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Comparison With Strain Gage Data of Centrifugal Stresses Predicted by Finite Element Analysis on the DOE/Sandia 17-M Darrieus Turbine

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COMPARISON WITH STRAIN GAGE DATA OF CENTRIFUGAL STRESSES PREDICTED BY FINITE ELEMENT ANALYSIS ON THE DOE/SANDIA 17-M DARRIEUS TURBINE*

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ABSTRACT

By the use of strain gages, the blade structural response to purely centrifugal loading was measured on the DOE/Sandia 17-m Darrieus rotor. The measurements obtained are compared in this report with MARC-H nonlinear finite element stress predictions. It was necessary to include gravitational effects in the finite element model to explain certain asymmetries in the data. The model with gravitational effects shows good agreement with the data. Examination of results suggests that refinement of the model to include more structural detail in the region where the blade joins the tower would probably enhance the accuracy of the model.

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INTRODUCTION

The MARC-H nonlinear finite element package has been used for static structural design of Darrieus rotor blades.[1 2] There exists only limited verification[3] of this analysis package because of the general difficulty in obtaining structural data on rotating blades.

This report compares the MARC predictions of the element configuration shown in Figure 1 with data from the DOE/Sandia 17-m rotor. The rotor blades are one-piece aluminum extrusions with a 24-in chord, NACA 0015 cross section. Both blades are instrumented with 350-ohm strain gages at the locations shown in Figure 2. The blade differs from the first composite blade on the 17-m wind turbine[4] in that the early blade used support struts, was a NACA 0012 cross section, and was joined to the tower with flatwise-free pins as opposed to the semirigid clamps of the current design.

The stress condition for this comparison is derived from purely centrifugal loading, i.e., rotational loading in negligible winds. This load case is appropriate for verification of the finite-element analysis primarily because it is a well-defined static load which produces a non-trivial structural response of the blade. The blade response for rotor operation in substantial winds is less suitable for verifying the analysis package because of both uncertainties in aerodynamic load models and dynamic effects which are not considered in the current version of the rotor model.

The results of this comparison indicate that, considering the simplicity of the model, the MARC nonlinear finite-element analysis produces encouraging predictions of the stress distribution in the rotor blades. Both computer analysis and the experimental data indicate that the blade response is influenced by substantial nonlinearities resulting from gravitational loads and centrifugal stiffening.

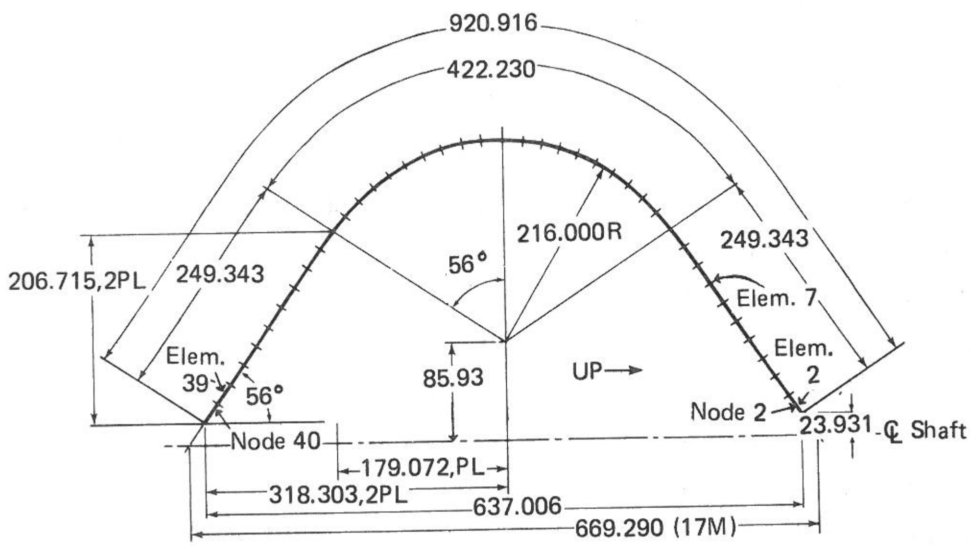

Figure 1. Model Configuration (dimensions in inches)

