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Probabilistic Assessment of National Wind Tunnel

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SUMMARY

A preliminary probabilistic structural assessment of the critical section of National Wind Tunnel (NWT) is performed using NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) computer code. Thereby, the capabilities of NESSUS code have been demonstrated to address reliability issues of the NWT. Uncertainties in the geometry, material properties, loads and stiffener location on the NWT are considered to perform the reliability assessment. Probabilistic stress, frequency, buckling, fatigue and proof load analyses are performed. These analyses cover the major global and some local design requirements. Based on the assumed uncertainties, the results reveal the assurance of minimum 0.999 reliability for the NWT. Preliminary life prediction analysis results show that the life of the NWT is governed by the fatigue of welds. Also, reliability based proof test assessment is performed.

INTRODUCTION

Assurance of safety of an aircraft or aerospace components/structures is verified by performing the test in a wind tunnel. A wind tunnel is a test facility structure where an aerodynamic environment similar to what the component/structure is anticipated to experience in flight conditions is simulated. In the simulated environment, the structure is subjected to the anticipated design loads for a proof test and/or study the effects of such impounding environment. Thus, the wind tunnel is a key structure to perform the proof test and evaluate the effects of various factors on structure.

Construction of a structure of this size requires many small plates to be connected together since the plates rolled out of the factory are limited in size. These plates are either rolled bent or are bent to the size and shape in the shop. Fabricated small pieces are connected together in the field using butt welds. During the fabrication and joining process, the uncertainties associated with the workmanship and handling result into the shape irregularities. Therefore, the geometry of the structure is never achieved to its accurate dimension and shape. Thus, the geometry of the structure has uncertainties associated with it. Variation in the geometry of structure not only affects its behavior but also become a source of boundary layer build up during the test conditions. Hence, geometric uncertainty in the structure plays a major role in the behavior of structure. Geometric uncertainties also include the location of stiffeners.

Most of the welding process is done in the field. Generally, field welds do not have as sound a quality as the shop welds. Also, it takes several passes of weld to connect thicker plates. As the number of passes increase, the weld and the base metal become prone to residual stress problems due to high temperature ambience during the welding process. Additionally, the possibility of air voids being entrained between the passes increase if the fabrication is not performed under the strict supervision and quality control. Thus, field welds have inherent defects and these defects could lead to failures under fatigue loads. Therefore, it is essential that the uncertainties associated with the existence of weld defects be considered in the design/analysis.

Since, varied aerodynamic test conditions for different aerospace components/structures are simulated in the wind tunnel structure, the uncertainties in the loads and their nature become very obvious. Also, the material properties of the structure are uncertain in nature. The NWT structure is used repetitively for different tests. During each test the pressure builds up in the shell and after the test is over the pressure is released. Thus, the material undergoes a cycle of stress from one test to another. Also, the NWT structure remains in use almost 95 percent of time round the year. Thus, the test loads are cyclic in nature and the material is subjected to fatigue type loads. Under fatigue load condition the pre-existing flaws in the material have a tendency to grow with repetitive load conditions and the material degrades in properties as well strength. After a while flaws may grow to a size which may become detrimental to the operation of the facility and result in a failure. Therefore, wind tunnel structure should be checked against uncertainties in the fatigue loads. Also, previously built wind tunnels have been found to have failed due to fatigue in the welds and the defects. Owing to its importance, it is necessary to design the wind tunnel structure against any lateral movement due to foundation settlement. Although, a rigorous analysis is necessary but due to the scope limitation of this work, uncertainties in the lateral movement of supports are considered to indirectly account for such effects.

Traditionally, the above design requirements and uncertainties are considered using deterministic safety factor approaches. Safety factor approach is conservative since it accounts for uncertainties by using upper bounds on loads and lower bounds on strength. Also, it does not provide an insight into the role of design variables to different failure modes. Probabilistic approach lends an excellent design and analysis technology to account for uncertainties in the design variables and quantify the reliability of structure. It also quantifies the sensitivity of failure to the design variables. It simulates uncertainties in primitive random variables and integrates it numerically to compute response uncertainties. The approach also keeps track of the sensitivity of response on design random variables during the computation process. Computed sensitivity becomes very useful in design revisions or determining the factors controlling reliability.

