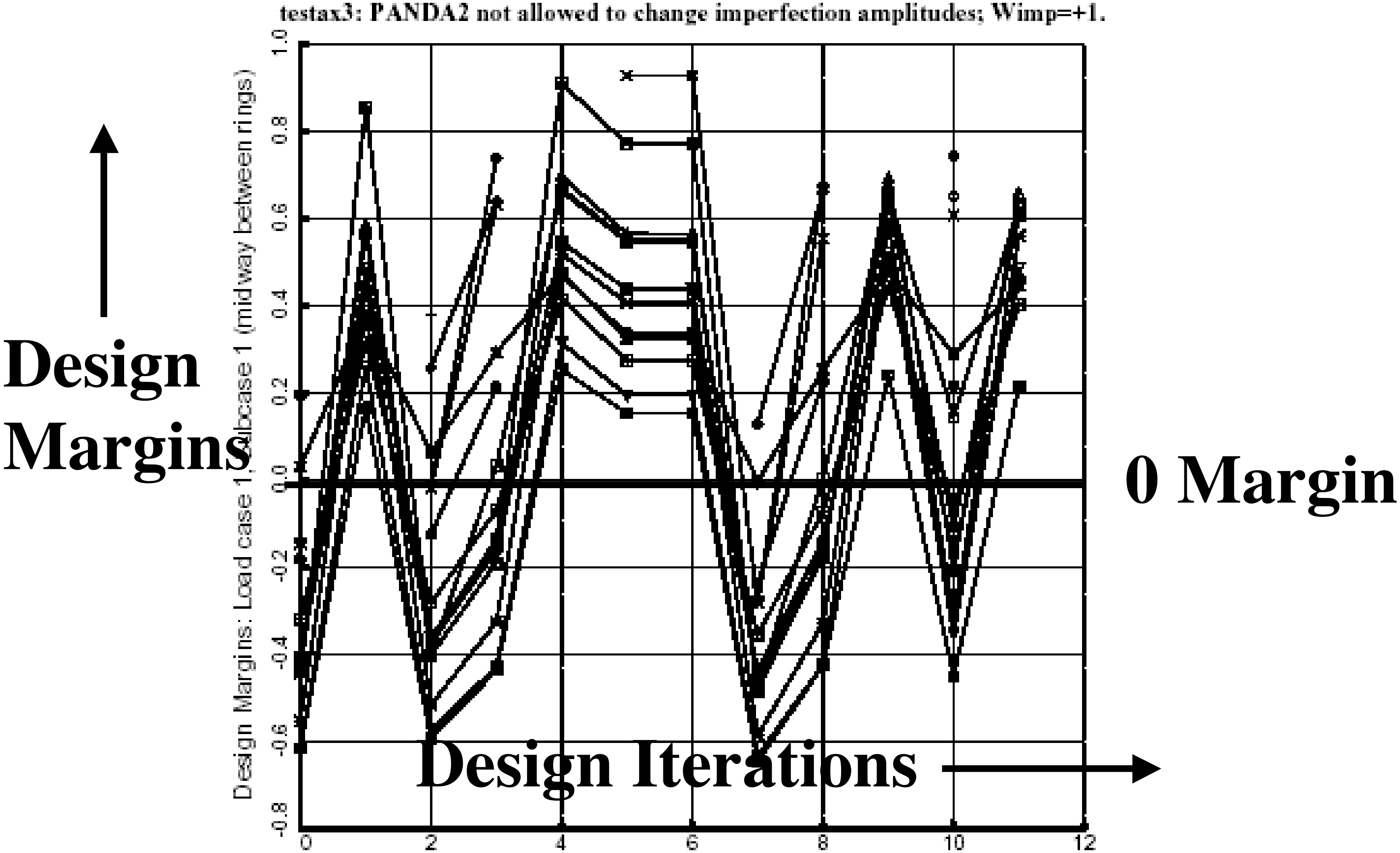
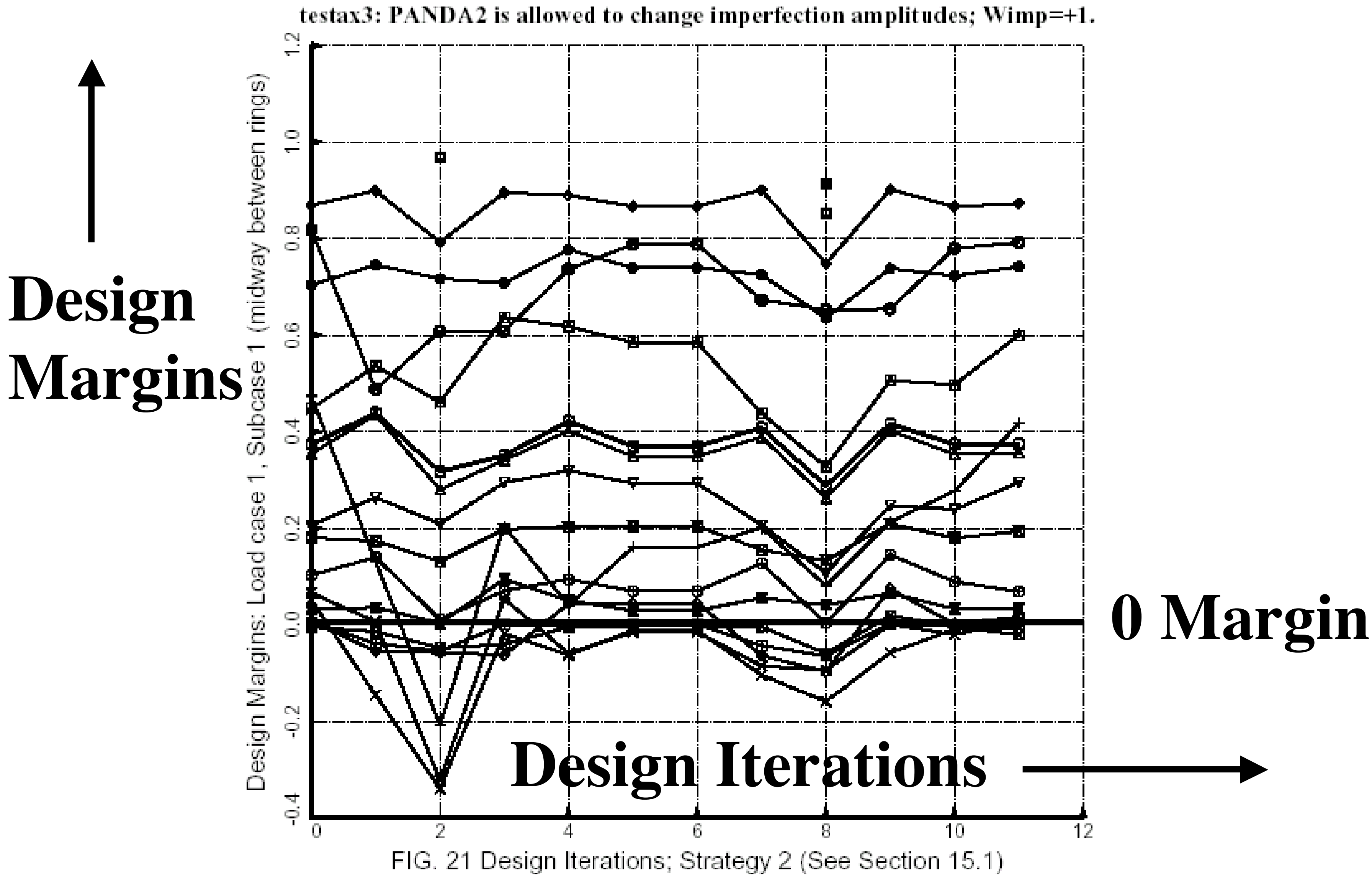


FIG. 20 Design Iterations; Strategy 1 (See Section 15.1)

"Oscillation" of margins with "yes change imperfection" option



THE MEANING OF “NO” AND “YES KOITER”

“NO KOITER” = no local postbuckling state is computed.

“YES KOITER” = the local post-buckling state is computed. A modified form of the nonlinear theory by KOITER (1946), BUSHNELL (1993) is used.

Local postbuckling: PANDA2

A single discretized skin-stringer module model (BOSOR4-type model) of the Case 4 optimum design as deformed at four levels of applied axial compression, Nx.

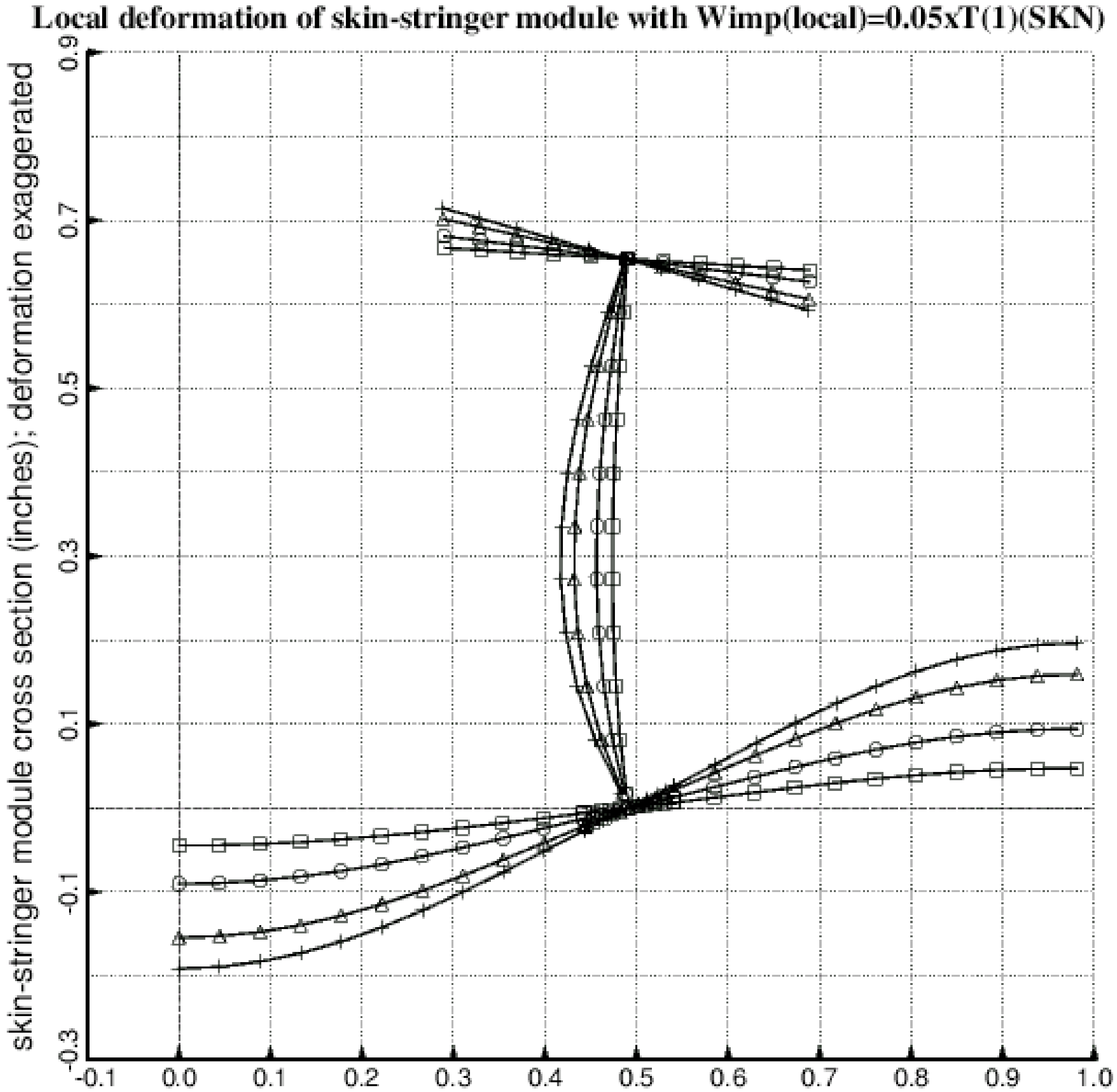


FIG. 4 Case 4 skin-stringer module cross section (inches) for 4 loads

Case 4 with “no Koiter” and with “yes Koiter”

