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LINEAR AND NONLINEAR FINITE ELEMENT ANALYSIS OF AN EXHAUST MANIFOLD WITH INCLUDED BELLOWS

Scott E. Steinbrink
Assistant Professor of Mechanical Engineering, Gannon University

Mahesh C. Aggarwal
Professor of Mechanical Engineering, Gannon University

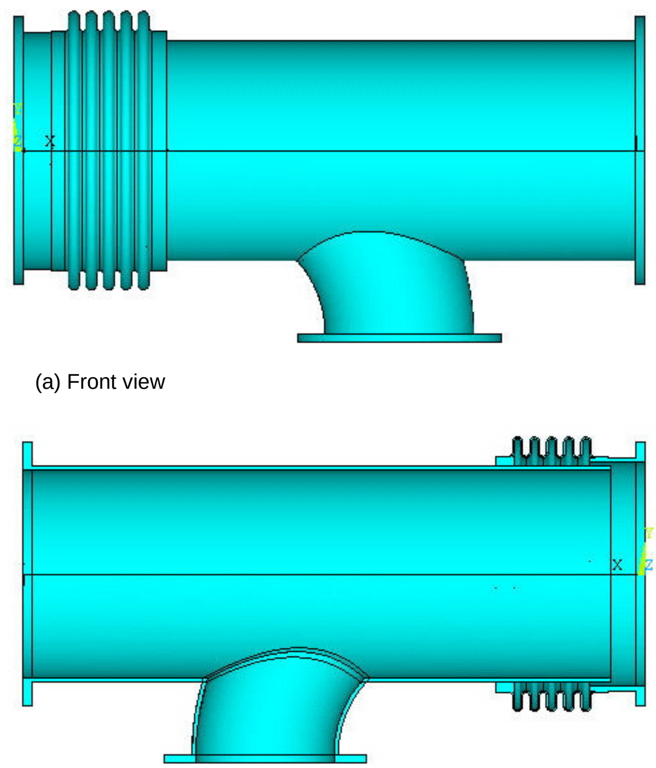
Kapilla I. M. Shepherd
Graduate Student in Mechanical Engineering, Gannon University

ABSTRACT:
The aim of this paper is to examine the utility of nonlinear analysis for structural response to thermal and mechanical loads, for a structure containing alternating regions of high and low stiffness as a result of inclusion of bellow sections. Utility is measured by comparison of results of linear and nonlinear analyses. The specific example used is that of an exhaust manifold for a large diesel engine. The paper discusses modeling of geometric and material nonlinearity, and makes recommendations in regard to which nonlinear effects are thought to be significant, based on the linear/nonlinear comparisons. The paper also contains general comments on the finite element modeling of structures containing bellows.

INTRODUCTION:
The exhaust manifold of a certain diesel engine used for locomotives consists of eight sections, bolted end to end. The engine has two exhaust manifolds, thus requiring 16 bellow sections. It is desirable for cost reasons to ascertain whether some of the bellows might safely be removed. Exact details of the manifold are considered to be proprietary; an approximation of the true manifold section is shown in Figure 1. Each section has a right, circular cylindrical portion, integrated bellow, and an inlet port. The inlet ports connect the manifold to the combustion cylinder, and are modeled as toroidal sections.

The bellows sections are thin metal plate, folded accordion-style. Dimensions for this model are:

- inside diameter: 75 mm
- wall thickness: 3 mm
- length: 450 mm
- inlet tube diameter: 90 mm
- flanges 6mm wide by 20 mm high