Ongoing research at NASA Lewis Research center over the past decade has culminated into a technology called PSAM (Probabilistic Structure Analysis Methods) (ref. 1). PSAM technology has been implemented in a general purpose finite element analysis computer code NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) (ref. 2). Probabilistic assessment of National Wind Tunnel (NWT) structure has been performed using PSAM technology and NESSUS computer code.

This report describes the preliminary probabilistic assessment of NWT structure and a set-up for detailed analysis considering several different failure modes. Different types of analyses such as stress, frequency, buckling, fatigue of metal, fatigue of weld and proof load analysis for testing are performed for the evaluation purpose. Reliability associated with each of these analyses has been computed. In the case of stress analysis, reliability against combined stress failure mode is investigated whereas in the frequency analysis, the reliability based frequency of the structure has been computed. Different modes of vibration are observed. Buckling analysis computes the reliability based buckling load and the probable mode of buckling. Fatigue analysis helps to determine the reliable and safe life of the wind tunnel structure. It can also be used to decide the inspection intervals. The reliability based proof analysis provides the information on proof loads for a given reliability and the variables that need to be controlled during the proof test. Once again, the results presented herein are preliminary and demonstrates a sound set-up for a detailed final reliability assessment.

PROBABILISTIC STRUCTURAL ANALYSIS COMPUTER CODE, NESSUS

NESSUS is a general purpose integrated probabilistic finite element analysis computer code to perform static, dynamic, buckling, and nonlinear analyses. Several reliability based probabilistic analysis algorithms including fast Monte-Carlo simulation techniques are incorporated in the code. The structure of NESSUS is modular and allows the user to perform analysis in different stages. The input to solve any probabilistic structural analysis problem involve identification of random variables, their statistical distributions, structural geometry, loads, boundary conditions, etc. Details of NESSUS computer code can be availed from reference 1.

Any Gaussian correlated random field defined at discrete finite element nodes can be used in the code. The code decomposes the Gaussian correlated field into a set of uncorrelated independent vectors using modal analysis.

Sensitivity evaluation of the structural response due to variation in different uncorrelated random variables is performed by perturbation analysis incorporated in the finite element module. Modified Newton's nonlinear algorithm is used to perform the perturbation analysis. Discrete representation of the response surface required for the probabilistic analysis is obtained by perturbing independent random variables.

Several reliability algorithms such as fast Monte-Carlo simulation, fast probability integration, first order and second order reliability analysis can be used to perform the probabilistic structural analysis. Generally, fast probability integration methods are efficient and give accurate results even in the lower and upper probability regions compared to many other numerical methods. Using the perturbation analysis results, an explicit response function is developed. Fast probability integration is performed using the explicit response function and probability distributions of random variables in order to obtain the cumulative distribution function of the structural response. Also, the sensitivity of response reliability to the random variables uncertainties is quantified. The computed sensitivity information can be used to control the design process in order to achieve improved reliability.

COMPUTATIONAL SIMULATION MODEL

Finite element model

The national wind tunnel structure is a horizontal cylinder with varying cross sections and stiffeners provided at certain intervals. A critical section of the NWT structure has been modelled as shown in figure 1 for the preliminary reliability analysis. The structure is considered to be supported on four vertical columns. The length of the critical section of the wind tunnel is approximately 132.9 ft and has approximate diameter of 41.25 ft at the annular diffuser section and 59.25 ft at the wide angle diffuser end. This section of the NWT is considered to have six stiffeners at locations x = 11.075, 31.21, 51.34, 71.48, 91.62, and 111.76 ft. The NWT structure is supported at two locations x = 36.25 and 76.52 ft by two supports each. The cross section of the structure changes abruptly at x = 11.075 ft. The region around this area is more critical from the failure view point. Also, the region around the support location is critical due to stress concentration problems. The finite element model of the NWT section consists of 1012 quadrilateral iso-parametric shell elements and 1384 nodes. Since, the focus of the study is on the shell portion of the NWT, the support sections were made fictitiously stiff. The stiffeners on the shell are also modeled using quadrilateral shell elements.