Stress margins computed with “no Koiter”

Stresses computed with “yes Koiter”

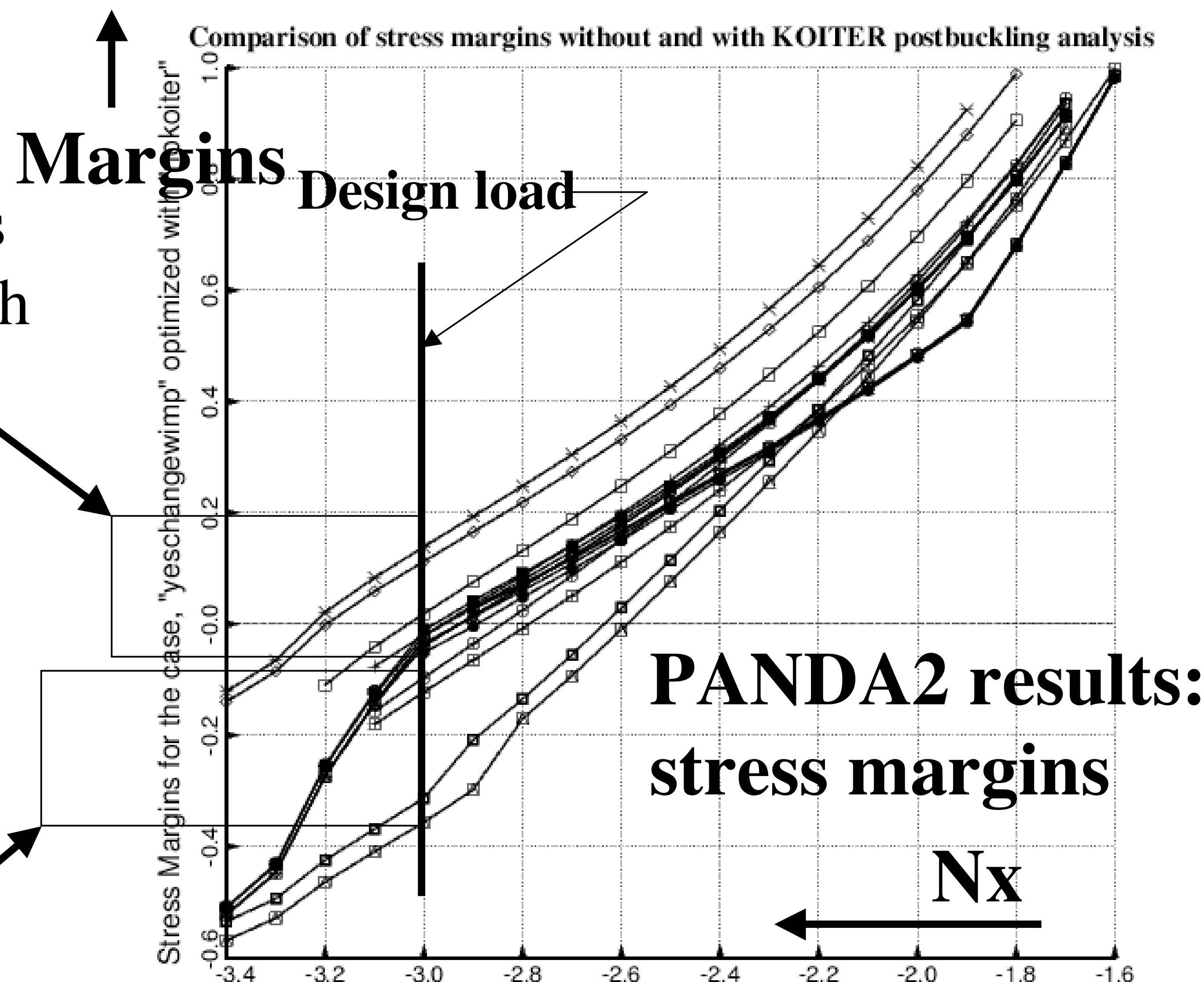
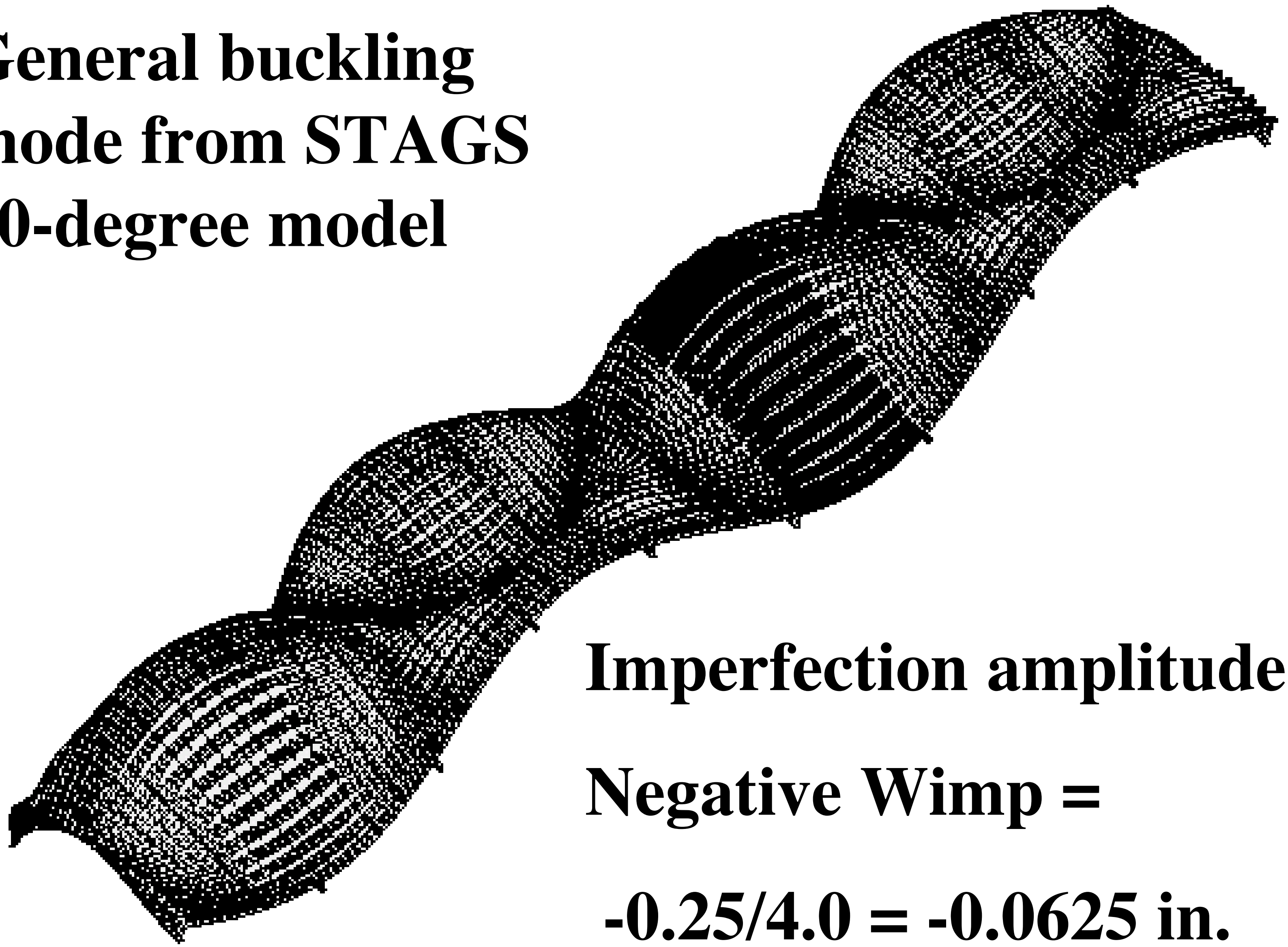


FIG. 6 Case 4, Table 4 optimum design: Axial Load, Nx (lb/in)

