

Investigating and Analyzing Applied Loads Higher Than Limit Loads

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The results of the analysis for Balance 1621 indicate that the stresses are high near sharp corners. It is important to increase the size of the fillets to relieve some of the high stresses for the balances that will be designed. For the existing balances, the stresses are high and do not satisfy the established criteria. Two options are considered here. One is a possible modification of the existing balances, and two is to consider other load options. Redesigning a balance can be done in order to enhance the structural integrity of the balance. Because an existing balance needs to be modified, it is not possible to increase the fillet sizes without some further modifications to the balance. It is required that some materials be extracted from the balance in order to have larger fillet sizes. Researchers are interested in being able to apply some components of the load on the balance above the limit loads assigned. Is it possible to enhance the load on the same balance and maintain the factor of safety required? Some loads were increased above their limit loads and analyzed here.

Nomenclature

F_x	= force in x direction
F_y	= force in y direction
F_z	= force in z direction
M	= moment
M_x	= moment about x axis
M_y	= moment about y axis
M_z	= moment about z axis

I. Introduction

The National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) has been designing strain-gauge balances for utilization in wind tunnels. A force balance is an inherently critically stressed component due to the requirements of measurement sensitivity. The utilization of balances spans over a wide variety of aerodynamic tests. The balances have been utilized in Langley's wind tunnels and the designs encompass a large array of sizes, loads, and environmental effects. Currently, Langley has more than 300 balances available for its researchers.

A strain gauge balance is a transducer used to measure the aerodynamic loads encountered by a wind tunnel model during a wind tunnel test. There are six degrees of freedom that a balance has to measure. The balance's task to measure these six degrees of freedom has introduced challenging work in transducer development technology. As the emphasis increases on improving aerodynamic performance of all types of air and spacecraft, this paper presents some of the analyses and research that were performed at NASA LaRC, the demand for improved balances is at the forefront.

II. Background

Force balance stress analysis and acceptance criteria are under review due to LaRC wind tunnel operational safety requirements. Balance 1621 is typical for LaRC designed balances and was chosen for this study due to its

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traditional high load capacity. Maximum loading occurs when all six components are applied simultaneously with their maximum allowable (limit) loads. The analysis results on Balance 1621 indicate that the stresses are high near sharp corners.¹

The size of the fillets needs to be carefully considered in the design stage. Increasing the size of the fillets helps to relieve some of the high stresses. However, what can be done for the existing balances? The stresses from the analysis are high and do not satisfy the established criteria. Two options are considered here: one is a possible modification of the existing balances and two is to investigate other load options.

Redesigning can be done in order to enhance the structural integrity of a balance. Because it is an existing balance that needs to be modified, it is not possible to increase the fillet sizes without some further modifications. Some materials can be extracted from the balance in order to have larger fillet sizes on the sharp corners. Another option is to reduce the limit loads for all components, which is neither beneficial nor encouraged. However, applying limit loads, not simultaneously on all components, is considered here. The analysis is done where some components of applied load have 100% and others some percentage of their limit loads. In the wind tunnel test, not all the loads are applied with their maximum values simultaneously. This is, in fact, a realistic situation of a wind tunnel test. Researchers are interested in being able to apply some components of the load on the balance above the limit loads. Is it possible to enhance the load on the same balance and maintain the factor of safety required? Because it is valuable to be able to use higher loads, some loads were increased above their limit loads and analyzed here.

III. Analysis

The limit loads for this balance are shown in Table 1. The loads given are in the coordinate system shown in Figure 1, which illustrates the balance with its coordinate axis located at the moment center.

Force and Moment Components	Force (lb) and Moment (in-lb) Values
Axial (F_x)	500
Side (F_y)	1800
Normal (F_z)	3000
Roll (M_x)	7500
Pitch (M_y)	10000
Yaw (M_z)	4500