The primary load imposed on the structure is internal pressure load. However, the current scope of work includes only pressure load and cyclic load due to repeated test condition. The NWT is subjected to an absolute pressure magnitude of 5.0 atm (73.0 psi). The material used in the analysis is A516 Grade 70 steel having a yield stress of 36.0 ksi. The modulus of elasticity of the material is 29.0 Mpsi and the Poisson's ratio is 0.3. Mild steel is a good ductile material to resist cyclic loads and does not result in brittle failures. It's characteristic against tensile and compressive loads is excellent having yield strain of approximately 0.2 percent. The supports are assumed to be fixed at the ground.

Probabilistic Analysis Model

As discussed in the introduction, the uncertainties in the primitive variables that affect the response have been considered in the simulation. Uncertainties associated with geometry, i.e., related to shape, material properties (modulus of elasticity, Poisson's ratio), support movement, pressure load, stiffener locations, and strength of the material have been considered in the analysis. The associated assumed probability distributions and scatter in terms of coefficient of variations or standard deviations have been summarized in table I. The distribution types and uncertainties associated with loads, material properties and strength were chosen based on the engineering judgment and common industry practice. However, the uncertainties associated with lateral support movement are chosen based on the assumption of normally allowable values whereas those related to stiffener locations are derived from commonly allowed construction tolerances. Thus, the variations considered in the analysis are in par with industry practices.

Probabilistic Structural Analysis

Any structural design in general involves performing the stress analysis, vibration analysis and buckling analysis and check the analysis results against their respective allowable values. In the case of probabilistic approach, similar analyses are performed and checked against the reliability requirements. Therefore, for the NWT structure also, probabilistic stress, frequency, and buckling analyses are performed and the pertinent results have been summarized in this report. Additionally, due to the cyclic nature of pressure loads and the use of the NWT structure for repetitive tests, a reliability based fatigue life analysis considering the metal fatigue and weld fatigue have been performed. To complete the evaluation procedure for verification purposes, a reliability based proof load assessment has also been performed and the proof test loads for a 0.9999 reliability and the variables controlling the proof test have been identified.

Probabilistic Stress Analysis

The static analysis involves computing stresses under static loads and check them against their respective allowable values. Thus, if R is resistance (strength) and S is stress then:

$$R - S \geq 0.0 \tag{1}$$

Then, the safety margin, f is given by:

$$f = \frac{R - S}{R} \tag{2}$$

However, the aim of the probabilistic analysis is to evaluate the probability of failure. The probability of failure is defined as the probability of exceeding a limiting value. In case of static analysis the limiting value is the resistance or strength. The probability of failure is then defined as the cumulative probability that the stress exceeds the strength. Mathematically:

$$P_f = P[(R - S) \leq 0.0] \tag{3}$$

where P_f stands for probability of failure and P stands for probability. The stress, S is a function of structural geometry, loads, boundary conditions, etc. and the strength, R is a function of material properties and loads. Since, these are functions of geometry, loads, boundary conditions, strength, etc. which have their own probability distributions, the response also has probability distribution. To compute the probability given in equation (3), one needs to integrate all the probability distributions of design random variables in the failure region. Mathematically, it can be written as:

$$P_f = \int_{-\infty}^{\infty} F_R(x) f_s(x) dx \tag{4}$$

where $F_R(x)$ denotes the cumulative probability distribution of resistance and $f_s(x)$ denotes the probability density function of stress recalling that the x represents numerous random variables mentioned above. Then, the reliability, $\boldsymbol{R} = 1 - P_f$.

