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DETAILED MODELING OF THE CYCLIC RESPONSE OF STRUCTURAL STEEL FRAME SUBASSEMBLAGES

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SUMMARY

This paper presents the authors' experiences with numerical simulation of cyclic response within steel frame subassemblages. Shell finite elements and a bounding surface plasticity model are employed to follow detailed local behavior including the spread of plasticity, cross-section distortion, and the interaction of local and overall instabilities. First, the most significant aspects of the cyclic stress-strain behavior of structural steel are discussed. Both uniaxial and multi-dimensional effects are considered. The implications of linear flow theory for the modeling of inelastic stability are addressed. Finally, results from the cyclic analysis of a simple cantilever beam are reviewed.

INTRODUCTION

Due to the rapid growth of computing power available to engineering researchers, refined numerical models have become an important companion to experimental testing for the study of structural behavior. Numerical simulations can be employed in the design of experimental tests, in the performance of parametric studies, and in the elucidation of complex three-dimensional behavior that may be difficult and/or costly to observe experimentally. This paper reports the results from research conducted at Cornell University on the finite element modeling of local behavior in steel frames. The focus here is on several phenomena that may need to be considered for accurate prediction of the structural response in general, and on the numerical predictions for a few simple test cases.

STRESS-STRAIN BEHAVIOR

The cyclic stress-strain response of structural steel is quite complex, especially if the loading at a material point follows a non-proportional path involving significant interaction between the different components of stress and strain. Although the predominant strains in most frame members are uniaxial, such interaction effects may be important at member locations where local buckles begin to form, or in structural components such as beam-to-column joints and the shear links of an eccentrically braced frame.

The strain history shown in Fig. 1 can be used to illustrate several stress-strain phenomena that merit consideration in the modeling of cyclic structural behavior. This history is the first part of a strain pattern applied in an axial-torsion test of A36 steel tubing, the results of which are reported in Ref 1. The test is divided into three parts for purposes of discussion. Part I corresponds to simple monotonic uniaxial extension of the tube specimen. Part II involves uniaxial cycling between fixed strain limits of 0.008 in./in. Finally Part III involves combined shear and axial cycling at 90 degrees out-of-phase. This path corresponds to cycling at a constant effective strain of 0.008 in./in., or to straining in a circular path of radius 0.008 in./in. in the normalized plane $\varepsilon/\varepsilon_{yi}-\gamma/\sqrt{3}\gamma_{yi}$.

Figs. 2 and 3 demonstrate the predictions of a specialized bounding surface plasticity model for this strain history. In these figures, the numerical results are indicated by the solid lines and the open circles indicate the peaks of the curves obtained by experiment. The predicted trends in the response are identical to those of the experiment, and in general, the experimental and numerical curves are a close match. The reader is referred to Ref. 2 for a detailed description of the plasticity relationships and for further comparisons of experimental and numerical results.

Consider the axial stress-strain curves for parts I and II of the strain history (Fig. 2). Two cyclic stress-strain phenomena are evident from these curves--the Bauschinger effect and cyclic hardening. The Bauschinger effect is related to a sharp decrease in the size of the yield surface from that of the virgin response (i.e., a decrease in the size of the elastic region for the cyclic curves). Cyclic hardening is evidenced by the gradual increase in the peak stresses achieved in each of the half-cycles. For cycling between fixed strain limits as performed in Fig. 2, the stress-strain curves eventually harden to a stable loop the size of which is dependent on the magnitude of the plastic straining.

The response curves for part III of the strain history illustrate an important nonproportional straining effect (see Fig. 3). Although the maximum effective strain for part III is the same as that for parts I and II, the material exhibits additional hardening due to the nonproportional straining path. The peak axial stress increases by approximately 23 percent from the end of part II to the end of part III. It can be concluded from the results shown in Figs. 2 and 3 that, for accurate modelling of the multi-dimensional cyclic response of structural steel, it is important not only to consider the magnitude or the extent of the plastic straining, but also it is necessary to consider the direction of the straining path.

INELASTIC BUCKLING PARADOX

The bounding surface plasticity model employed in this work is based on linear flow theory. The term "linear flow theory" implies a smooth yield surface, normality of the plastic strain rate with respect to the yield surface, and linear dependence of the strain rate magnitude on the magnitude of the stress rate. Unfortunately, for inelastically loaded plates, buckling predictions using linear flow theory can grossly over-estimate experimentally observed collapse loads. Correspondingly, for the case of monotonic loading, predictions of collapse using a deformation theory of plasticity are generally quite good even though it is widely recognized that, physically, flow theory is more sound than deformation theory [see Ref. 2]. This problem, termed the "inelastic buckling paradox" has been recognized in the mechanics literature for more than 30 years, and it is discussed in more detail in Refs. 2 and 3.