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

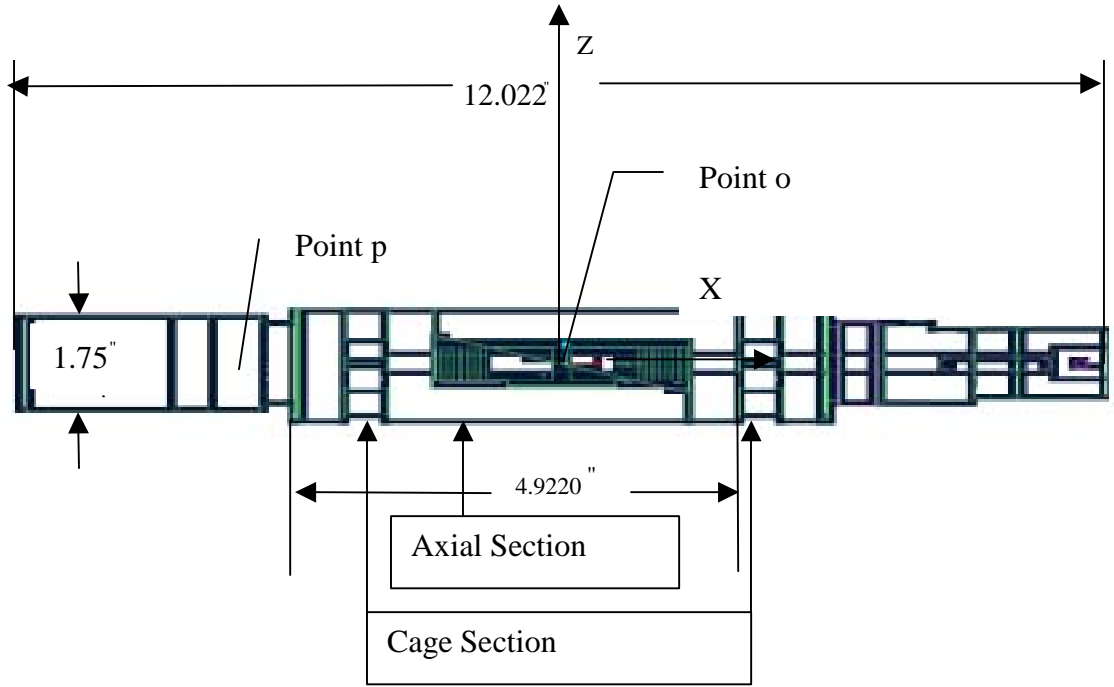


Figure 1. Balance 1621 with its coordinate axis located at the moment center.

The force and moment components for one load combination are considered and shown below:

$$\begin{aligned}\vec{F}_x &= -500 \hat{i} \\ \vec{F}_y &= 1800 \hat{j} \\ \vec{F}_z &= -3000 \hat{k} \\ \vec{M}_o &= 7500 \hat{i} + 10000 \hat{j} + 4500 \hat{k}\end{aligned}$$

The values given are valid for loads applied at Moment Center (MC), point *o*. In the Finite Element Model, the loads are applied at point *p*; hence, a transformation is required. The transformation is done using equation 1.

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

Moment components obtained after substituting into equation 1 are shown below:

$$\vec{M}_p = 7500 \hat{i} + 22300 \hat{j} + 11880 \hat{k} \quad (2)$$

Linear and some nonlinear analyses were done for this balance.¹ This load case was considered in the analysis. It should be mentioned here that not all the load combinations are considered here, only one of the load combinations that resulted in high stress value is considered.

A. Meshed Model

This balance was designed using Pro/Engineering. Preliminary analysis using Pro/Mechanica indicated stresses above yield. Because the stresses are above linear region, it was necessary to perform nonlinear analysis. The

balance was modeled in PATRAN to be used for analysis in NASTRAN. NASTRAN is capable of linear and nonlinear analysis. The loads are applied at point p and transferred to the balance through a rigid element. One of the load cases that produces regions of high stress on the balance is used here. The components of the load applied at point p are shown in the previous section. This load case has all positive components except axial force (F_x) and normal force (F_z). The results from the analysis are expected to be accurate away from the applied load due to St. Venant's principal.

The balance is meshed in PATRAN with almost 400,000 tetrahedral, tet4 elements. Tet4 is used because NASTRAN tet10 elements do not allow material nonlinearity in the NASTRAN version used for the present work. Figure 2 shows the balance meshed in PATRAN and the close-up view of the mesh is shown in Figure 3. In order to capture stress gradient, dense mesh is used. Due to computer limitations, dense mesh cannot be used in every corner with a small fillet; it is used near the end of the axial sections.



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

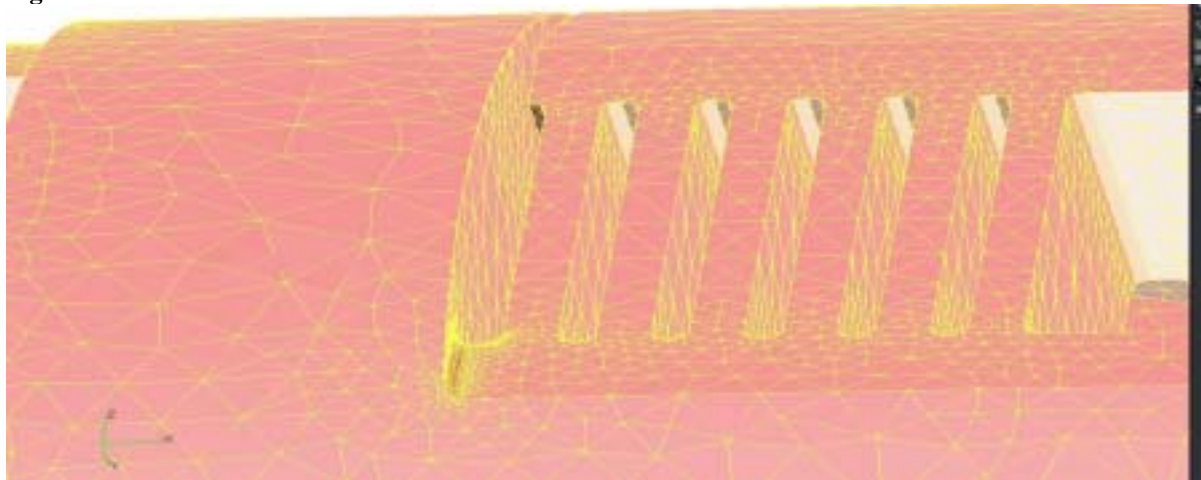


Figure 3. A close-up view of the end of the axial section.

