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MINIMUM-WEIGHT DESIGN OF A STIFFENED PANEL VIA PANDA2 AND EVALUATION OF THE OPTIMIZED PANEL VIA STAGS

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(This is an abridged version. See the full-length paper for more: panda2.papers/1995.p2stags.pdf)

ABSTRACT

A minimum-weight design of a T-stiffened panel is found with the PANDA2 program. The panel, subjected to axial compression, in-plane shear, and normal pressure, is designed for service in its locally postbuckled state. A program called STAGSMODEL has been written for transforming output from PANDA2 to input for STAGS, a general-purpose nonlinear finite element code. STAGS is then used to evaluate the optimum design. Agreement between results obtained with PANDA2 and STAGS is reasonable for this very complex, very nonlinear problem. Therefore, PANDA2 qualifies as a preliminary design tool for panels operating in their locally postbuckled states.

INTRODUCTION

There is an extensive literature on the buckling and postbuckling behavior of stiffened plates and shells. This literature covers metallic panels and panels fabricated from laminated composite materials. Leissa [1] has gathered results from almost 400 sources on the buckling and postbuckling behavior of flat and cylindrical panels made of composite material with various stacking sequences and boundary conditions and subjected to various in-plane loads. The emphasis in his survey is on theoretical results, although some experimental results are included. He includes several examples in which the effect of transverse shear deformation is explored. Emphasis is given also to the effects of anisotropy on bifurcation buckling and on postbuckling behavior. Wiggenraad [2] surveys the literature on design of composite panels permitted to buckle locally under operating loads. Included in his survey are damage tolerance, fatigue, and optimization. Arnold and Parekh [3] emphasize in their survey and theoretical development the effect of in-plane shear load on the postbuckling behavior of stiffened, composite cylindrical panels. Surveys of earlier work on buckling of stiffened panels and shells appear in [4-6].

Among the foremost contributors of information about buckling of stiffened shells are Singer and his colleagues at the Technion in Haifa, Israel. In particular, the Baruch-Singer theory [7] for averaging the properties of stiffeners over a shell surface while retaining the important eccentricity effects has been incorporated into many widely used computer programs for the stress, vibration, and buckling analysis of stiffened shells.

The literature in the field of buckling of stiffened shells can be divided into three categories, one in which test results are emphasized, a second in which structural analysis is emphasized, and a third in which optimum designs are obtained. References [8-18] feature test results for plates, shells, and stiffeners made of laminated composite material; [19-26] feature structural analysis with structural properties fixed; and [27-38] feature structural analysis with optimum configurations sought in most cases via the widely used optimizers CONMIN or ADS, written by Vanderplaats and his colleagues [39-41].

This is just a sample of the literature on the subject. The reader is referred to the surveys given in [1-6] and references cited there for other sources.

CAPABILITIES OF PANDA2

PANDA2 finds minimum weight designs of laminated composite flat or curved cylindrical panels or cylindrical shells with stiffeners in one or two orthogonal directions. Stiffeners can be blades, tees, angles, or hats. Truss-core sandwich panels can also be handled. The panels or shells can be loaded by as many as five combinations of in-plane loads, edge moments, normal pressure, and temperature. The material properties can be temperature-dependent. The axial load can vary across the panel. The presence of overall (bowing) imperfections as well as local imperfections in the form of the local buckling mode are included. Constraints on the design include crippling, local and general buckling, maximum displacement under pressure, maximum tensile or compressive stress along the fibers and normal to the fibres in each lamina, and maximum in-plane shear stress in each lamina.

Local and general buckling loads are calculated with use of either closed-form expressions or with use of discretized models of panel cross sections. The discretized model is based on one-dimensional discretization similar to that used in the BOSOR4 computer code [42]. An analysis branch exists in which local postbuckling of the panel skin is accounted for. In this branch a constraint condition that prevents stiffener popoff is introduced into the optimization calculations. The postbuckling theory incorporated into PANDA2 is similar to that formulated by Koiter for panels loaded into the far-post-buckling regime [43].

PANDA2 can be run in five modes: simple analysis of a fixed design, optimization, test simulation, design sensitivity, and load-interaction. Plots of decision variables, margins, and weight versus design iterations can be obtained following use of PANDA2 in the optimization mode. Plots of user-selected behaviors versus load can be obtained following use of PANDA2 in the test-simulation mode. Plots of margins versus a user-selected design variable can be obtained following use of PANDA2 in the design sensitivity mode. Plots of in-plane load interaction curves and margins versus load combination number can be obtained following use of PANDA2 in the load-interaction mode.

There is a processor in the PANDA2 system that automatically generates an input file for the STAGS computer program [22, 23]. Thus, STAGS, which is a general-purpose nonlinear finite element analyzer, can easily be used to check the load-carrying capacity of panels designed with PANDA2.

Note that the theory on which PANDA2 is based is valid only if the panel is either unstiffened or, if stiffeners exist in either or both coordinate directions, there are several of them within the span of the panel. One cannot accurately determine the behavior of a panel with only one stiffener, for example. The panel, if axially stiffened, for example, has a 'field' of equally spaced, identical stringers.

In PANDA2 local buckling behavior is predicted from analysis of a single module that is assumed to repeat several times over the width of the panel. A single discretized module is displayed at the bottom of Fig. 1. The entire panel shown in Fig. 1 has three modules across its width.

A panel module consists of one stiffener plus skin of width equal to the spacing between stiffeners. The single module is considered to be composed of segments, each of which has its own laminated wall construction. The reference surface for each segment of the panel module is the middle surface of that segment. Details concerning the one-dimensional discretization (strip method) are provided in [42].

General instability is predicted from a model in which the stiffeners are 'smeared' in the manner of Baruch and Singer [7] over the width (stringers) and length (rings) of the panel. More details about PANDA2 appear in [44-47].

************* **NOTE** *************
The following text about STAGS (4.0 Description of STAGS [18 – 21) is taken from the PANDA2 2007 paper, **“Optimization of an axially compressed ring and stringer stiffened cylindrical shell with a general buckling modal imperfection”,** AIAA 48th Structures, Structural Dynamics, and Materials Conference, AIAA Paper 2007-2216, 2007
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4.0 DESCRIPTION OF STAGS [18-21] (Most of the text in this section “4.0” was written by Dr. Charles C. Rankin, email address = crankin@rhombuscgi.com. Dr. Rankin is one of the developers of the STAGS general purpose finite element computer program.)

In most of the PANDA2 references listed under [1] and in [22, 23] and in this paper optimum designs obtained by PANDA2 are evaluated later via STAGS models.

STAGS (**ST**ructural **A**nalysis of **G**eneral **S**hells [18–21]) is a finite element code for **general-purpose nonlinear analysis of stiffened shell structures of arbitrary shape** and complexity. Its capabilities include stress, stability, vibration, and transient analyses with both material and geometric nonlinearities permitted in all analysis types. STAGS includes enhancements, such as a higher order thick shell element, more advanced nonlinear solution strategies, and more comprehensive post-processing features such as a link with STAPL, a postprocessor used to generate many of the figures in this paper: figures that display the STAGS model, such as Figs. 1a-c and 2, for example.

Research and development of STAGS by Rankin, Brogan, Almroth, Stanley, Cabiness, Stehlin and others of the Computational Mechanics Department of the Lockheed Martin Advanced Technology Center has been under continuous sponsorship from U.S. government agencies for the past 40 years. During this time particular emphasis has been placed on improvement of the capability to solve difficult nonlinear problems such as the prediction of the behavior of axially compressed stiffened panels loaded far into their locally postbuckled states. STAGS has been extensively used worldwide for the evaluation of stiffened panels and shells loaded well into their locally postbuckled states. See [21], for example.

