LINEAR AND NONLINEAR ANALYSES OF A WIND-TUNNEL BALANCE

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INTRODUCTION

The NASA Langley Research Center (LaRC) has been designing strain-gauge balances for utilization in wind tunnels since its inception. The utilization of balances span a wide variety of aerodynamic tests. A force balance is an inherently critically stressed component due to the requirements of measurement sensitivity. Force balance stress analysis and acceptance criteria are under review due to LaRC wind tunnel operational safety requirements.

This paper presents some of the analyses done at NASA LaRC. Research and analyses were performed in order to investigate the structural integrity of the balances and better understand their performance. The analyses presented in this paper are helpful in understanding the overall behavior of an existing balance and can also be used in design of new balances to enhance their performance. As a first step, maximum load combination is used for linear structural analysis. When nonlinear effects are encountered, the analysis is extended to include the nonlinearities.

Balance 1621 is typical for LaRC designed balances and was chosen for this study due to its traditional high load capacity, Figure 1. Maximum loading occurs when all 6 components are applied simultaneously with their maximum value allowed (limit load). This circumstance normally will not occur in the wind tunnel. However, if it occurs, is the balance capable of handling the loads with an acceptable factor of safety? Preliminary analysis using Pro/Mechanica indicated that this balance might experience nonlinearity. It was decided to analyze this balance by using NASTRAN so that a nonlinear analysis could be conducted.

Balance 1621 was modeled and meshed in PATRAN for analysis in NASTRAN. The model from PATRAN/NASTRAN is compared to the one from Pro/Mechanica. For a complete analysis, it is necessary to consider all the load cases as well as use a dense mesh near all the edges. Because of computer limitations, it is not feasible to analyze model with the dense mesh near all edges. In the present study, the dense mesh is limited to the surface on the end of the axial sections.

APPLIED LOAD

Preliminary linear analysis indicated that some of the load cases produce high stresses on the balance, above yield stress. Four different load combinations are used for the current analysis. Two of the load cases produce stresses above yield stress and the other two result stresses below yield. Linear analysis is performed for each load case. In the case where the stress value is above the linear elastic region, it is necessary to perform a nonlinear analysis.

The limit loads for this balance were obtained from drawing (LD-931502) and are shown in Table 1. The loads given are in the coordinate system shown in Figure 1. Transformation is necessary since the loads are applied at Point p and the values given below are valid for loads applied at Moment Center, o.

Force and Moment Components	Force (lb) and Moment (in-lb) Values
Axial (Fx)	500
Side (Fy)	1800
Normal (Fz)	3000
Roll (Mx)	7500
Pitch (My)	10000
Yaw (Mz)	4500

Table 1. Maximum Forces and Moments (Limit Loads) for Balance 1621

Four different load combinations are considered and shown below.

Case 1:

$\vec{F}_x = -500\ \hat{i}$

$\vec{F}_y = 1800\ \hat{j}$

$\vec{F}_z$ =-3000 $\hat{k}$
$\vec{M}_o$ =7500 $\hat{i}$ +10000 $\hat{j}$ +4500 $\hat{k}$

Case 2:
$\vec{F}_x$ =-500 $\hat{i}$
$\vec{F}_y$ =1800 $\hat{j}$
$\vec{F}_z$ =3000 $\hat{k}$
$\vec{M}_o$ =7500 $\hat{i}$ -10000 $\hat{j}$ +4500 $\hat{k}$

Case 3:
$\vec{F}_x$ =-500 $\hat{i}$
$\vec{F}_y$ =1800 $\hat{j}$
$\vec{F}_z$ =-3000k
$\vec{M}_o$ =-7500 $\hat{i}$ +10000 $\hat{j}$ +4500 $\hat{k}$

Case 4:
$\vec{F}_x$ =-500 $\hat{i}$
$\vec{F}_y$ =1800 $\hat{j}$
$\vec{F}_z$ =3000 $\hat{k}$
$\vec{M}_o$ =-7500 $\hat{i}$ -10000 $\hat{j}$ +4500 $\hat{k}$

The transformation of the loads from Moment Center (MC) at point o to Point p is done using equation (1):

$$\vec{M}_p = \vec{R}_{po} \times \vec{F} + \vec{M}_o = 4.1\ \hat{i} \times (\vec{F}_x + \vec{F}_y + \vec{F}_z) + \vec{M}_o \qquad \text{Equation (1)}$$

Moment components for each case are obtained after substituting into equation (1):

$\vec{M}_p$ = 7500 $\hat{i}$ +22300 $\hat{j}$ +11880 $\hat{k}$ Case 1
$\vec{M}_p$ = 7500 $\hat{i}$ -22300 $\hat{j}$ +11880 $\hat{k}$ Case 2
$\vec{M}_p$ = -7500 $\hat{i}$ +22300 $\hat{j}$ +11880 $\hat{k}$ Case 3
$\vec{M}_p$ = -7500 $\hat{i}$ -22300 $\hat{j}$ +11880 $\hat{k}$ Case 4

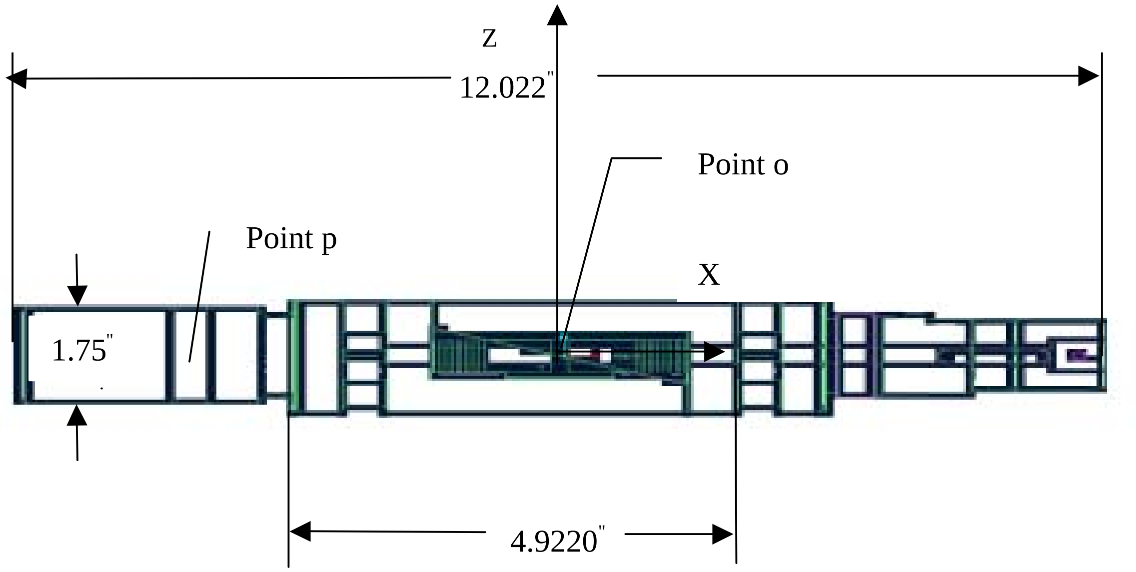

Figure 1. Balance 1621 with its coordinate axis located at the Moment Center

MODAL ANALYSIS

Initial analyses were performed with Pro/Mechanica and later analyses with NASTRAN. In order to better understand the structural behavior of this balance and compare models generated in PATRAN with models generated in Pro/E, a modal analysis was performed. The natural frequencies and mode shapes were obtained from Pro/Mechanica and NASTRAN and compared. Single-pass adaptive (SPA) analysis was used in obtaining these results from Pro/Mechanica. The first 3 frequencies are shown below from both Pro/Mechanica and NASTRAN. The frequencies from the two models are close. The results indicate that the models, Pro/E and PATRAN, are roughly equivalent.

Mode	Frequency (HZ) Pro/Mechanica	Frequency (HZ) NASTRAN	Mode Shape
1	335.3	344.42	Bending about Z-axis
2	341.9	350.65	Bending about Y-axis
3	1066	1225.5	Axial

Table 2. Frequencies from NASTRAN and Pro/Mechanica

LINEAR ANALYSIS

The present model was generated and meshed using PATRAN. The section of the material where the load is applied is not modeled in order to reduce the number of elements. The load is applied at Point p and transferred to the balance through a rigid element. The results are expected to be accurate away from the applied load due to St. Venant's principal.

GLOBAL ANALYSIS

Because of computer limitations, the model was meshed using a little less than 200,000 elements, all 10-node tetrahedral elements, tet10. The result of this run is used for Global-Local analysis. Global-Local analysis is used in order to obtain more accurate results for the selected parts of the model. With this method, a desired section (local model) is meshed and loads and boundary conditions are obtained from the results of the global model analysis. A 3-D view of the meshed global model used in the present work is shown in Figure 2.