Case 4: Initial imperfection shape

General buckling mode from STAGS 60-degree model

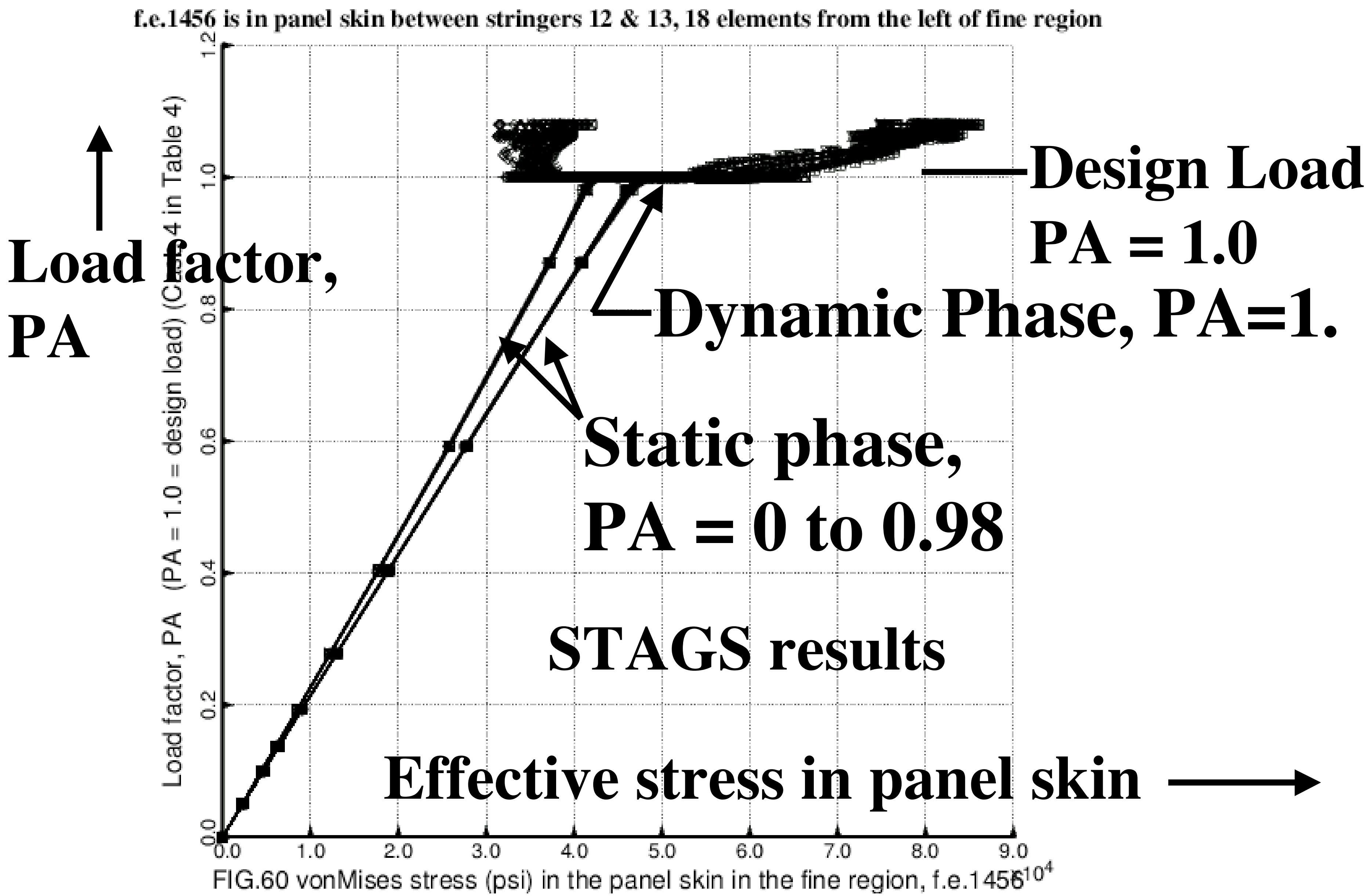


Imperfection amplitude,

Negative Wimp =

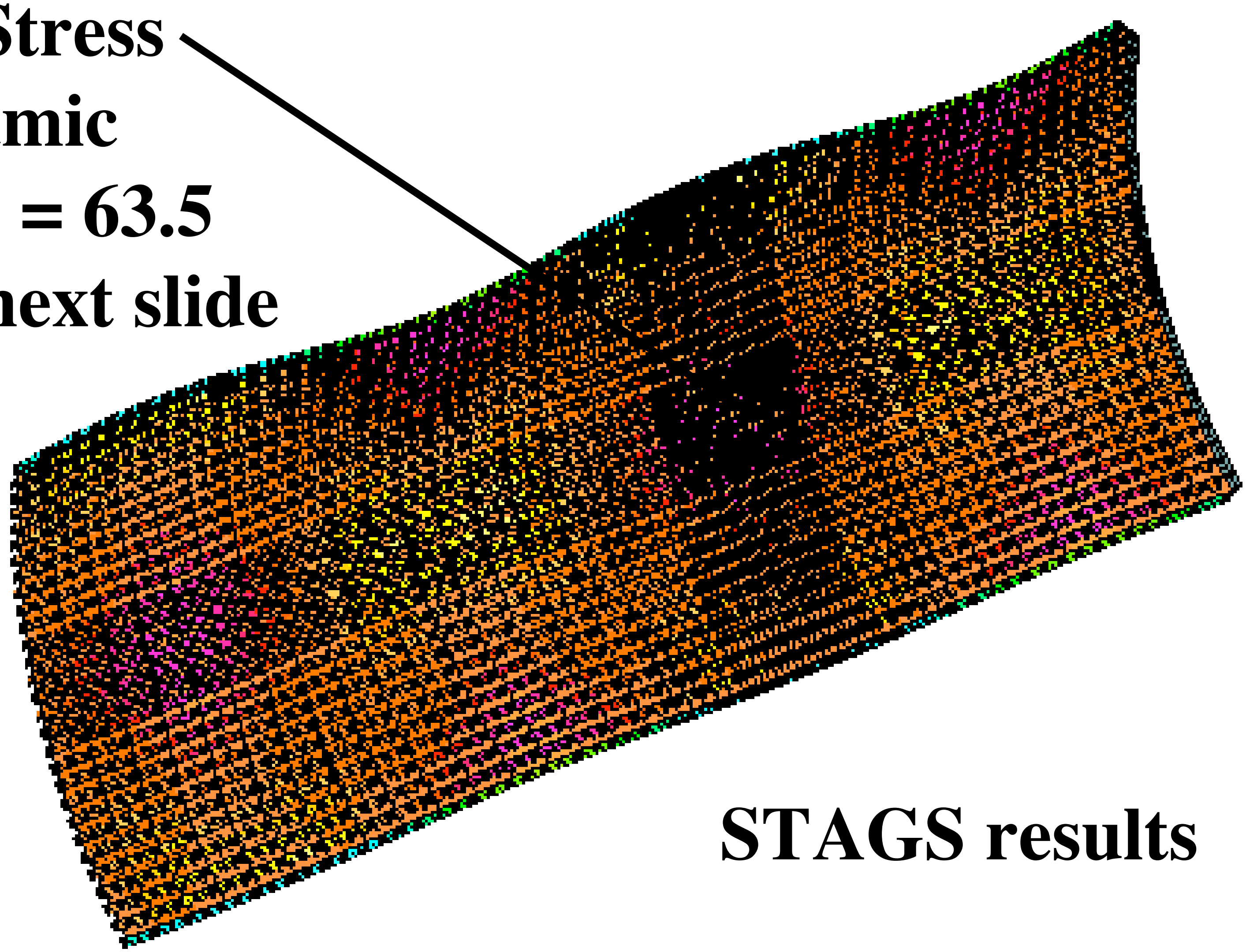
-0.25/4.0 = -0.0625 in.

Load-stress curve: static & dynamic



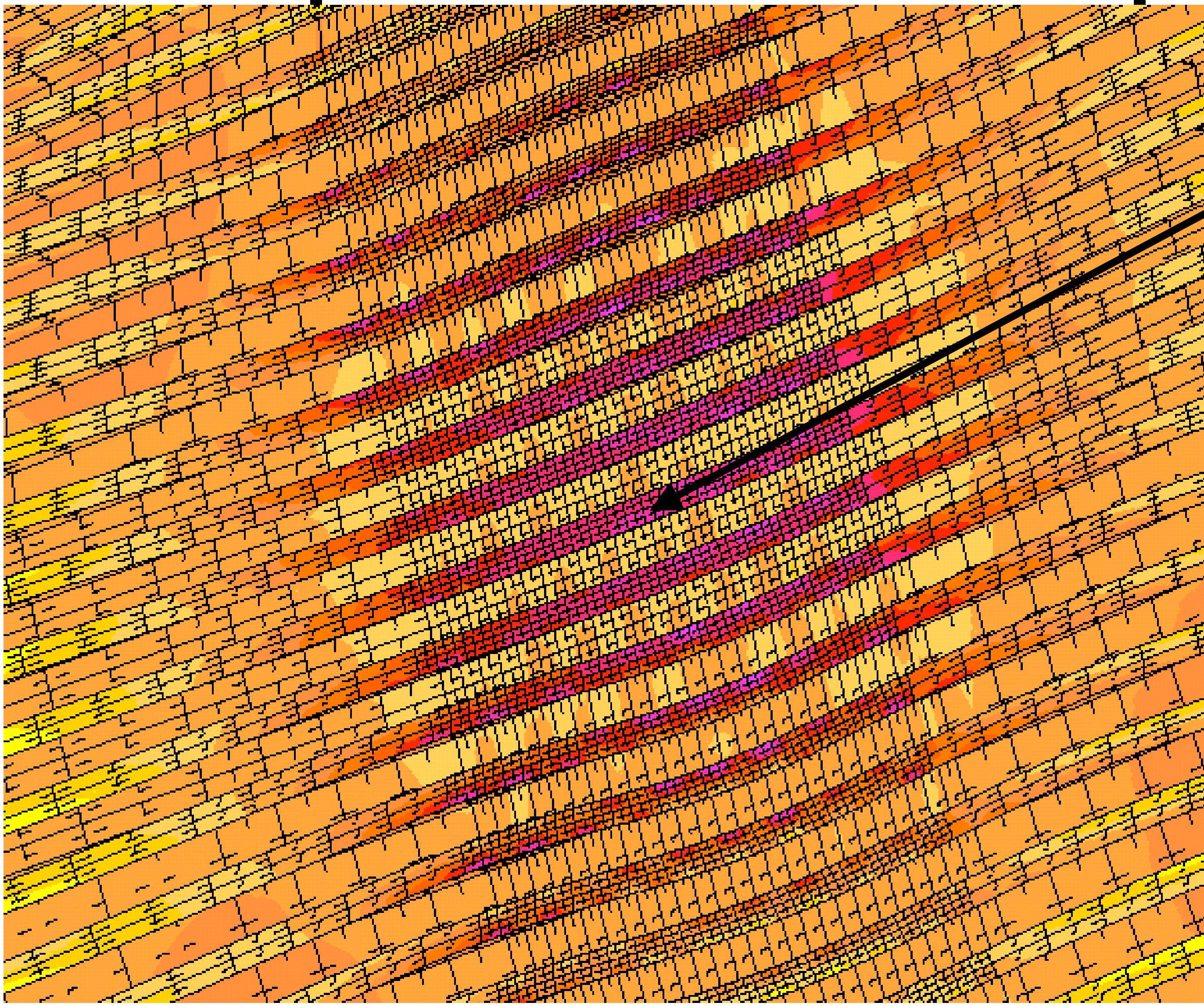
Deformed panel at PA=0.98

Maximum Stress before dynamic STAGS run = 63.5 ksi See the next slide for detail.



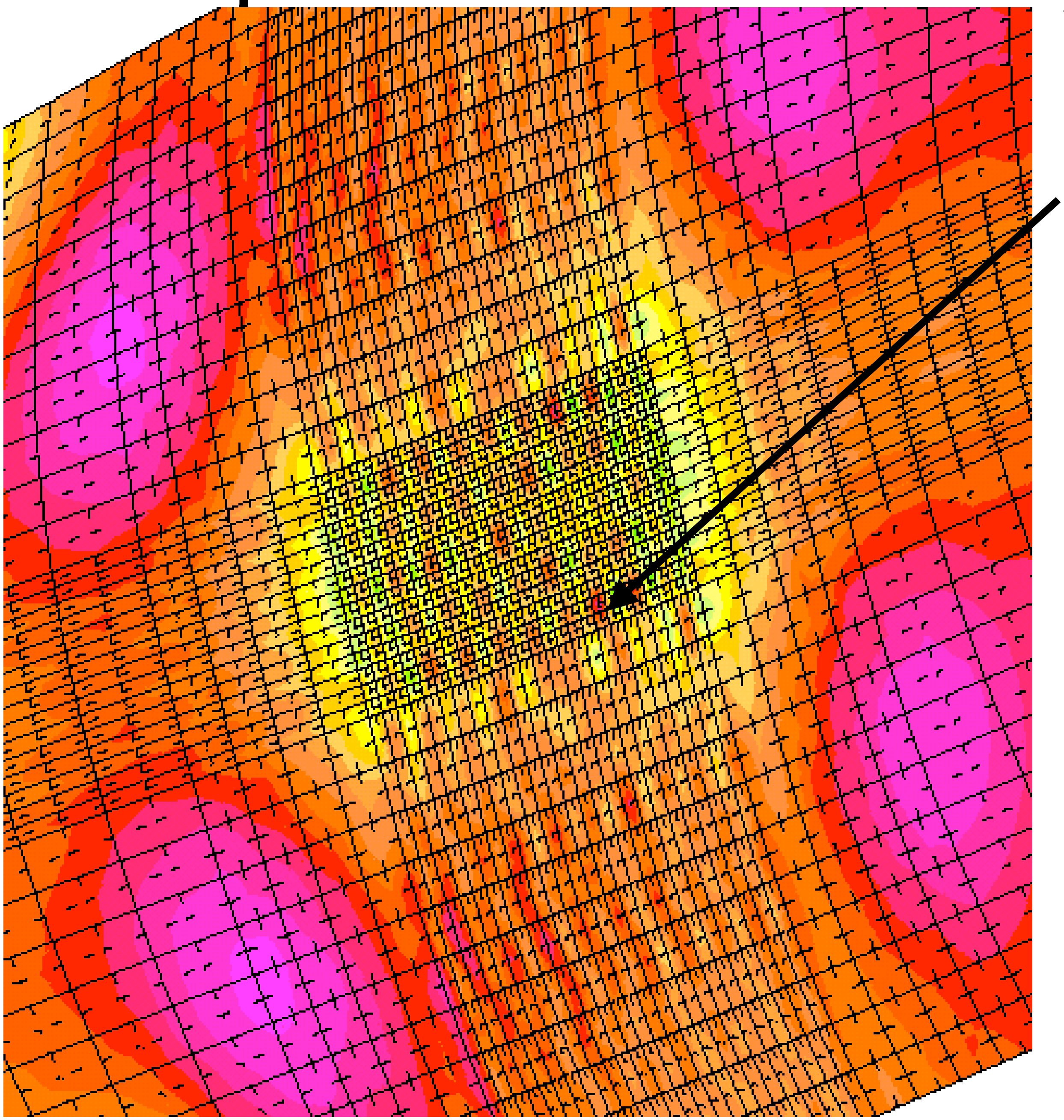
STAGS results

Example 1 of stress in the imperfect panel



Maximum effective (von Mises) stress in the entire panel, 63.5 ksi. (Case 4 nonlinear STAGS static equilibrium at load factor, PA = 0.98, before the STAGS dynamic run)