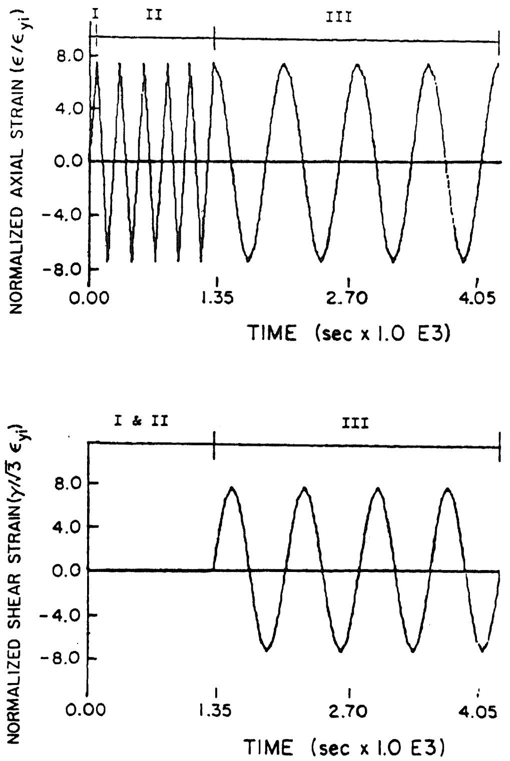


Fig. 1 Biaxial strain history, axial-torsion tube specimen [Ref. 1]

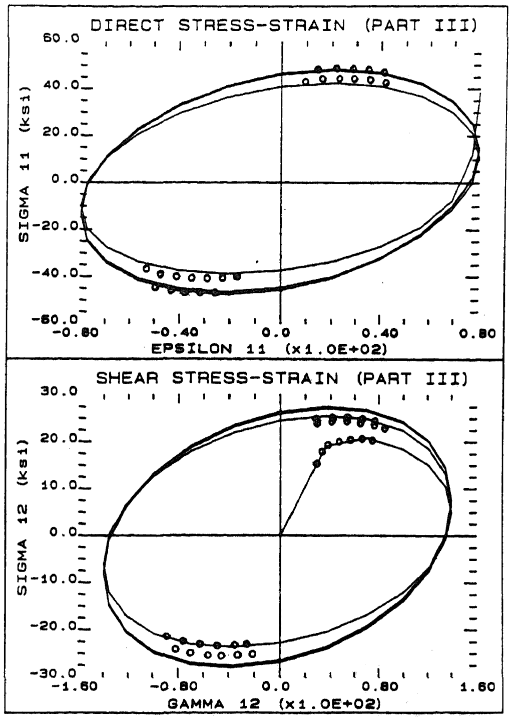


Fig. 3 Comparison of numerical and experimental curves--part III

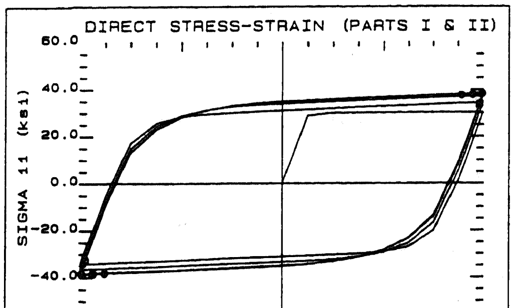


Fig. 2 Comparison of numerical and experimental curves--parts I and II

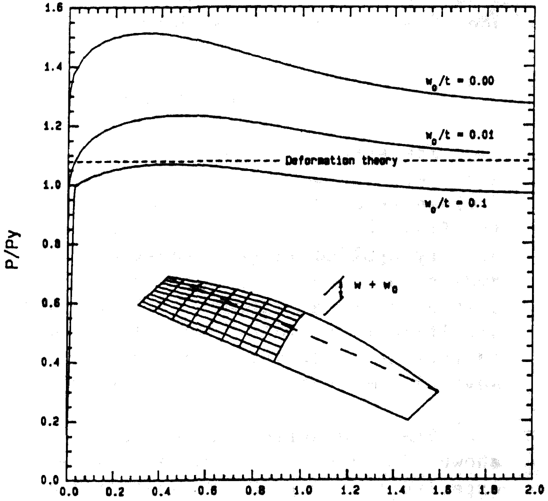


Fig. 4 Axial load vs. midspan deflection--ss plate, free on one side

Fig. 4 illustrates typical analysis results for a simply supported plate with one free edge. The analytical buckling solution using deformation theory is shown by the dashed line in the figure. Several plots of axial load versus midspan deflection, obtained from incremental-iterative finite element analysis, are shown by the solid lines. The different plots correspond to different magnitudes of the initial imperfection w_o/t at the midspan of the plate. The initial imperfections vary as a sine wave along the length of the plate.