In the static analysis, the cumulative probability distributions of the stresses at all the nodes were computed. von-Mises failure criteria is used as limit state function to compute the reliability. The mean von-Mises stress contours are plotted in figure 2. It can be seen that the stresses are quite low compared to the yield strength of 36 ksi. Therefore, a judgment can be made that the expected probability of failure should be low. The probability of failure contours are plotted in figure 3. The highest probability of failure is at node 1111 (see fig. 1 for node location) and its magnitude is 4.025E-06. The cumulative probability distribution functions for critical nodes are plotted in figure 4(a) and the sensitivity of stress to the primitive random variables is shown in figure 4(b). It is seen from these figures that the stress for 0.9999 cumulative probability at node 1111 (see fig. 1 for node location) is 21.3 ksi. The variables controlling the stress at 0.9999 probability level are pressure, thickness and movement of supports in the z-direction. However, the variables controlling the probability of failure at node 1111 (see fig. 1 for node location) are material strength, pressure and thickness as shown in figure 5. Therefore, to reduce the probability of failure the uncertainties in the strength should be controlled i.e. minimize the scatter in the strength.

Probabilistic Frequency Analysis

The vibration response of the wind tunnel structure is important to control its shaking in order not to damage the model being tested in the wind tunnel and reduce additional loads on it. Also, low frequency of vibration improves the durability of the structure. Therefore, it is desired that the frequency of dominating low modes of vibration of the structure be as low as possible to minimize the dynamic displacement of the structure when the air under pressure is forced in the structure. The low vibration amplitudes will also help simulate the aerodynamic effects on the model being tested. As discussed before, due to uncertainties in the primitive random variables, the frequencies of the structure would also have scatter in them. Therefore, it is important to study uncertainties associated with those frequencies. Uncertainties in the mass density were considered in probabilistic frequency analysis in addition to those mentioned for stress analysis. The mean natural frequency of vibration for the first four modes of vibrations are 1.29, 3.58, 3.61, and 7.012 Hz. The shape of these four modes of vibrations are shown in figures 6 to 9 respectively. Generally, the first mode of vibration is important for vibration design purpose because it has the largest amplitude for the loading. Cumulative distribution functions for the first four natural frequencies are shown in figures 10(a) to 13(a) and their respective sensitivities to the random variables are quantified as depicted in figures 10(b) to 13(b). It is seen from figure 10(a) that the frequency for 0.0001 cumulative probability is 1.09 Hz which means that the load frequency should be below 1.09 Hz to achieve a reliability of 0.9999 for designing against that frequency. Also, it can be seen from figures 10(b) to 13(b) that modulus is the most significant variable followed by the mass density and the thickness at 0.0001 cumulative probability level. It means that controlling the uncertainties in the stiffness of structure is very important to achieve a higher reliability. Therefore, reduction in the uncertainties of elastic modulus will result in the improved reliability.

Probabilistic Buckling Analysis

Buckling analysis is performed to check the overall stability and any local failure under design load conditions. The stability of the structure under a given set of loads may be impaired if the structure does not have enough geometric stiffness. Probabilistic stress analysis as explained in section a, checks the failure in material. Failure due to the lack of geometric stiffness is checked in the buckling analysis. Structure derives the geometric stiffness from the actual geometry of the structure as well as the existing displacement/stress conditions. Therefore, the buckling analysis is performed by applying certain magnitude of stress under a given load configuration. Using the state of stress under this load conditions, the geometric stiffness of the structure is computed. The eigenvalues and eigenvectors of the geometric stiffness defines the critical buckling loads and the shape. It should be noted here that the buckling of supports has been ignored in the analysis since the focus of the study is on shell portion only. Uncertainties in the random variables given in table I are considered in the analysis. figure 14 shows the buckled mode shape and the corresponding mean buckling pressure of 13.15 atm external. CDF of the critical buckling load is shown in figure 15(a). Reliability based design requires a lower value of probability of occurrence of the buckling load. For a design cumulative probability of 0.0001 (a reliability of 0.9999), the design buckling load value should be less than 2.632 atm (38.4 psi) external (fig. 15(a)). The critical buckling load at 0.0001 cumulative probability is most sensitive to the support movement in Y-direction at location x = 918 in., followed by external pressure, the modulus of material and the thickness as shown in figure 15(b). The structure will not buckle under test conditions since the normally occurring load on the structure is internal pressure. The NWT structure is externally subjected to atmospheric pressure only when a vacuum is developed internally. The critical buckling load for 0.9999 reliability is much higher (fig. 14) than atmospheric pressure. Therefore, a structural reliability of at least 0.9999 is achievable under buckling design criteria. Thus, the analysis shows that the NWT structure would not globally buckle under external pressure due to internal vacuum created while cleaning the tunnel.