Example 1 of stress in the panel skin



Maximum effective (von Mises) stress in the panel skin= 47.2 ksi (Case 4 nonlinear STAGS static equilibrium at load factor, PA = 0.98, before the STAGS dynamic run)

STAGS nonlinear dynamic response

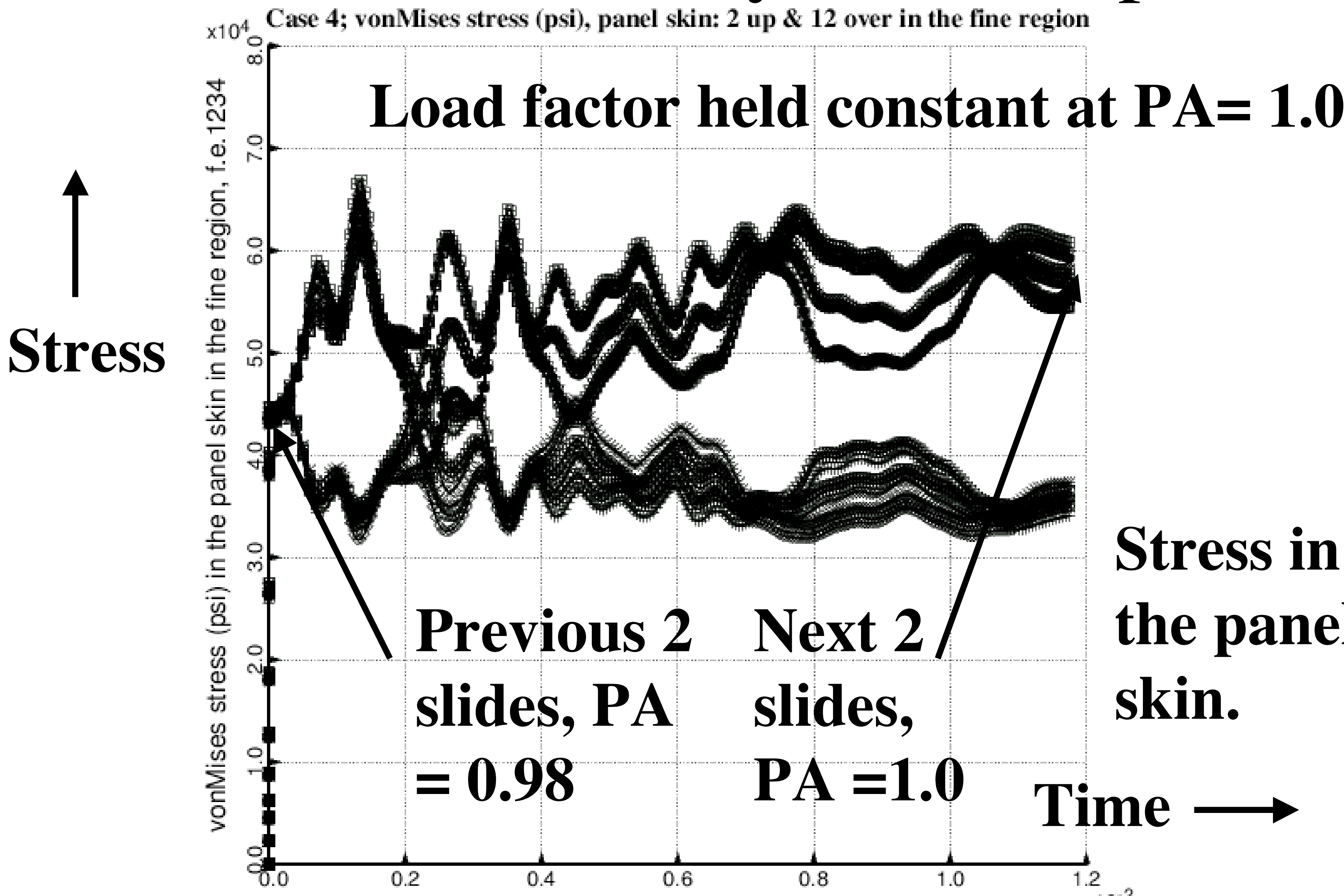
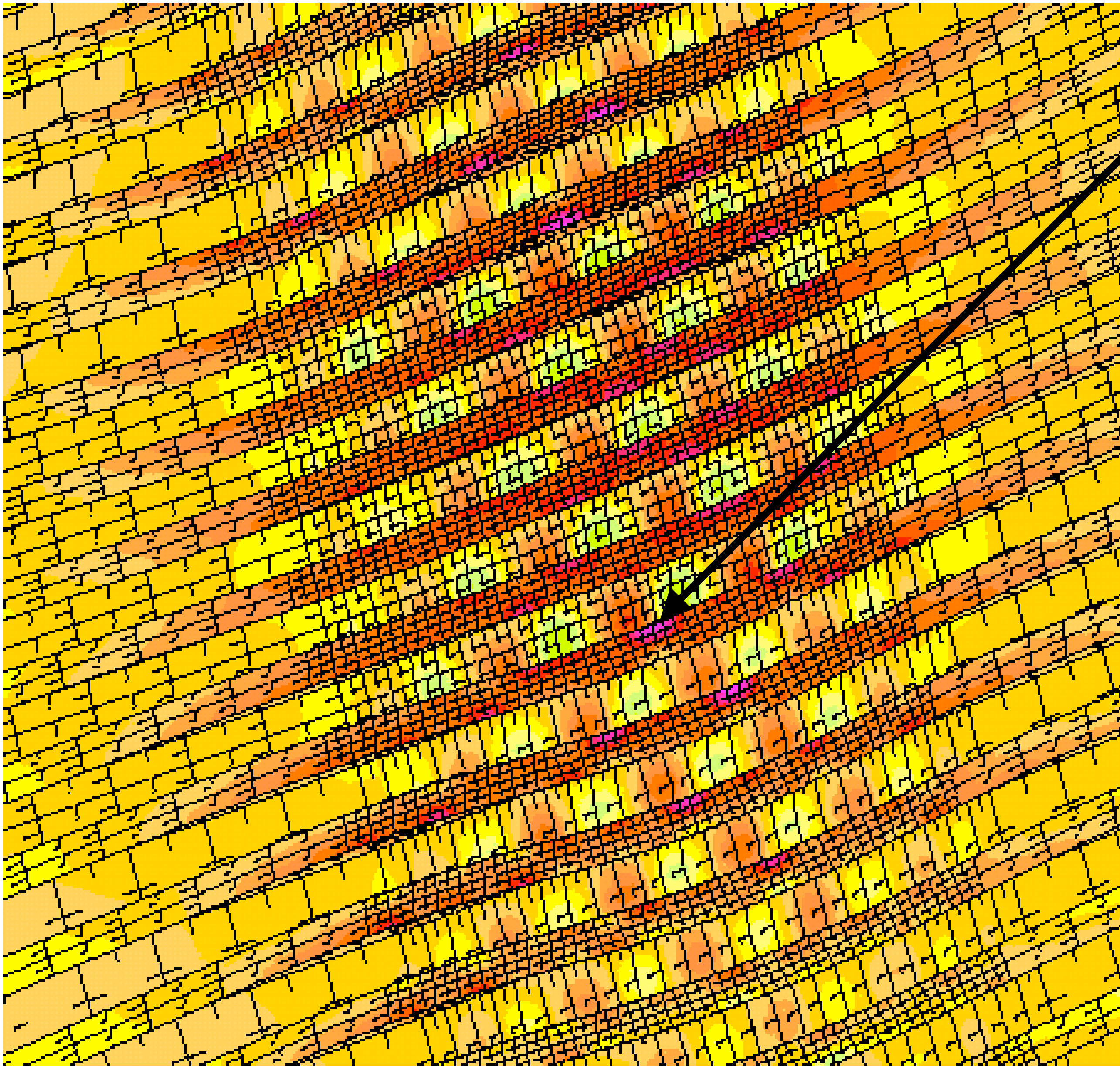


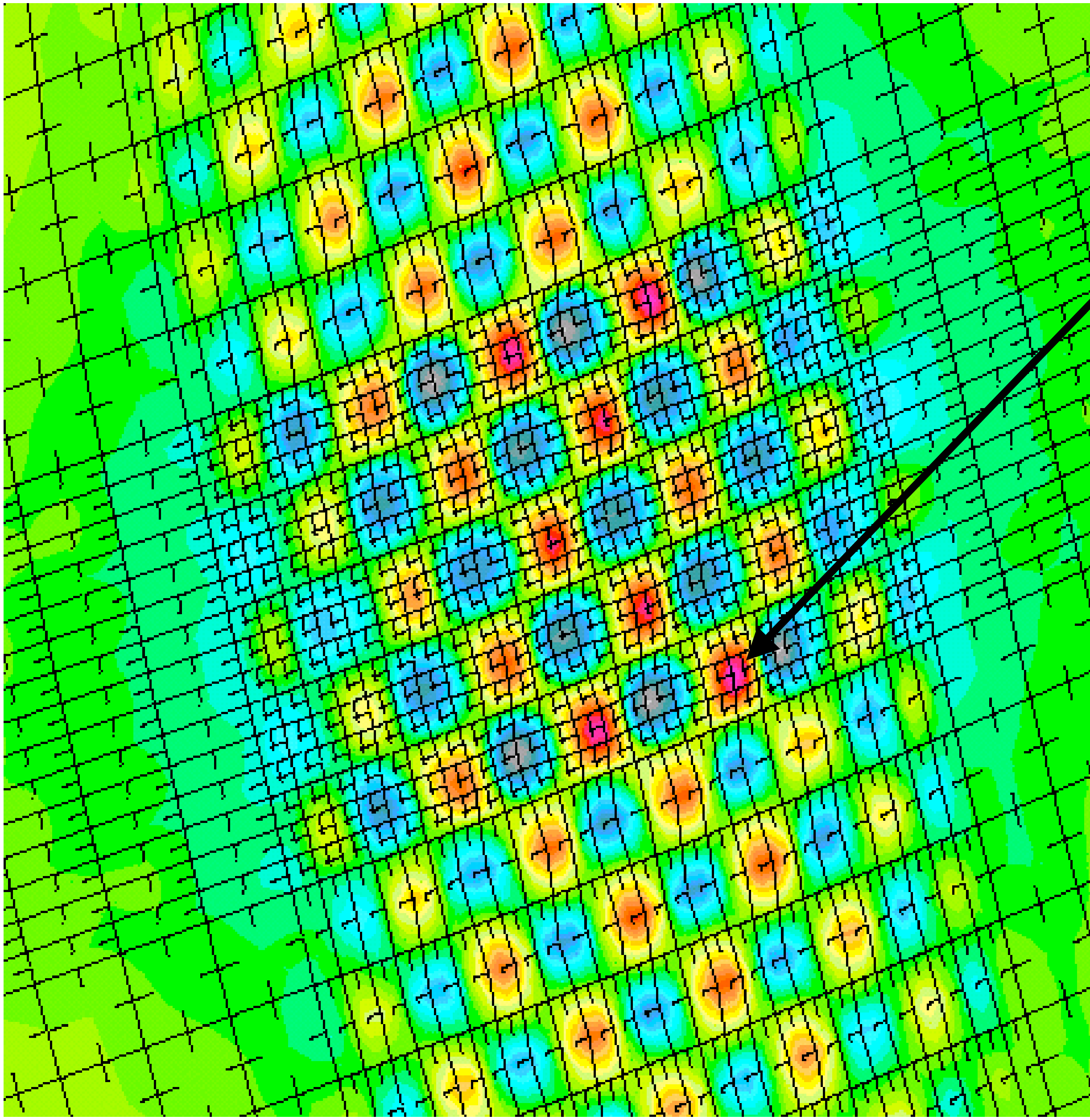
FIG. 52 Time (seconds); Data points at Time=0 are from the static run.

