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OPTIMIZATION OF COMPOSITE, STIFFENED, IMPERFECT PANELS UNDER COMBINED LOADS FOR SERVICE IN THE POSTBUCKLING REGIME

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(This is an abridged version. See the full-length paper for more: panda2.papers/1993.postbuck.pdf)

ABSTRACT

Local buckling and postbuckling of panels stiffened by stringers and rings and subjected to combined in-plane loads is explored with the use of a single module model that consists of one stringer and a width of panel skin equal to the stringer spacing. The cross-section of the skin-stringer module is discretized and the displacement field is assumed to vary trigonometrically in the axial direction. Local imperfections in the form of local buckling modes and overall initial axial bowing of the panel are included in the numerical model. The local postbuckling theory, based on early work of Koiter, is formulated in terms of buckling modal coefficients derived from integrals of products of the discretized displacement field and its derivatives. The principle of minimum potential energy is used to derive nonlinear algebraic equilibrium equations in terms of four unknowns, the amplitude **f** of the postbuckling displacement field, a postbuckling 'flattening' parameter **a**, the slope **m** of the nodal lines in the postbuckling displacement field, and an axial wavelength parameter **N**. The nonlinear equations are solved by Newton's method. An elaborate strategy is introduced in which the incidence of non-convergence is minimized by removal and re-introduction of the unknowns **f, a, m, N** on a one-by-one basis. This nonlinear theory has been implemented in the PANDA2 computer program, which finds minimum-weight designs of stiffened panels made of composite materials. PANDA2 is used to find the minimum weight of a cylindrical panel made of isotropic material with rectangular stringers mounted on thickened bases. The panel is optimized for three load sets, axial compression with negative axial bowing, axial compression with positive axial bowing, and combined axial compression and in-plane shear with no axial bowing. The optimum design is loaded well beyond local buckling for each load set. Critical margins of the optimized design include maximum allowable effective stress, bending-torsion buckling and general instability. The optimum design is evaluated by application of a general-purpose finite element program, STAGS, to finite element models generated by PANDA2 for each of the three loadsets. The agreement of results between PANDA2 and STAGS is good enough to qualify PANDA2 as a preliminary design tool.

1. **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]. 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; [19-27] feature structural analysis with structural properties fixed, and [28-39] feature structural analysis with optimum configurations sought in most cases via the widely used optimizers CONMIN or ADS, written by Vanderplaats and his colleagues [40-43]. 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.

2. 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. Recently the capability of finding optimum designs of isogrid panels has been added. 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 local buckling of the stiffener parts and rolling of the stiffeners, local and general buckling of the panel, maximum displacement under pressure, maximum tensile or compressive stress along the fibers and normal to the fibers in each lamina, and maximum in-plane shear stress in each lamina.

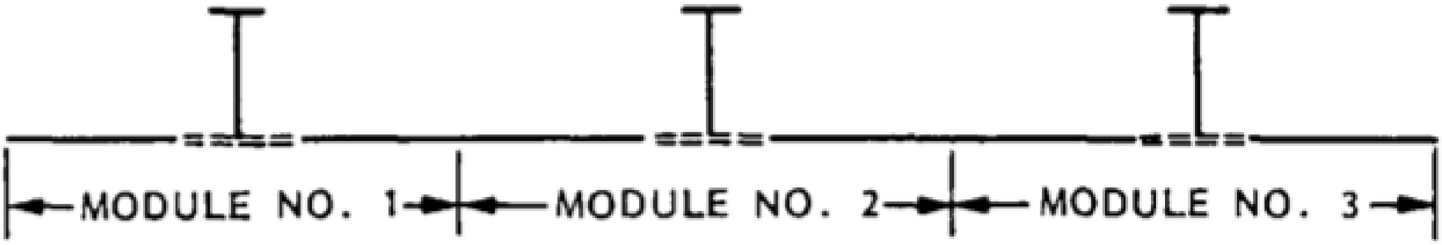


Fig. 1 Tee-stiffened panel with three modules. (From Computer Methods in Applied Mechanics and Engineering 103 (1993) 43-114)