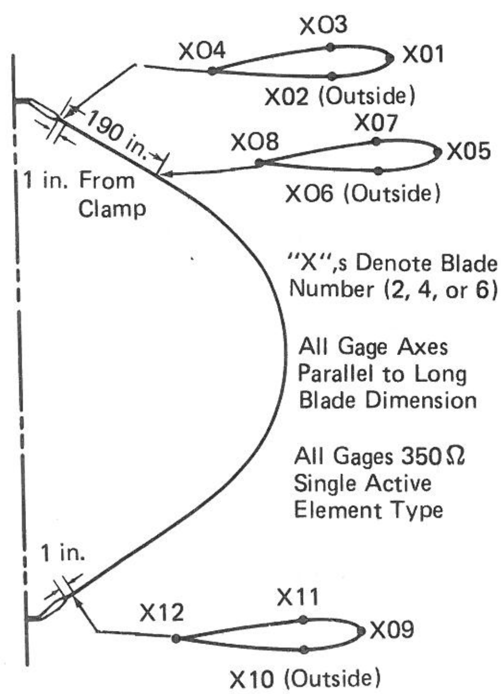

Figure 2. Blade Strain Gage Locations and Numbering System

ANALYSIS

The MARC model that we used for comparison was a flatwise (element type 16), 40-element, full-blade configuration (Figure 1). Displacements were prevented on nodes 2 and 40 to represent the semirigid end clamps of the actual rotor. Element type 16 has a rectangular cross section. The element width and thickness were set to 3.75 and 4.0 in, respectively, to match the actual blade section properties of 15-in^2 area and 20-in^4 flatwise moment of inertia. Nodal forces were applied by using a 24-increment relaxation procedure to allow for nonlinear effects.

We obtained turbine data by initially zeroing the strain gages (Figure 2) with the rotor parked in negligible winds (less than 3 mph). At low windspeeds, the average strain registered by the gages during operation represented blade response to centrifugal loads. The turbine data displayed an asymmetry in centrifugal strain about the horizontal midplane of the rotor. This effect appears inconsistent since the centrifugal loads are symmetric about the midplane. To explain the asymmetry, we tested the hypothesis that gravity produces a nonlinear effect on centrifugal stresses.

Two computer analyses were performed at turbine speeds of 32.9, 47.8, and 75.0 rpm. The computer runs referred to as "RPM" involve centrifugal loading only while the "R&G" computer runs contain both centrifugal and gravitational forces. A third set of results, referred to as "(R&G)-G" are obtained by substracting the pure gravitational stresses from the R&G stress predictions. Any nonlinear gravity effect would result in a discrepancy between RPM and (R&G)-G stresses. Because of zeroing the strain gages by the technique discussed above, the actual strain gage readings are in effect measurements of response modeled by the (R&G)-G runs.

The flatwise MARC element produces a linear stress gradient through the thickness of the blade. Since the actual blade thickness is 3.636 in, rather than the 4.0 in of the beam element, calculated stresses were corrected according to

$$(\sigma_{corrected})_{i,o} = (\sigma_i + \sigma_o)/2 \pm (\sigma_i - \sigma_o)\ .909/2$$

where "i" and "o" represent the element stresses at the innermost and outermost layers, respectively.

RESULTS

In the MARC analysis, Layers 1 and 11 represent the inside and outside of the beam element respectively. Figure 3 shows the gravitational stresses obtained from a stationary MARC run. Figures 4 through 6 compare the corrected stress results of RPM and (R&G)-G. Turbine strain gage data have been plotted in Figures 4 and 5.