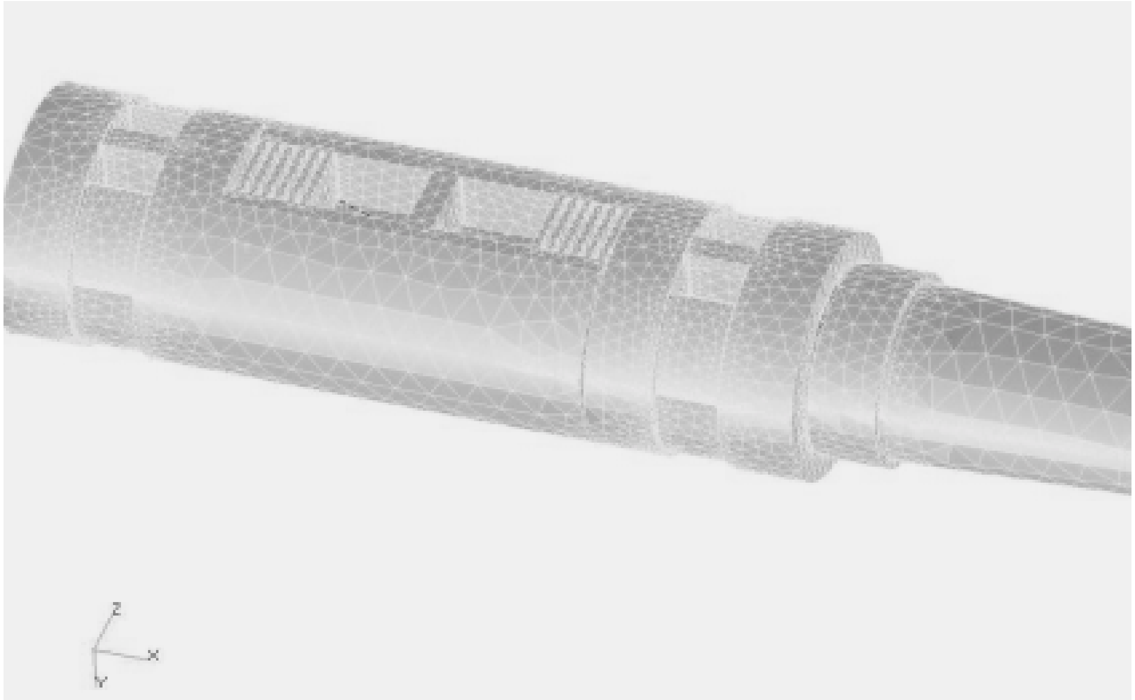

Figure 2. A 3-D view of the balance modeled and meshed in PATRAN

The von Mises stress and principal stresses for the axial section near the applied load are shown in Figures 3 and 4, load case 1. As the figures indicate, maximum von Mises stress (267 KSI) and principal stress (274 KSI) both occur near the applied load. It should be mentioned that the values shown are for the coarse mesh. To obtain more accurate results, more elements are needed, particularly near the corners. VascoMax C-300 is the material for this balance and according to the manual from TELEDYNE VASCO, it has a yield stress of 287 KSI.

Figure 3. The von Mises stress for the balance, load case 1

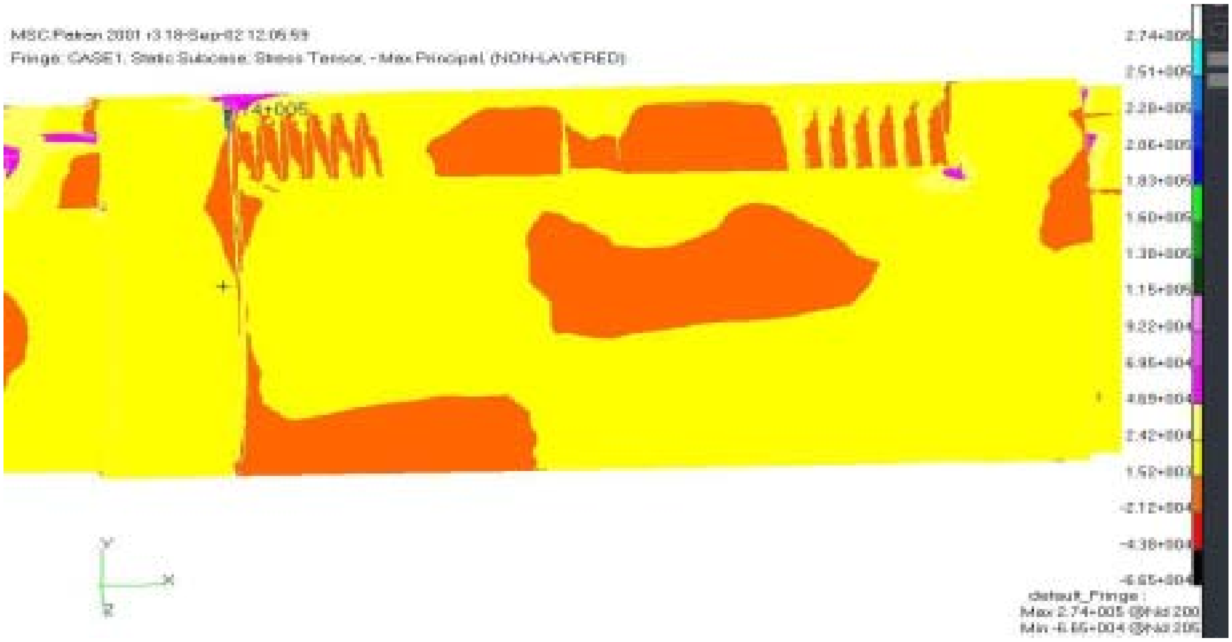

Figure 4. The maximum principal stress for the balance, load case 1

LOCAL ANALYSIS OF AXIAL SECTION NEAR THE APPLIED LOAD

There are many corners on the balance and in order to capture the stress gradient, a dense mesh is required near these corners until convergence occurs. In order to use more elements, because of the computer limitations, the global model has to be divided into smaller local sections.

A section near the applied load was extracted and meshed, Figure 5. The results of the global model were used as the boundary condition for this local model. The von Mises and principal stresses are shown in Figures 6 and 7. As the results indicate, the maximum principal stress is above ultimate and the maximum von Mises stress is above yield. Hence, nonlinear analysis is needed.

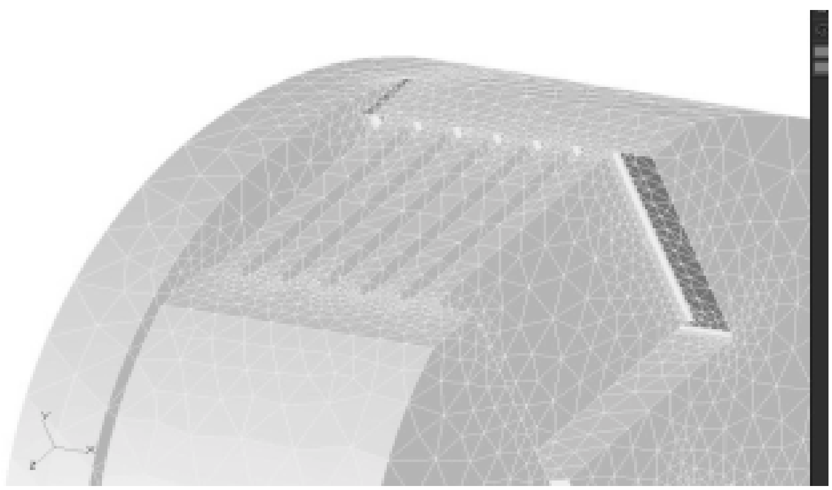

Figure 5. A meshed view of the section of the balance near the applied load

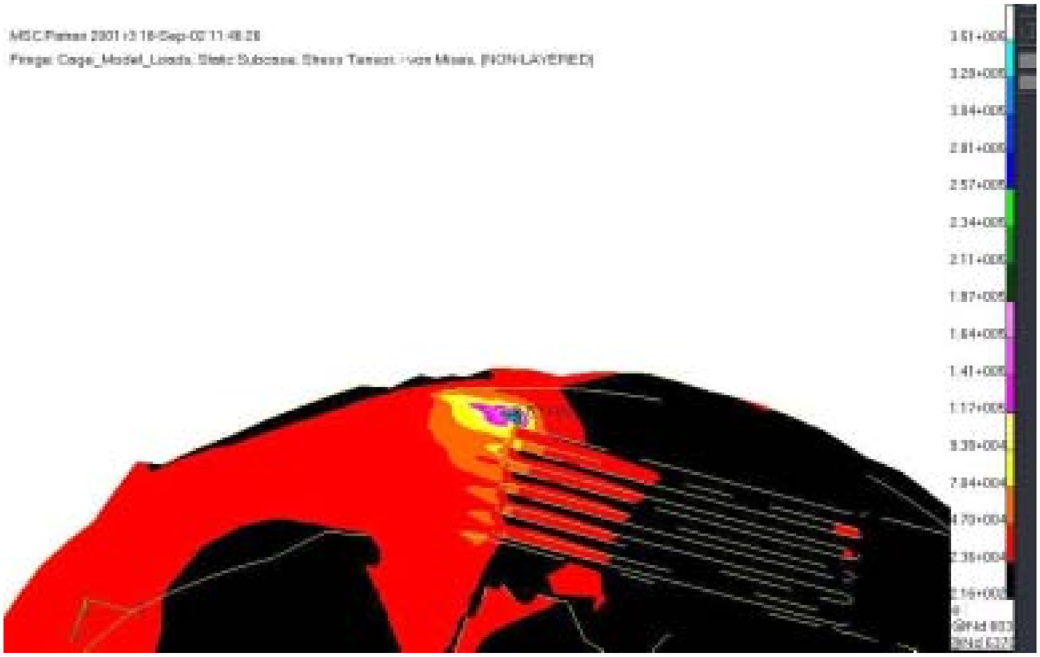

Figure 6. Von Mises stress for the section of the balance near the applied load

Figure 7. Principal stress for the section of the balance near the applied load

MODEL FOR NONLINEAR ANALYSIS

The results from the linear analysis indicate that the stress value is above the linear elastic region; hence, nonlinear analysis is required. Because NASTRAN tet10 elements do not allow some nonlinearity in the version used here, the model used for nonlinear analysis is meshed with 4 node tetrahedral elements, tet4. The balance is meshed with almost 400,000 tet4 elements, Figure 8. More elements are used near sharp corners. A dense mesh is used near the end of the axial sections, Figure 9. Linear analysis was performed on the balance with the new mesh and all four load cases were considered. If the linear analysis indicated a maximum stress value below yield stress, nonlinear analysis was not performed.