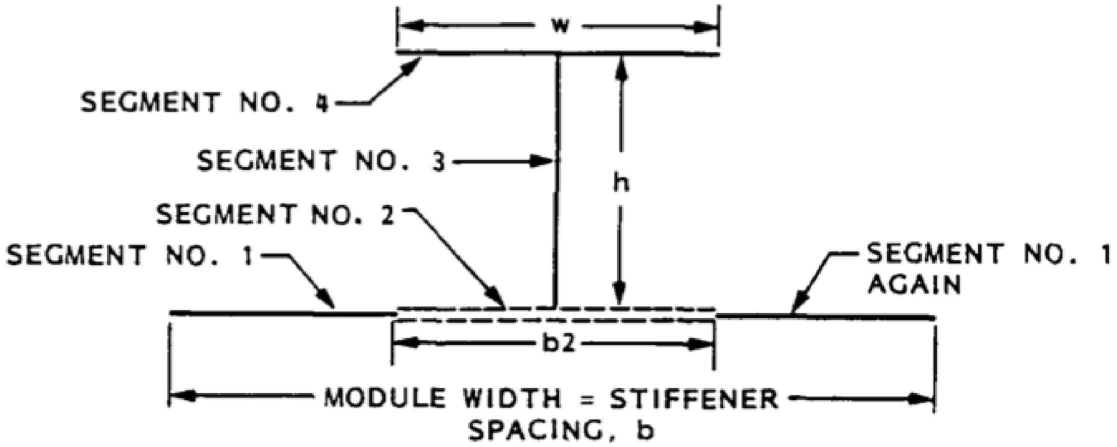


Fig. 2 A single panel module. Each segment may have its own composite laminate. (From Computer Methods in Applied Mechanics and Engineering 103 (1993) 43-114)

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 [44]. An analysis branch exists in which local post buckling 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-postbuckling regime [45].

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.

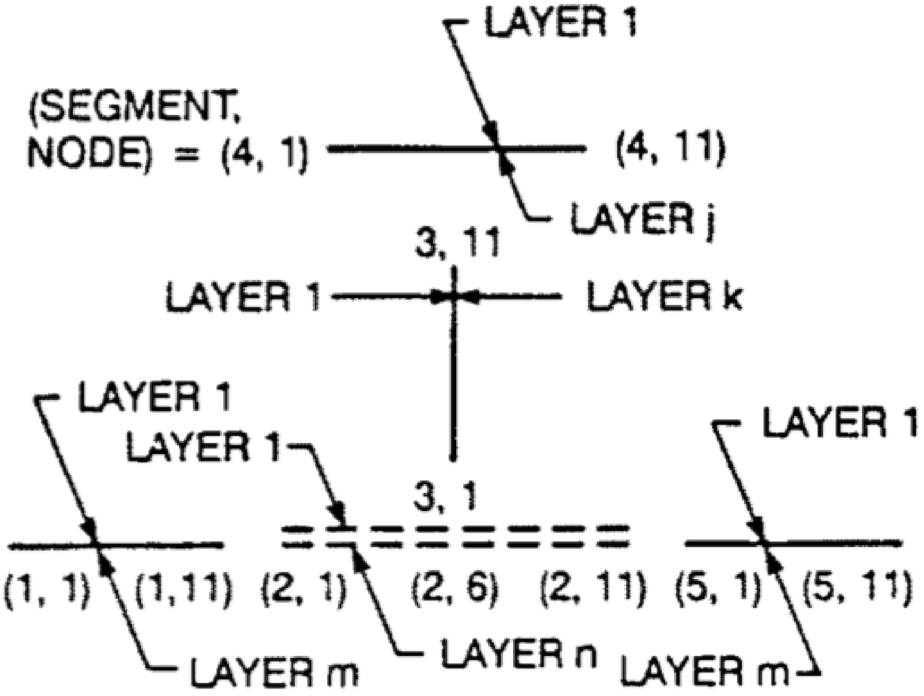


Fig. 3 Segment and nodal point numbering and layer numbering convention for a single panel module. (From Computer Methods in Applied Mechanics and Engineering 103 (1993) 43-114)