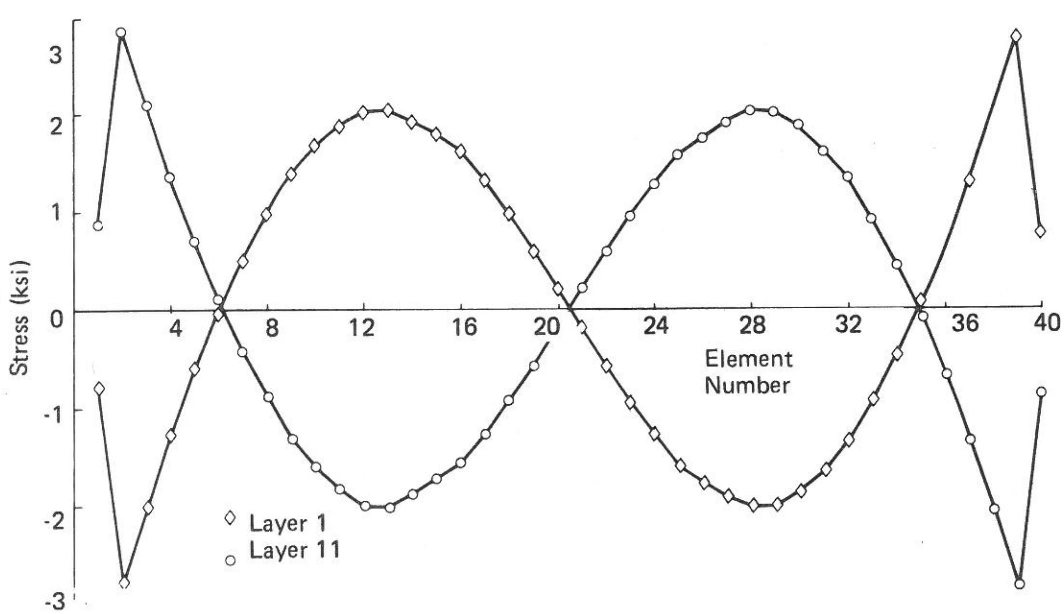

Figure 3. Gravitational Stresses

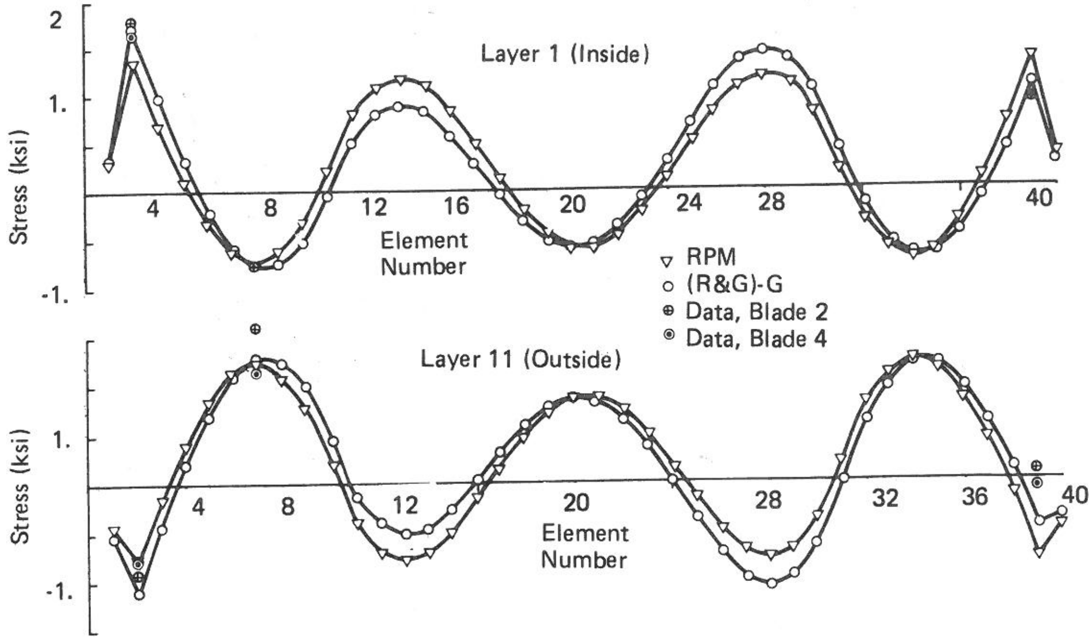

Figure 4. 32.9 RPM Results

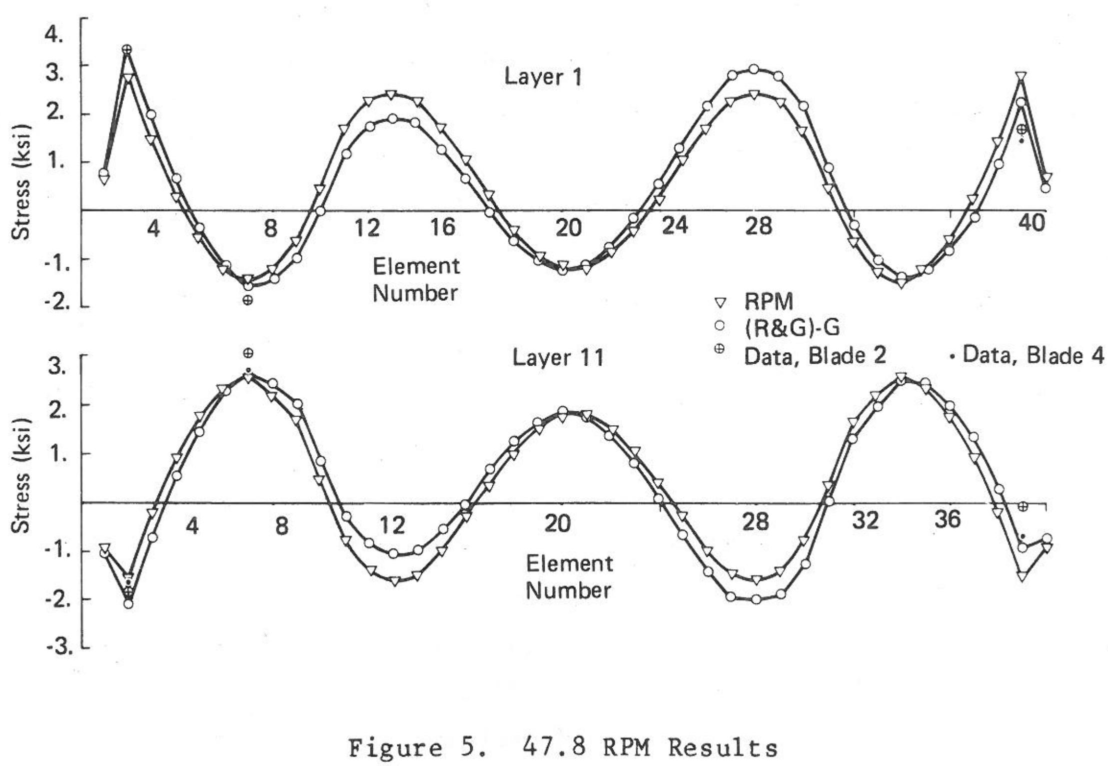

Figure 5. 47.8 RPM Results

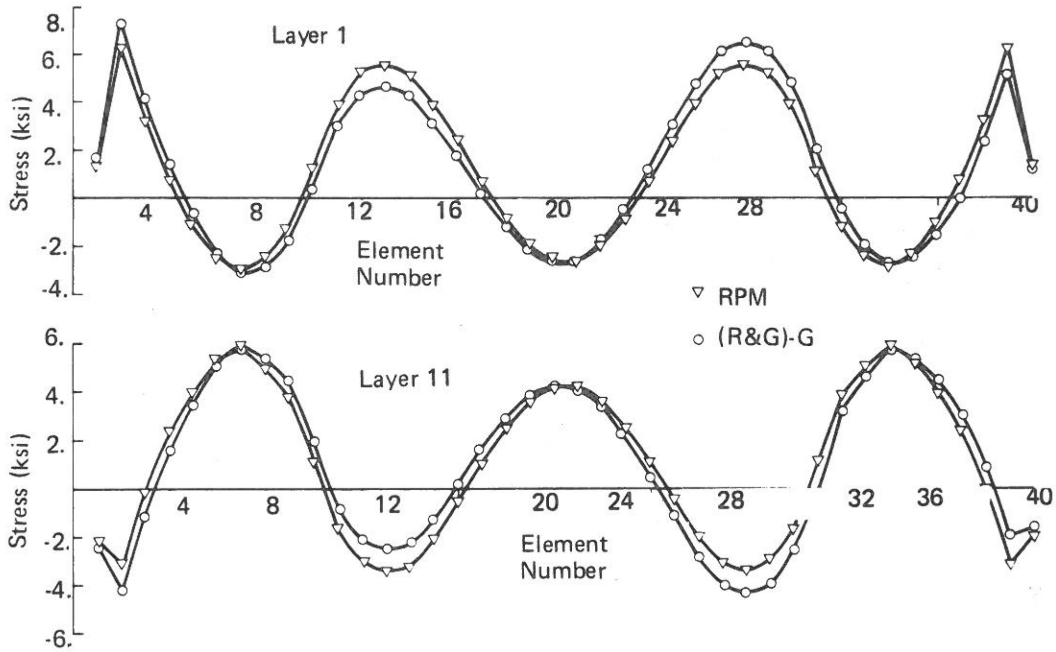

Figure 6. 75 RPM Results

As can be seen from these figures, gravity does produce a nonlinear effect on centrifugal stresses, particularly near the end clamps. This effect results from centrifugal stiffening which causes the incremental stresses induced by gravity to be lower on a spinning rotor than on a stationary one. The asymmetry produced by the gravity nonlinearity coincides with the trend of the strain gage data.

Comparisons of the centrifugal stresses vs turbine speed are given in Figures 7 through 9. The linear solutions, i.e., where stresses are proportional to the square of the rotor speed, have been superimposed on these figures.

Part of the difference between the turbine data and the MARC results can be attributed to the steep stress gradient near the clamps and the fluctuation of the strain gage zeroes. Most important, however, is the error produced by modeling the semirigid end clamps by pinning Nodes 2 and 40. At the top clamp, gravitational and centrifugal stresses are of opposite sign, and the two errors produced by the clamp deflecting downward while parked (to zero strain gages) and deflecting upward during operation negate each other. The bottom clamp has centrifugal and gravitational stresses in the same direction, doubling the effect of the clamp not being completely rigid. Thus, Element 2 shows good correlation between strain gage data and MARC analysis while Element 39 contains significant error.

Of interest in this investigation is the significant decline of nonlinear effects in the finite element analyses as compared to that of the previous composite blade,[2] part of which may be explained by the present clamped-end configuration. Probably more important, however, is the notable increase in the flatwise moment of inertia of the all-aluminum extruded blade. Both of these possibilities contribute to relatively increased elastic stiffness of the system, thereby reducing the nonlinear stiffening effect of the centrifugal tension in the blade.