B. Maximum Stress

Linear analysis on this balance indicates the maximum von Mises stress to be above yield (361 KSI) and is shown in Figure 4. Because the stress is above linear region, nonlinear analysis was done. Figure 5 shows maximum von Mises stress for the nonlinear analysis. The von Mises stress reduced to 278 KSI and the maximum von Mises stress from the nonlinear analysis is in the vicinity of the yield stress. This is the case when all six components of the limit loads are applied simultaneously. The stress values are high and do not satisfy the factor of safety required from document LAPG 1710.15 (Wind Tunnel Model System Criteria). Two options are considered here:

- 1) Modify the existing balances, if possible, in order to enhance structural integrity.
- 2) Modify the loads applied to the balance.

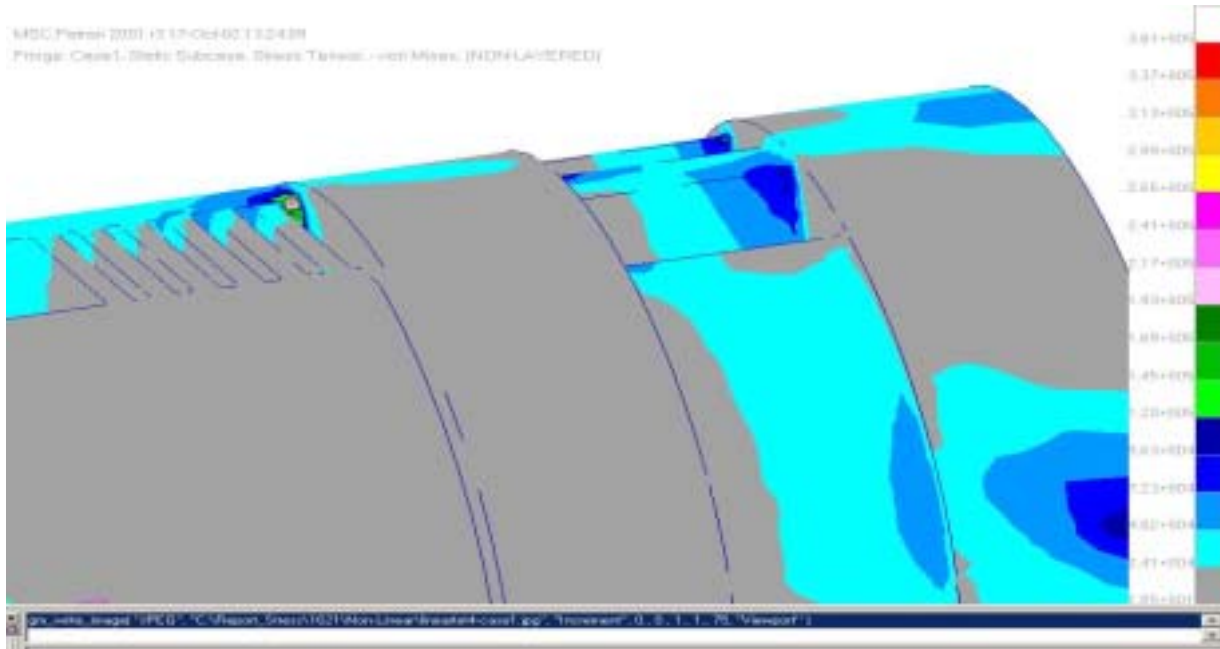


Figure 4. The von Mises stress for the balance from the linear analysis.

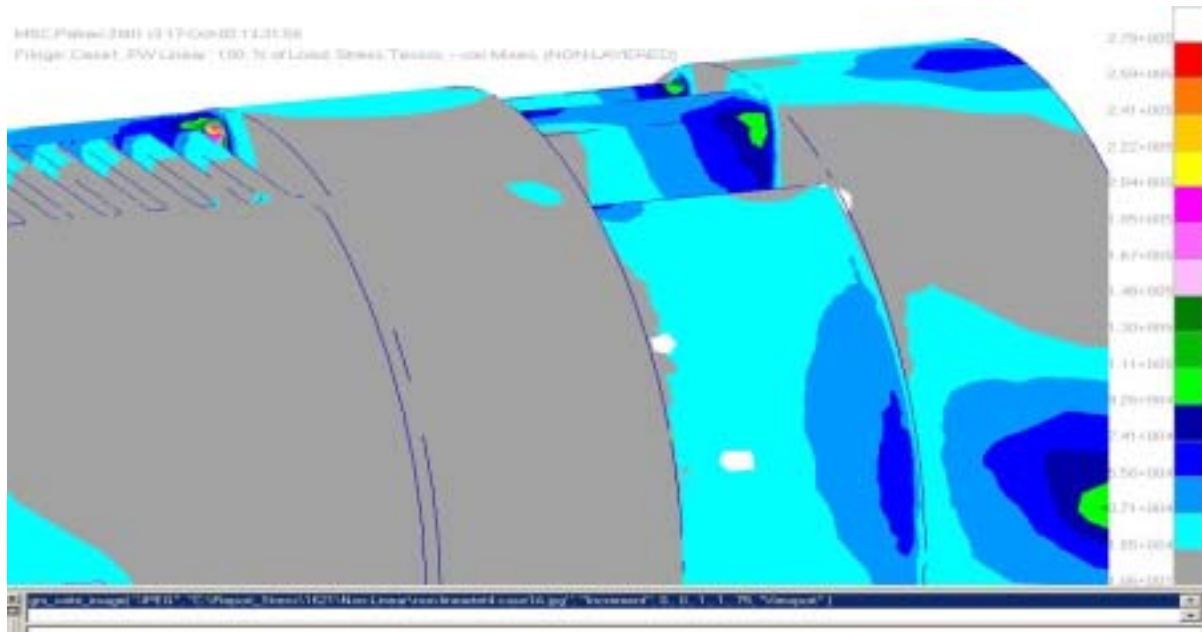


Figure 5. The von Mises stress for the balance from the nonlinear analysis.