(a) Front view

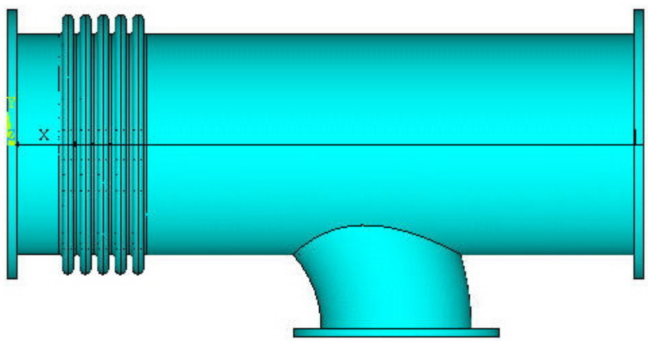
(b) Rear cutaway view

Figure 1: EXHAUST MANIFOLD WITH INCLUDED BELLOW

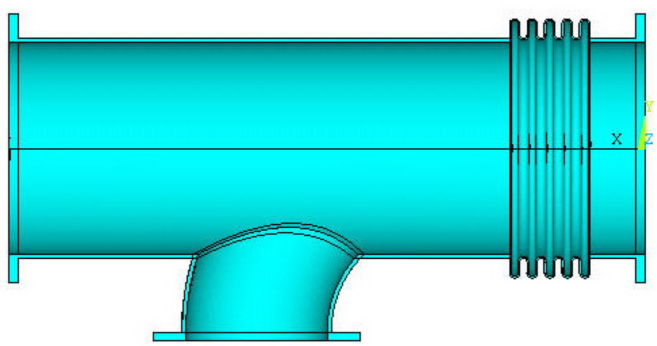
- five-convolution bellow, with total length of 60 mm, material thickness of 1.2 mm
- bellow is attached 40 mm from left side of manifold, in front view

Note that the intent of this work is only to look at the effects of inclusion of specific nonlinearities in the analysis, not to design a manifold appropriate for use. Thus, the manifold dimensions, while inspired by a functional design, are unsuitable for actual application.

The design for the actual manifold was originally created using standard linear analysis. But linear analysis results are often quite conservative, thus leading to overdesigned structures. A better analysis can often be obtained using nonlinear analysis, but the nonlinear analysis process can be very time consuming, and often can fail to converge, for anyone other than a very knowledgeable analyst. This paper aims to consider nonlinear finite element analysis of the thermal stress problem in comparison to results of the linear thermal stress problem, to determine which nonlinear analyses seem to be warranted for this structure, with a highly flexible region.



(a) Front View



(b) Rear cutaway view

FIGURE 2: MANIFOLD SECTION WITH SIMPLIFIED BELLOW

This work proceeds by first performing linear analysis of a single manifold section, with the bellow replaced by a straight tubular section. Nonlinear analysis follows, incorporating geometric and material nonlinearities, to demonstrate the level of conservatism in the linear analysis. Following completion of the analysis of the model with no bellow, a simplified bellow section is inserted (Figure 2) and the linear and nonlinear analyses are repeated. Conclusions are drawn by comparison of the linear and nonlinear analysis results of the model with included bellow section.

MODELING ISSUES:

Thermal loads on the structure include convection on both inner and outer surfaces. Convection occurs on the inner surface due to hot exhaust gases, forced by piston motion. The outside of the manifold is exposed to ambient temperature of the engine compartment, with flow effectively forced by motion of the train. Radiative heat transfer is neglected. Internal bulk temperature is taken to be 600C, with a convective heat transfer coefficient of 387 W/m^{2}K, at a pressure of 2.7 Bar. The external bulk temperature is assumed to be 75C, at 1 Bar, with a film coefficient of 7.9 W/m^{2}K.

Mechanical loads include internal pressurization due to exhaust gases and reaction forces due to manifold constraints. The exterior of the manifold is at atmospheric pressure. It is assumed that the engine block is rigid, so that the cylinder exhaust ports experience no motion at the location where they meet the engine block.

A 3-dimensional model is required. The manifold has one plane of symmetry. Structural boundary conditions are taken from symmetry conditions on the one symmetry plane, and rigid fixation at the connection to the engine block. Additional (approximate) boundary conditions are taken from an assumed cyclic symmetry: because the left end of the section connects to the right end of an identical section, the motions of left and right ends must be coupled. That is, the left end expands to match right end contraction and no bending can occur at the ends. These same boundary conditions apply to the manifold section with the included bellow.