Example 2 of stress in the imperfect panel



Maximum effective (von Mises) stress in the entire panel, 70.38 ksi (Case 4 STAGS nonlinear static equilibrium after the dynamic STAGS run at load factor, PA = 1.00)

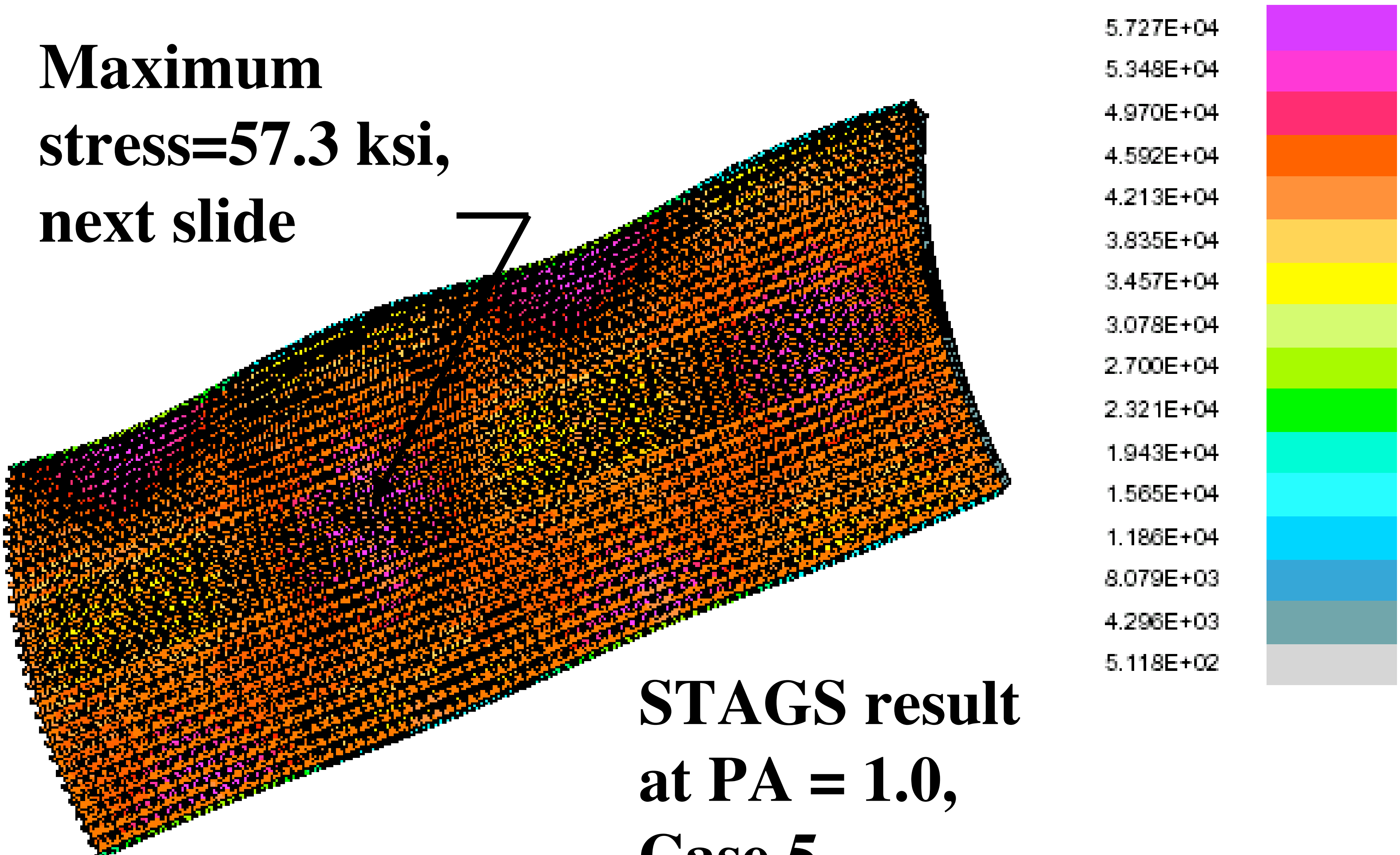
Example 2 of stress in the panel skin



Maximum effective (von Mises) stress in the panel skin=60.6 ksi (Case 4 nonlinear STAGS static equilibrium after dynamic STAGS run at load factor, PA = 1.00)

Shell optimized with "yes Koiter"

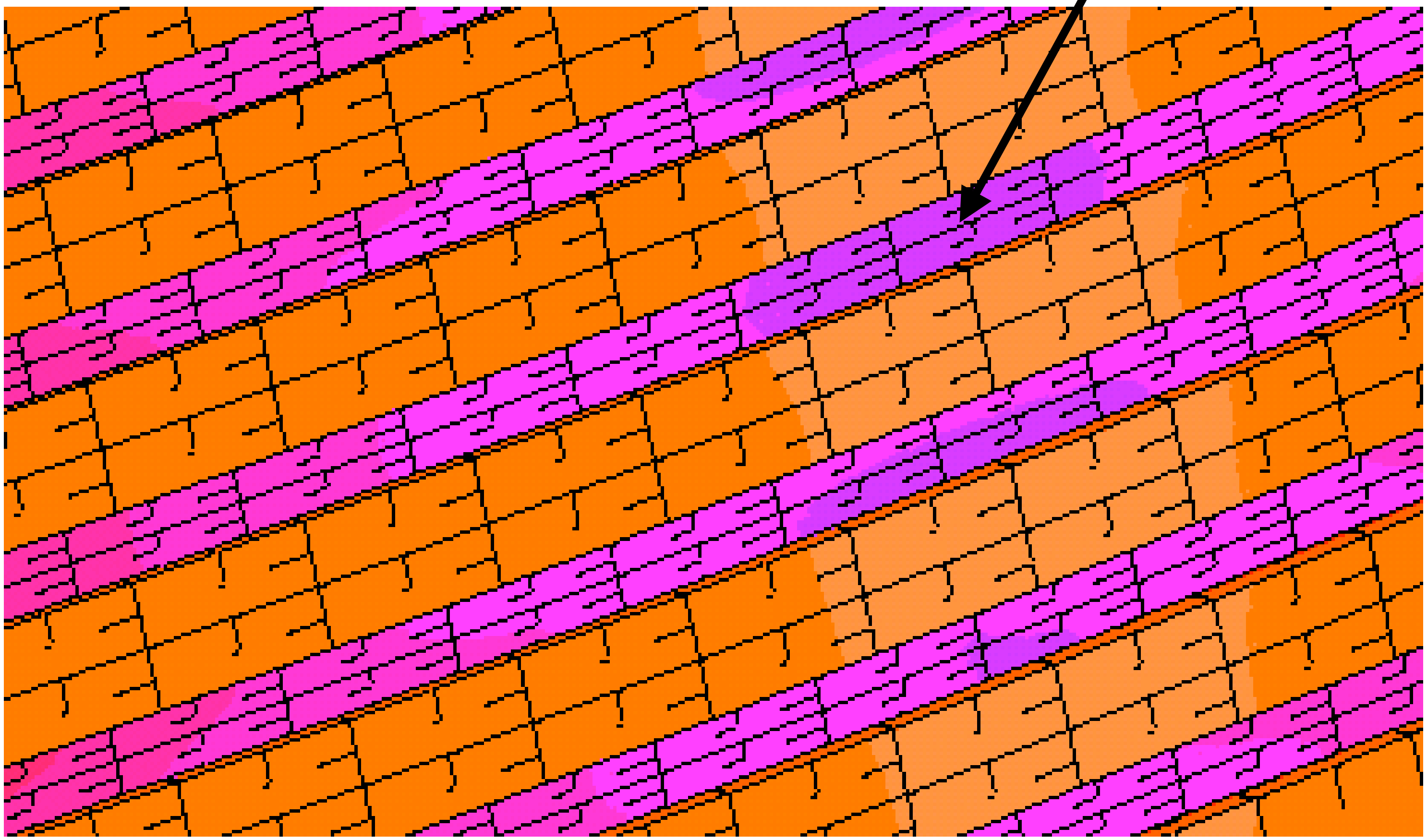
Maximum stress=57.3 ksi, next slide



STAGS result at PA = 1.0, Case 5

Detail from previous slide: PA = 1.0

Maximum stress=57.3 ksi



OPTIMIZED WEIGHTS FOR CASES 1 - 7: PANDA2

CASE	WEIGHT(lb)	COMMENT
1	**31.81**	perfect shell, no Koiter, ICONSV=1
2	**39.40**	imperfect, no Koiter, yes change imp., ICONSV=-1
3	**40.12**	imperfect, no Koiter, yes change imp., ICONSV= 0
4	**40.94**	imperfect, no Koiter, yes change imp., ICONSV= 1
5	**41.89**	imperfect, yes Koiter, yes change imp., ICONSV= 1
6	**46.83**	as if perfect, no Koiter, Nx = -6000 lb/in, ICONSV= 1
7	**56.28**	imperfect, no Koiter, no change imperf., ICONSV=1