A large rotation algorithm that is independent of the finite element library has been incorporated into STAGS [20B]. With this algorithm there is no artificial stiffening due to large rotations. The finite elements in the STAGS library do not store energy under arbitrary rigid-body motion, and the first and second variations of the strain energy are consistent. These properties lead to quadratic convergence during Newton iterations.

Solution control in nonlinear problems includes specification of load levels or use of the **advanced Riks-Crisfield path parameter [21]** that enables traversal of limit points into the post-buckling regime. Two load systems with different histories (Load Sets A and B) can be defined and controlled separately during the solution process. Flexible restart procedures permit switching from one strategy to another during an analysis, including shifts from bifurcation buckling to nonlinear collapse analyses and back and shifts from static to transient and transient to static analyses with modified boundary conditions and loading. STAGS provides solutions to the generalized eigenvalue problem for **buckling** and vibration **from a linear (Fig. 24) or nonlinear (Figs. 26, 27) stress state.**

Quadric surfaces can be modeled with minimal user input as individual substructures called **"shell units"** in which the analytic geometry is represented exactly. "Shell units" can be connected along edges or internal grid lines with partial or complete compatibility. In this way complex structures can be assembled from relatively simple units. Alternatively, a structure of arbitrary shape can be modeled with use of an "element unit".

Geometric imperfections can be generated automatically in a variety of ways, thereby permitting imperfection-sensitivity studies to be performed. For example, **imperfections can be generated by superposition of several buckling modes determined from previous linear and nonlinear STAGS analyses of a given case**. (See Parts 4-7 of Table 9 and Figs. 24, 26, and 27, for example).

A variety of material models is available, including both plasticity and creep. STAGS handles isotropic and anisotropic materials, including composites consisting of up to 60 layers of arbitrary orientation. Four plasticity models are available, including isotropic strain hardening, the White Besseling (mechanical sublayer model), kinematic strain hardening, and deformation theory.

Two independent load sets, each composed from simple parts that may be specified with minimal input, define a spatial variation of loading. Any number of point loads, prescribed displacements, line loads, surface tractions, thermal loads, and "live" pressure (hydrostatic pressure which remains normal to the shell surface throughout large deformations) can be combined to make a load set. For transient analysis the user may select from a menu of loading histories, or a general temporal variation may be specified in a user-written subroutine.

Boundary conditions (B.C.) may be imposed either by reference to certain standard conditions or by the use of single- and multi-point constraints. Simple support, symmetry, anti-symmetry, clamped, or user-specified B.C. can be defined on a "shell unit" edge. Single-point constraints that allow individual freedoms to be free, fixed, or a prescribed non-zero value may be applied to grid lines and surfaces in "shell units" or "element units". A useful feature for buckling analysis allows these constraints to differ for the prestress and eigenvalue analyses. Langrangian constraint equations containing up to 100 terms may be defined to impose multi-point constraints.

STAGS has a variety of finite elements suitable for the analysis of stiffened plates and shells. Simple four node quadrilateral plate elements with a cubic lateral displacement field (called "410" and "411" elements) are effective and efficient for the prediction of postbuckling thin shell response. A linear (410) or quadratic (411) membrane interpolation can be selected. For thicker shells in which transverse shear deformation is important **(and for the thin-shell cases described in this paper),** STAGS provides the **Assumed Natural Strain (ANS) nine node element (called "480" element).** A two node beam element compatible with the four node quadrilateral plate element is provided to simulate stiffeners and beam assemblies. Other finite elements included in STAGS are described in the STAGS literature [18-21].

5.0 WHY MUST STAGS OR SOME OTHER GENERAL-PURPOSE CODE BE USED TO CHECK OPTIMUM DESIGNS FROM PANDA2?

PANDA2 uses many approximations and "tricks" in models for stress and buckling. Some of these are described in Sections 8 - 10 of [1K]. For example, knockdown factors are derived to compensate for the inherent unconservativeness of smearing stiffeners [1K] and to account for the effects of transverse shear deformation [1A]. The effect of initial local, inter-ring, and general imperfections in the shapes of critical local, inter-ring, and general buckling modes are accounted for in an approximate manner as described in [1D] and [1E]. The distribution of prebuckling stress resultants in the various segments of a discretized skin-stringer module [1A and Fig. 4 in this paper] and of a "skin"-ring discretized module [1G] of an imperfect and therefore initially bent stiffened shell are approximate. For example, stabilizing (**tensile**) axial and hoop resultants in the panel skin that arise from prebuckling bending of an initially globally imperfect shell are neglected in order to avoid the production of unconservative optimum designs.

PANDA2 has been developed over the years with the philosophy that the use of many relatively simple approximate models will lead to optimum designs that are reasonable and for which no complicated "combined" modes of failure will inadvertently be missed. Because of the approximate nature of these multiple simple PANDA2 models, one **MUST** use STAGS or some other general-purpose finite element code to evaluate optimum designs obtained by PANDA2.

The particular advantage of using STAGS is that there exists a PANDA2 processor called STAGSUNIT [1**I**] that automatically generates input files, ***.bin** and ***.inp**, for STAGS. As described in [1**I**], the processor STAGSUNIT is written in such a way that "patches" (sub-domains) of various portions of a complete panel or shell can be analyzed with STAGS. **The correct prebuckled state of a perfect panel is preserved independently of the size of the "patch" to be included in the STAGS sub-domain model**. The minimum size "patch" must contain at least one stiffener spacing in each coordinate direction. In a stringer-stiffened shell stringers are always included along the two straight edges of the "patch". There may or may not be rings running along the two curved edges of the "patch", depending on input to STAGSUNIT provided by the user of PANDA2. **Stiffeners that run along the four boundaries of the "patch" have half the stiffness and half the loading of those that lie within the "patch".** It is primarily this characteristic of the STAGS models produced by STAGSUNIT that preserves the correct prebuckled state of the "patch" independently of its size.

The STAGS models are constructed by the PANDA2 processor, STAGSUNIT, in such a way that all stiffeners are connected only to the panel skin. That is, where stiffeners intersect they simply pass through one another with no constraints between them along their lines of intersection, if any. This is a conservative model with respect to buckling. The same model is used in PANDA2. The STAGSUNIT processor can generate models in which all stiffeners may be composed of shell units, one or more sets of stiffeners may be composed of beams, or one or more sets of stiffeners may be "smeared" as prescribed by Baruch and Singer [12].

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[18] Almroth, B. O. and Brogan, F. A., "The STAGS computer code", NASA CR-2950, NASA Langley Research Center, Hampton, VA, 1978.

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[20] (**A**) Rankin, C.C., Stehlin, P., and Brogan, F.A., "Enhancements to the STAGS computer code", NASA CR-4000, NASA Langley Research center, Hampton, VA, 1986. See also: (**B**) Rankin, C.C, “Application of Linear Finite Elements to Finite Strain Using Corotation.” AIAA Paper AIAA-2006-1751, 47th AIAA Structures, Structural Dynamics and Materials Conference, May 2006; (**C**) Rankin, C.C., Brogan, F.A., Loden, W.A., Cabiness, H.D., “STAGS User Manual – Version 5.0,” Rhombus Consultants Group, Inc., Palo Alto, CA, Revised January 2005 (on-line). Previously Report No. LMSC P032594, Lockheed Martin Missiles and Space Company, Palo Alto, CA, June 1998; (**D**) Rankin, C.C., “The use of shell elements for the analysis of large strain response, AIAA Paper 2007-2384, 48th AIAA Structures, Structural Dynamics and Materials Conference, Hawaii, April 2007.