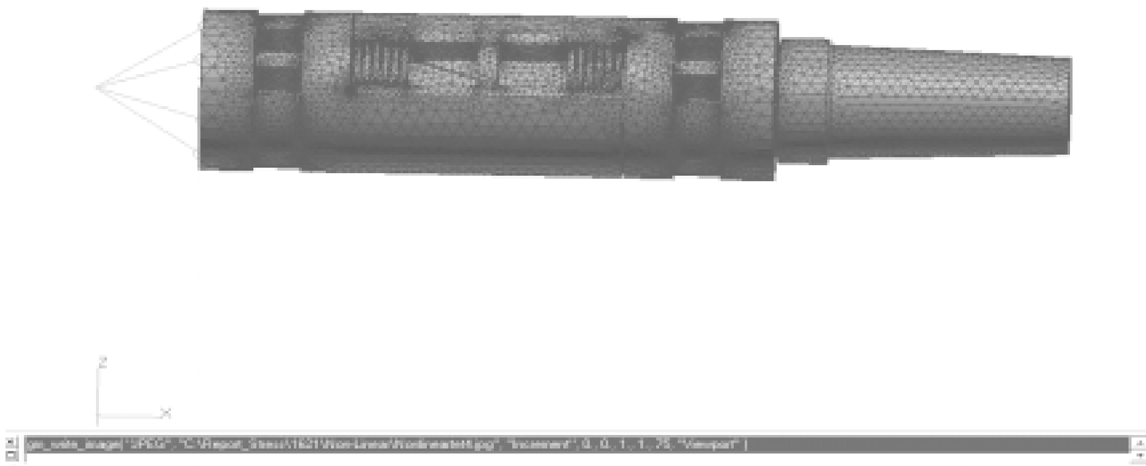

Figure 8. Meshed balance for nonlinear analysis

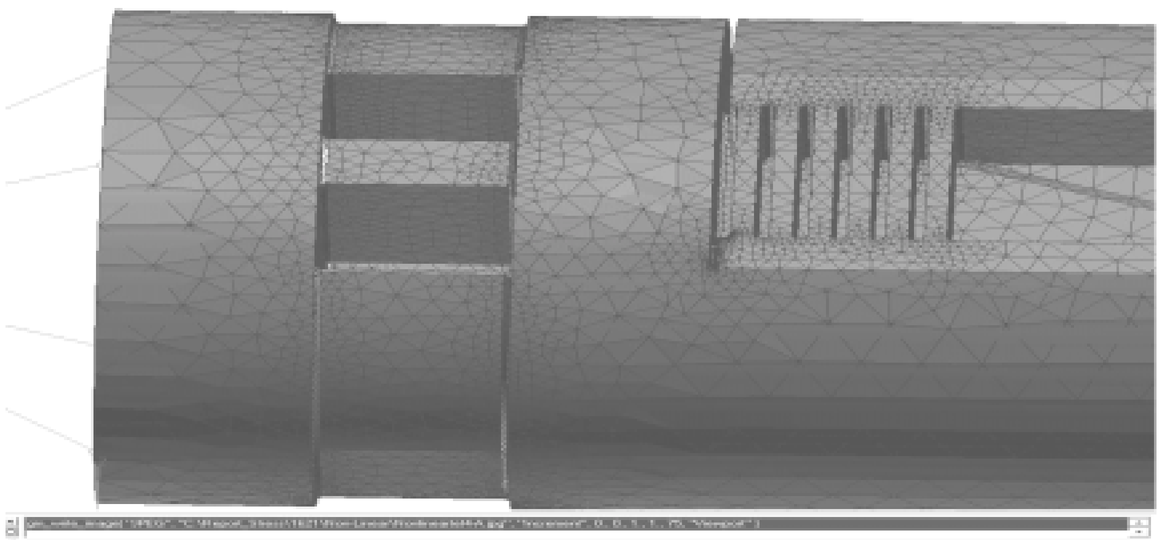

Figure 9. A close-up view of the end of the axial section

1. CASE 1 LOADING

The full model is used for the linear and nonlinear analysis. Also a local model, used in the linear analysis, is used here again for comparison.

A. GLOBAL MODEL

The results of the analysis for the load combination of Case 1 are shown in this section. The full model is used and the results from the linear and nonlinear analyses are shown.

LINEAR ANALYSIS

The von Mises stress from the linear analysis for the balance is shown below. As Figure 10 indicates, the maximum stress occurs at the end of the axial section and is above the ultimate stress.

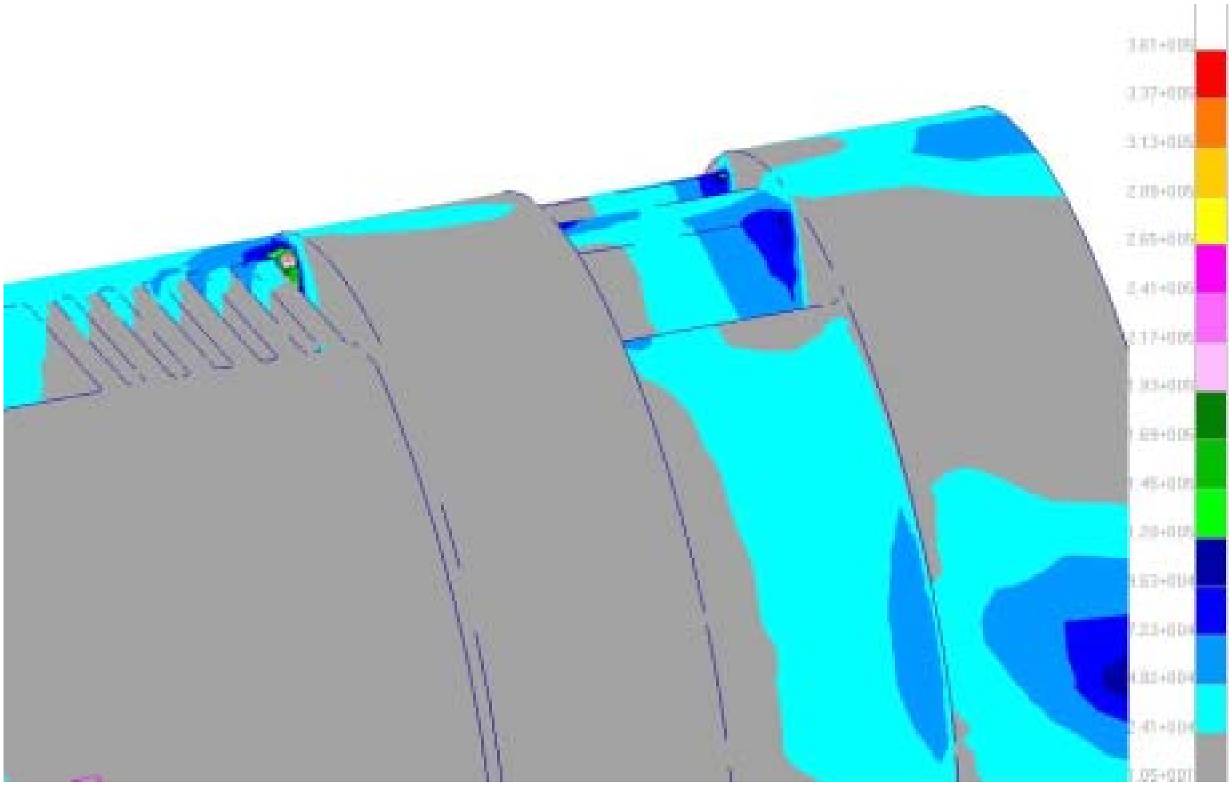

Figure 10. The von Mises stress for the balance from the linear analysis, Load Case 1

NONLINEAR ANALYSIS

The von Mises stress from the nonlinear analysis of the balance is shown below, Figure 11. As expected, the value of the maximum von Mises stress dropped in comparison with the linear case. The maximum stress predicted by the nonlinear analysis is below the yield point.

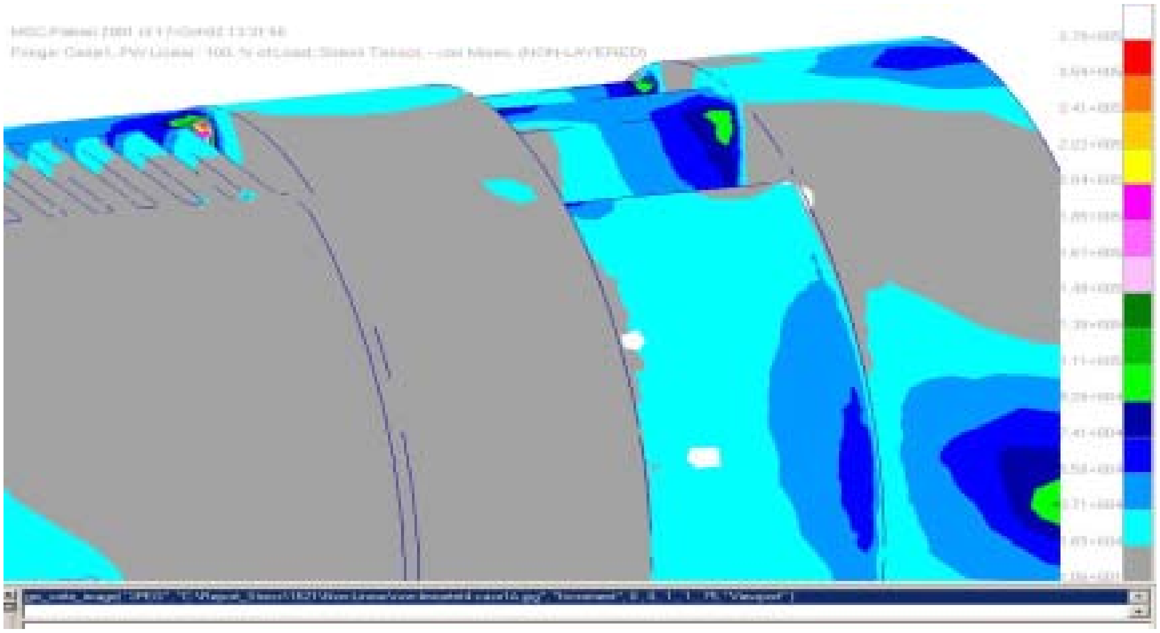

Figure 11. The von Mises stress for the balance from the nonlinear analysis, Load Case 1

In order to have an overall view of the stresses everywhere on the balance, Figure 12 is plotted. Figure 12 shows the position versus von Mises stress for all points on the balance. The figure clearly indicates that the high stress regions are localized and the two peak stresses occur at the end of the axial sections. It should be noted that the maximum stress value near other corners might increase as more dense mesh is used near those corners. However, in the present work, the interest is at the end of the axial section.