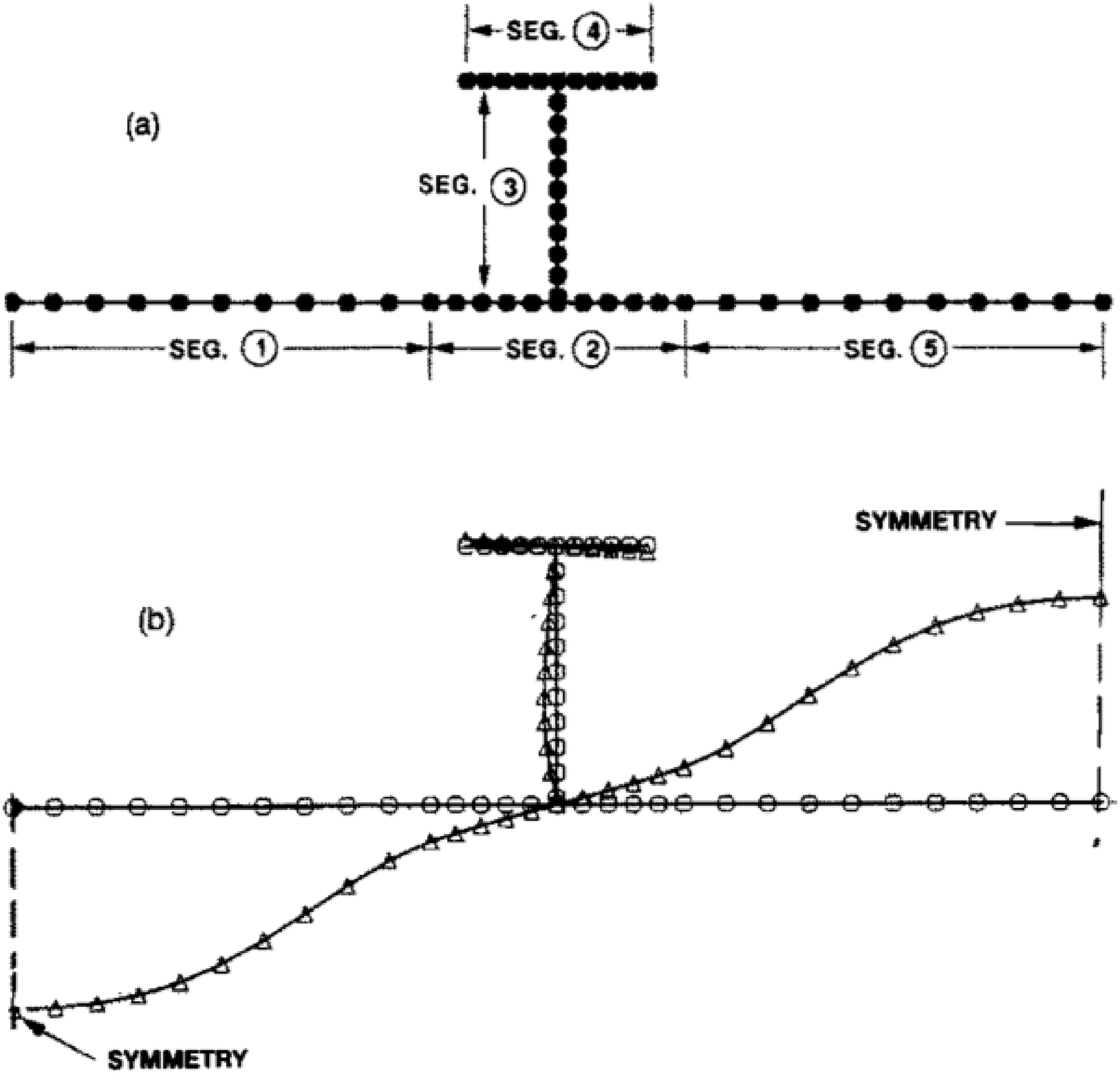


Fig. 4 (a) Discretized single panel module with Tee-shaped stiffener. (b) Local buckling mode that is antisymmetric. The power n in Eq. (24b) is three for this type of stringer. (From Computer Methods in Applied Mechanics and Engineering 103 (1993) 43-114)