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[1] Bushnell, D., et al (**A**) "PANDA2 - Program for minimum weight design of stiffened, composite, locally buckled panels", Computers and Structures, Vol. 25 (1987) pp. 469-605. See also: (**B**) "Theoretical basis of the PANDA computer program for preliminary design of stiffened panels under combined in-plane loads", Computers and Structures, v. 27, No. 4, pp 541-563, 1987; (**C**) "Optimization of composite, stiffened, imperfect panels under combined loads for service in the postbuckling regime", Computer Methods in Applied Mechanics and Engineering, Vol. 103, pp 43-114, 1993; (**D**) "Recent enhancements to PANDA2" 37th AIAA Structures, Dynamics, and Materials (SDM) Conference, April 1996; (**E**) "Approximate method for the optimum design of ring and stringer stiffened cylindrical panels and shells with local, inter-ring, and general buckling modal imperfections", Computers and Structures, Vol. 59, No. 3, 489-527, 1996, with W. D. Bushnell; (**F**) "Optimum design via PANDA2 of composite sandwich panels with honeycomb or foam cores", AIAA Paper 97-1142, AIAA 38th SDM Conference, April 1997; (**G**) "Additional buckling solutions in PANDA2", AIAA 40th SDM Conference, p 302-345, April 1999, with H. Jiang and N. F. Knight, Jr.; (**H**) "Minimum-weight design of a stiffened panel via PANDA2 and evaluation of the optimized panel via STAGS", Computers and Structures, Vol. 50, 569-602 (1994); (**I**) "Optimization of perfect and imperfect ring and stringer stiffened cylindrical shells with PANDA2 and evaluation of the optimum designs with STAGS", AIAA Paper 2002-1408, pp 1562-1613, Proceedings of the 43rd AIAA SDM Meeting, April, 2002, with C. Rankin; (**J**) “Optimum design of stiffened panels with substiffeners, AIAA Paper 2005-1932, AIAA 46th SDM Conference, April 2005, with C. Rankin; (**K**) “Difficulties in optimization of imperfect stiffened cylindrical shells, AIAA Paper 2006-1943, AIAA 47th SDM Conference, April 2006, with C. Rankin; (**L**).../panda2/doc/panda2.news, a continually updated file distributed with PANDA2 that contains a log of all significant modifications to PANDA2 from 1987 on; (**M**) “Optimization of Stiffened Panels in Which Mode Jumping is Accounted For,” AIAA Paper No. AIAA 97-1141, AIAA 38th SDM Conference, April 1997, with C. Rankin and E. Riks.; (**N**) “Global Optimum Design Of Externally Pressurized Isogrid Stiffened Cylindrical Shells With Added T-Rings,” International Journal of Non-Linear Mechanics Vol. 37, pp. 801–831, 2002; (**O**) “Optimization of an axially compressed ring and stringer

stiffened cylindrical shell with a general buckling modal imperfection," AIAA Paper No. AIAA 2007-2216, AIAA 48th SDM Conference, April, 2007; (**P**) "Optimization of panels with riveted Z-shaped stiffeners via PANDA2", in *Advances in the Mechanics of Plates and Shells,* Durban, D, Givoli, D., and Simmonds, J.G., Eds, Kluwer Academic Publishers, pp 79-102, 2001; (**Q**) "Global Optimum Design Of Externally Pressurized Isogrid Stiffened Cylindrical Shells With Added T-Rings," International Journal of Non-Linear Mechanics Vol. 37, pp. 801–831, 2002.

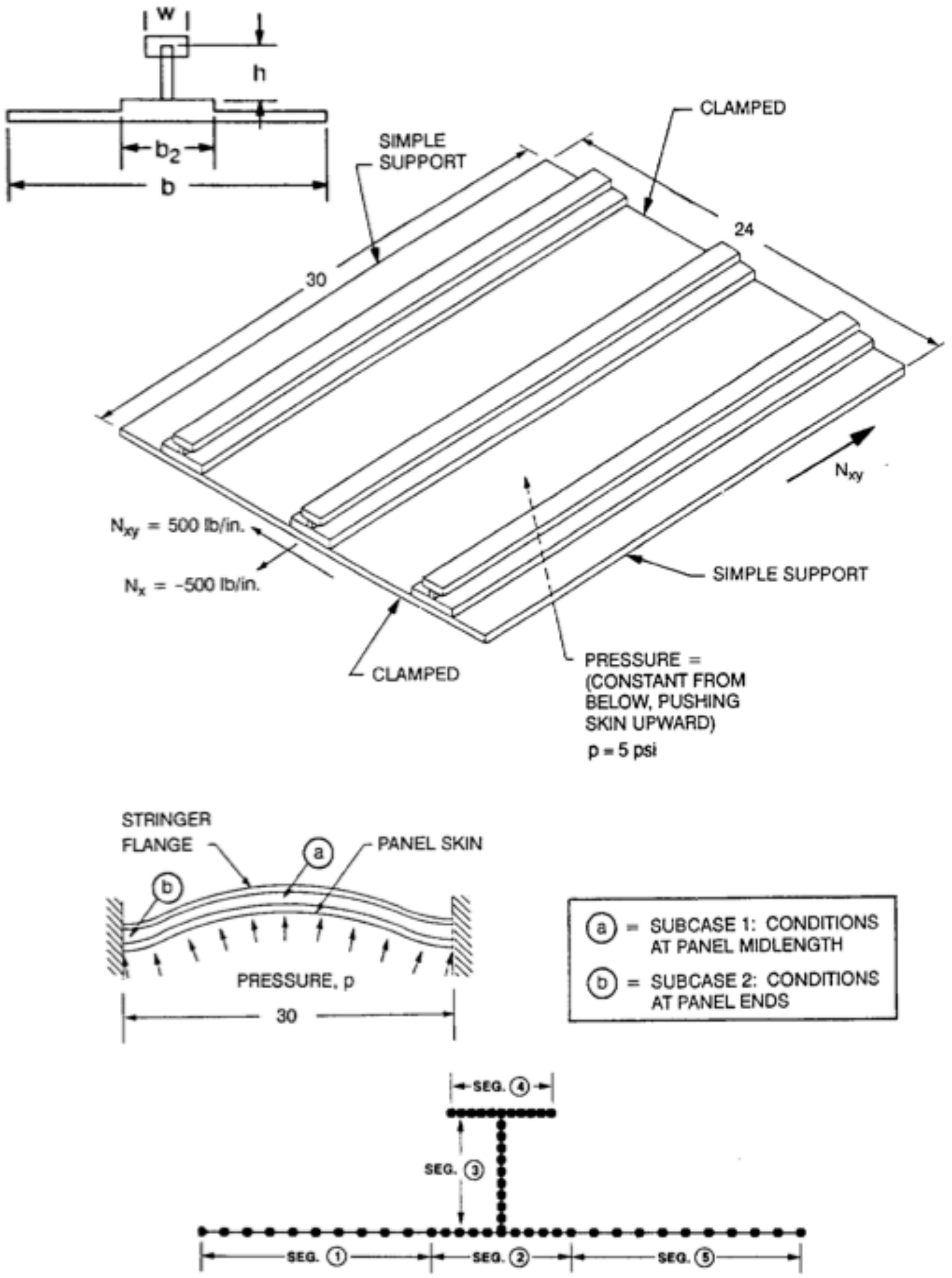
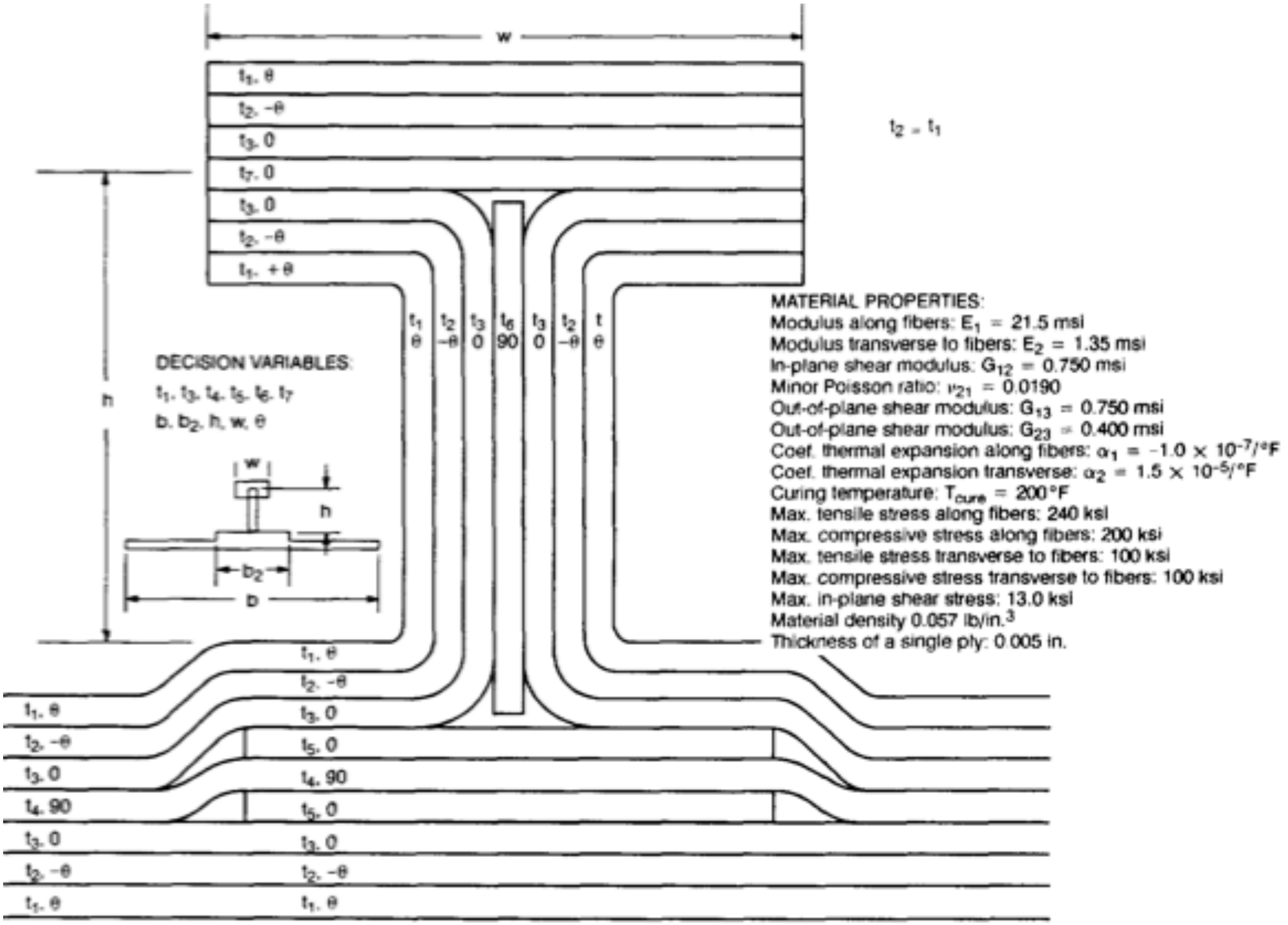