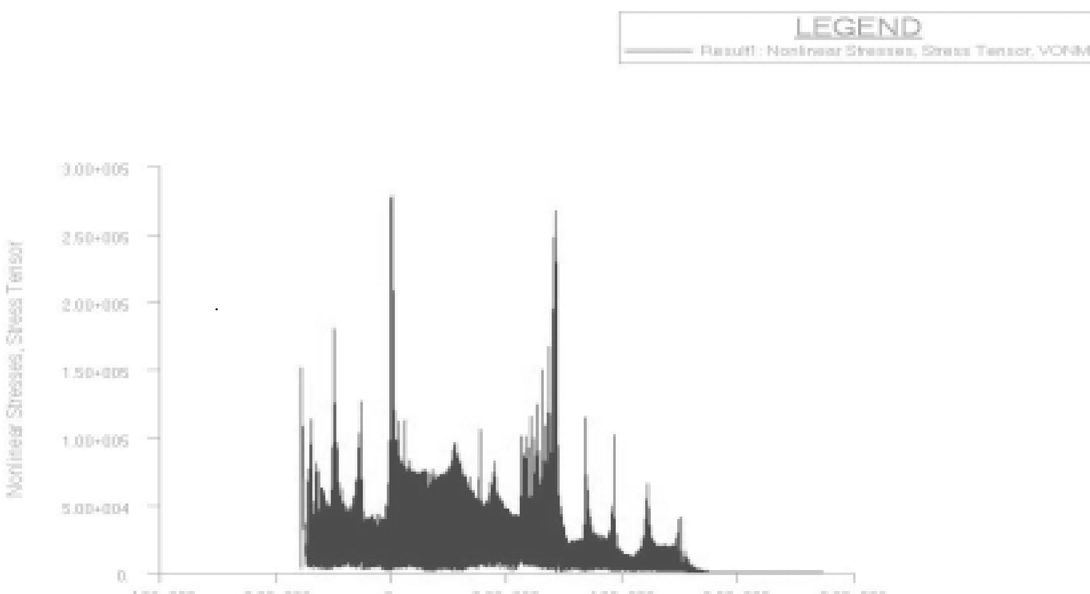

Figure 12. Axial position vs. von Mises stress for all points on the balance, Load Case 1

The stress values on the +Y and –Y sides of the balance are plotted individually and shown in Figures 13 and 14. As shown, the maximum stress occurs on the –Y side of the balance for this load case.

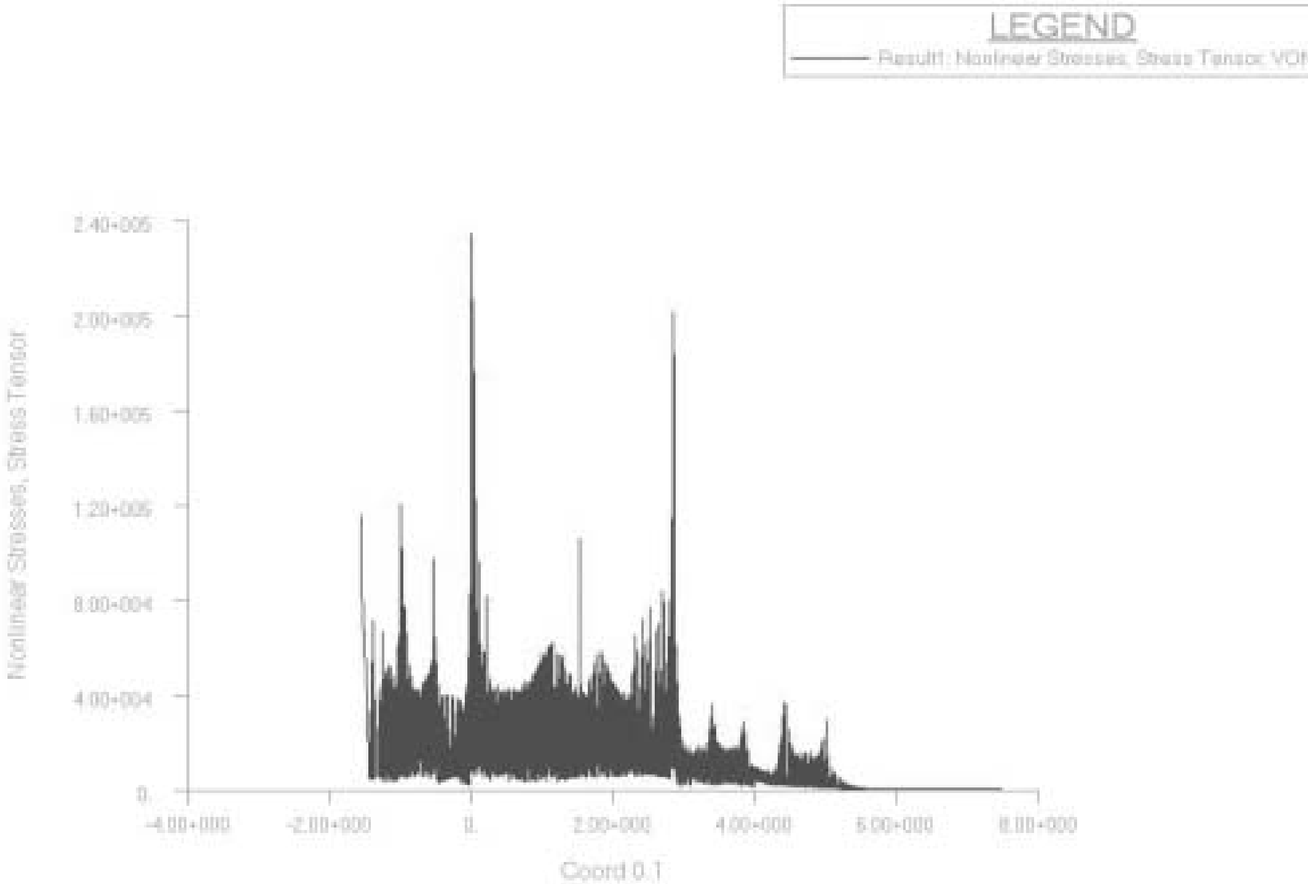

Figure 13. Position vs. von Mises stress for points located on the +Y side of the balance, Load Case 1

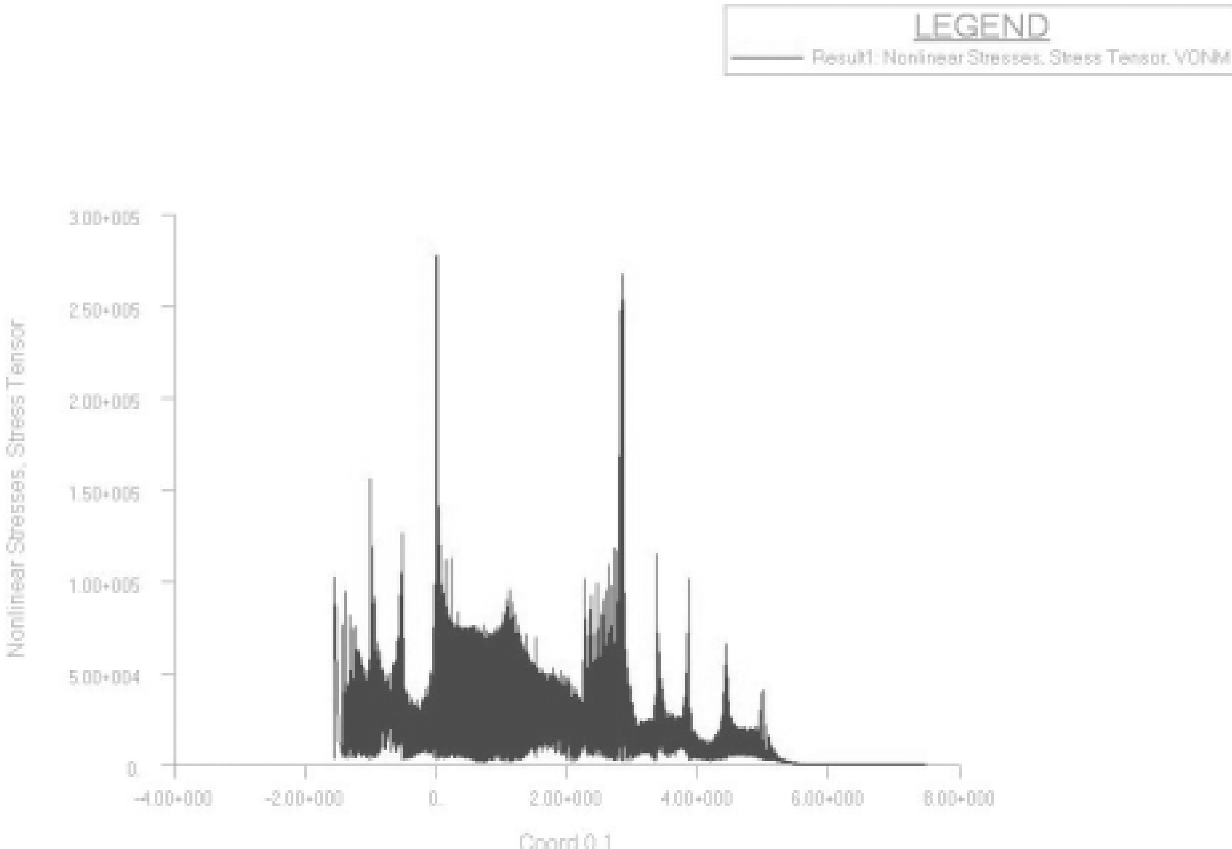

Figure 14. Position vs. von Mises stress for points located on the -Y side of the balance, Load Case 1

B. LOCAL MODEL

The local model of the balance used for the linear analysis, from the previous section, is used here again for Global-Local analysis. The local model is meshed with tet4 elements for the nonlinear analysis, Figure 15. The boundary conditions are obtained from the linear run. The von Mises and principal stresses for the nonlinear analysis are shown in Figures 16 and 17.