The element chosen for this analysis is a 20-noded hexahedral element, which is allowed to degenerate into a 10-noded tetrahedron [1]. The model without included bellow contains 13,920 elements connecting 27,606 nodes (82,818 structural DOF). The model with the included bellow contains approximately 29,000 nodes connecting approximately 9200 elements (87,000 DOF). Note that the software used for this analysis is node-limited to 32,000 nodes. Thus, the mesh is not as dense as is likely necessary for absolute reliability of computed results. Considerable care was taken to make the densest possible mesh of elements. It is assumed that the fundamental goal of this work, comparison of techniques, is not compromised by potential inaccuracies in absolute structural response.

The material of the manifold and bellow is taken to be austenitic stainless steel, with properties [2]:

- Poisson's ratio: $\nu = 0.3$;
- Average thermal expansion coefficient: $\alpha = 19.3 \times 10^{-6}$ per degree K;
- Average coefficient of thermal conductivity: $k = 22.1 \times 10^{-3}$ W/mm^2 K;
- Initial elastic modulus: $E = 193$ GPa;

The approximate nonlinear elastic stress-strain curve is depicted in Figure 3.

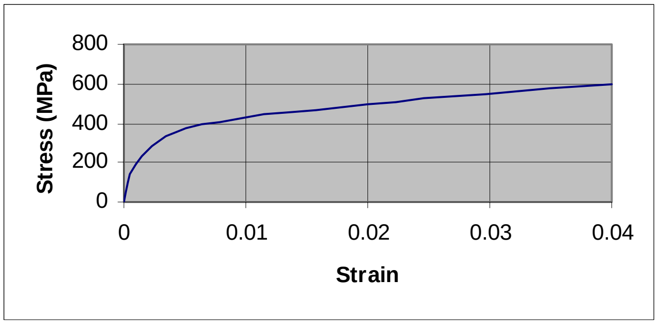


FIGURE 3: ASSUMED STRESS-STRAIN RELATIONSHIP (MODELED AFTER AUSTENITIC STAINLESS STEEL)

POSSIBLE SOURCES OF NONLINEARITY:

It is assumed for this problem that deformations will not notably affect heat transfer properties of the structure, and we neglect radiative heat transfer for this analysis. There is thus no included provision for nonlinearity in analysis of thermal response.

Load-bearing properties may be affected by temperature and deformation, but we analyze only for the common use temperature. We thus incorporate temperature-independent material properties with values taken at the expected use temperature of approximately 600 C. We include the possibility of large strain (geometric nonlinearity). In addition, austenitic stainless steels exhibit very nonlinear stress-strain behavior. This model thus includes a nonlinear stress-strain curve appropriate to the material of the manifold, as shown in Figure 3.

Four analysis cases are considered as shown in matrix form in Table 1. Definition of terms follows the table.

TABLE 1: ANALYSIS CASES

Geometric \ Material	Linear Elastic	Nonlinear Elastic
Geometrically Linear	gLmL	gLmN
Geometrically Nonlinear	gNmL	gNmN

Material property assumptions:
- Linear elastic (materially linear, mL)
- Multilinear elastic, temperature dependent (materially nonlinear, mN)

Geometric conditions:
- Small strain (geometrically linear, gL)
- Large strain (geometrically nonlinear, gN)

ANALYSIS OF THE MANIFOLD WITHOUT INCLUDED BELLOW:

Linear analysis was performed first (case gLmL), for the manifold without included bellows. The results of that analysis suggest that the maximum stress in the model occurs at the joint between the connection flange and the inlet port, and between the inlet port and the manifold proper. These high stresses are alleviated in practice by inclusion of fillets which are not modeled for this work. Of more interest is the von Mises stress felt in the main section of the manifold, which ranges up to 2878 N/mm^2 (2878 MPa). The yield strength of the material is taken to be 120 MPa at 600 C, thus the safety factor against yielding is calculated as 0.04, which is obviously unacceptable. Clearly, linear analysis results suggest a bellow is needed for stress alleviation. Figure 4 shows the pattern of thermal stress for this simplest analysis case.