Fig. 1 Panel geometry, loading, boundary conditions, and panel module discretization for the T-stiffened panel (from Computers & Structures, Vol.55, No. 5, pp. 819-856, 1995)



DECISION VARIABLES:
t_1, t_3, t_4, t_5, t_6, t_7
b, b_2, h, w, θ

MATERIAL PROPERTIES:
Modulus along fibers: $E_1 = 21.5$ msi
Modulus transverse to fibers: $E_2 = 1.35$ msi
In-plane shear modulus: $G_{12} = 0.750$ msi
Minor Poisson ratio: $\nu_{21} = 0.0190$
Out-of-plane shear modulus: $G_{13} = 0.750$ msi
Out-of-plane shear modulus: $G_{23} = 0.400$ msi
Coef. thermal expansion along fibers: $\alpha_1 = -1.0 \times 10^{-7}/°F$
Coef. thermal expansion transverse: $\alpha_2 = 1.5 \times 10^{-5}/°F$
Curing temperature: $T_{cure} = 200°F$
Max. tensile stress along fibers: 240 ksi
Max. compressive stress along fibers: 200 ksi
Max. tensile stress transverse to fibers: 100 ksi
Max. compressive stress transverse to fibers: 100 ksi
Max. in-plane shear stress: 13.0 ksi
Material density 0.057 lb/in.^{3}
Thickness of a single ply: 0.005 in.

Fig. 2 Composite panel layup geometry, decision variables, and material properties. (from Computers & Structures, Vol.55, No. 5, pp. 819-856, 1995)

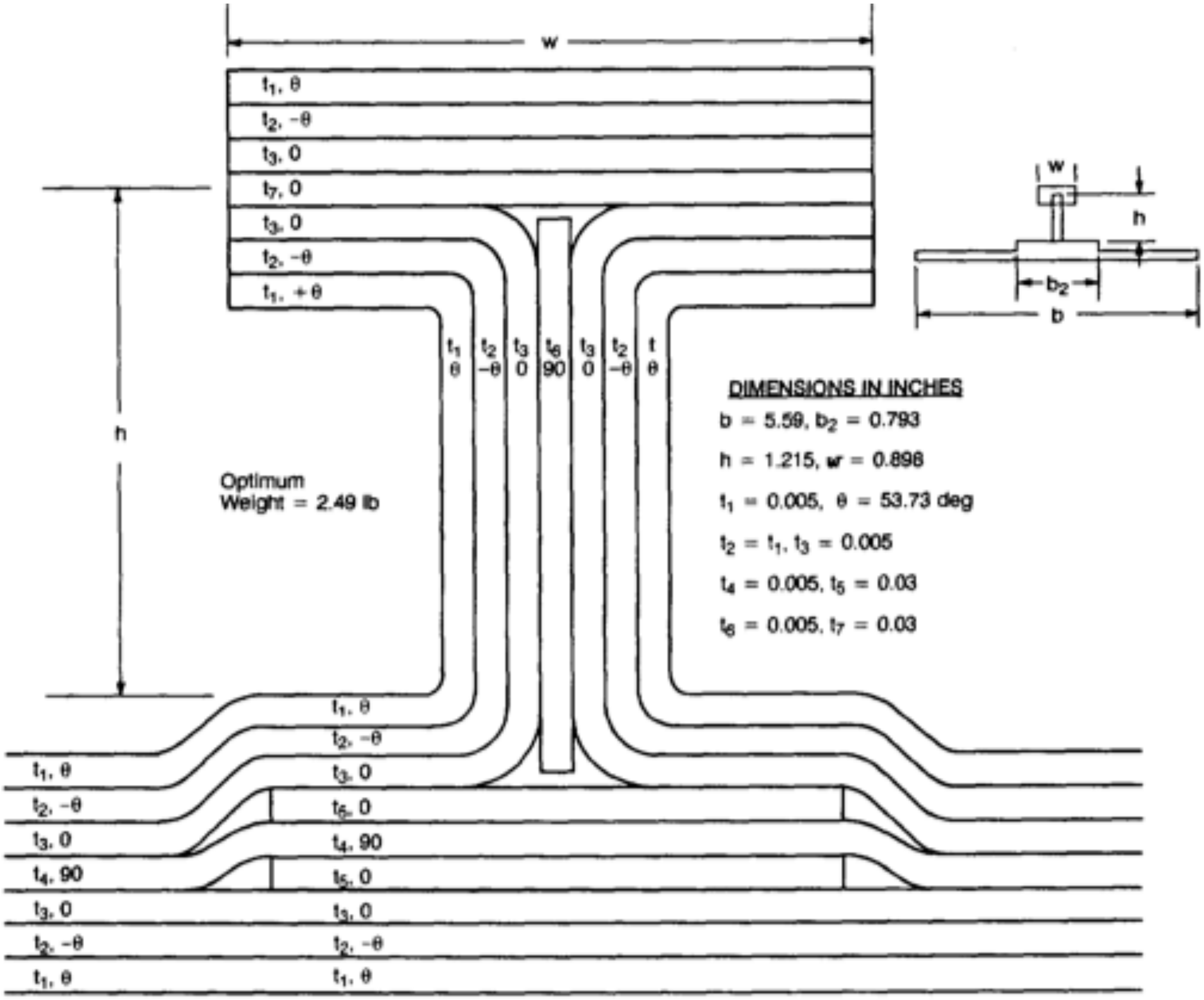


Fig. 3 Optimum design of the T-stiffened panel found with the use of PANDA2. (from Computers & Structures, Vol.55, No. 5, pp. 819-856, 1995)