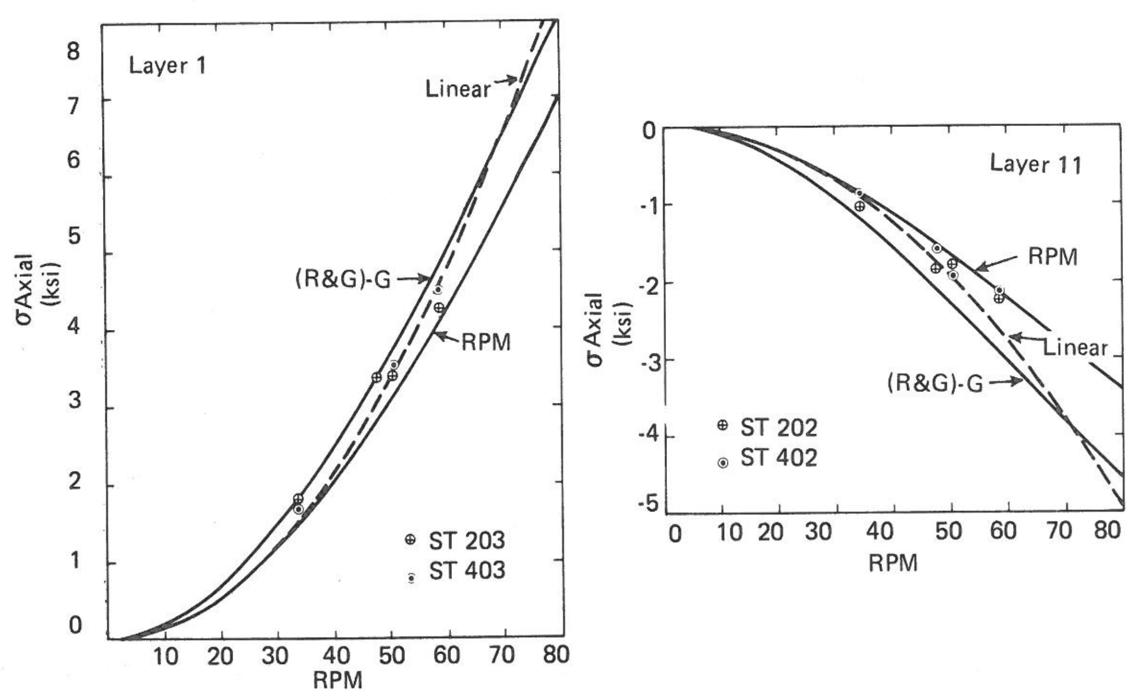

Figure 7. Element 2 Comparisons

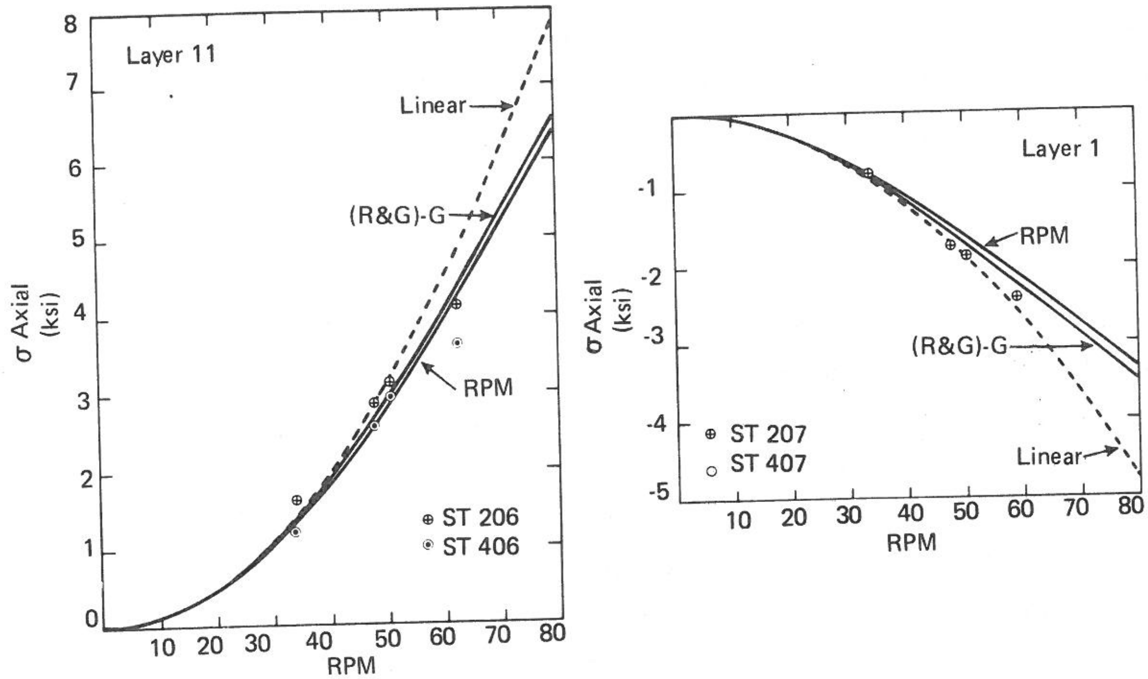

Figure 8. Element 7 Comparisons

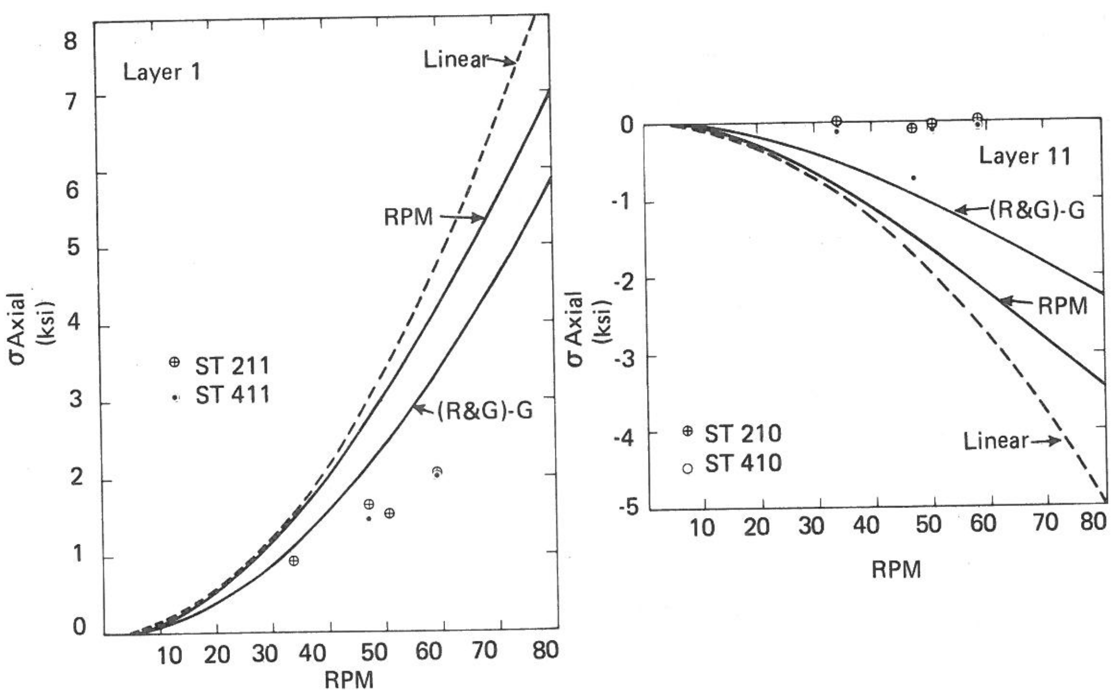

Figure 9. Element 39 Comparisons

CONCLUSIONS

The MARC-H nonlinear finite-element package produced encouraging results in predicting rotor stresses resulting from centrifugal loading. A nonlinear gravity effect on centrifugal stiffening produces asymmetry of centrifugal stresses about the central axis. Pinning nodes against displacements to model semirigid clamps provides a conservative model for stress evaluation. Improved modeling of the blade in the vicinity of the clamp would be desirable to provide more accurate stress predictions at the clamp.

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1000 G. A. Fowler
1200 L. D. Smith
3161 J. E. Mitchell (15)
3161 P. S. Wilson
4533 J. W. Reed
4700 J. H. Scott
4710 G. E. Brandvold
4710 C. J. Mora
4715 R. H. Braasch (100)
4715 R. D. Grover
4715 E. G. Kadlec
4715 R. O. Nellums
4715 W. N. Sullivan
4715 M. H. Worstell
5520 T. B. Lane
5521 D. W. Lobitz
5523 R. C. Reuter, Jr.
5523 T. G. Carne
5523 P. J. Sutherland
5600 D. B. Schuster
5620 M. M. Newsom
5630 R. C. Maydew
5632 C. W. Peterson
5632 P. C. Klimas
5633 S. McAlees, Jr.
5633 R. E. Sheldahl
8266 E. A. Aas
3141 T. L. Werner (5)
3151 W. L. Garner (3)
DOE/TIC (25)
(R. P. Campbell, 3154-3)