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OPTIMIZATION OF STIFFENED PANELS IN WHICH MODE JUMPING IS ACCOUNTED FOR

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(This is an abridged version. See the full-length paper for more: panda2.papers/1997.modejump.pdf)

ABSTRACT

PANDA2 is a computer program for the minimum weight design of stiffened composite, flat or cylindrical, perfect or imperfect panels and shells subject to multiple sets of combined in-plane loads, normal pressure, edge moments and temperature. STAGS is a general nonlinear finite element code that is specifically designed to analyze especially difficult stability problems in shell structures. Weight optimization of stiffened panels can be particularly troublesome when local buckling is allowed to occur in the pre-collapse state. For these systems, designs may be affected by interaction between local modes, a mechanism that manifests itself as mode jumping and is difficult to characterize. In this paper we describe how in PANDA2 mode jumping is detected and suppressed in optimized panels. Two axially compressed blade stiffened panels optimized by PANDA2 for service in the far postbuckling regime were numerically tested by STAGS. Mode jumping was permitted to occur below the design load in the first panel and suppressed in the second. Results obtained by STAGS are in reasonably good agreement with predictions by PANDA2. The first panel exhibits mode jumping well below the design load. Application of STAGS to this panel reveals that even though the mode jump involves little change in potential energy, it generates large amplitude oscillating stresses with significant stress reversal that might well cause fatigue and delamination. The oscillating stresses are caused by postbuckling lobes moving to and fro along the panel axis immediately after initiation of the mode jump.

INTRODUCTION

The PANDA2 code [1,2,3] is a fast interactive computer program that provides the user with the optimum design of stiffened panels of various shapes and materials including composite fabrications. Because of the particular nature of this code with its simplifying assumptions and the inherent nonlinear behavior of locally postbuckled panels, the results must be checked thoroughly either by an experiment or by an analysis with an independent general-purpose finite element code (or both). In PANDA2 it is easy to check the results with the robust finite element code STAGS because PANDA2 automatically translates its output design into model input for STAGS [4,5]. The STAGS code can thus easily be used to check optimized designs that have previously been produced by the PANDA2 user.

Weight optimization of stiffened panels designed for service in the local postbuckling regime can lead to a behavior dominated by mode interactions such as mode jumping [6 – 9] whereby the deformation state of the panel jumps from one mode shape to another as the load is increased. This phenomenon may or may not have a detrimental effect on the integrity of a panel, depending on the energy content of the jumps, on whether or not stresses oscillate significantly because of the jumps, and on the details of panel fabrication. For example, delamination in a composite panel can initiate or propagate as a result of mode jumps that release energy or otherwise alter the response significantly. Early fatigue failure might occur if the locations of maximum stress oscillate during the mode jumping. Consequently, the designer might want to prevent serious mode jumping from occurring in his or her design. To provide this option, PANDA2 has been equipped with a "prevent mode jump" constraint. We describe results of tests of this constraint here.

Until recently it was very difficult to use STAGS to analyze panels in which mode jumping occurs before failure. This behavior, which is transient, cannot be analyzed with the traditional static path-following technique that the STAGS code employs. This difficulty has recently been overcome by judicial combination of the path-following technique and transient integration methods. Now it is possible to check PANDA2 designs that exhibit mode jumping in their load-deformation response [8,9]. A short description of the STAGS solution strategy is given in the paper.

The objectives of this paper are:

1. To describe how the results from PANDA2 and STAGS compare for a stiffened panel optimized by PANDA2. The panel is designed to carry loads far in excess of the local buckling load of the panel skin.

2. To describe and evaluate the constraint condition in PANDA2 that is supposed to prevent serious mode jumping before the design load is reached.

3. To demonstrate the capability of STAGS to obtain the nonlinear collapse load of panels in which mode jumping occurs at loads below the design load.

MODE JUMPING

It has long been known that the optimization of plates, stiffened panels and other thin-walled structural components designed to carry compressive loads may lead to a panel behavior that is governed by clustered bifurcation points or compound bifurcation points [22]. By clustered bifurcation points we mean that along the pre-buckling equilibrium curve of the panel under load, bifurcations occur at values of the load that are very close together, see Fig. 1. It is also well known that under such conditions the equilibrium branches of these bifurcation points are intertwined and display secondary bifurcations. Some of these branches have stable parts, but most of them are unstable. This may in general imply imperfection sensitivity because the bifurcations may have become unstable. Improperly formulated automated panel optimization may therefore lead to designs that fail long before the bifurcation load is reached; the computed design optimum does not in fact represent a feasible design [22].