The comparison of the linear and the nonlinear runs for the axial section near the applied load is shown in Table 3. As expected, stresses obtained from the nonlinear analysis dropped in comparison with the linear analysis and are in agreement with the analysis of the global model.

	Linear Analysis	Nonlinear Analysis
Von Mises Stress	351 KSI	287 KSI
Principal stress	312 KSI	249 KSI

Table 3. Maximum von Mises and principal stresses from the local model

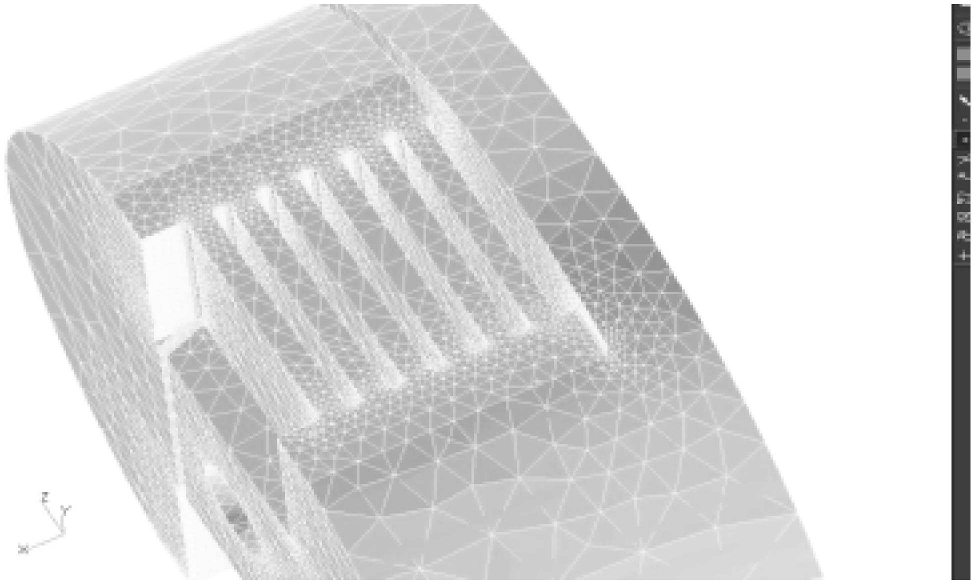

Figure 15. Axial section of the balance near the applied load

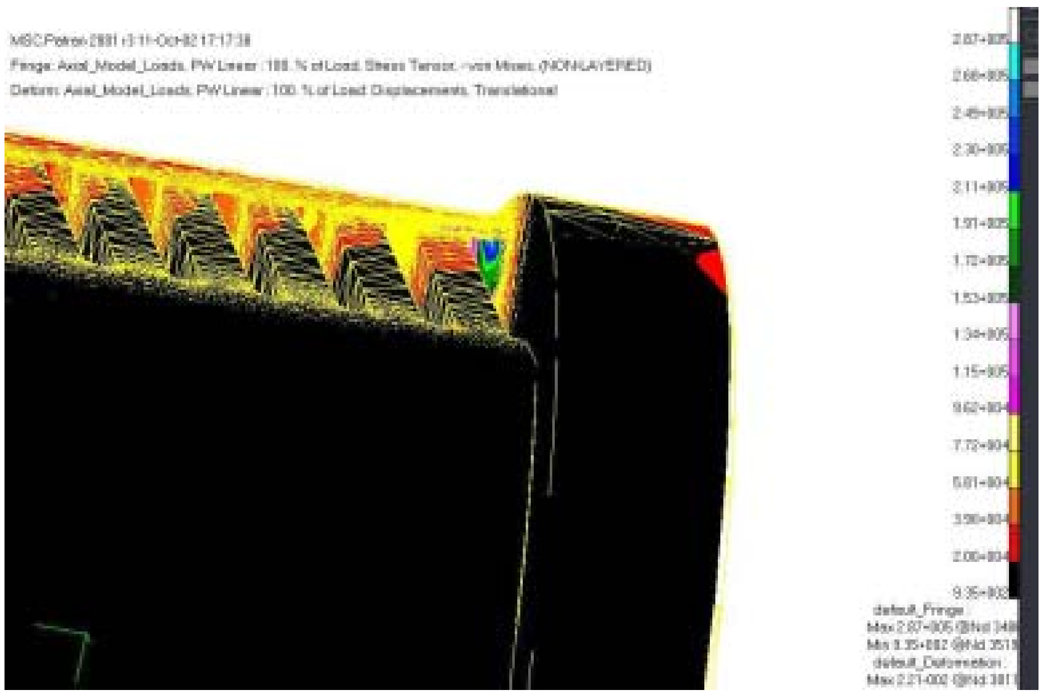

Figure 16. Von Mises stress for the section of the balance near the applied load from the nonlinear analysis, Load Case 1

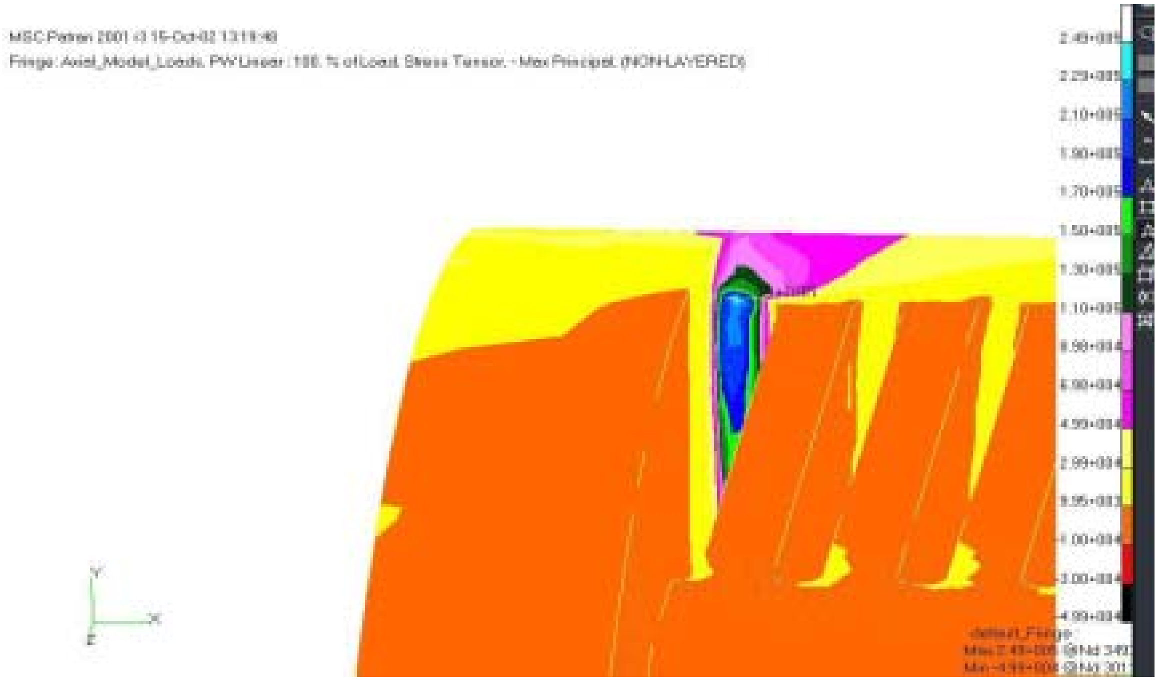

Figure 17. Principal stress for the section of the balance near the applied load from the nonlinear analysis, Load Case 1

2. CASE 2 LOADING

LINEAR ANALYSIS

The von Mises stress from the linear analysis for the balance is shown below. As the figure indicates, the high stress occurs at the end of the axial section.

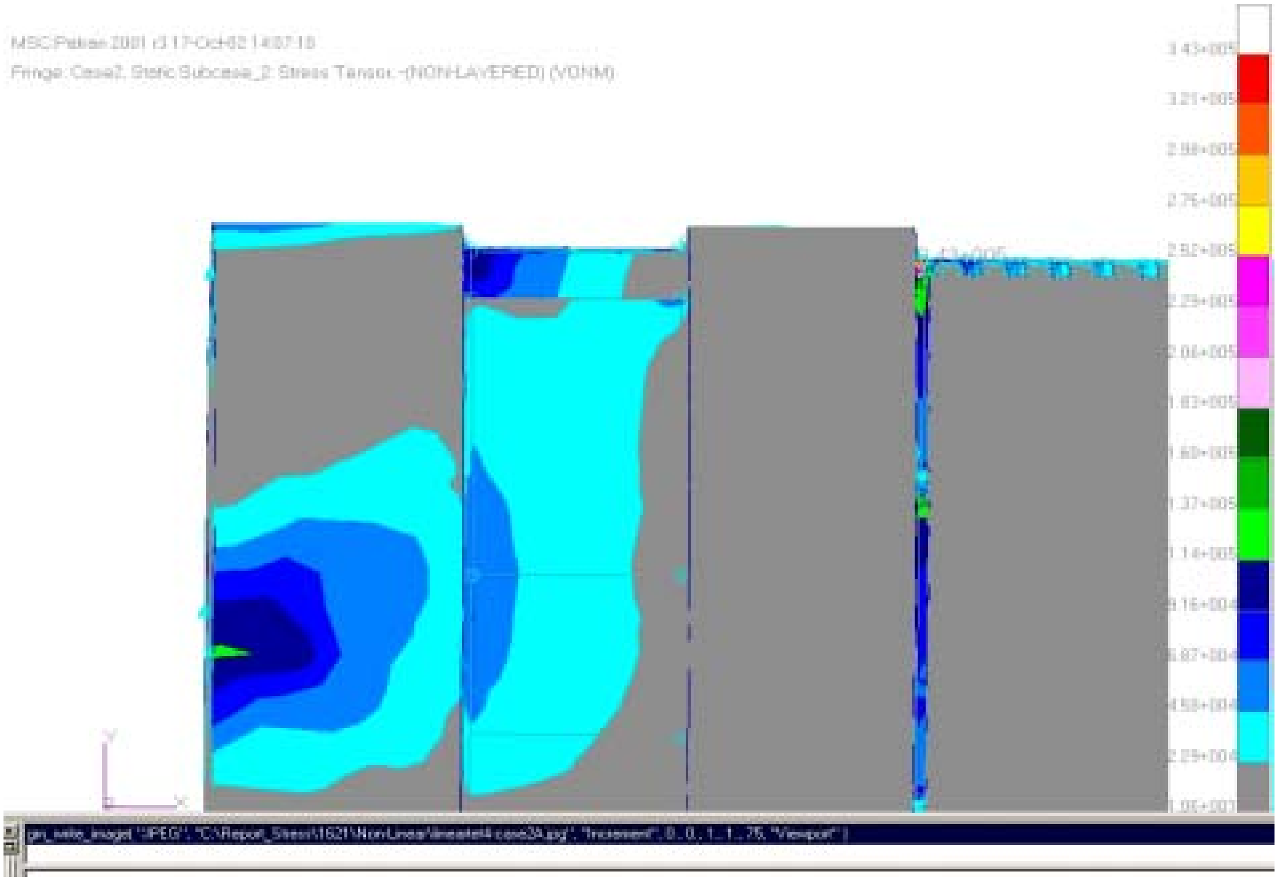

Figure 18. The von Mises stress for the balance from the linear analysis, Load Case 2