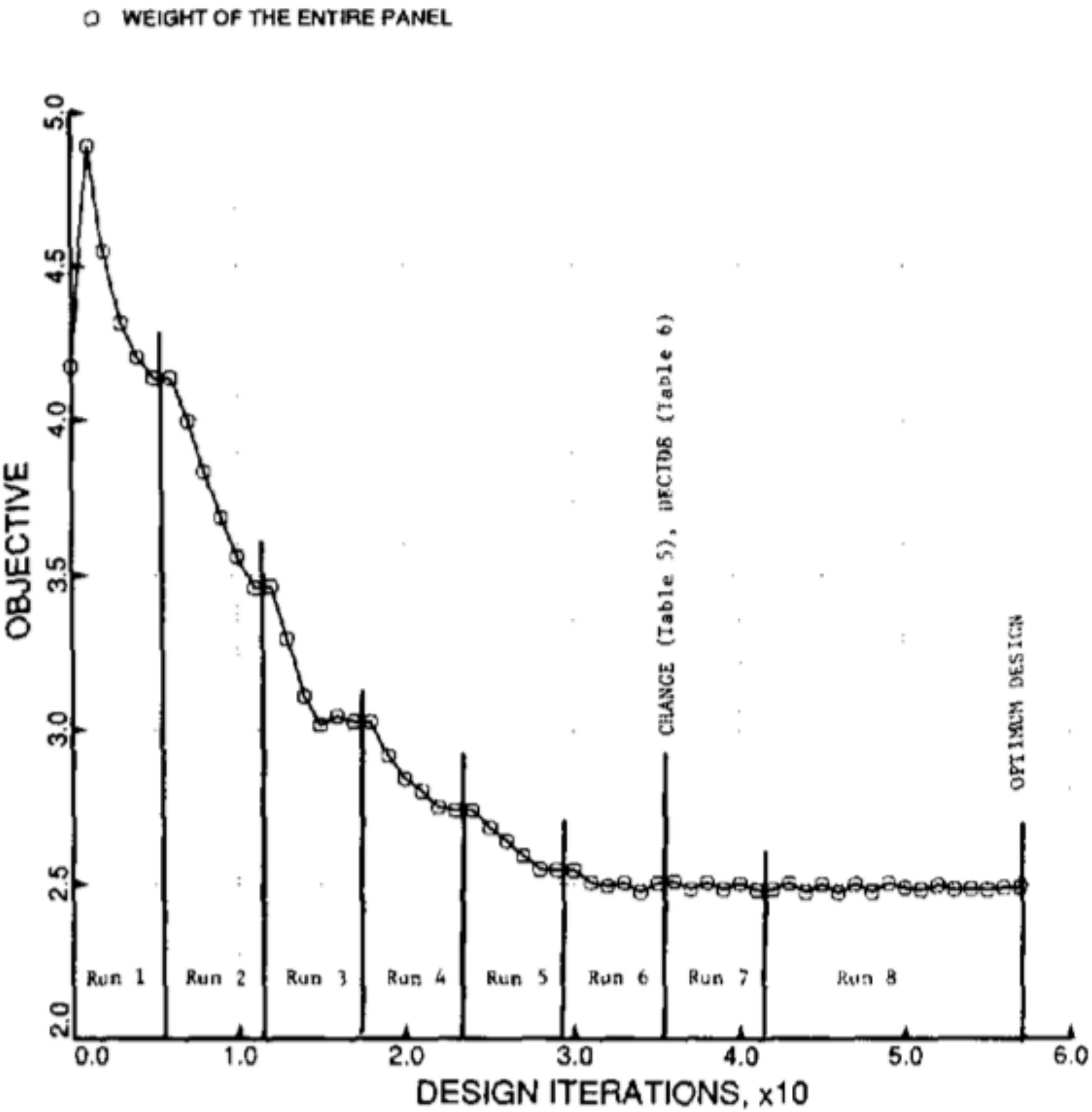


Fig. 4 Objective (lb) for the eight PANDA2 optimization runs (8 executions of the PANDA2 processor called “PANDAOPT”) required for the determination of an optimum design. At the time the results presented here were published the PANDA2 processor called “SUPEROPT” did not yet exist. (from Computers & Structures, Vol.55, No. 5, pp. 819-856, 1995)