With plates and stiffened panels that are only mildly curved in the transverse direction, the clustering sketched in Fig. 1 may still occur but it does not always lead to a direct lowering of the failure load. There are two subjects that have attracted attention in the literature that are associated with this clustering effect.

The first is called "mode interaction", defined as an interaction between a buckling mode of a long wave length with one or more modes of a short wavelength. Structures that exhibit mode interactions may be imperfection sensitive. They have been studied extensively in the literature [23,24,25].

The second subject is called "mode jumping", defined as interaction between mode shapes of short wave length and other so called "local modes" [6, 7, 26 – 30]. Structures that exhibit mode jumping (Stein's [6,7] is a perfect example) can be loaded above the initial buckling load as shown in Fig. 2a, in which stable equilibrium exists along branch 2. This initial stable postbuckling phase is followed by a loss of stability as soon as a secondary bifurcation point is reached. Further loading will then result in a dynamic departure from branch 2 to a neighboring stable equilibrium branch 3. During this transient event the mode shape changes from its current postbuckling form into a different form that belongs to the new stable tertiary branch. This branch may or may not be (statically) connected to the previous branch from which the jump started. The precise situation will depend on the structural configuration and loading. Further loading along stable branch 3 may then end with another jump to yet another stable branch 4 and so on (see Fig. 2a).

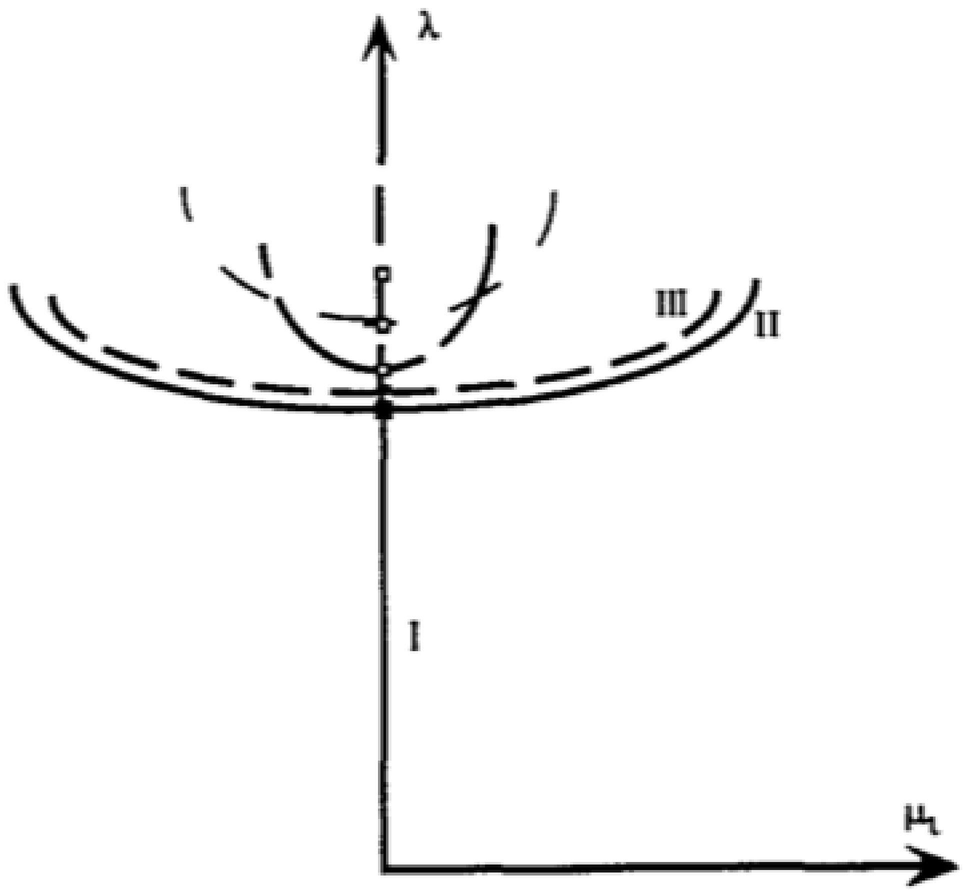

Fig. 1 Clustered bifurcation points. mu is the buckling modal displacement amplitude, and I, II, III are possible equilibrium branches for a perfect axially compressed plate. (from AIAA 38th Structures, Structural Dynamics and Materials Conference, AIAA Paper 97-1141, 1997)