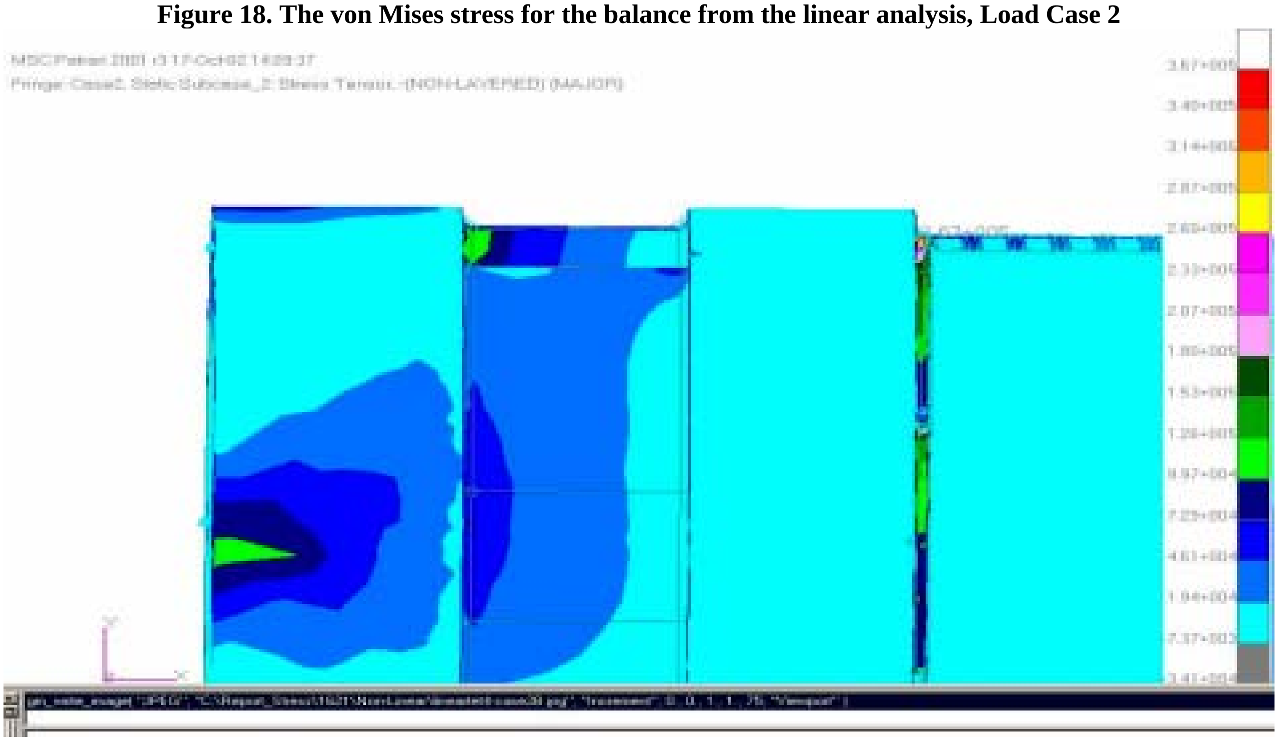

Figure 19. The principal stress for the balance from the linear analysis, Load Case 2

NONLINEAR ANALYSIS

The von Mises and principal stresses from the nonlinear analysis are shown in Figures 20 and 21. As expected, the maximum stress value for the von Mises and principal stresses dropped in comparison with the linear analysis.

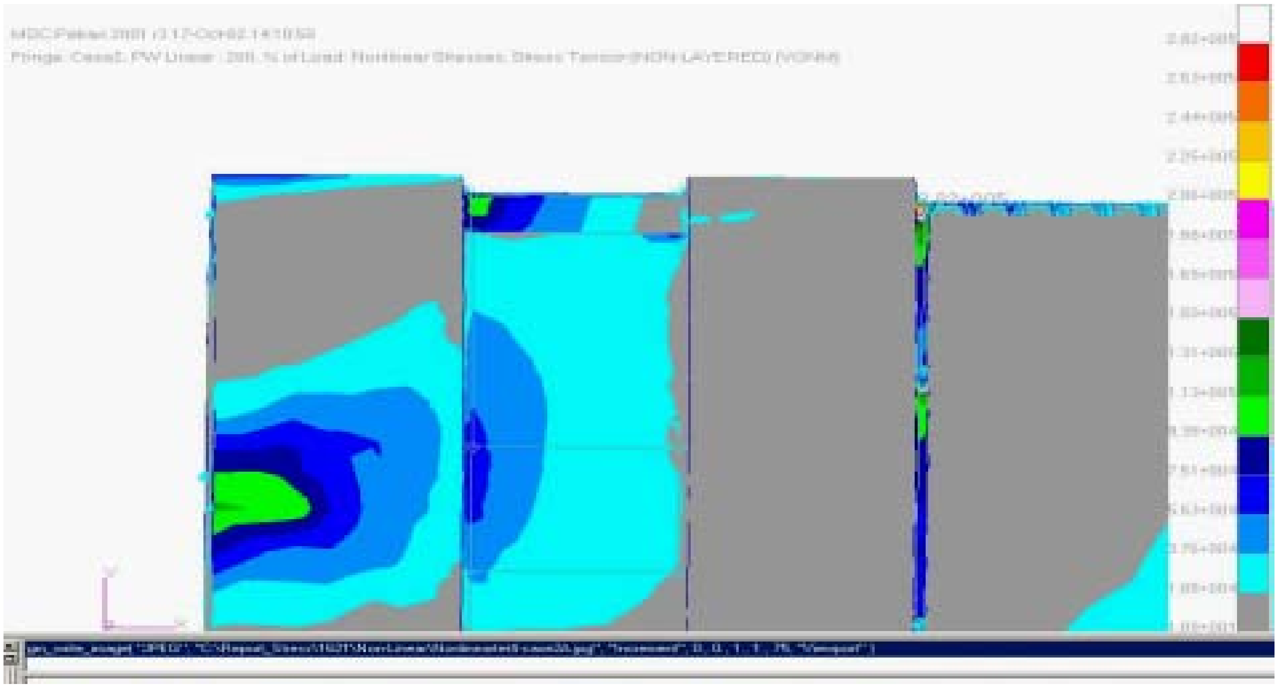

Figure 20. The von Mises stress for the balance from the nonlinear analysis, Load Case 2

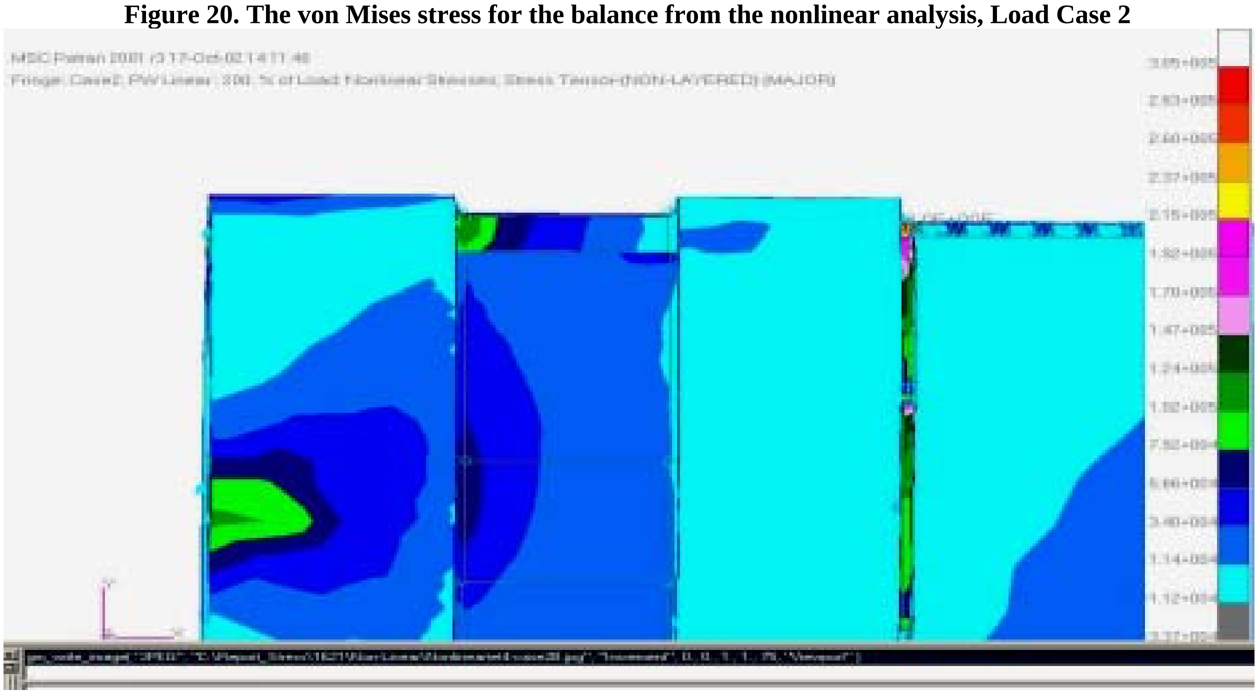

Figure 21. The principal stress for the balance from the nonlinear analysis, Load Case 2

In order to have an overall view of the stresses everywhere on the balance for this load case, Figures 22 and 23 are plotted. Figure 22 shows the stress for the von Mises and Figure 23 shows the principal stress on the balance.