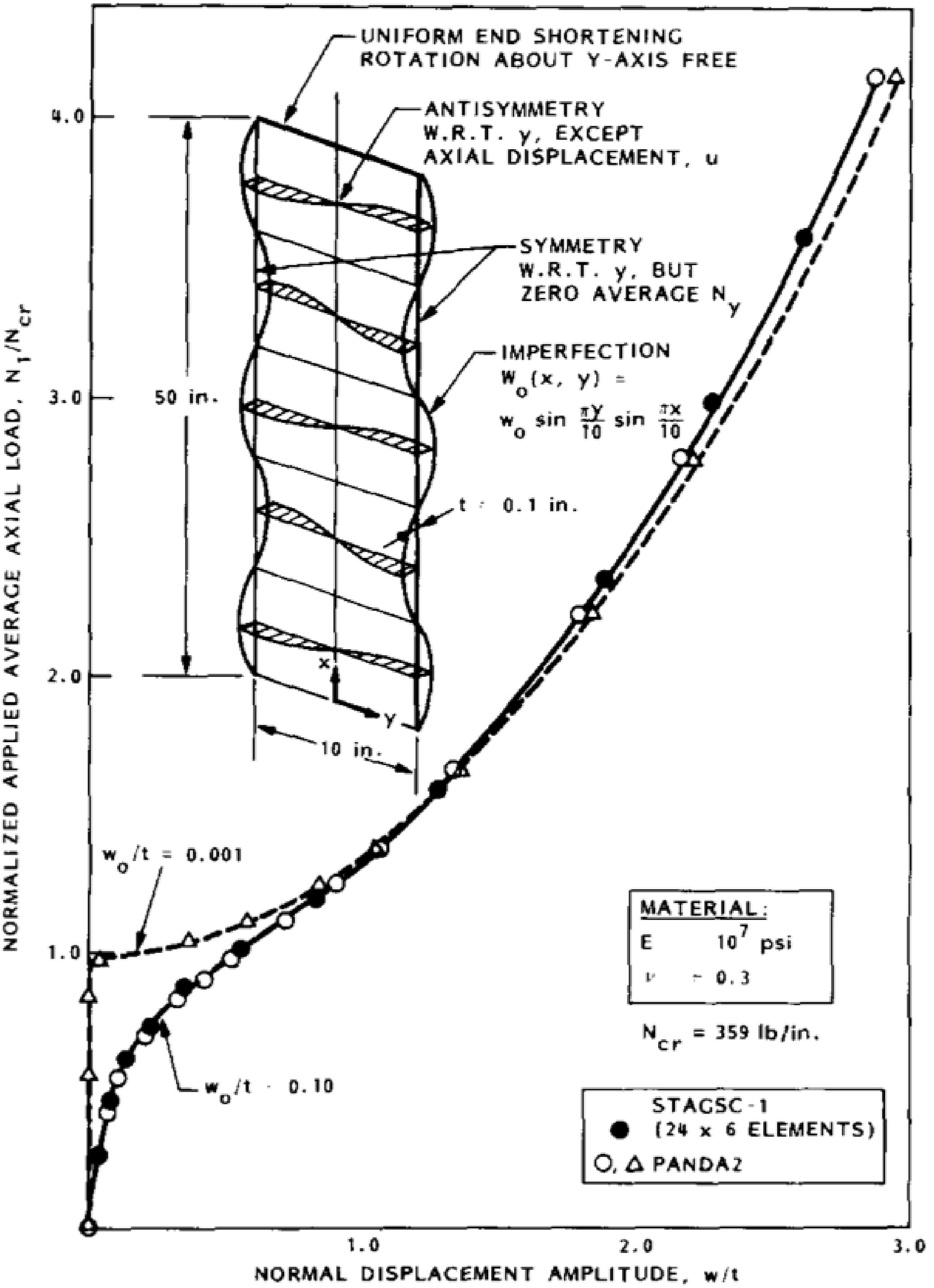