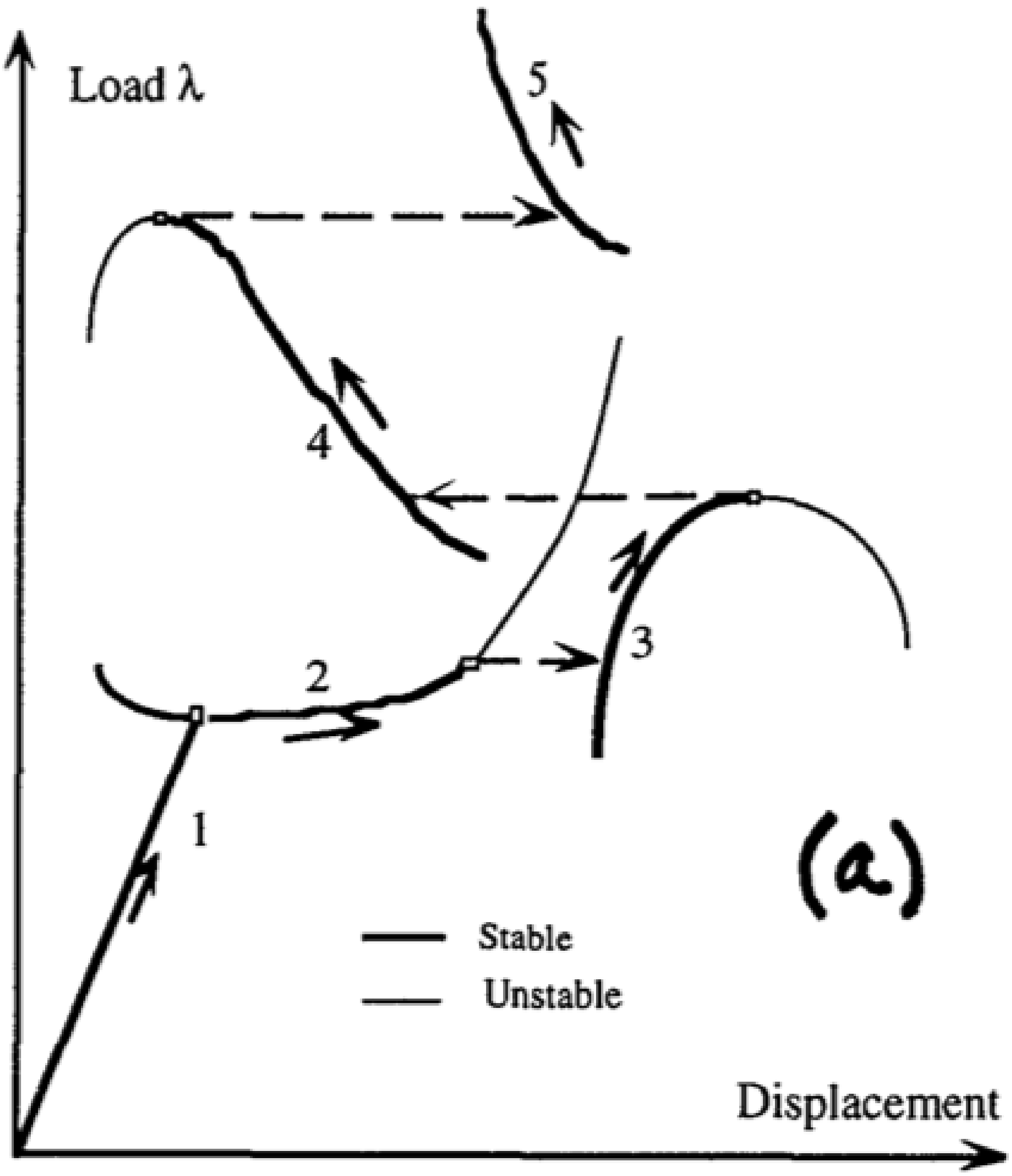

Fig. 2 (a) Mode jumping in general. (from AIAA 38th Structures, Structural Dynamics and Materials Conference, AIAA Paper 97-1141, 1997)