Probabilistic Fatigue Analysis

The NWT structure is designed to have a long life. Past experience of similar structures has revealed that the failures mostly occur at welds due to cyclic load conditions. Therefore, it is important to perform the fatigue life analysis. Uncertainties in the random variables described in table I affect the stress magnitude and in turn affect the fatigue behavior of structure. Since the life expectancy of NWT is long and stress magnitudes are generally low as shown in the probabilistic stress analysis, the probability of strains occurring in plastic regime are very low. Therefore, a stress based high cycle fatigue analysis would be sufficient. A unified multi-factor interaction equation (ref. 3) (MFIE) model has been used to perform the fatigue life analysis. Due to cyclic loads the material properties and the strength degrade with number of load cycles on the structure. Therefore, it is necessary to account for the degradation of material properties and strength in the analysis to evaluate a proper fatigue life.

It is known that accounting for all the physical variables and their effects on the material properties is complex. Over the years, research in developing a unified model describing the material behavior driven by primitive variables has been an on going activity at NASA Lewis Research Center. The result of this research is the development of a unified multifactor interaction equation (MFIE) model (ref. 3). MFIE model described in reference 3 has been used to compute degradation of material behavior due to cyclic pressure load effect. The general form of the equation is:

$$\frac{P}{P_o} = \prod_{i=1}^{n} \left(\frac{V_{fi} - V_i}{V_{fi} - V_{oi}} \right)^q \tag{5}$$

where P denotes the material property, V the primitive variable effect, subscripts f and o denote the condition at final and reference stages respectively, n - the number of effects and q - the exponent for a given effect. Terms in parentheses account for a specific physical effect. Any number of effects can be included in one single equation as seen by the nature of the equation. The exponents are determined from the available experimental data or estimated from the anticipated material behavior due to a particular primitive variable. Each primitive variable and the exponent in the above equation can be random with a statistical distribution. The insufficiency of a set of experimental data can be taken into account by means of uncertainties in the exponent and in the reference and the final values.

An important part of the above model is the fact that only one equation includes all the effects with any nonlinearity in the material behavior and follow the physics of behavior. It can describe all the interacting effects of different variables (thermal, metallurgical, mechanical, chemical, load, etc.). Since variables used are at a primitive level, it simulates the in situ degradation in material properties due to applied cyclic and environmental effects. The equation for the fatigue behavior can be represented as:

$$\frac{P}{P_o} = \left(1 - \frac{\sigma}{S_f} \right)^p \left(1 - \frac{\sigma_m N_m}{S_f N_{mf}} \right)^q \tag{6}$$

where P is the material property, P_o is the reference property, σ is the mean stress, σ_m is the mechanical stress amplitude, S_f is final strength, N_m is the number of cycles, N_{mf} is maximum number of cycles (assumed to be 1,000,000 cycles in this analysis), and p, q are exponents.

Uncertainties in the primitive random variables listed in table I are considered in the fatigue analysis. The values of p and q used herein for metal fatigue analysis are 0.5 and 0.4. Fatigue life contours based on metal fatigue is performed and the life for 0.9999 and 0.999 reliability are computed. Based on the results, the life of NWT structure for 0.9999 reliability is 1.1 million cycles and that for 0.999 reliability is 1.4 million cycles. The fatigue life contours for the entire structure for 0.9999 and 0.999 reliability are shown in figures 16 and 17 respectively. Also, it was found that the fatigue life for both 0.9999 and 0.999 reliability levels is controlled by pressure, strength and thickness as shown in figure 18. It means that the stress (load), strength and stiffness of the structure controls the life expectancy of the structure. The life predicted by the analysis is fairly high and is in the endurance limit region. Therefore, it can be easily concluded that the NWT structure is safe under base metal fatigue with a reliability of 0.9999.