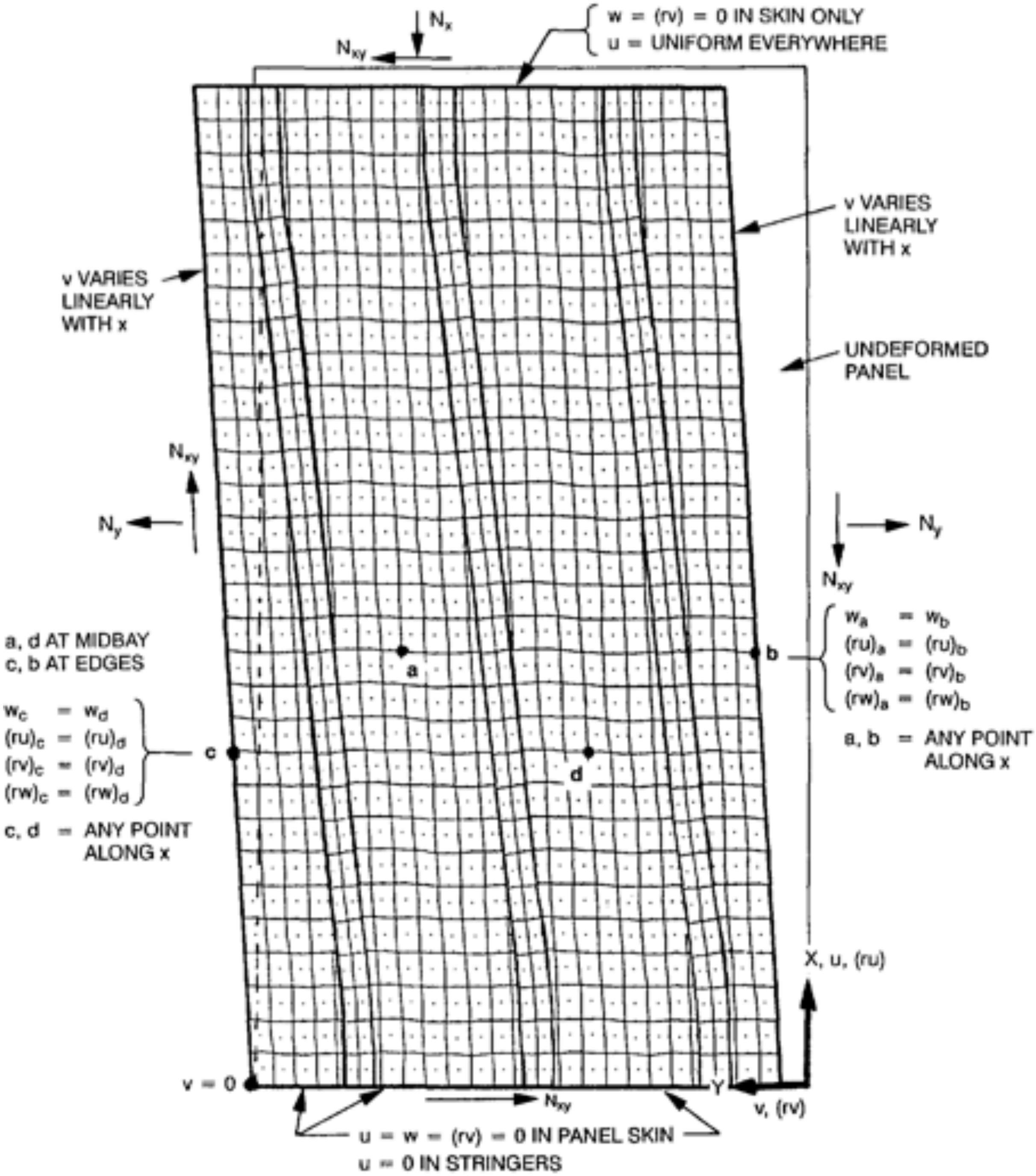


Fig. 25 Plan view of undeformed and deformed STAGS finite element model of the T-stiffened panel. The in-plane loading components, Nx and Nxy, are shown, as well as the boundary conditions for the case in which the two edges parallel to the stringers (longitudinal edges) are prevented from warping in the plane of the panel skin. (from Computers & Structures, Vol.55, No. 5, pp. 819-856, 1995)

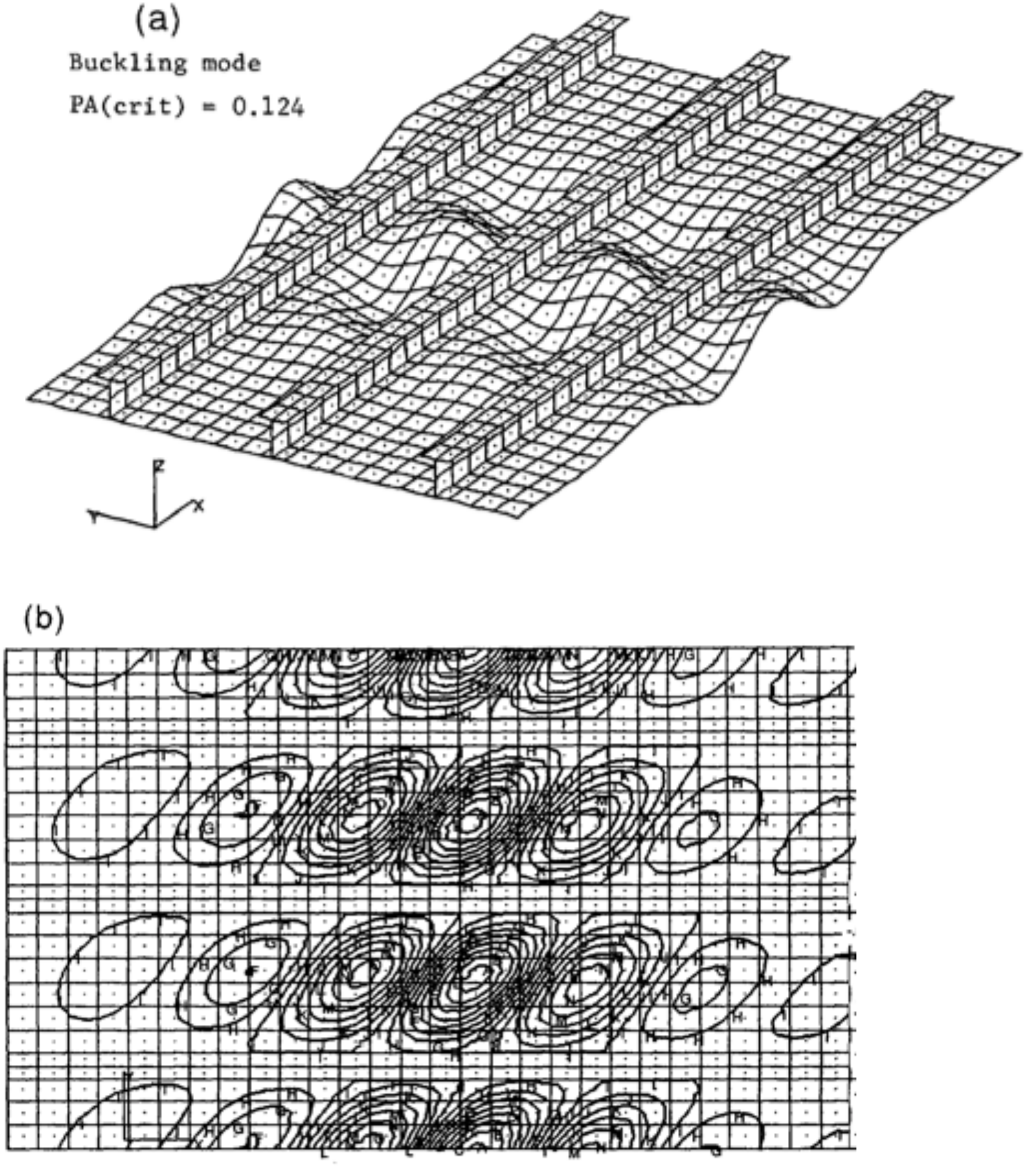


Fig. 26 STAGS prediction of buckling mode and critical load factor from linear bifurcation buckling theory. This mode shape is used as an initial imperfection in the nonlinear equilibrium STAGS analysis. (a) Three-dimensional view of buckling mode; (b) contour plot that shows the slope of the nodal lines of the local buckling mode and its axial wavelength. (from Computers & Structures, Vol.55, No. 5, pp. 819-856, 1995)