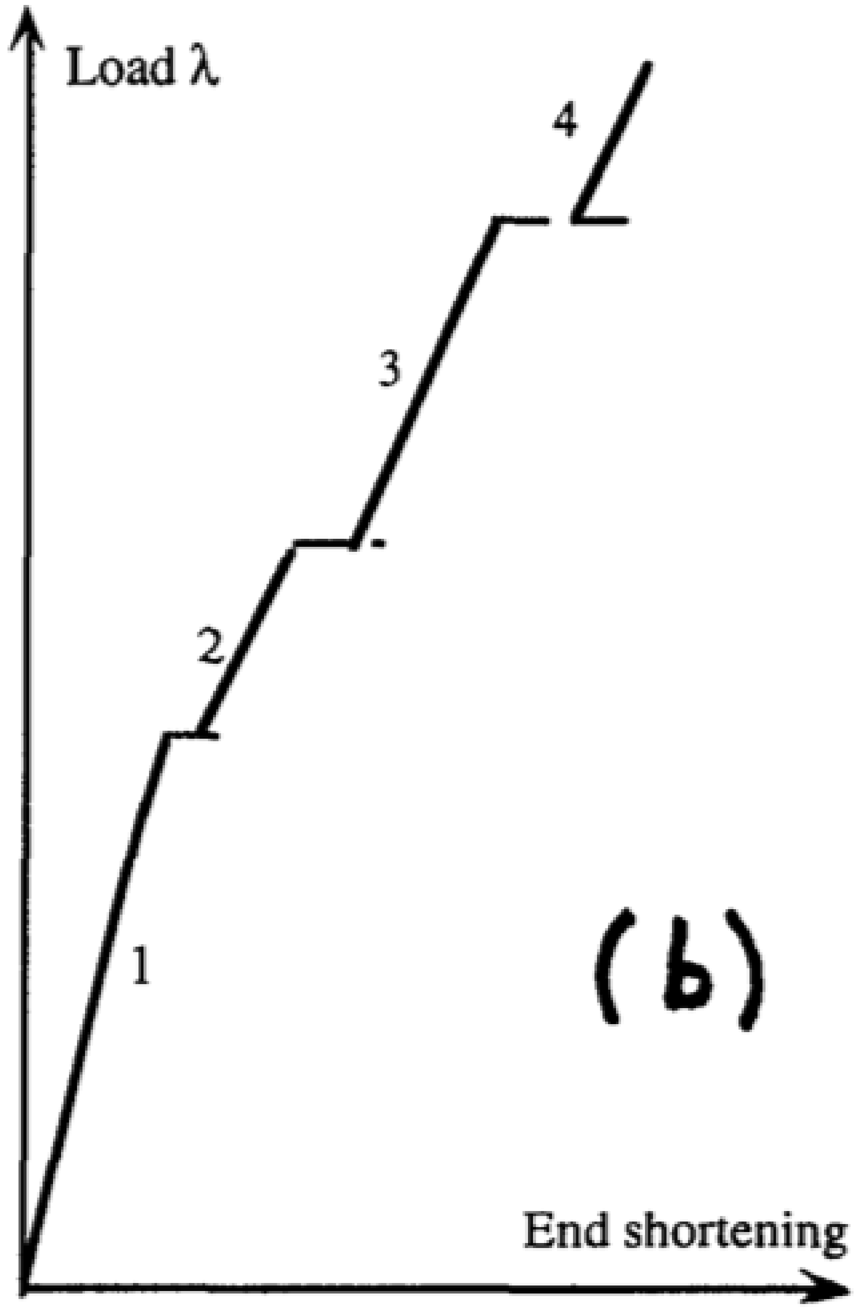

Fig. 2(b) Mode jumping in an axially compressed flat panel. The numbers, 2, 3, 4, are post-buckling equilibrium paths. (from AIAA 38th Structures, Structural Dynamics and Materials Conference, AIAA Paper 97-1141, 1997)