It is worth mentioning here that the fatigue life prediction should not be based upon base metal fatigue only. The NWT structure is huge and made by joining pieces of different sizes and shapes of steel plates. Joining of plates is done using butt welds. High temperature is developed during the welding process which affects the base metal. It also generates residual stresses in the base material. Also, joining thick plates by butt welds involve several passes of weld. During the welding process there are chances of air voids going into the welds as well as cracks may develop due to thermal differentials. Furthermore, the weld metal is generally brittle in nature at high loads. Fatigue resistance of weld material is lower in comparison to that of Grade 70 steel. Therefore, it is essential that the life prediction based on weld fatigue considering defects in welds be performed. Since the defects in the welds occur randomly, it is appropriate to treat the existence and size of defects probabilistically. However, this initial evaluation did not account for defects in the welds and their effects on fatigue life.

Data available from Lincoln Arc Welding Foundation (ref. 4) handbook were used to determine the exponent in the MFIE for the reliable fatigue life computation based on failure in weld metal ($p = 0.5$ and $q = 0.18$). The results show a reduction in fatigue life of NWT structure if the weld fatigue was included. Fatigue life contours for 0.9999 and 0.999 reliability are shown in figures 19 and 20 respectively. Fatigue life for the weld was performed assuming that there is a weld at every node in the structure. Minimum fatigue life obtained from all the nodes was taken as the life for the structure. Thus, the analysis would cover any possibility of shape and size of the plates joined in the structure. Based on the results, it was found that the fatigue life based on welds for 0.9999 and 0.999 reliability is 442,616 and 620,343 cycles respectively. Thus, the life of the NWT structure is governed by the fatigue behavior of welds.

Probabilistic Proof Load Analysis

Any pressure vessel type structure designed and built has to be proof tested under a set of loads higher than the expected loads during the life time before it is opened for service. Proof test ensures the safety and reliability against any major defects or quality of construction and design. Since, the proof testing also involves uncertainties at different scales, it is necessary to account for uncertainties in the design for proof test. Rational consideration of uncertainties associated with proof test would eliminate the occurrence of catastrophic events and avoid major as well as local damage to the structure. The NWT structure is expected to be tested at 125 percent of the 5 atm design pressure. Therefore, uncertainties around 125 percent of design pressure has been considered and reliability analysis is performed. Thus, the reliability under proof test load conditions is given by:

$$\boldsymbol{R} = 1.0 - P_f = 1.0 - P[R - y * S] \qquad (7)$$

where y is the proof load factor. For the NWT structure it is considered to be 1.25. Proof load analysis for different magnitudes of y has been performed for critical nodes (see fig. 1 for labelled critical nodes). Contours showing the probability of failure for 125 percent of the design pressure have been plotted in figure 21. It can be seen that the highest probability of failure under proof load condition is 0.0001569. Thus, a reliability of 0.999 is achieved under proof load condition. The NWT structure can be tested at 125 percent of the design pressure with a reliability of 0.999. Also, the reliability based design chart for proof load at most critical nodes is plotted in figure 22. The ordinate axis in figure 22 represents u which is standard normal variable. The actual probabilities are given in the parenthesis next to the u-value. This chart can be used to estimate the reliability of a proof test at any given magnitude of proof load condition.