C. Balance Modifications

Analyses have shown that maximum stresses occur in corners with small fillet sizes. Increasing the size of the fillets can help 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. Doing so will reduce the maximum value of stress from those corners. Some modifications were done on the balance and are shown in Figure 6. This is an existing balance and there are limitations on how it can be modified. Pro/Engineering was used for redesign of the balance and Pro/Mechanica was used for linear analysis. Analysis was done on this balance before and after the modifications for comparison. The results obtained are encouraging; the maximum von Mises stress reduced considerably because of the modifications.²

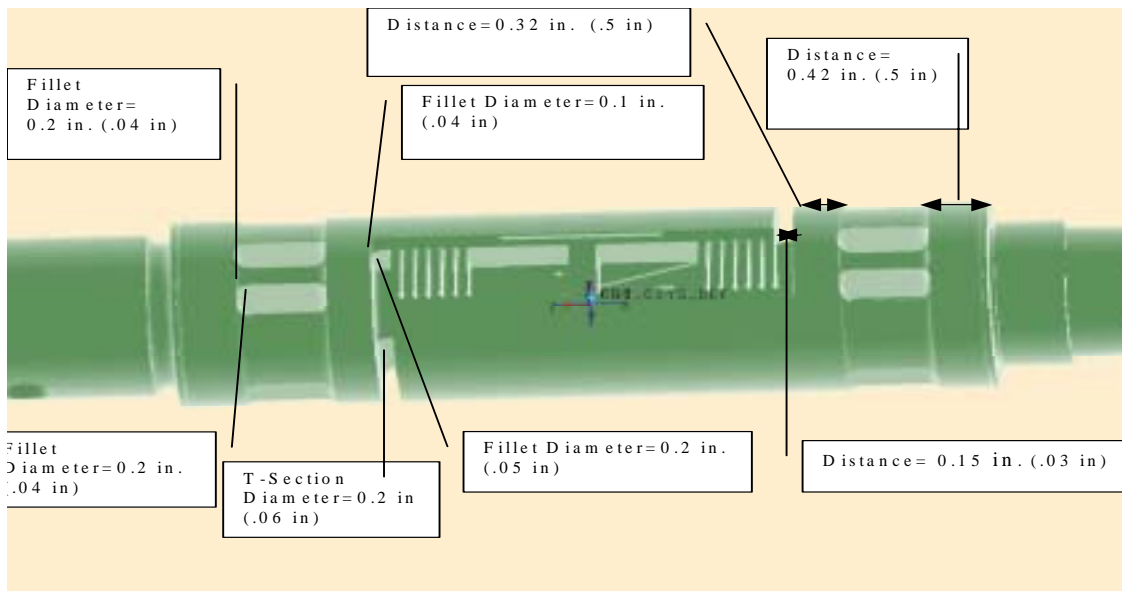


Figure 6. Balance 1621 after some modifications. The dimensions before modifications are shown in the parentheses.

The potential impact of design modifications cannot be ignored. Design modifications to existing balances, such as increased fillet sizes, can impact performance. It may decrease bulkhead stiffness that will lead to additional deflection. This additional deflection may lead to a decrease in sensitivities and an increase in interactions. Both of these factors will degrade balance accuracy. The impact of the design modifications needs to be further investigated.

IV. Changes in Applied Load

Maximum loading occurs when all six components are applied simultaneously with their maximum allowable loads, a circumstance that normally does not occur during wind tunnel testing. Normally, the loads applied to a balance are dominated by certain components with some percent of the limit load in other components. What happens if some components are used with their limit loads and others have some percentage of their maximum allowable loads? It is a realistic situation and is considered here. Limit loads are used, but not for all components occurring simultaneously. Three load cases analyzed are:

Case 1) Limit loads of normal force (F_z) and pitch moment (M_y) and 10% on other components.

Case 2) Limit loads of side force (F_y) and yaw moment (M_z) and 10% on other components.

Case 3) Limit load of roll moment (M_x) and 10% on other components.

Same model was used for the present work with NASTRAN. The model has about 400,000 tetrahedral elements. Figure 7 shows the maximum von Mises stress for case 1. As the figure indicates, the maximum stress is 148 KSI and occurs at the T-section. For convergence, more elements may be needed at the T-section. However, the maximum stress is not occurring at the axial section, indicating the stress value at this section reduced. Figure 8 shows the maximum von Mises stress for case 2, which is 178 KSI and it occurs near the applied load. The result for case 3 is shown in Figure 9. The maximum von Mises stress for this case is 184 KSI and occurs near the applied load. The results for all three cases show the stresses are comfortably below yield stress. The value of other components can increase above 10% a comfortable margin. Also, more than two components may have their limit loads, if needed.