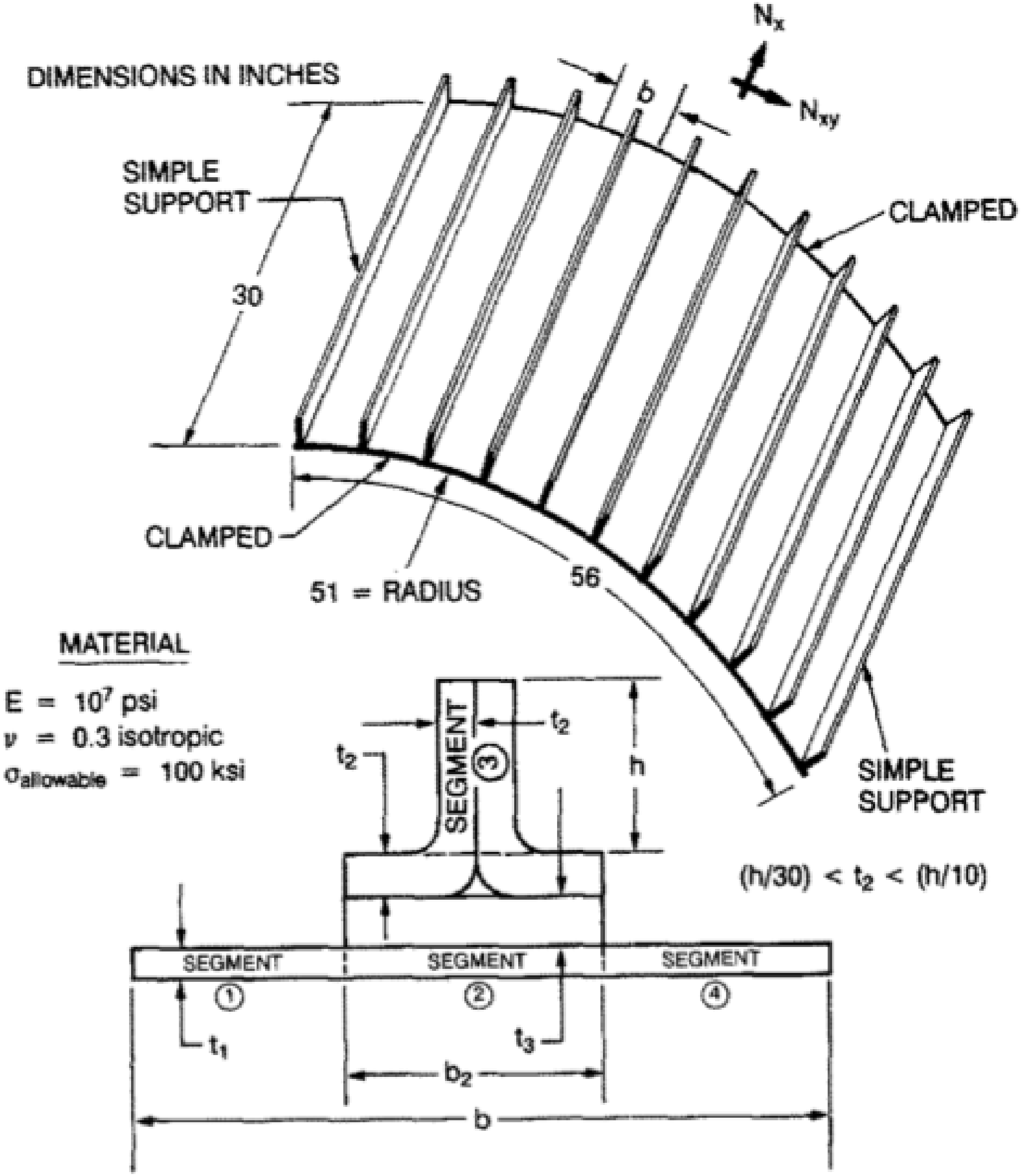