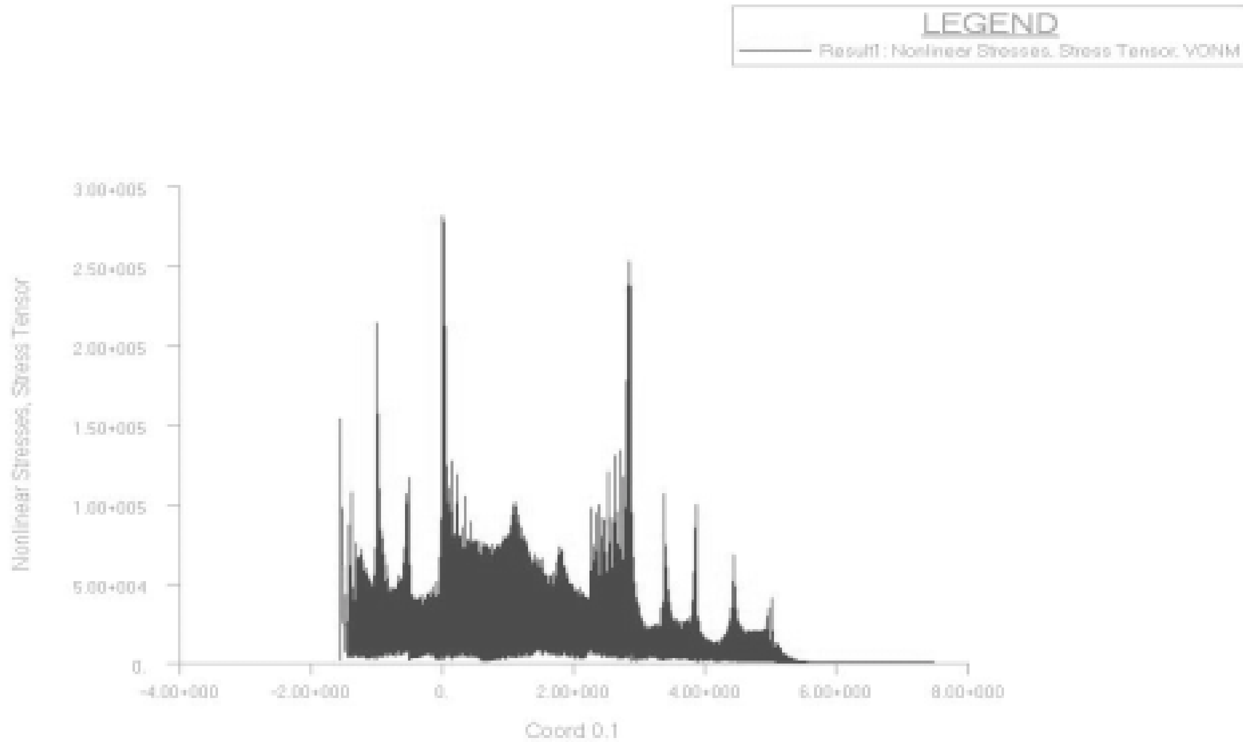

Figure 22. Position vs. von Mises stress for all points on the balance, Load Case 2

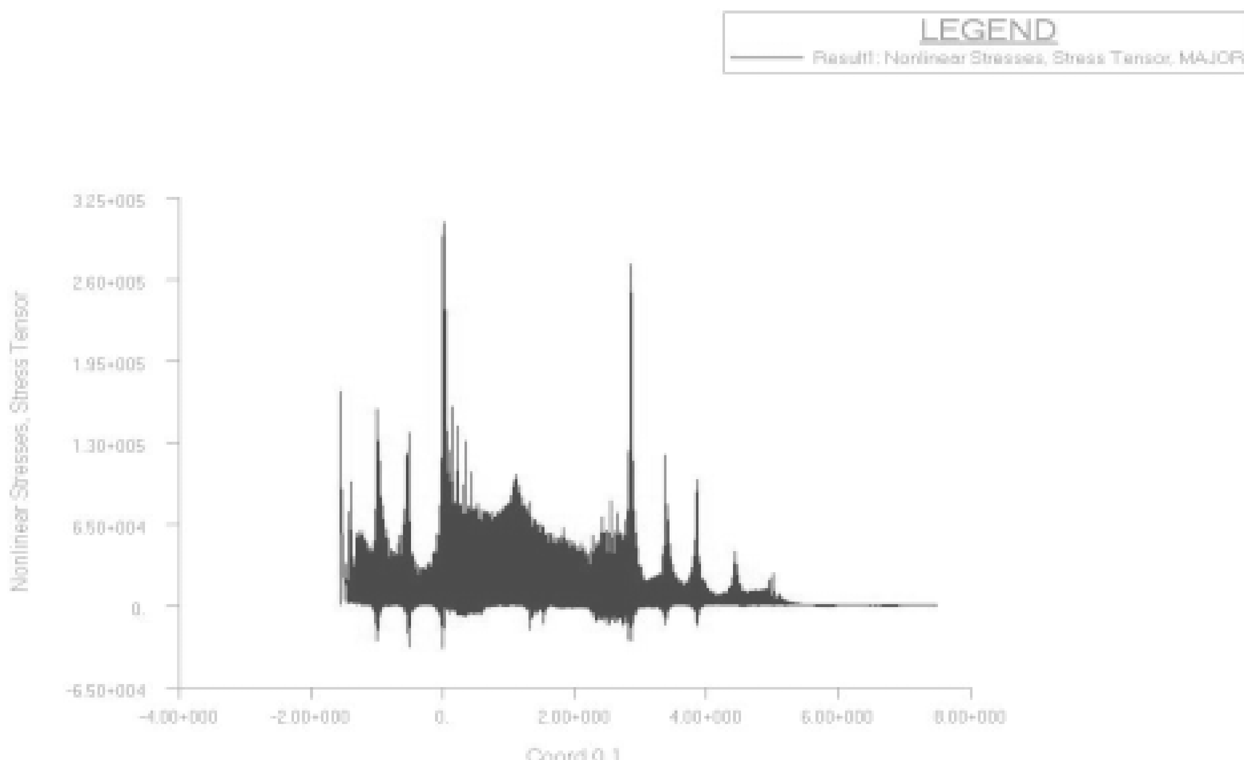

Figure 23. Position vs. principal stress for all points on the balance, Load Case 2

3. CASE 3 AND CASE 4 LOADING

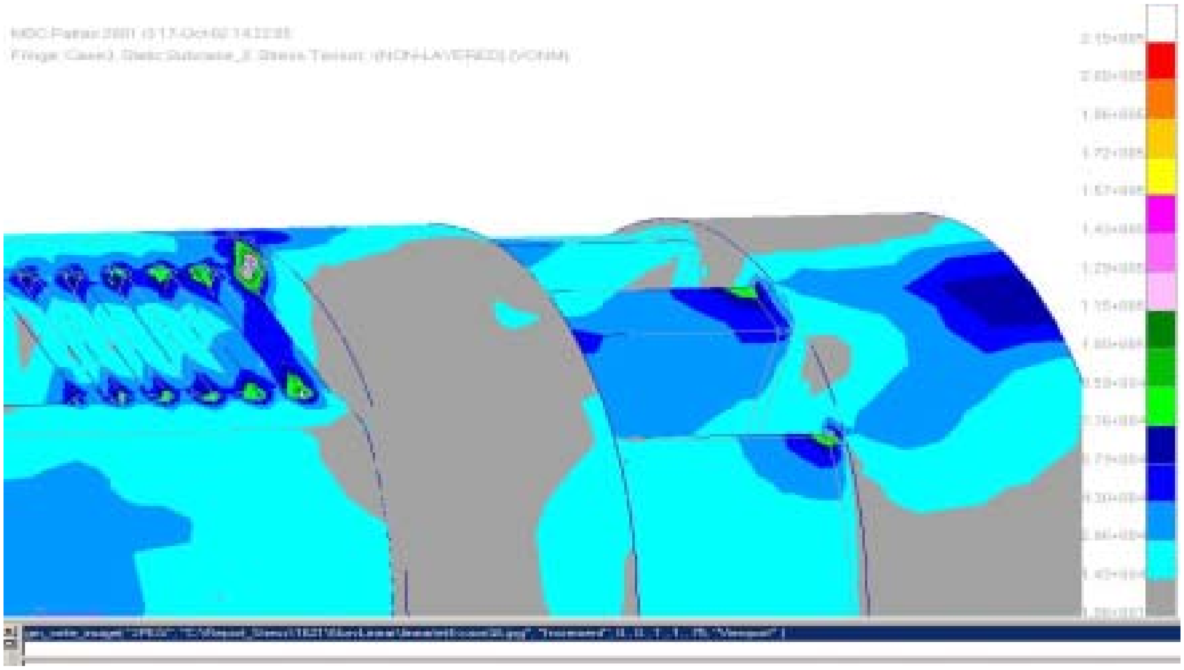

Figure 24. The von Mises stress for the balance from the linear analysis, Load Case 3