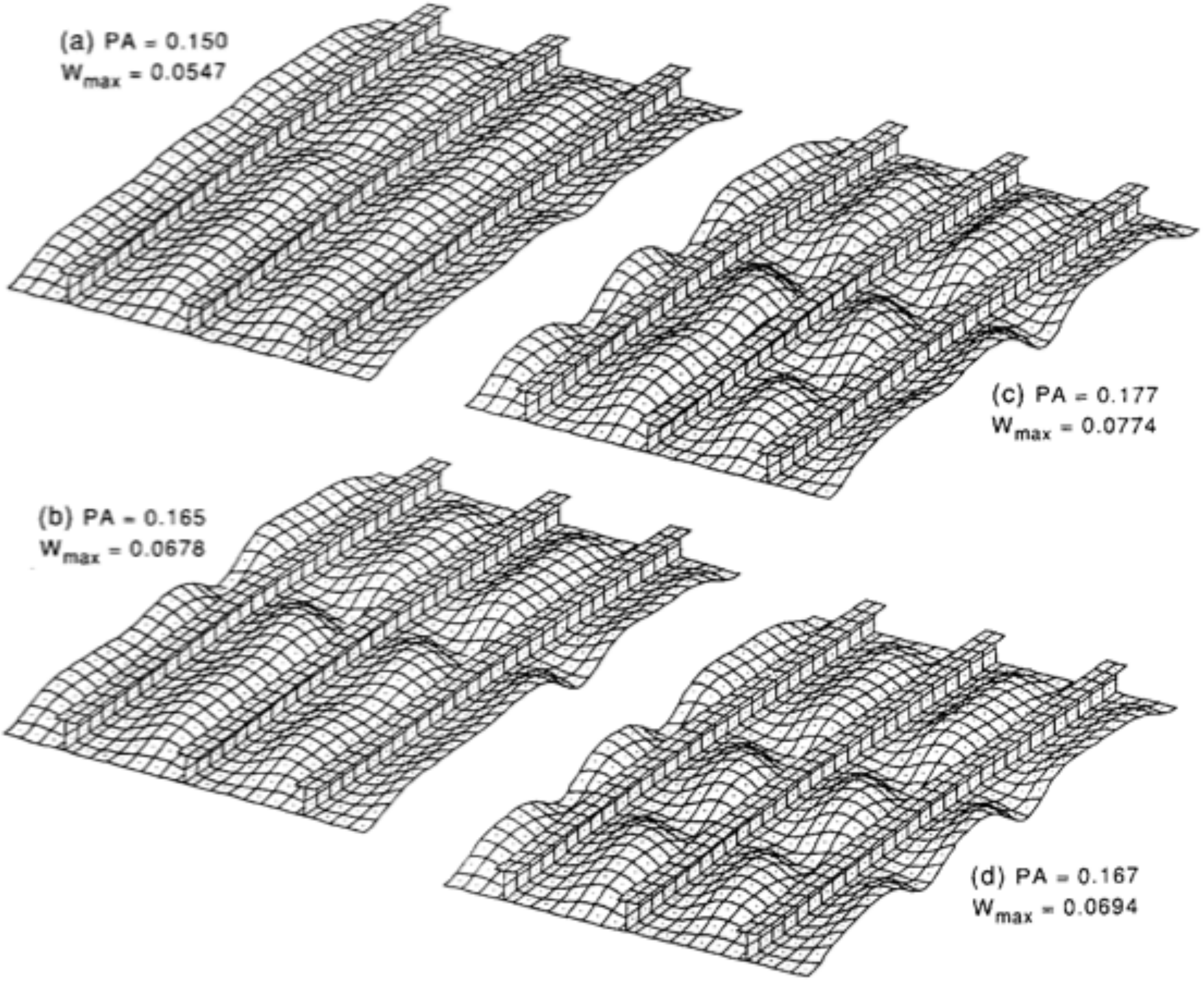


Fig. 28 Deformed panel at load step (a) 7, (b) 19, (c) 29, (d) 44. The “pillowing” between stringers is caused by the normal pressure. The presence of the initial imperfection shown in Fig. 25 gives rise to the axial non-uniformity of the “pillowing” in (a). Note that the load factor, PA, does not increase monotonically (see the next figure) and that the post-locally-buckled deformation pattern develops an additional axial half-wave from states (b) to (c) to (d). In a load-control test this panel would experience a “mode jump” from state (c) at load factor, PA = 0.177 to state (d) at PA = 0.167. From Computers & Structures, Vol. 55, No. 5, pp. 819 – 856, 1995.

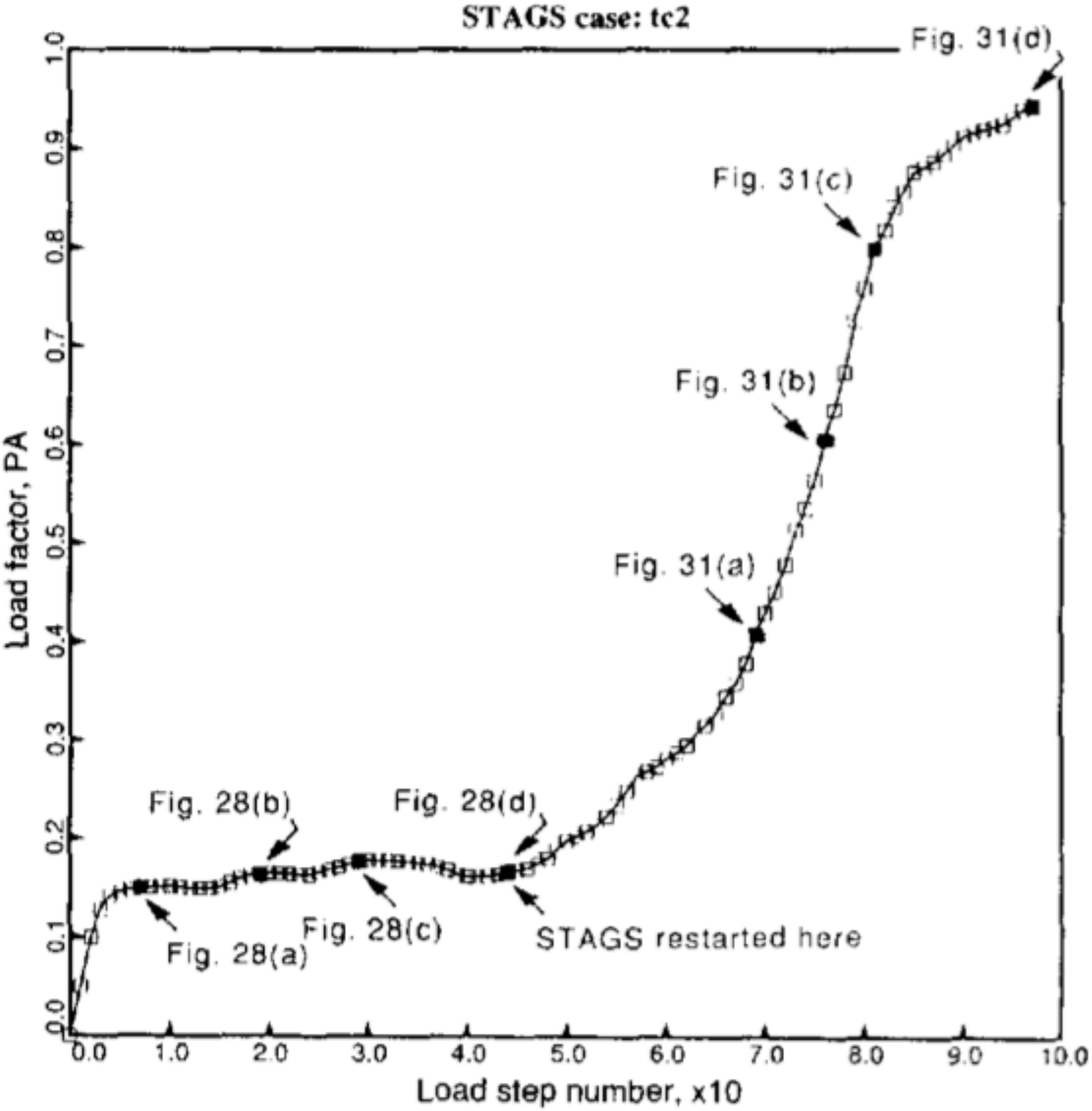


Fig. 29 Results from two successive STAGS nonlinear runs. In a load-controlled experiment the "mode jump" referred to in the previous figure caption would occur between the states 28(c) and 28(d) because the applied load at state 28(d) is lower than that at state 28(c). The deformed states of the panel are displayed in Figs. 28 and 31. The load factor, PA = 1.0 is the design load. Static nonlinear equilibrium solutions were found up to PA = 0.943. From Computers & Structures, Vol. 55, No. 5, pp. 819 – 856, 1995.