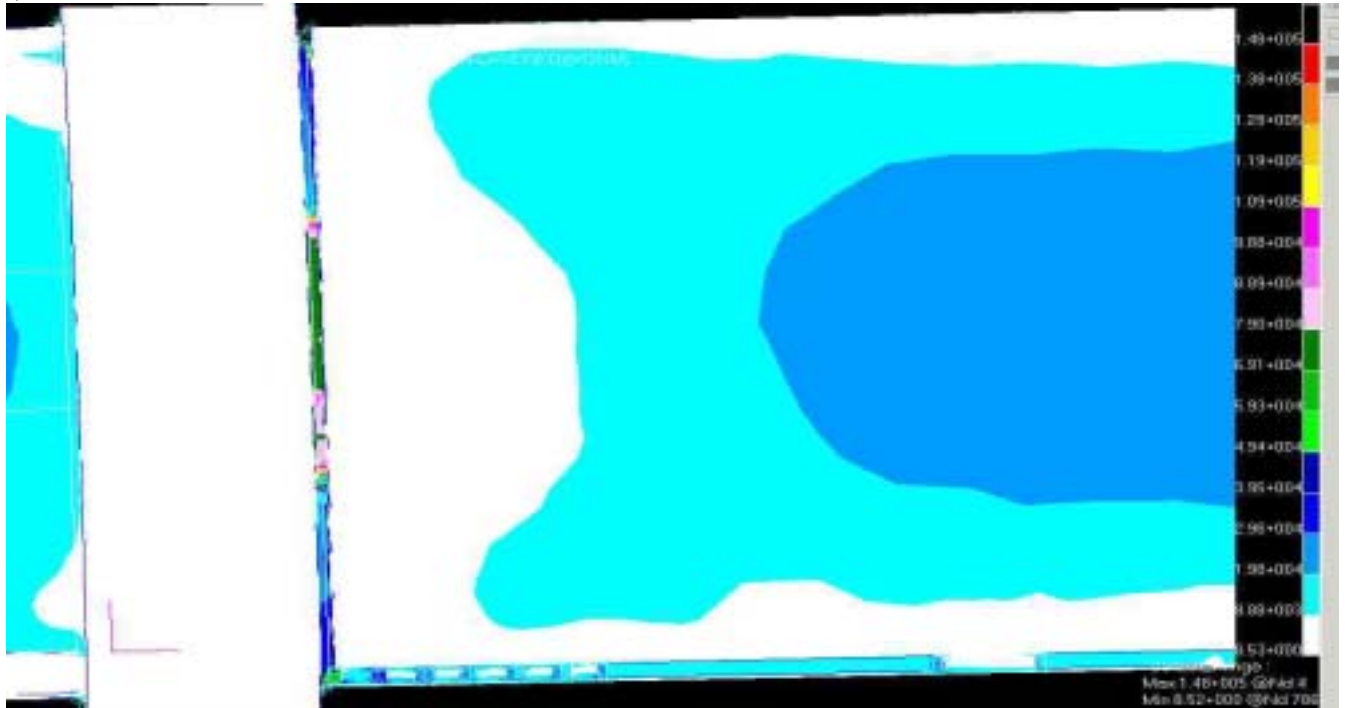


Figure 7. F_z and M_y are applied 100% and the other four components 10% of their values. The maximum von Mises stress occurs on the T-section near the applied load.