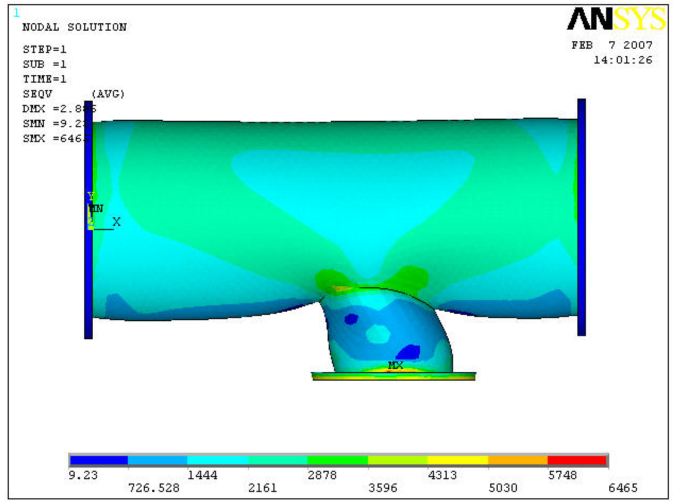


FIGURE 4: VON MISES STRESS PATTERN: LINEAR ANALYSIS OF MANIFOLD WITHOUT BELLOW

Following the full linear analysis, other analysis cases were performed for the manifold without bellows. The results are tabulated in Table 2.

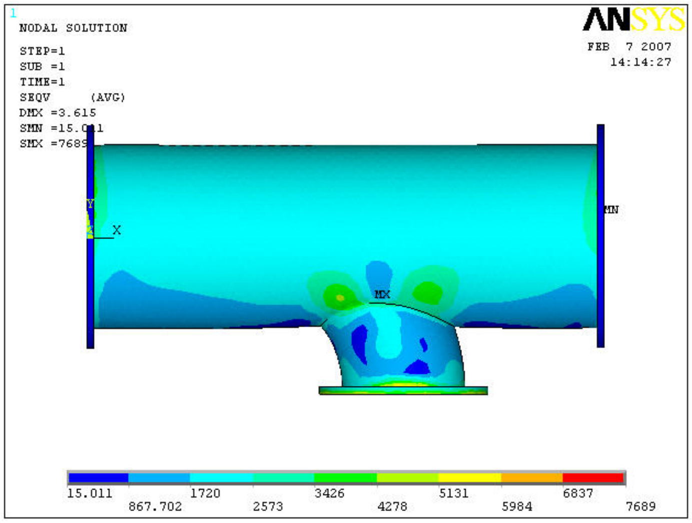
TABLE 2: RESULTS OF ANALYSIS OF MANIFOLD WITHOUT INCLUDED BELLOW SECTION

Case \ Result	Maximum Stress in Main Section (MPa)	% Change
gLmL	2878	--
gLmN	467	-83.8
gNmL	2573	-10.6
gNmN	UNCONVERGED	N/A

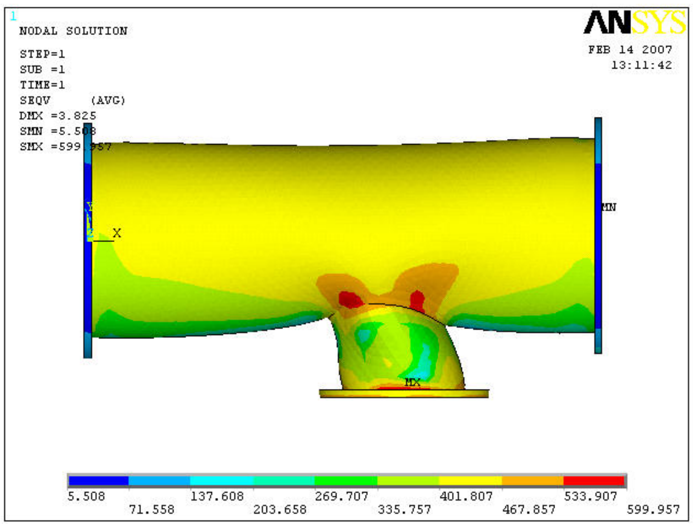
A geometrically nonlinear analysis was performed next, with linear elastic material properties. This analysis resulted in calculated von Mises stresses somewhat higher than the stresses predicted in the linear analysis. Thus, the nonlinear analysis results would tend to bolster rather than detract from the argument for inclusion of the bellows. This analysis was easily and rather quickly completed using the default convergence criterion of the software [3].