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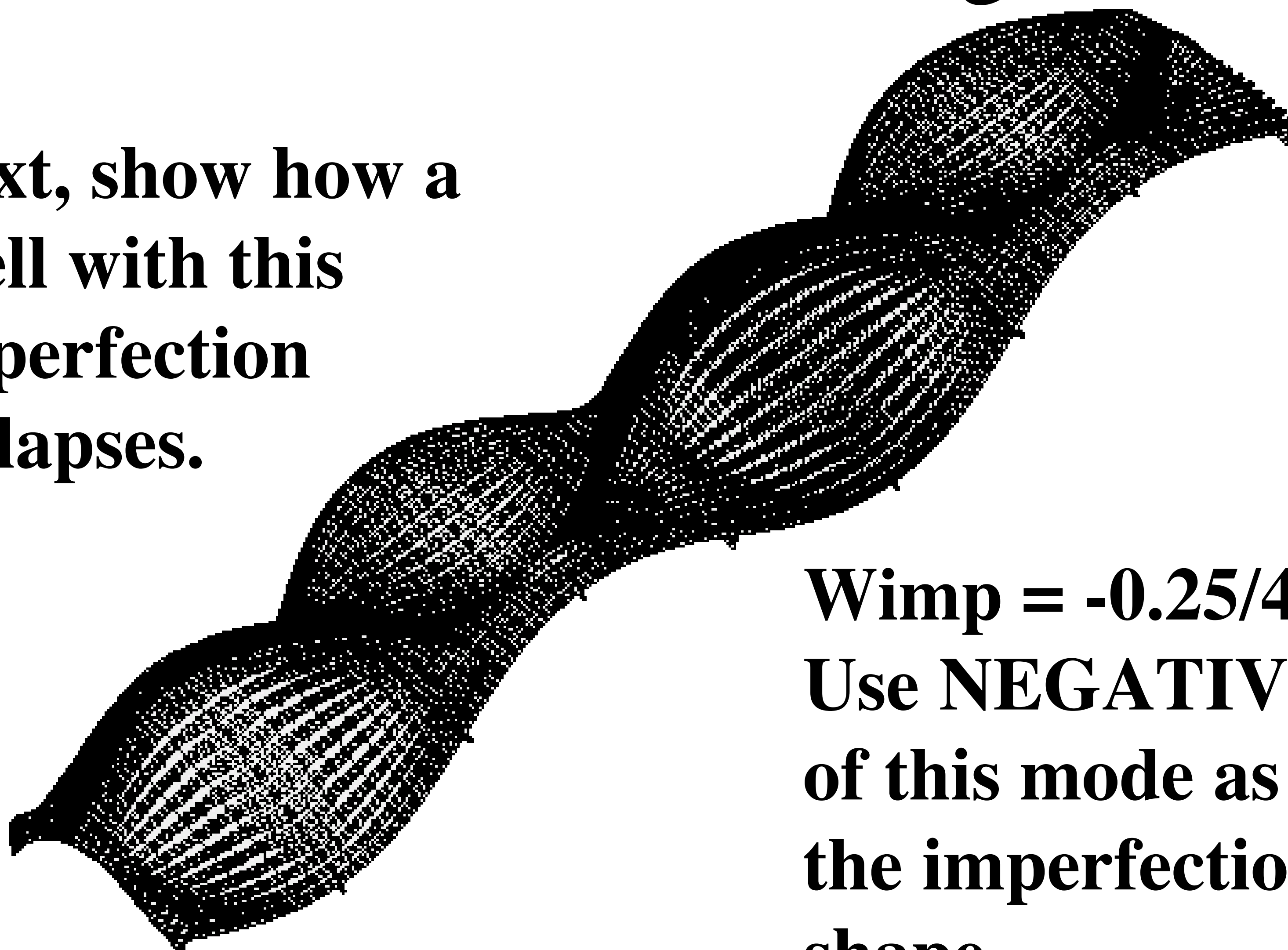
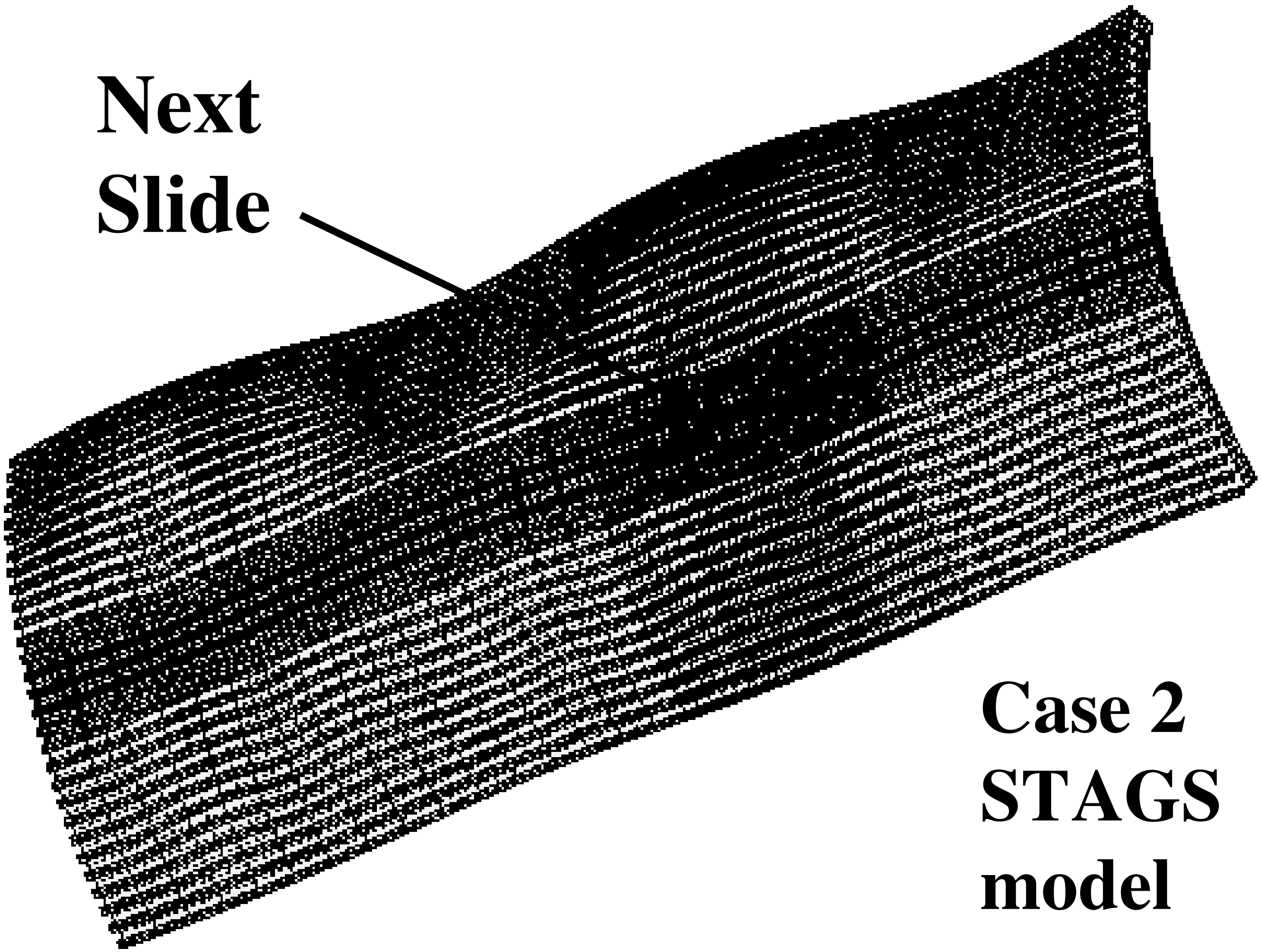
60-degree STAGS model of Case 2: General buckling mode

Next, show how a shell with this imperfection collapses.

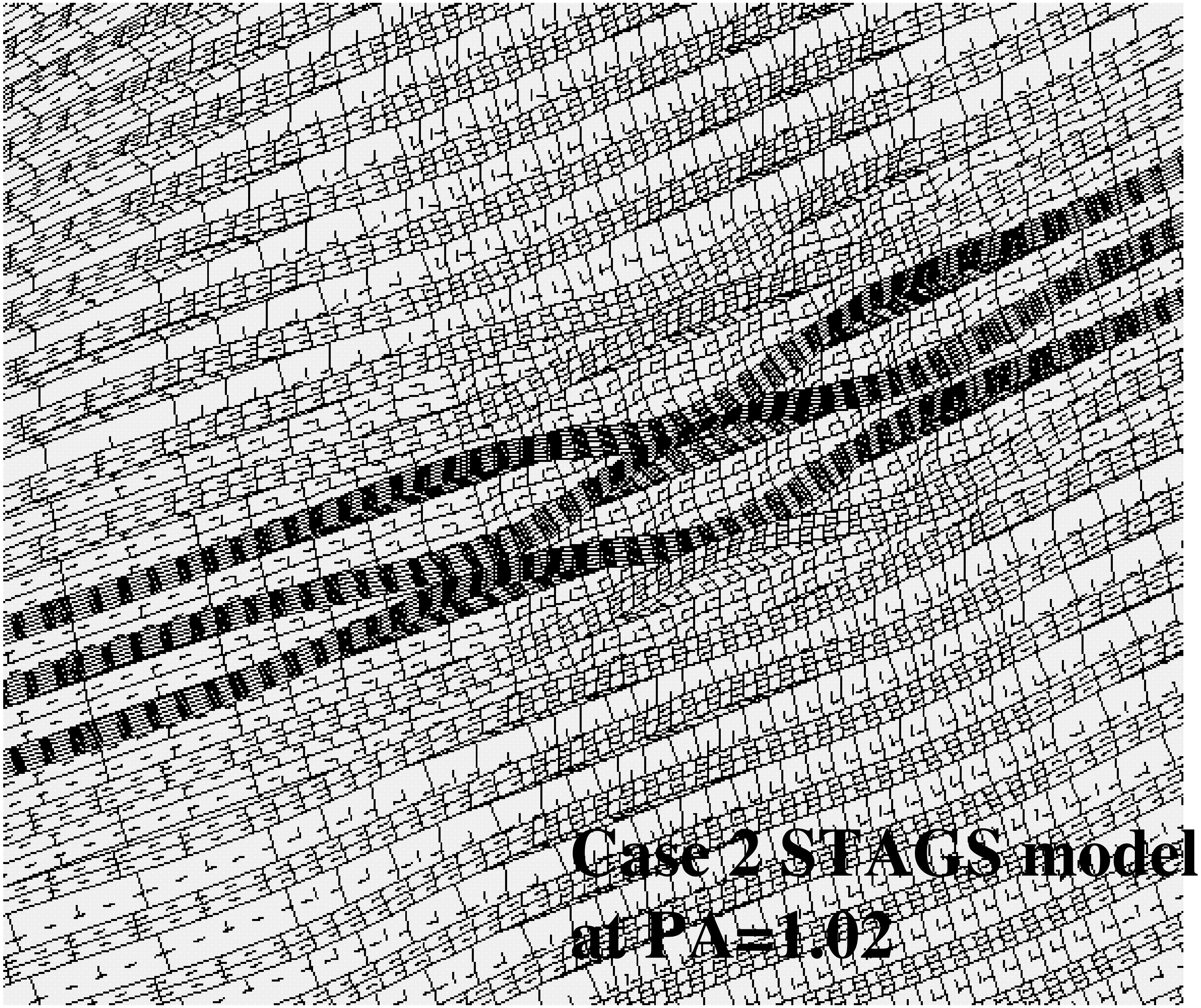


Wimp = -0.25/4.0
Use NEGATIVE of this mode as the imperfection shape.