Fig. 6 axially compressed imperfect flat plate: comparison of results from PANDA2 and STAGS (from [50])
(From Computer Methods in Applied Mechanics and Engineering 103 (1993) 43-114)



	DECISION VARIABLES					
	b	b_2	h	t_1	t_2	t_3
STARTING VALUES	8.0	1.0	2.0	0.080	0.030	0.040
OPTIMUM VALUES	5.0	1.0	1.4	0.054	0.0663	0.0231

Fig. 8 Blade stiffened cylindrical panel and decision variables. (From Computer Methods in Applied Mechanics and Engineering 103 (1993) 43-114)

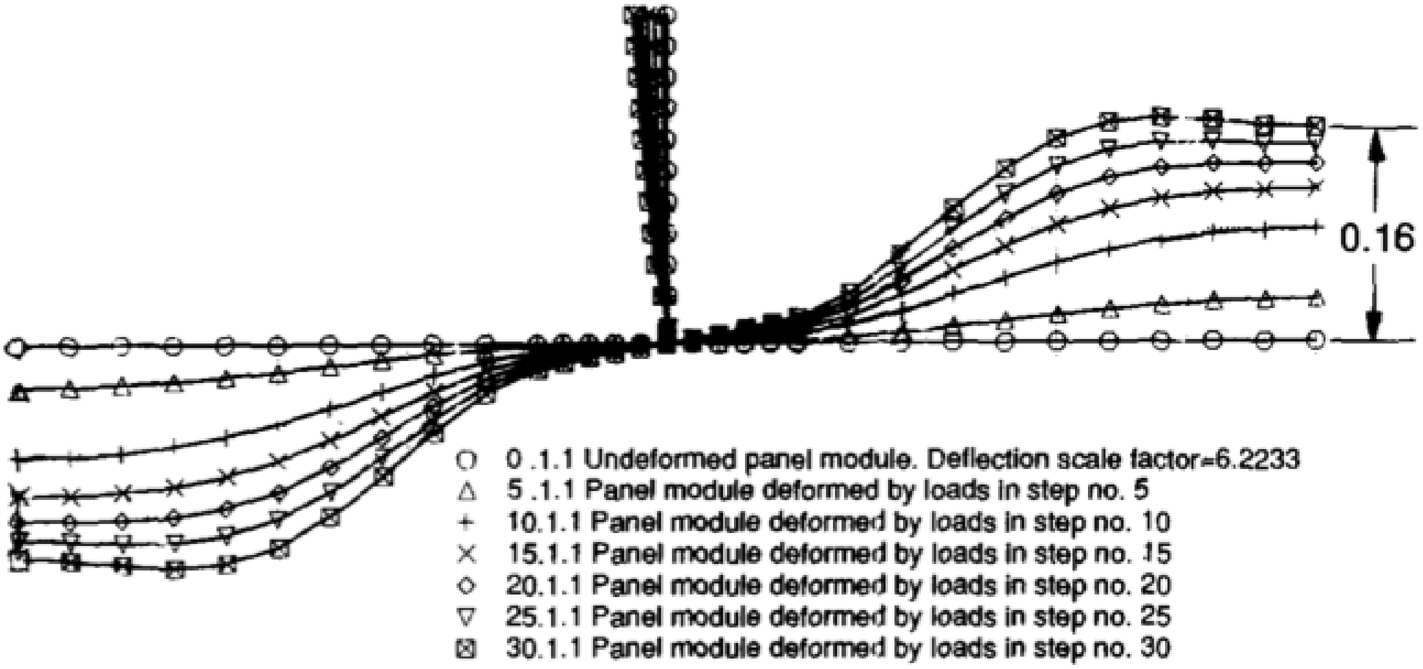


Fig. 16 PANDA2 prediction of deformation of a cross section of the locally post-buckled panel module for Load Set 1 with axial load Nx = 0, -1000, -2000, -3000, -4000, -5000, -6000 lb/inch. The axial compression Nx acts normal to the screen.(From Computer Methods in Applied Mechanics and Engineering 103 (1993) 43-114)