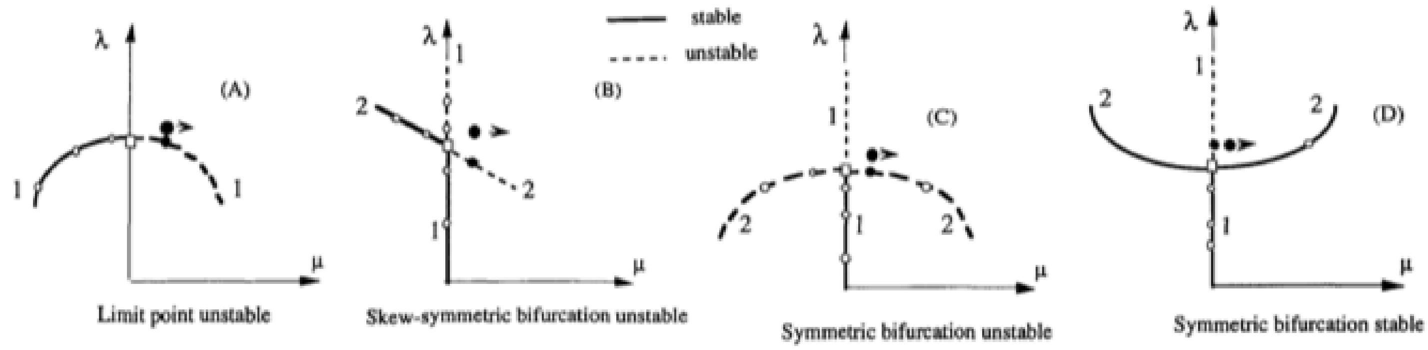

Fig. 3 Types of branching and initial conditions in STAGS for mode jumping. Mu is the buckling modal amplitude in the perfect plate or shell, and lambda is the applied load. (from AIAA 38th Structures, Structural Dynamics and Materials Conference, AIAA Paper 97-1141, 1997)