The imperfection sensitivity of the finite element results, which is indicated by the differences between the three solid curves in the figure, is a product of the linear flow theory assumptions of the plasticity model. The experimental collapse of the plate is expected to be approximately equal to the deformation theory solution, regardless of the magnitude of the imperfections. Although the finite element solution for an imperfection of $w_o/t=0.1$ predicts an average stress at collapse which is approximately equal to the deformation theory value, this imperfection is probably too large to be considered as a realistic value. The imperfection $w_o/t=0.01$ might be considered to be realistic and unavoidable, but the maximum average stress predicted by use of this imperfection is 14.3 percent greater than the deformation theory value. The maximum load obtained for the zero imperfection case is 39.7 percent greater than the deformation theory solution.

Fig. 5 provides an explanation for the false imperfection sensitivity exhibited by the above finite element solutions. In the case of the plate shown in Fig. 4, the deformations change from axial to primarily torsion as the collapse load is approached. Fig. 5 is a plot of the tangent shear modulus for a tube specimen that has been axially pre-strained into the strain-hardening region, and then subjected to a torque while the axial load is held constant. It can be observed from this plot that flow theory overestimates the tangent shear stiffness of the material for small shear strains. Since the shear strains due to twisting are small at the onset of inelastic instability in the plate, this explains why the strength of the plate is overpredicted. This problem possibly can be alleviated by considering yield surface corner effects in the plasticity model, i.e, by use of a nonlinear flow theory.

CYCLIC RESULTS FOR A SIMPLE CANTILEVER BEAM

The structure shown in Fig. 6 is an idealization of a cantilever beam employed in one of the cyclic experimental tests reported by Popov and Stephen (see Ref. 4). In the current study, the displacement history shown in Fig. 7 is applied to the end of the beam. This is the same as the history applied in the experimental test, except that (1) initial elastic cycles are not applied, and (2) only one cycle is applied at each displacement amplitude. Unfortunately, divergence is obtained as significant yielding and local deformations begin to develop in the fifth half-cycle. However, the results obtained are sufficient for discussion of several important aspects of the finite element modelling.

The load-deflection curves predicted by the finite element analysis are shown in Fig. 8. These curves are similar to those obtained in the experiment, the peak stresses of the numerical simulation being slightly larger. The Bauschinger effect and some cyclic hardening are evident, but nonproportional cyclic plasticity effects do not appear to be important in this case (i.e., the material straining is predominantly uniaxial). The local deformations at the fixed end of the beam are shown for the end of the third and fourth half-cycles in Figs. 9 and 10.

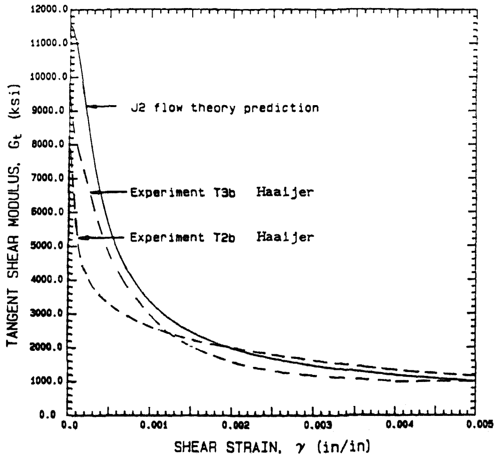


Fig. 5 Tangent shear modulus vs. shear strain

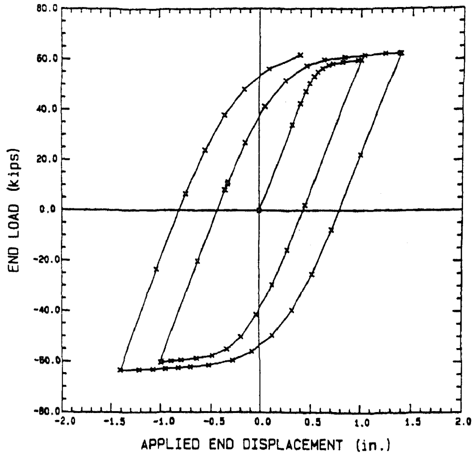
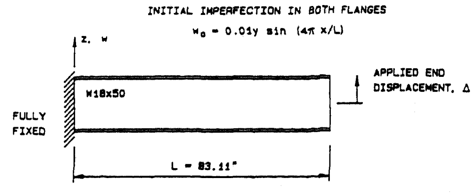
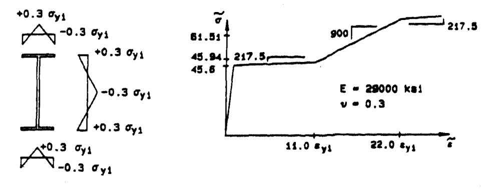