Following the geometrically nonlinear analysis, a geometrically linear analysis was performed, with nonlinear elastic material properties as depicted in Figure 3. Here again, convergence was achieved using the default settings. The convergence was considerably slowed, though, by the nonlinear elastic material behavior.

Assuming the results of the nonlinear analysis are more accurate than the results of the linear analysis, one can see that the linear result overpredicts stress by 500%, relative to the materially nonlinear case, and by 11%, relative to the geometrically nonlinear analysis. Clearly, material nonlinearity is significant for this structure. Graphical depiction of the predicted von Mises stress patterns for nonlinear analysis cases are shown in Figure 5.



(a) Geometrically nonlinear



(b) Materially nonlinear

FIGURE 5: VON MISES STRESS PATTERNS WITH INCLUDED NONLINEARITIES

Finally, the effects of large strain AND material nonlinearity were included. The resulting model is highly nonlinear in response, such that the software failed to converge using the default settings. Relaxation of convergence criterion (force and displacement) was not sufficient to allow convergence. Convergence failure occurred consistently at about 70% of the total load. In order to combat this phenomenon, the analysis model was re-run under arc length control. The resulting analysis proceeded very slowly, and remained unconverged. A prudent action to improve convergence, namely increased mesh density, was not possible, owing to software limitations. Although the exact times for analysis are not available, it can be stated that the time for these analyses ranged from less than 1 second (for the fully linear case) to a few seconds (for geometric nonlinearity, only) to less than 5 minutes (for material nonlinearity, only) to several hours (for the fully nonlinear case, prior to automated abortion of the analysis.)

Although no analysis of the manifold without included bellow indicates a safe design, it seems apparent that the material nonlinearity is by far the more important one in prediction of structural response. The results indicate that the inclusion of material nonlinearity is an almost essential consideration.

ANALYSIS OF THE MANIFOLD WITH INCLUDED BELLOW:

Following the analysis of the manifold without included bellow, a similar set of analyses was performed for the manifold with a bellow. Here again, the materially nonlinear model predicts stresses that are much lower than those of linear analysis, while the effects of geometric nonlinearity are much less noteworthy.

Inclusion of geometric nonlinearity seems, in fact, not to have any real utility. The inherent large deformations of the bellow are adequately predicted in linear analysis. The maximum predicted vector displacements for all three analysis cases are nearly identical, ranging from 3.44 mm in the linear case to 3.47 mm in the materially nonlinear case. The deformed geometries for the three analysis cases are visually indistinguishable. It appears the bellow experiences inextensional bending, such that large strains are not predicted. Thus, the predicted stress relief in the manifold main section is unaffected by inclusion of geometric nonlinearity. Refer to Figures 6(a) and (b).

For the linear and geometrically nonlinear analysis cases, the von Mises stress patterns are nearly identical. Each predicts a nearly uniform stress in the manifold tubular section, with value up to approximately 670 MPa. Each also predicts maximum von Mises stress in the bellow up to about 2000 MPa. Note that while the geometrically nonlinear analysis results differed from the linear results by a small amount in the manifold without bellow, the difference between linear and geometrically nonlinear results is negligible for the manifold with included bellow.

The materially nonlinear analysis indicates a maximum stress in the tubular section of approximately 177 MPa, occurring at the junction of the bellow and the tubular section, and a nearly uniform stress in the tubular section ranging up to something less than 118 MPa. This is clearly more important than the geometric nonlinearity. In particular, note that the linear analysis overpredicts maximum stress by approximately 275%. Thus, if the manifold is designed by linear analysis to a safety factor of 3, the materially nonlinear analysis would suggest a potential safety factor in excess of 11. This presents a clear opportunity for design optimization.