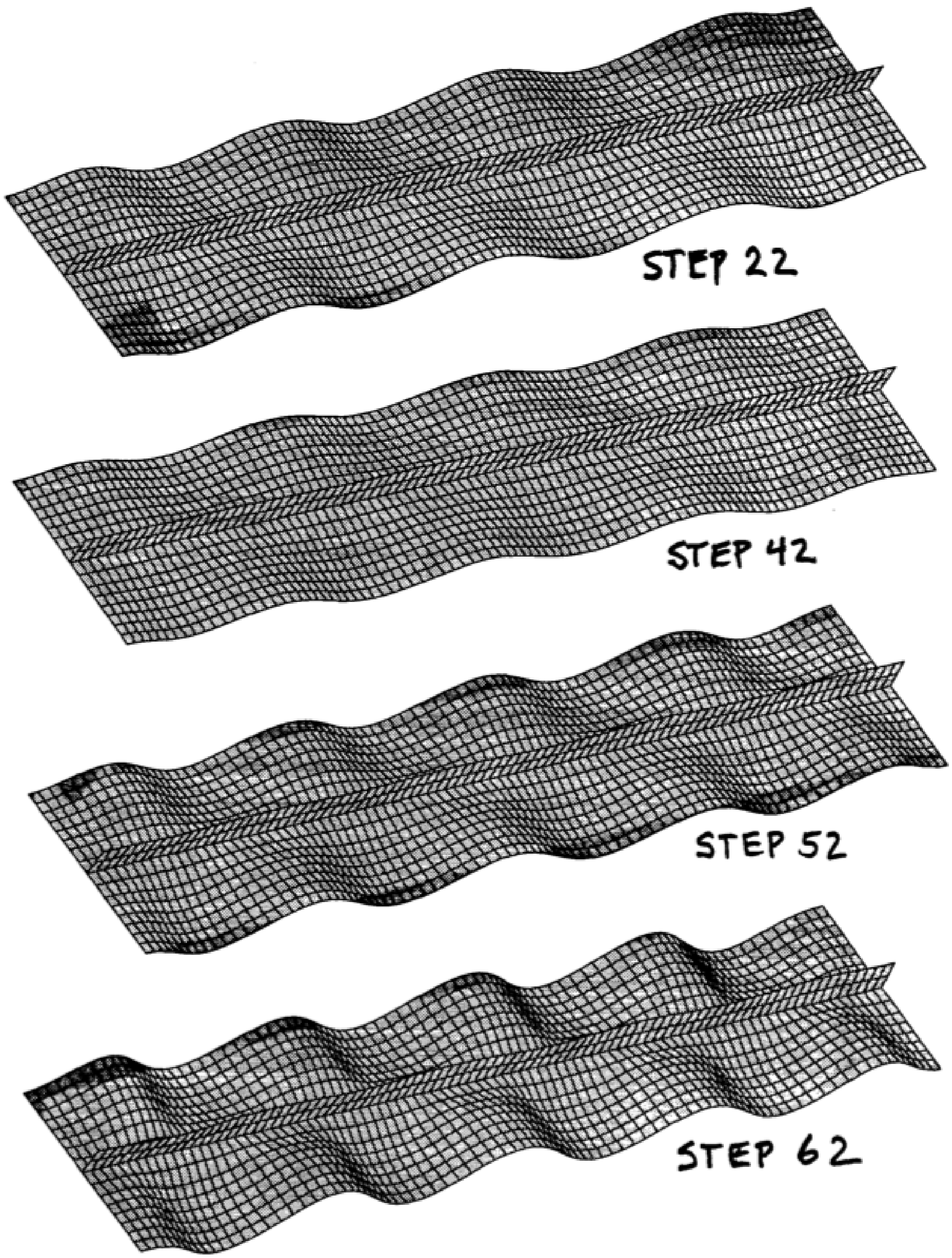

Fig. 21 A one-skin-stringer STAGS module model of an axially compressed blade-stiffened plate. Symmetry boundary conditions are applied along the two edges parallel to the stringer. View of the post-buckling deformation of PANEL I during the initial static phase of loading. PANEL I is the panel optimized by PANDA2 with the “mode jumping” switch turned off, that is, with mode jumping ignored during optimization cycles (no mode jumping behavioral constraint present). The same scale factor is used for all four frames. (from AIAA 38th Structures, Structural Dynamics and Materials Conference, AIAA Paper 97-1141, 1997).

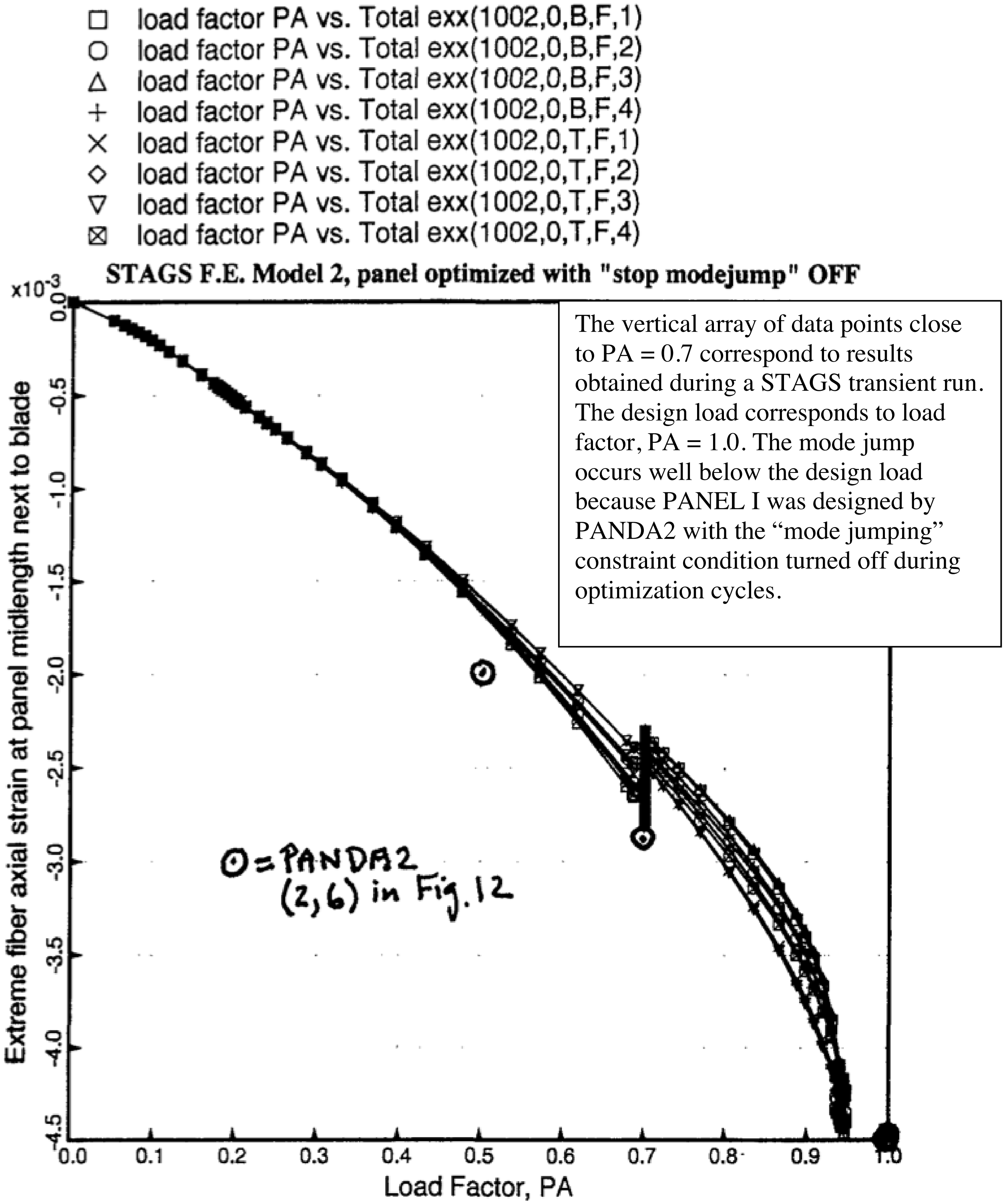

Fig. 26 History of axial strain in PANEL I at the top and bottom surfaces of the panel skin next to the blade stiffener. Mode jumping occurs at a load factor, PA, close to 0.7. PA = 1.0 is the design load. (from AIAA 38th Structures, Structural Dynamics and Materials Conference, AIAA Paper 97-1141, 1997)