Fig. 8 Load-deflection curves

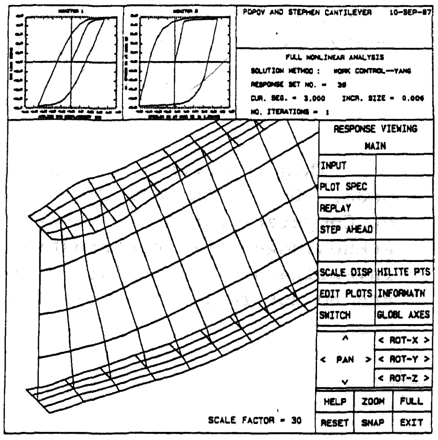


(a) Geometry, loading, and boundary conditions



(b) Residual Stresses (c) Effective stress-strain response

Fig. 6 Cantilever beam specimen [Ref. 4]



POPOV AND STEPHEN CANTILEVER 10-SEP-87

FULL NONLINEAR ANALYSIS

SOLUTION METHOD : WORK CONTROL--YANG

RESPONSE SET NO. = 39

CUR. SEG. = 3.000 INCR. SIZE = 0.006

NO. ITERATIONS = 1

Fig. 9 Deformations at end of 3rd half-cycle

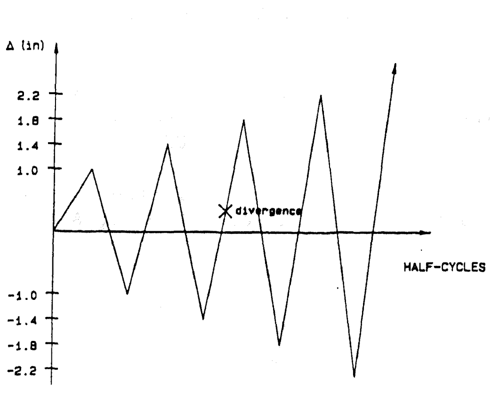
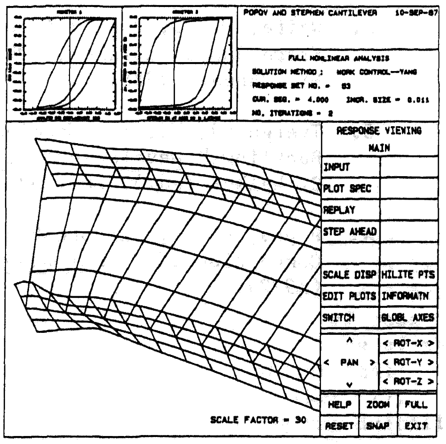


Fig. 7 Applied displacement history



POPOV AND STEPHEN CANTILEVER 10-SEP-87

FULL NONLINEAR ANALYSIS

SOLUTION METHOD : WORK CONTROL--YANG

RESPONSE SET NO. = 83

CUR. SEG. = 4.000 INCR. SIZE = 0.011

NO. ITERATIONS = 2

Fig. 10 Deformations--end of 4th half-cycle

The most significant observations from this study are: (1) local distortion of the compression flange is evident at the support even in the first half-cycle, but it is visible at that time only when the deformations are highly magnified, (2) the local buckles straighten when the direction of loading is reversed and the flange is placed in tension, (3) local distortion in the flanges at the support becomes more and more prominent in each half-cycle, and (4) although initial imperfections are specified in the flanges to help initiate the local deformations, the local distortions at the support do not resemble the initial imperfections.

CONCLUDING REMARKS

The results presented in this paper are from several preliminary test cases. Further work remains to investigate the significance of the phenomena discussed for more complex structural components such as beam-to-column joints and the shear links of an eccentrically braced frame. The imperfection sensitivity of the results should be addressed for the simple cantilever problem studied here. For this and a number of other cases, it is possible that the predicted imperfection sensitivity is small and that a plasticity model based on linear flow theory is adequate to follow the behavior. This work is currently being pursued by the authors.

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