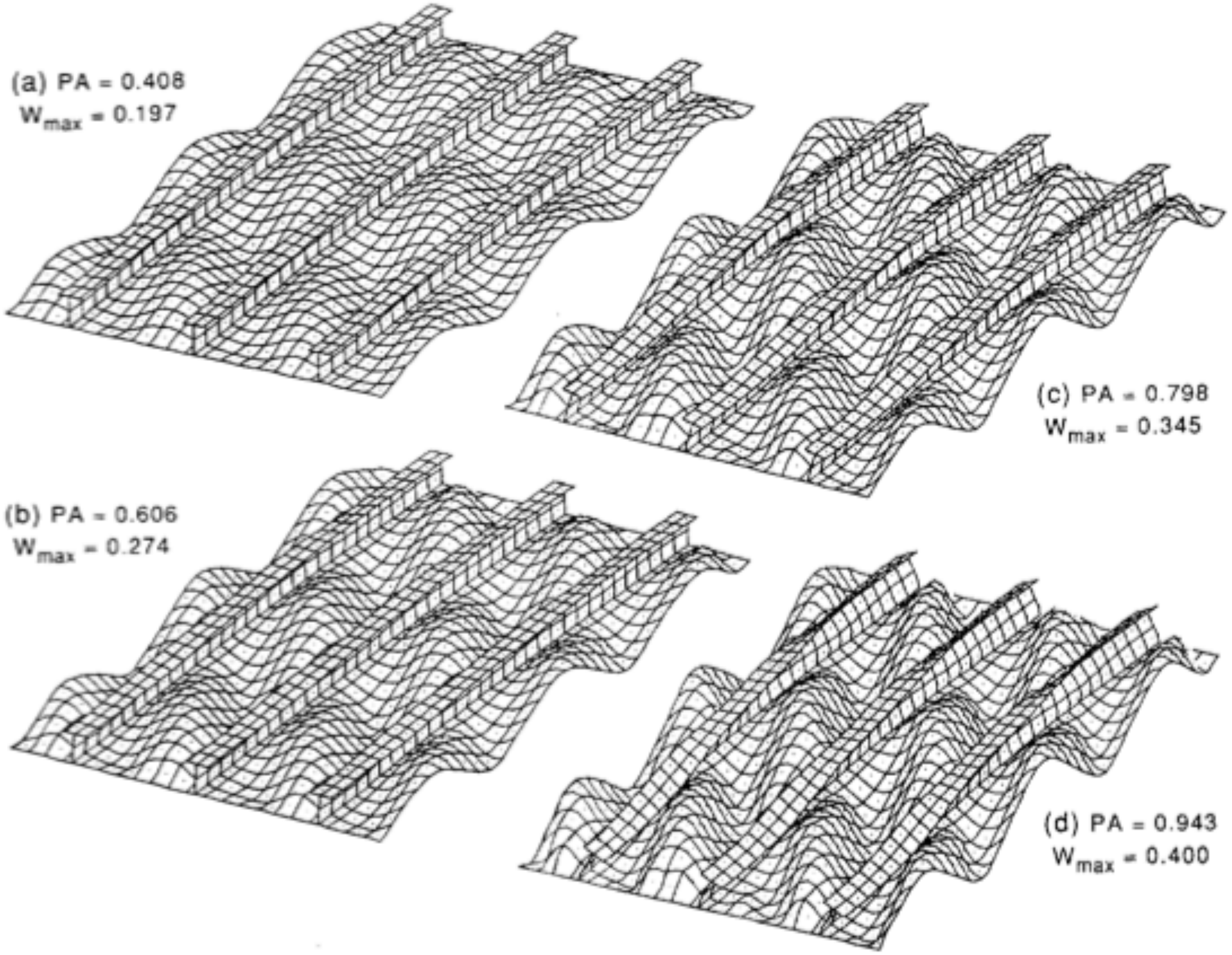


Fig. 31 How the panel deforms with increasing load factor PA. The scale factor used for the deformation in this figure is one fourth of that used in Fig. 28. (from Computers & Structures, Vol.55, No. 5, pp. 819-856, 1995)

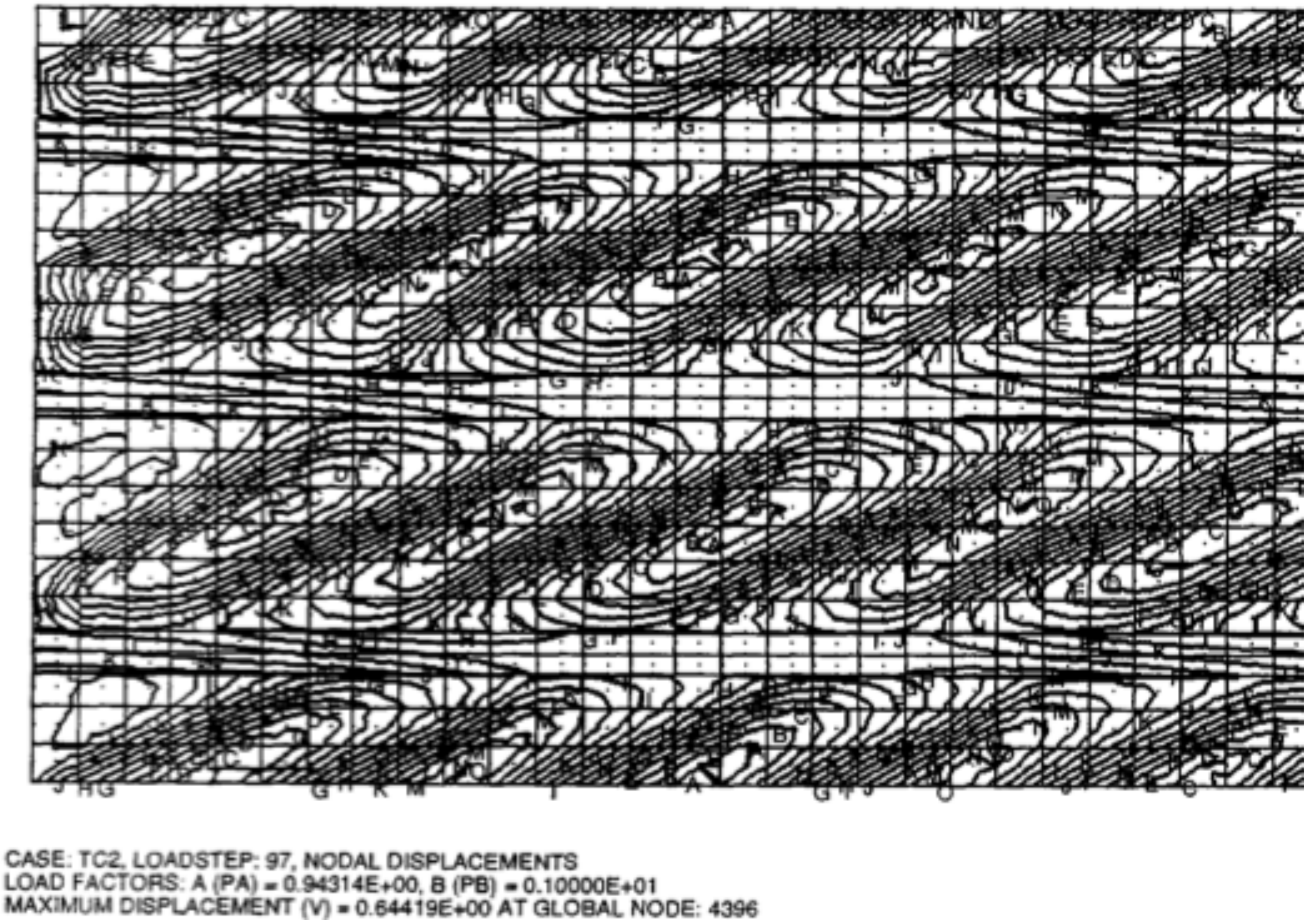


Fig. 33 Contours of normal displacement w at the highest load factor reached in the nonlinear STAGS run: PA = 0.943. From Computers & Structures, Vol. 55, No. 5, pp. 819 – 856, 1995