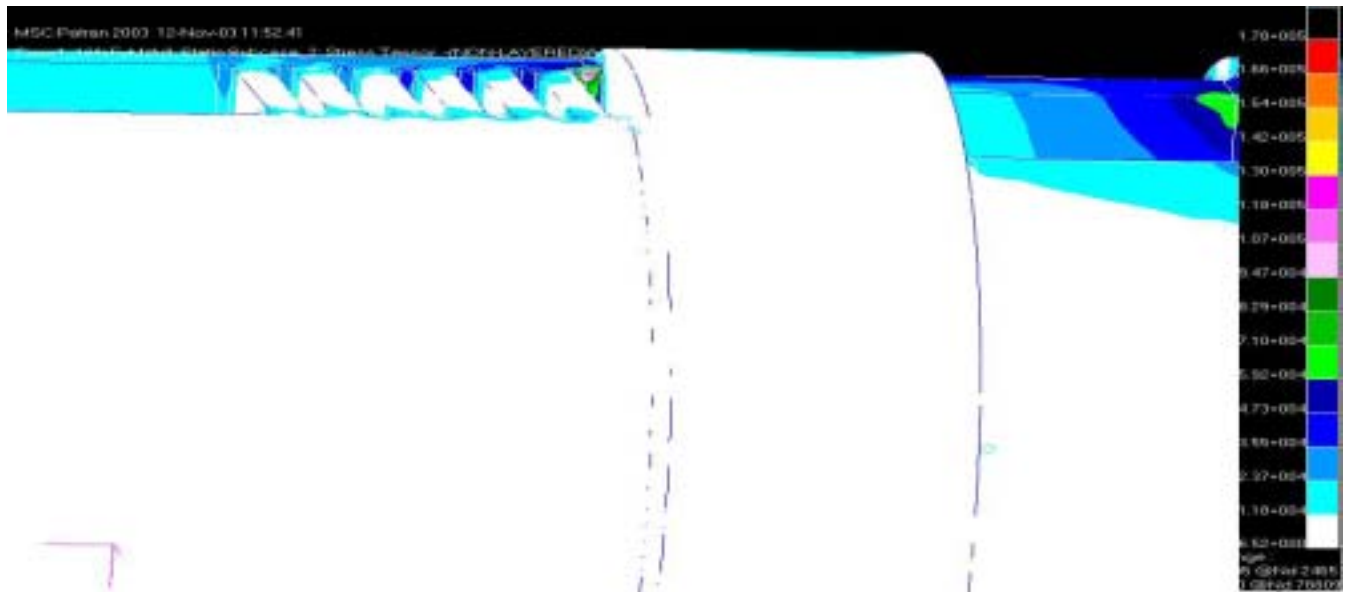


Figure 8. F_y and M_z are applied 100% and the other four components 10% of their values. The maximum von Mises stress occurs near the applied load.

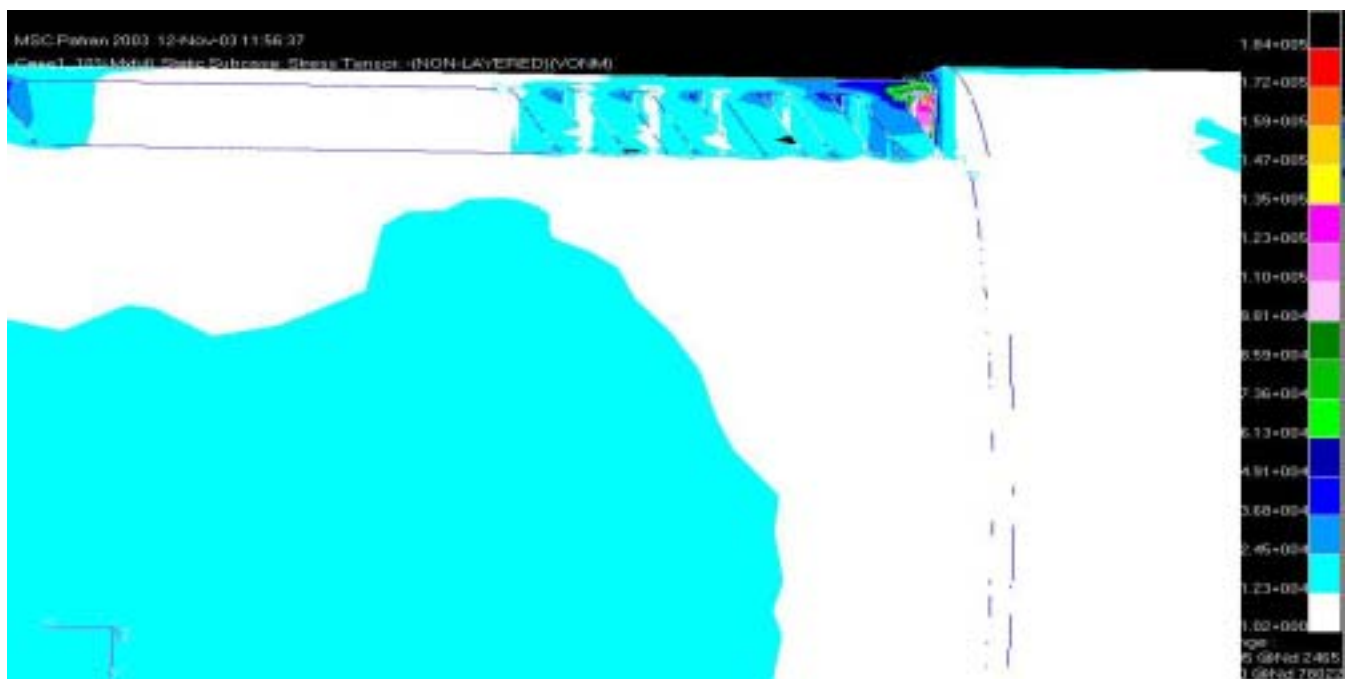


Figure 9. M_x applied 100% and the other five components 10% of their values. The maximum von Mises stress occurs near the applied load.

It is valuable for researchers to be able to increase the applied load to a balance in certain components above 100%. Another three load cases are considered here.

Case 1) Normal force (F_z) and pitch moment (M_y) to 120% and 12% on other components.

Case 2) Side force (F_y) and yaw moment (M_z) to 120% and 12% on other components.

Case 3) Roll moment (M_x) to 120% and other components to 12%.

Figure 10 shows the maximum von Mises stress for case 1. The maximum stress is 176 KSI and occurs, as expected, in the T-section, just as it did previously. The maximum von Mises stress for case 2 is 213 KSI and occurs near the applied load. The result for this case is shown in Figure 11. The result for case 3 is shown in Figure 12 and the maximum von Mises stress is 221 KSI, occurring near the applied load. Hence, it may be possible to use loads above their limit loads. Here, the maximum stress value increased in comparison with the previous analysis using limit loads.

When most of these balances were designed, little or no computer resources were available. The analyses were limited to analytical work. With today's available resources, detailed analysis can be done on the balances for any type of loadings with reasonable time and effort spent. Complex analysis can also be done. Loads higher than limit loads are very desirable in the research community and may be acceptable structurally; however, further analysis needs to be performed.