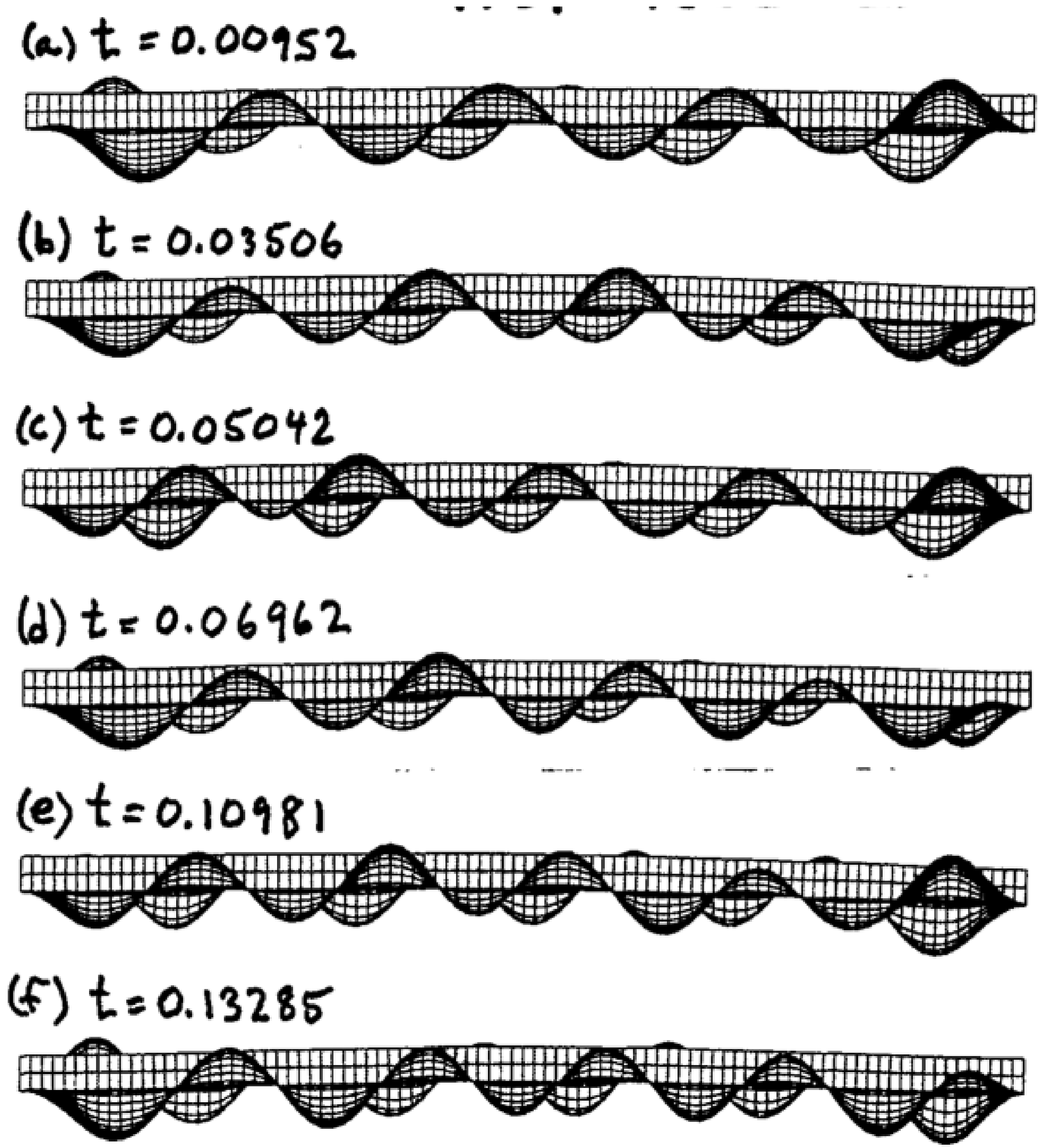

Fig. 29 Edge-on view of post-buckled PANEL I during STAGS transient phase at constant load factor, PA = 0.7013. The transient behavior is characterized primarily by the buckling waves sliding to and fro along the axis of the blade-stiffened panel. Each frame corresponds to a peak value of hoop stress in the next figure. (from: AIAA 38th Structures, Structural Dynamics, and Materials Conference, AIAA Paper No. AIAA-97-1141, 1997)