Deformed shell at PA=1.02 with negative of general buckling mode



Enlarged view of collapsing zone



Sidesway of central stringers vs PA

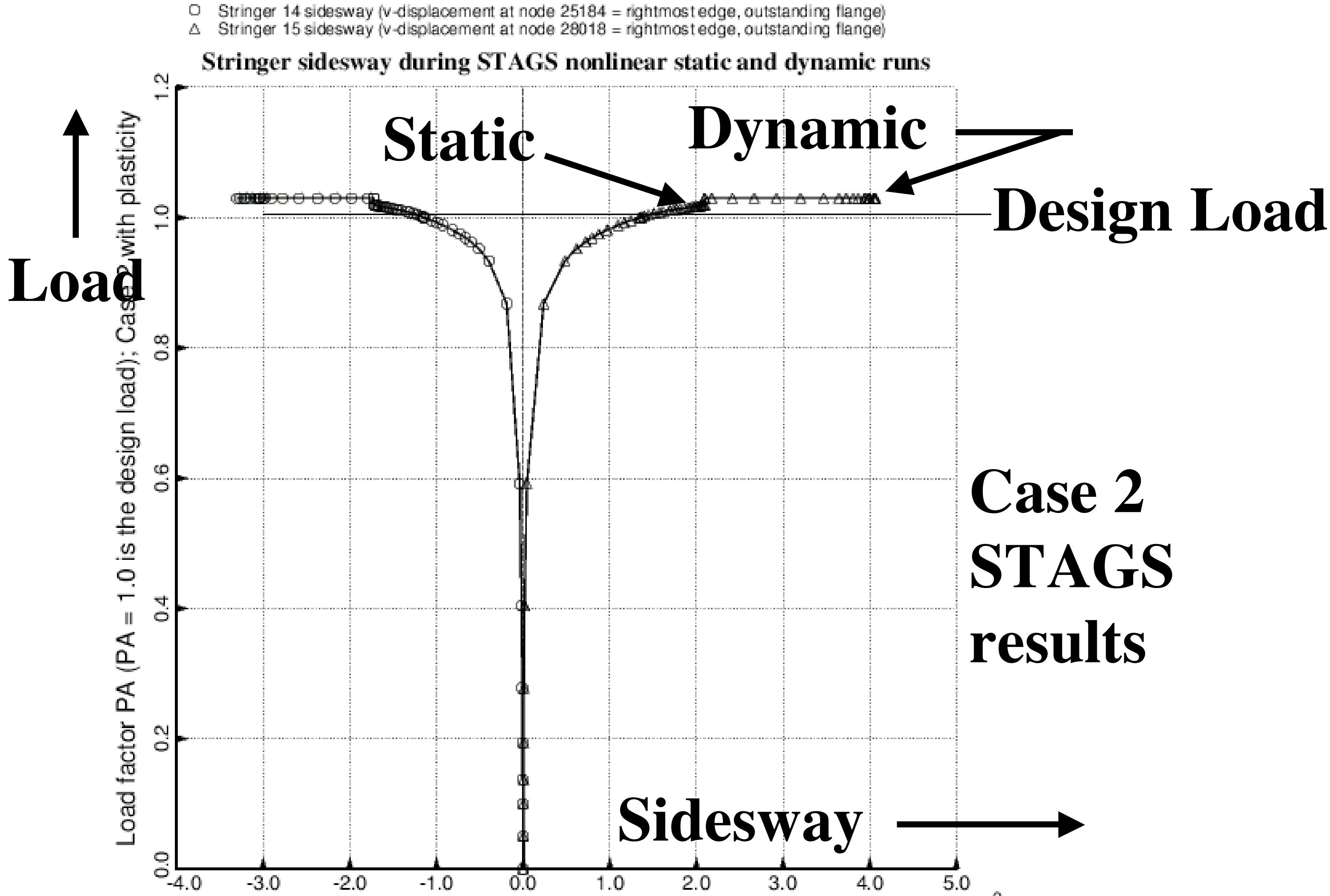
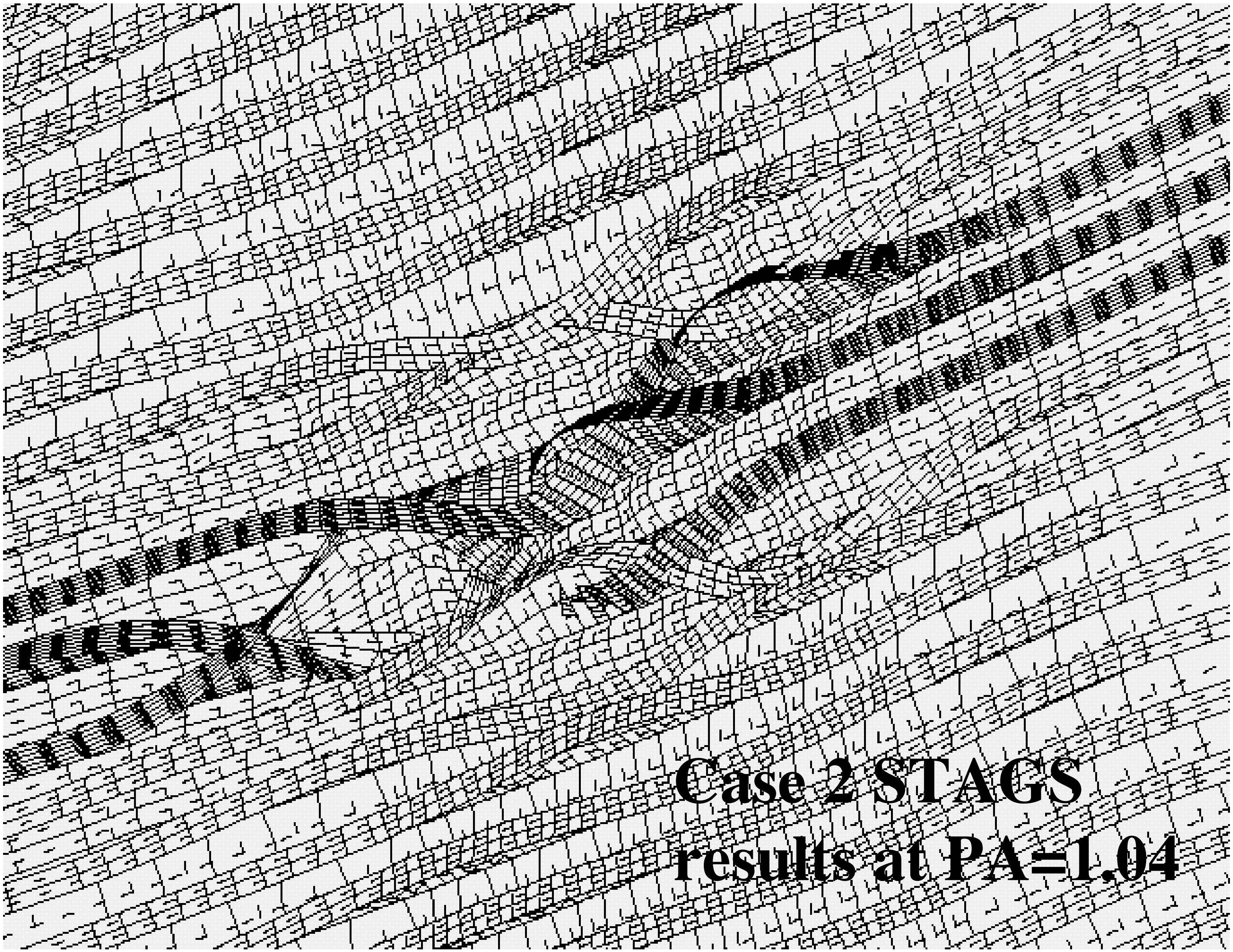


FIG.84 Stringer 14 & 15 sidesway (in.); PA held at 1.03 in dynamic run

Deformation after dynamic run



Summary of talk

1. **The configuration studied here**
2. **Two effects of a general imperfection**
3. **PANDA2 and STAGS**
4. **PANDA2 philosophy**
5. **Seven cases studied here**
6. **The optimization problem**
7. **Buckling and stress constraints**
8. **Seven cases explained**
9. **How the shells fail**
10. **Imperfection sensitivity**

Imperfection sensitivity, Case 5

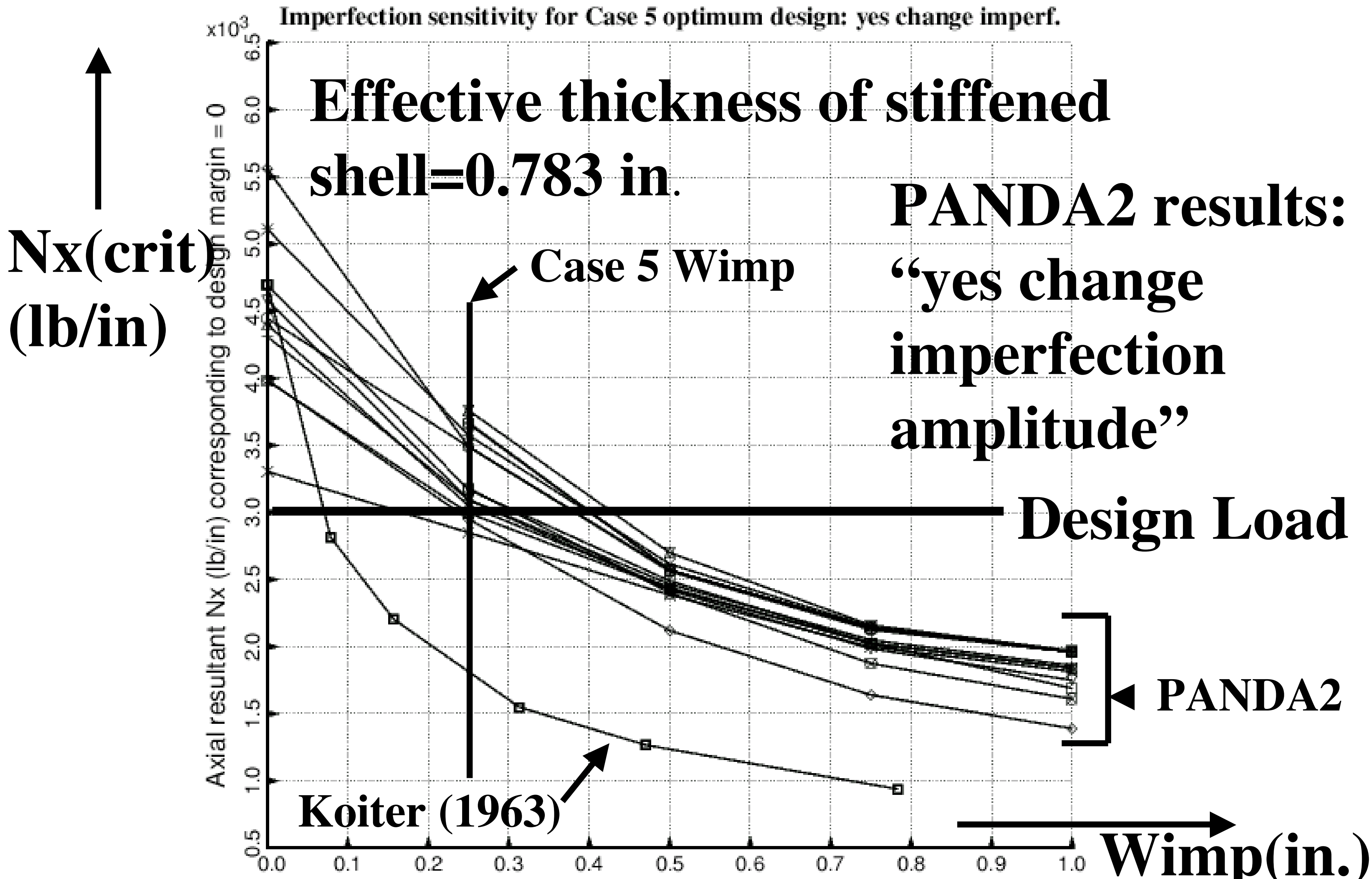


FIG. 97 User-specified initial imperfection amplitude (inches)