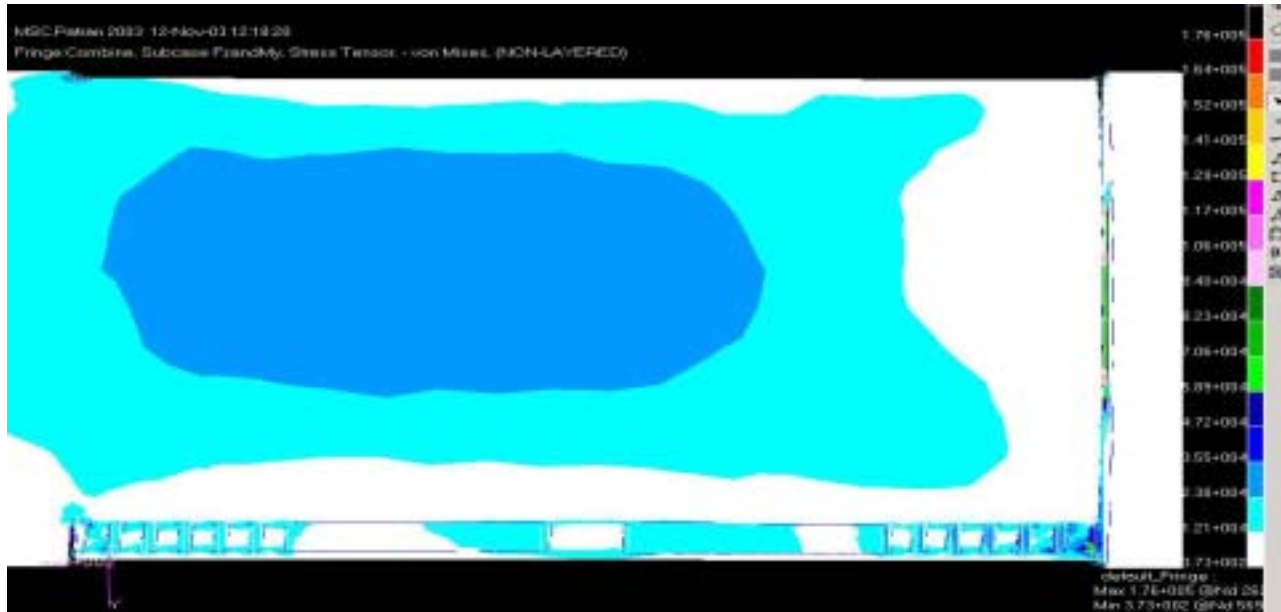


Figure 10. F_z and M_y are applied 120% and the other four components 12% of their values. The maximum von Mises stress occurs on the T-section near the applied load.

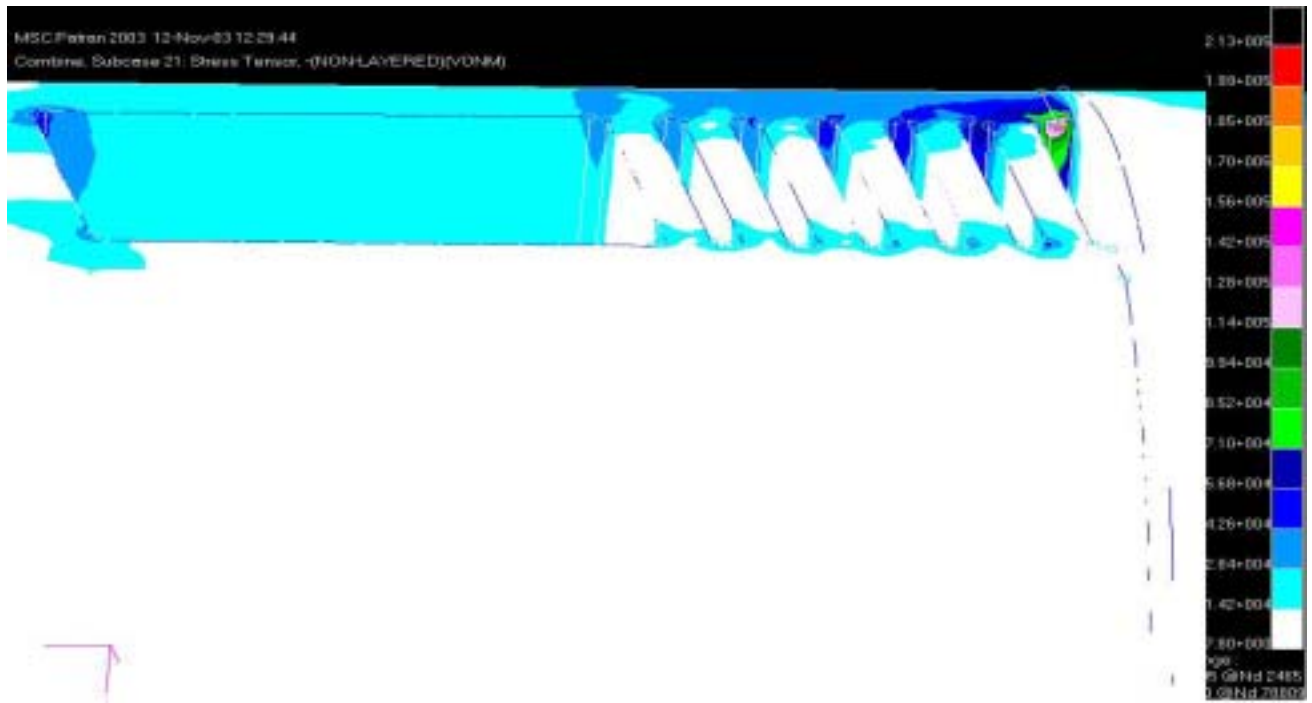


Figure 11. F_y and M_z are applied 120% and the other five components 12% of their values. The maximum von Mises stress occurs near the applied load.