TABLE 3: RESULTS OF ANALYSIS OF MANIFOLD WITH INCLUDED BELLOW SECTION

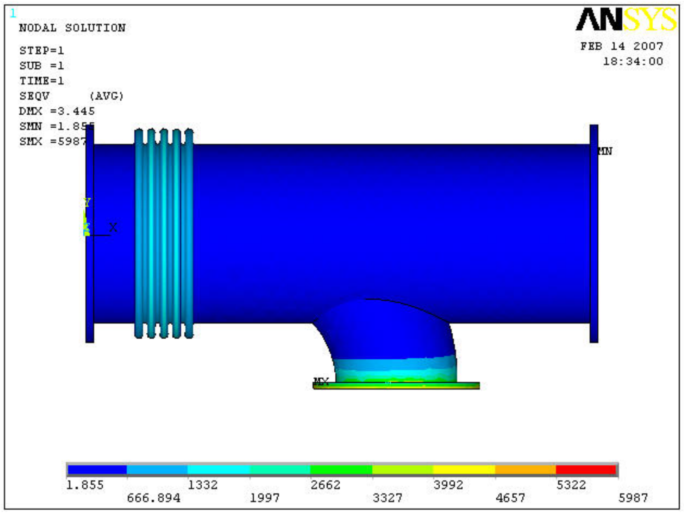
Case \ Result	Maximum Stress in Main Section (MPa)	% Change
gLmL	666	--
gLmN	177	-73.4
gNmL	669	+0.45
gNmN	UNCONVERGED	N/A

RECOMMENDATIONS:

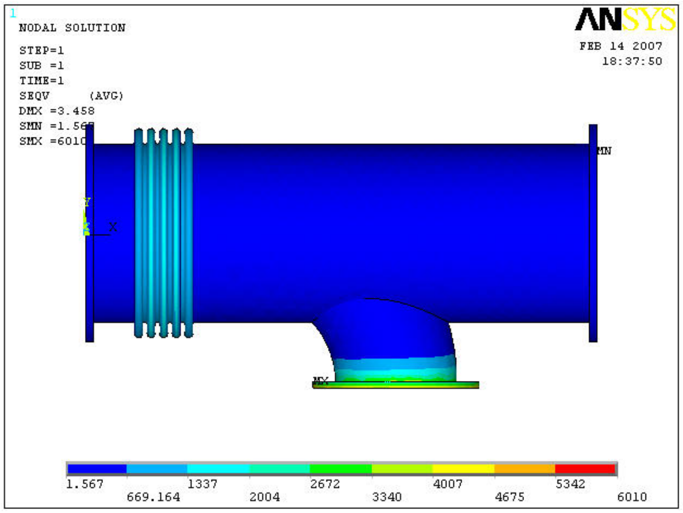
It is recommended that material nonlinearity be included in analyses of structures with included compliant sections. The effect of geometric nonlinearity seems to be much less important for the case of a bellow as the high-compliance region. In view of the complexity of the nonlinear problem when both geometric and material nonlinearities are included, it is recommended that this analysis not be performed, unless absolutely necessary. Note, however, that the high level of compliance is achieved in the example problem by use of a bellow. Thus, compliance is achieved as a result of structural, rather than material, effects. If high compliance is achieved using material differences, then geometric nonlinearity may become more necessary.

It is possible in FEA to have only a portion of the model display nonlinear response, and doing so could greatly reduce the computational effort needed to solve the problem. Such a model could be made by using a substructuring technique, where a portion of the model is replaced by a single superelement. Superelements can only have linear behavior, but all other portions of the model can have nonlinear response. A fairly simple expansion of converged results would then provide the full set of results for the hybrid linear/nonlinear model. However, it appears it would not be advisable to substructure this problem, because the effects of material nonlinearity seem to be distributed throughout the model.