Margins from PANDA2 vs Nx

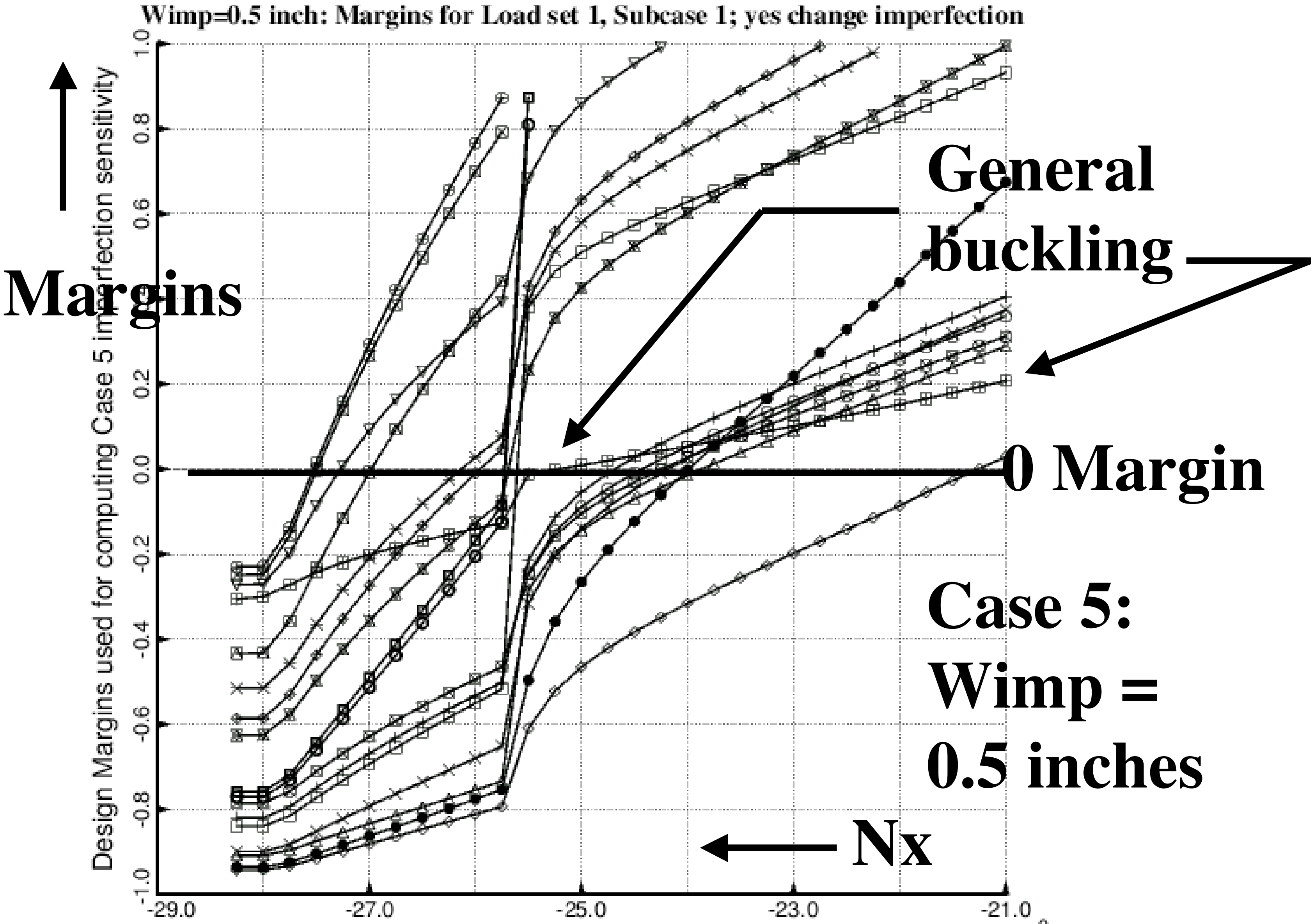


FIG.96 Case 5 imperfection sensitivity study: Axial Load, Nx (lb/in)

Imperfection sensitivity: Case 5

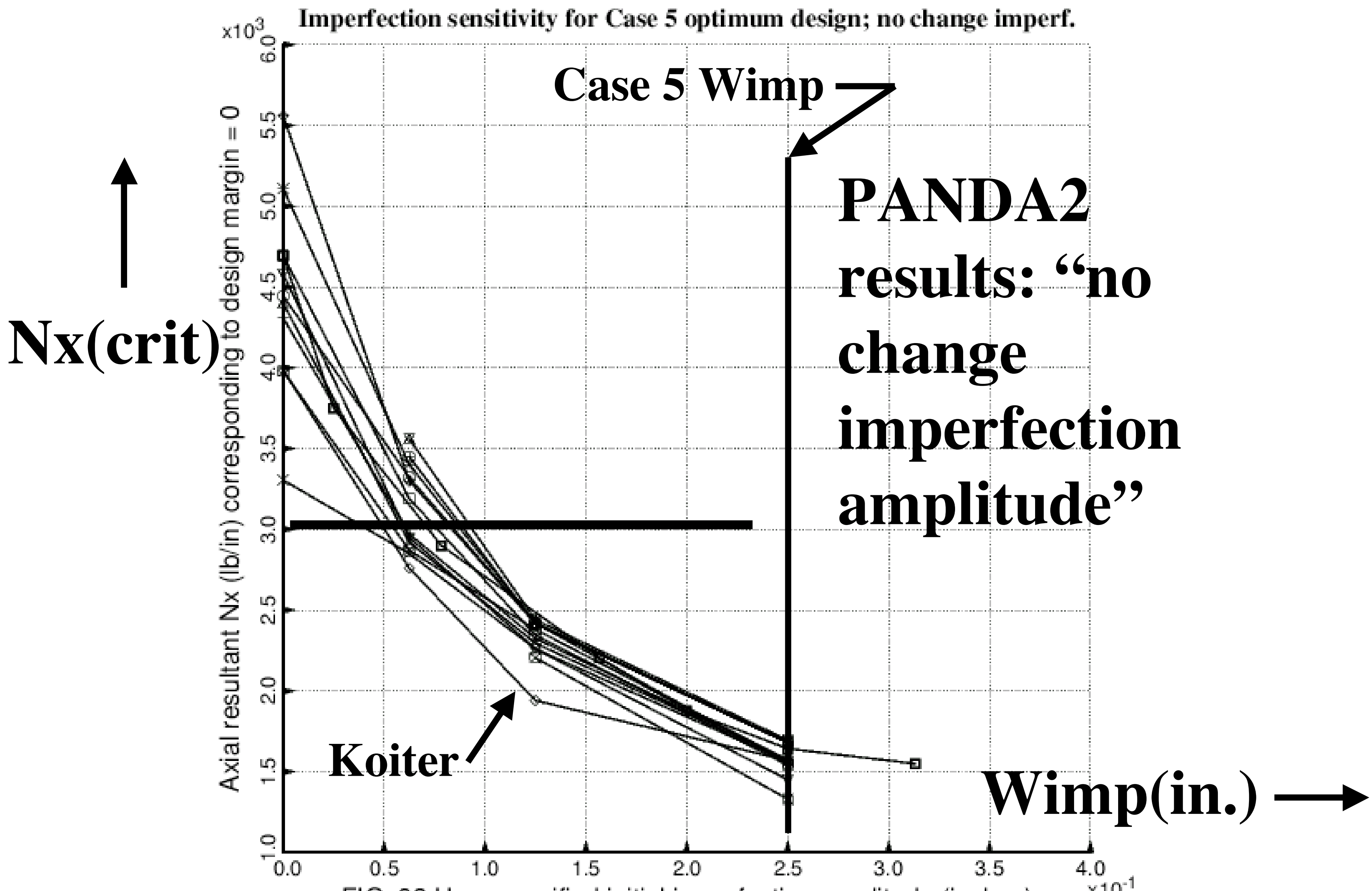


FIG. 98 User-specified initial imperfection amplitude (inches)

Results of survey of Wimp(m,n)

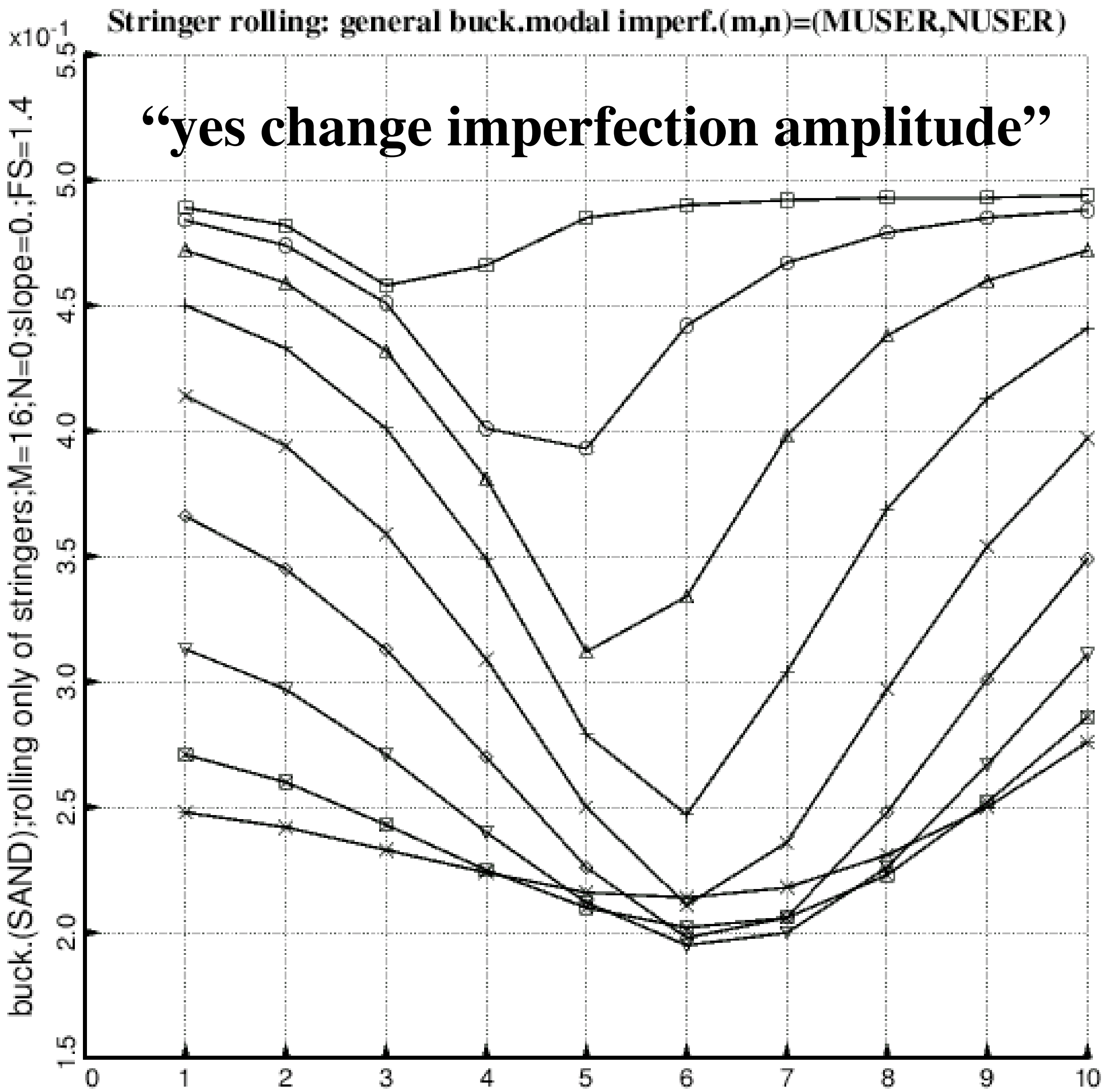


FIG. 15 NUSER=no.of circ.halfwaves over 180 degrees; Case 2 in Table 4

Case 2 stringer rolling margin as function of general buckling modal imperfection shape, A(m) x wimp(m,n)

Conclusions

1. **There is reasonable agreement of PANDA2, STAGS, & BIGBOSOR4**
2. **Use "Yes Koiter" option to avoid too-high stresses.**
3. **Use "Yes change imperfection" option to avoid too-heavy designs.**
4. **There are other conclusions listed in the paper.**