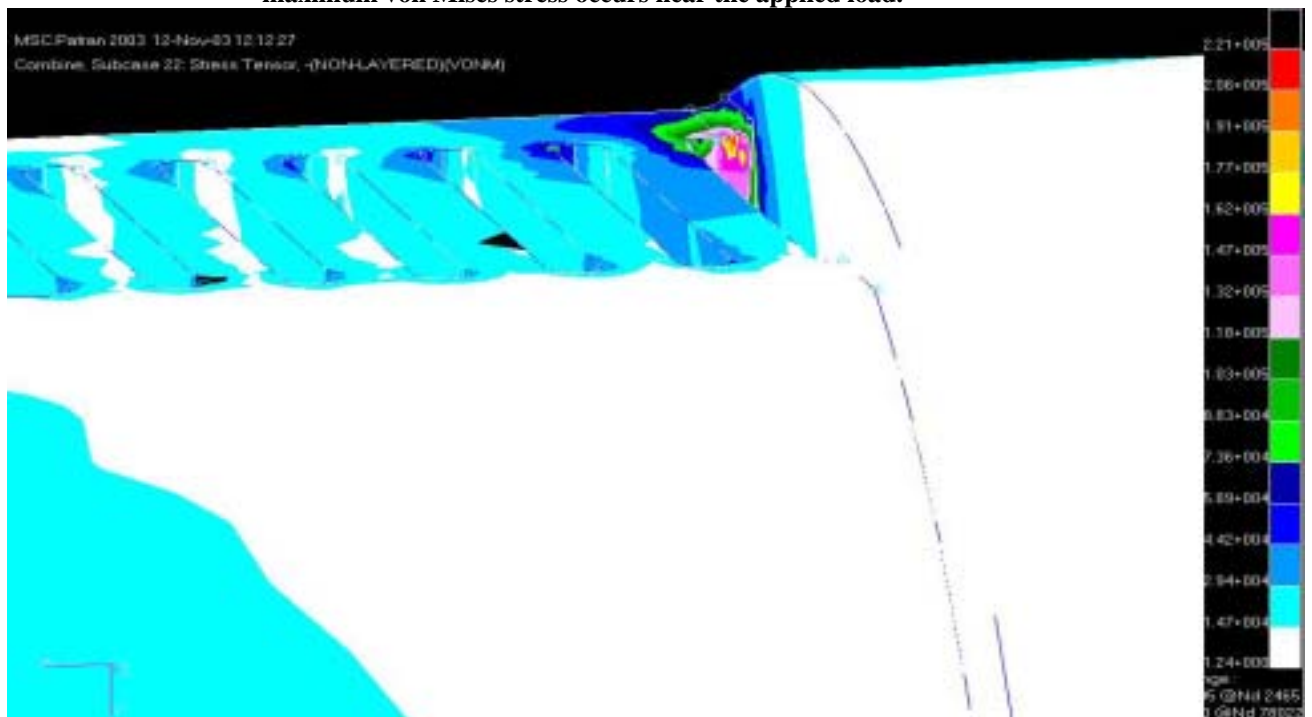


Figure 12. M_x applied 120% and the other five components 12% of their values. The maximum von Mises stress occurs near the applied load.

V. Conclusion

All balances and load combinations do not result in high stresses. If the maximum stress value obtained is beyond yield, either a change in the design is needed or the maximum allowable loads need to be reduced, an undesirable limitation. Another option is not to use limit loads on all components simultaneously, a situation which normally occurs. These options were analyzed and discussed.

Some modifications were done on an existing balance in order to reduce the maximum stress value near corners. The results were compared with analysis of the original model and considerable reduction was obtained. The results are encouraging; however, the potential impact of design modification cannot be ignored, and the potential impact on the performance needs to be further investigated.

The second option, reduction of the force, can be utilized in certain components. In most cases, the wind tunnel tests do not require maximum value of the loads occurring simultaneously on all of the components. In some cases, the wind tunnel test may require some components above their limit loads while the other components can have a percentage of their limit loads. Limit loads were used for some components and a percentage on the other components. One load combination was used for analysis here and the results are encouraging. The limit loads were also increased above their limit loads and encouraging results were obtained. The results show that loads above their limit loads may be used for some components. To be able to use higher loads, above their limit loads, is highly desirable.

References

¹ Karkehabadi, R., Rhew, R., "Structural Integrity of a Wind Tunnel Balance," 42nd **AIAA Aerospace Sciences Meeting and Exhibit**, Paper No. AIAA-2004-1293, Reno, Nevada, January 2004.

² Karkehabadi, R., Hope, D. J., and Rhew, R., "The Structural Integrity of the Balances, Modifications and Factors Affecting them," **Fourth International Symposium on Strain Gauge Balances**, San Diego, CA, May 2004.