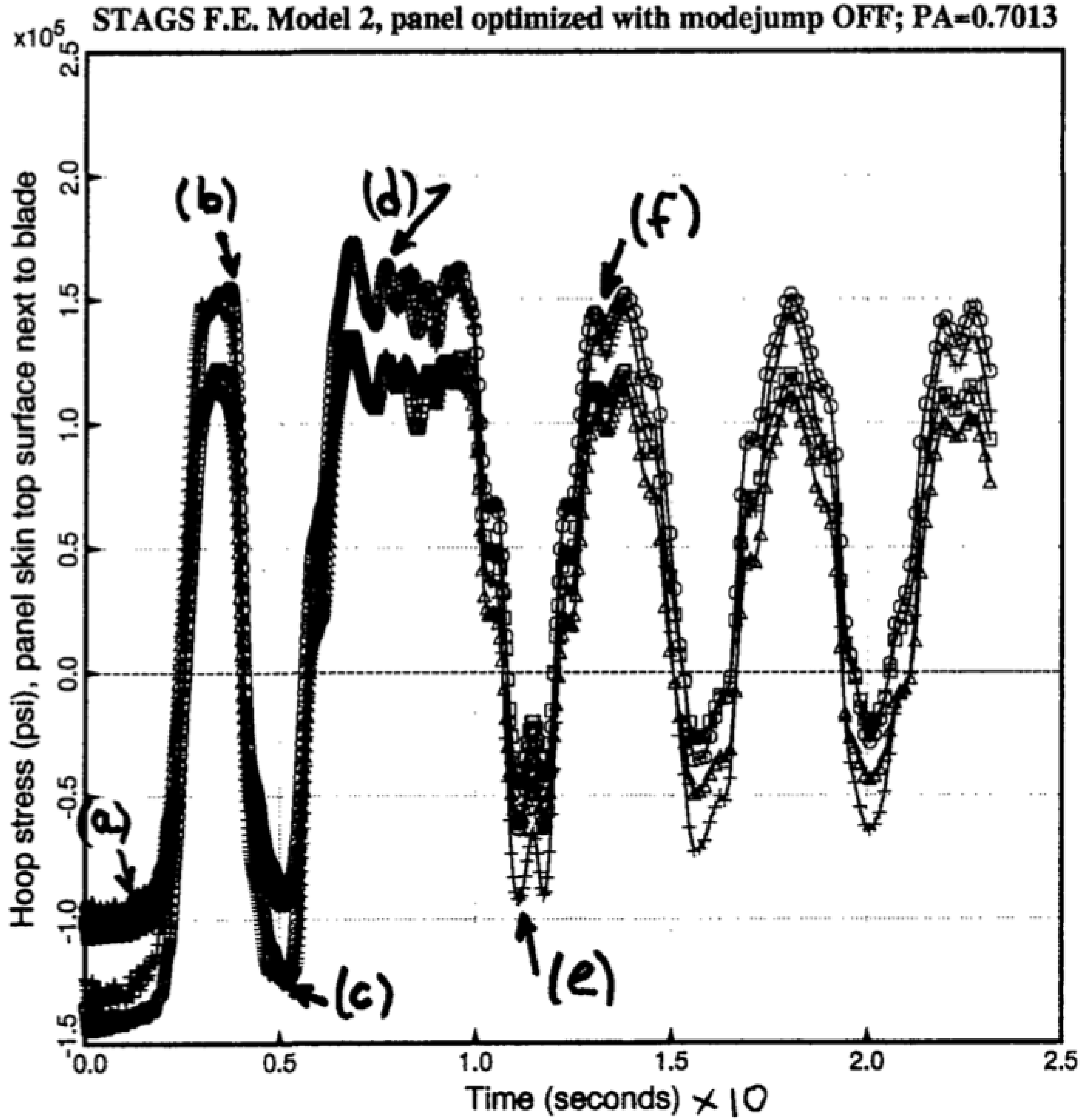

Fig. 30 Oscillations of the maximum hoop stress during the transient phase of the STAGS analysis (dynamic mode jump). The callouts, (a – f), refer to the "snapshots" in the previous figure. (from: AIAA 38th Structures, Structural Dynamics, and Materials Conference, AIAA Paper No. AIAA-97-1141, 1997)