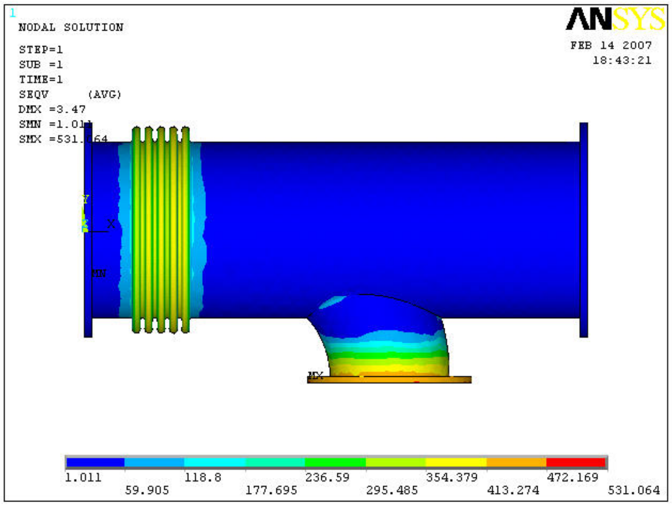
The effect of the material nonlinearity is clearly felt in the bellow. In addition, it may be seen by examination of Figure 6 that the maximum von Mises stress at the connection to the cylinder head is also affected by material nonlinearity. The predicted maximum stress at that location drops from approximately 6000 MPa to approximately 530 Mpa, when material nonlinearity is included. Thus, the only reasonable candidate sections for substructuring would be the tubular manifold sections to the left and right of the bellow. But these are relatively uninteresting areas with regard to the response of the structure, and not likely to cause great problems with convergence. The authors feel it is unlikely that the substructuring approach would provide significant simplification of the finite element modeling process.



(a) Linear



(b) Geometrically nonlinear



(c) Materially nonlinear

FIGURE 6: VON MISES STRESS PROFILES: MANIFOLD WITH INCLUDED BELLOW

Boundary conditions are problematic in this analysis, as for many other finite element models. In particular, the non-rotation assumption used seems appropriate for the case with no included bellow, but may not be appropriate when a bellow is included. The low stiffness of the bellow could allow a significant amount of bending. The connection of this bellow section to adjacent sections at each end can be used to model boundary conditions, but it is not certain whether the section should bend into an “S” shape or a “C” shape, nor which orientation (concave up or concave down) that shape should take.

FUTURE DIRECTIONS FOR THIS WORK:

The assumed boundary conditions for the manifold with included bellow will be altered, in order to allow for bending in the bellow section. Such bending is likely to affect the magnitude and location of maximum stress in the manifold.

The effects of radiative heat transfer, neglected for this work, are thought to be significant, particularly as the manifold ages. The emissivity of the manifold is expected to increase with heating cycles, potentially leading to a more adverse temperature profile. Thus, future work will incorporate radiative heat transfer with consideration of changes over time.

Further opportunities for future investigation lie in the areas of strength and remaining life predictions. It is planned that future investigation of fatigue life will be undertaken.

CONCLUSIONS:

An example problem is used to investigate the utility of inclusion of various nonlinearities in the structural analysis of structures with a highly compliant included section. Results from analysis performed on the example structure suggest that material nonlinearity is important, geometric nonlinearity is relatively unimportant. It is seen that the combination of these two nonlinearities leads to severe convergence problems. Thus, it appears that analysis of the fully nonlinear problem is unjustified, in this case. It is also apparent that the effect of the material nonlinearity should be assumed to be important everywhere in the model, so that mesh reduction by substructuring seems unwise.

REFERENCES:

[1] *ANSYS Element Reference*, Release 8.1, ANSYS Incorporated, Canonsburg, PA, Chaps. 90, 95

[2] *Engineering Properties of Steel*, American Society for Metals, 1982, Pages 304-307

[3] “*Nonlinear Structural Analysis*,” ANSYS Structural Analysis Guide, Release 8.1 ANSYS Incorporated, Canonsburg, PA, Chap. 8

[4] “*Substructuring*,” ANSYS Advanced Analysis Techniques Guide, Release 8.1, ANSYS Incorporated, Canonsburg, PA, Chap. 8