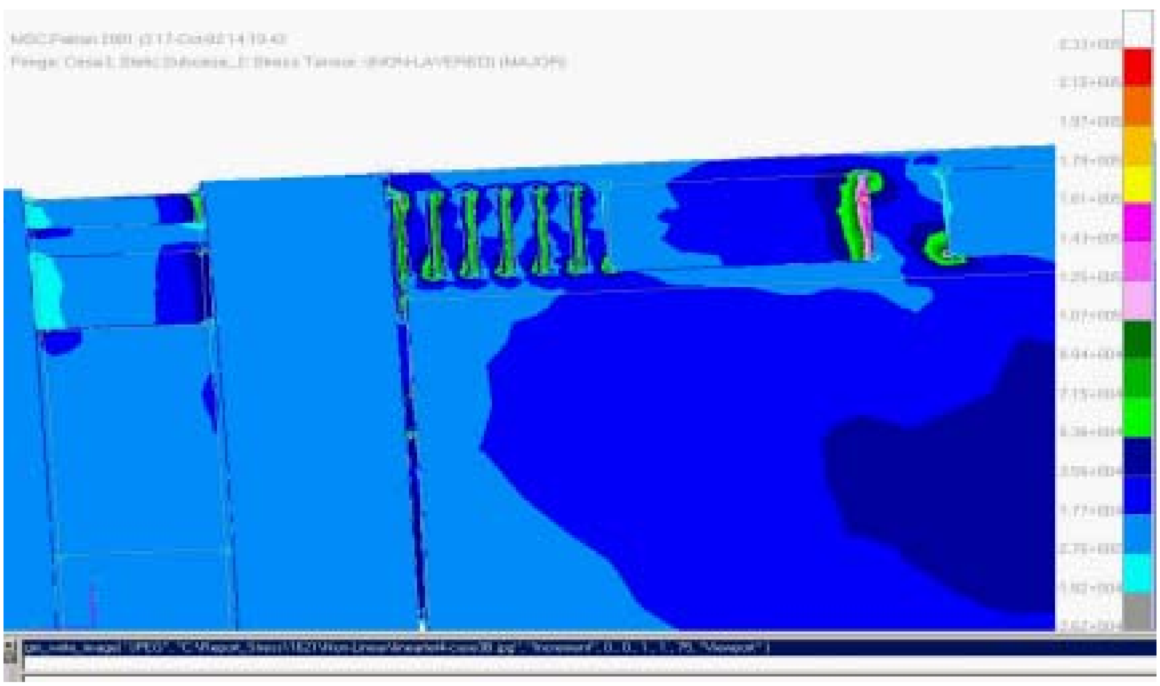

Figure 25. The principal stress for the balance from the linear analysis, Load Case 3

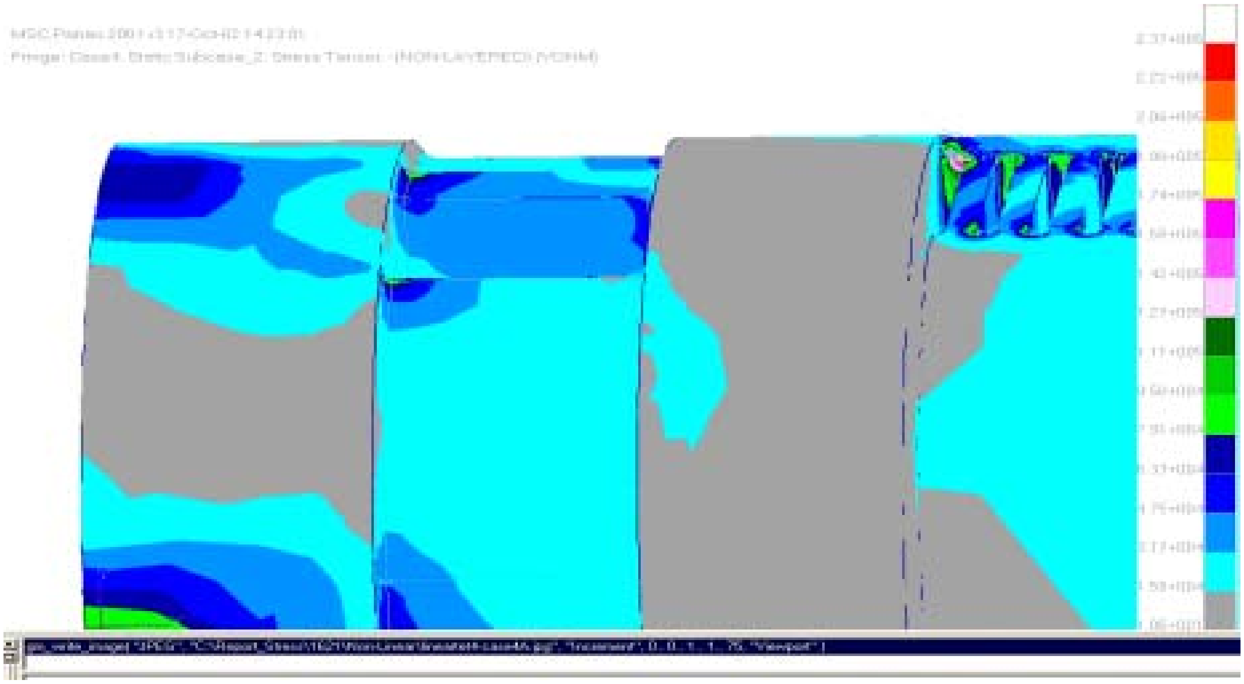

Figure 26. The von Mises stress for the balance from the linear analysis, Load Case 4

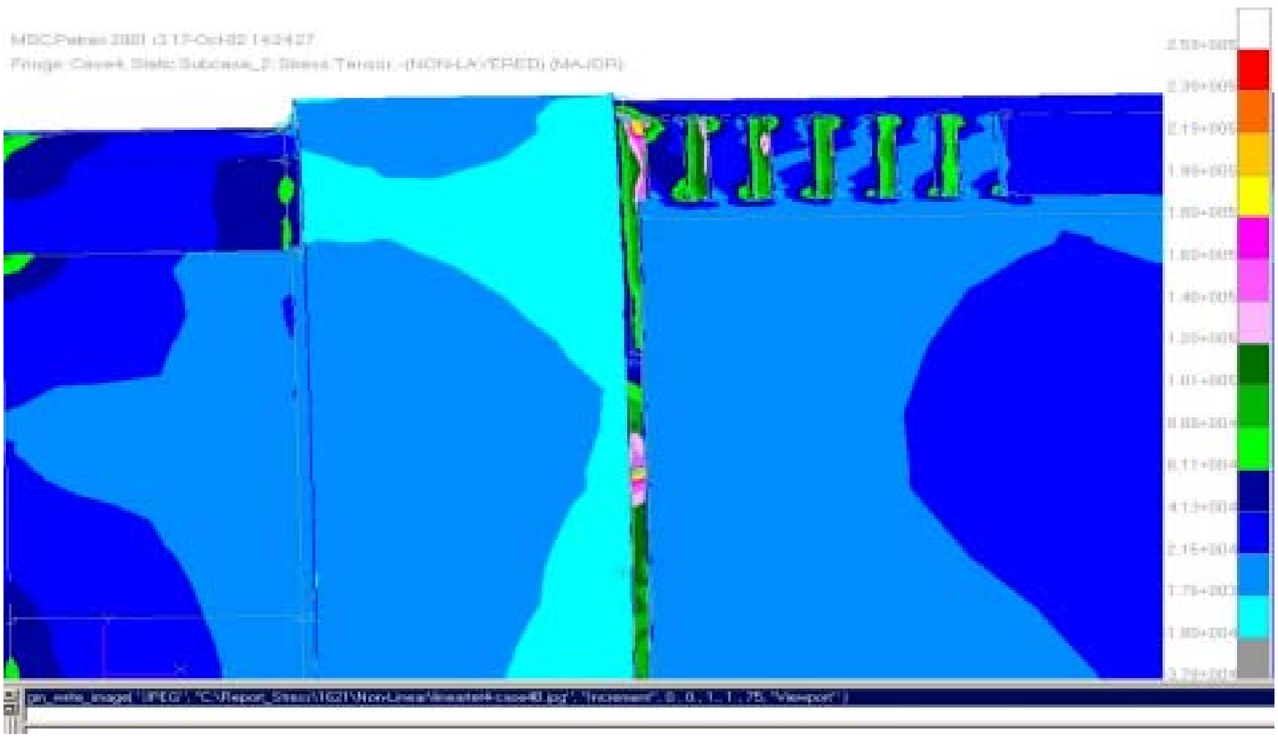

Figure 27. The principal stress for the balance from the linear analysis, Load Case 4

DISCUSSION AND CONCLUSION

Modal analysis was performed to compare the models from Pro-Engineering/Pro-Mechanica and PATRAN/NASTRAN. Four different load combinations were used and two of the load combinations required nonlinear analysis. As the table below indicates, the maximum von Mises stresses predicted by the nonlinear analysis are below yield, however there is little or almost no factor of safety.

	Linear Analysis Von Mises (KSI)	Linear Analysis Principal (KSI)	Nonlinear Analysis Von Mises (KSI)	Factor of Safety
Case 1	361		278	1.03
Case 2	343	367	282	1.02
Case 3	215	233		1.33
Case 4	237	253		1.21

Table 4. Comparison table between linear and nonlinear analysis

RECOMMENDATIONS

ANALYSIS

It should be noted that not all the balances and not all the load combinations require nonlinear analysis. For the existing balances, Pro/Mechanica, NASTRAN, or other Finite Element software can be used for linear analysis. For a complete analysis, all the load cases need to be considered. Having the model in Pro/Engineering makes Pro/Mechanica a good candidate for stress analysis. If the maximum stress value obtained is beyond yield, either a change in the design is needed or the maximum loads allowed need to be reduced. The reduction of the force can be in certain components, and this is practical, since in most cases the wind tunnel tests do not require the simultaneous application of all maximum load components. In some cases the wind tunnel test may require some components above their maximum value while the maximum value of the other components are not needed and can be reduced.

DESIGN

For the balances that will be designed in the future, it is important to consider the factor of safety in the design stage. Increasing the size of the fillets helps to relieve some of the high stresses, which occur locally. In some locations such as the end of the axial section, the sharpness on one side can be removed by taking the unnecessary sharp corners out. This can be done on the new or existing balances. Doing so, will reduce the maximum value of stress from those corners with little effect on the overall performance of the balance.