SUMMARY OF RESULTS

Preliminary reliability assessment of the National Wind Tunnel structure was performed using NESSUS computer code. Uncertainties in the geometry, material properties, mass density and pressure loads were considered in the analysis. Preliminary probabilistic stress, frequency, buckling, fatigue and proof load analyses were performed and reliability with respect to each analysis was assessed. Also, the sensitivity of failure modes to the random variables in different analysis was quantified. Based on the preliminary assessment the following results were obtained:

- The NWT structure has a reliability of at least 0.9999.
- The pressure, thickness and lateral movement of the support at 36.25 ft location governs the failure probability.
- The first natural frequency for 0.9999 reliability is 1.09 Hz and is most sensitive to the modulus of elasticity and the mass density of the material.
- The predicted life based on the base-metal and weld fatigue for a reliability of 0.9999 is 442616 cycles.

- The fatigue life is controlled by the fatigue of welds.
- Internal pressure, strength and thickness controls the fatigue life at 0.9999 reliability. Therefore, scatter in the pressure loads should be reduced to increase the life of the NWT structure.
- A reliability of 0.999 is assured for the proof pressure of 6.25 atm (90.25 psi, 125 perecnt of the design pressure)

The proof analysis ensures the reliability of the NWT during test conditions. Any major defects in the quality or design or construction/fabrication will be captured in the proof analysis. Thus, reliability of 0.9999 is achievable for the NWT structure as per the preliminary assessment. Also, it is important to mention that the NESSUS computer code can be used to perform the reliability assessment of the NWT structure.

RECOMMENDATIONS FOR FURTHER WORK

The evaluation described herein outlines only the preliminary assessment required for the initial design stage of the National Wind Tunnel structure. Many reliability issues related to other failure modes and system as a whole need to be addressed and evaluated. However, the evaluation provides an excellent starting point for detailed analysis and evaluation of further concerned reliability issues discussed below:

As mentioned in the introduction, the NWT structure is made of steel plates connected together by weld. Process of welding thick plates is prone to inclusion of defects such as voids, microcracks, etc. in the welds. Since the weld metal is brittle in nature its resistance to fatigue loads diminishes further due to cracks. Therefore, it is important to account for the possibility of the defect existence in welds in the reliability assessment of the structure. Also, the residual stresses developed during welding due to high temperatures are to the magnitude of the yield. However, the experiments (ref. 5) suggest that these high stresses relax out in the first few cycles of loads to magnitudes much lower than yield. Nonetheless, these residual stresses should not be neglected in the reliability assessment especially for the proof testing.

The present reliability assessment is performed at the nodes only. It means that the analysis looks at the failures at a point only. In reality, the simultaneous failure at different nodes may cause the overall structural failure. Also, the material properties/strength are random fields in reality. Therefore, mathematically more precise way of modelling these uncertainties would be to have a larger set of random variables. It can be achieved by modelling each individual plate as a separate random variable with different probabilistic variations in the properties. Despite the analysis at nodes shows very high reliability, it would be appropriate to perform the system reliability by modeling the random fields and considering the simultaneous failures at different nodes.

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TABLE I.—UNCERTAINTIES IN THE DESIGN RANDOM VARIABLES

Uncertain Variable	Unit	Distribution Type	Mean	Standard Deviation
Thickness	in.	Normal	0.71 - 2.79	0.05
Mass density	slug	Weibull	7.33863E-04	3.6693E-05
Modulus	Mpsi	Weibull	29.8	1.49
Poisson's Ratio	---	Weibull	0.3	0.015
Yield strength	psi	Weibull	36000	2700
Pressure	psi	Weibull	73	7.3
Stiffener location in X-direction at X = 16.17 ft	in.	Normal	0	1.
Stiffener location in X-direction at X = 36.25 ft	in.	Normal	0	1.
Stiffener location in X-direction at X = 56.33 ft	in.	Normal	0	1.
Stiffener location in X-direction at X = 76.5 ft	in.	Normal	0	1.
Stiffener location in X-direction at X = 96.67 ft	in.	Normal	0	1.
Stiffener location in X-direction at X = 116.75 ft	in.	Normal	0	1.
Support movement in Y - direction at X = 36.25 ft	in.	Normal	0	2
Support movement in Z - direction at X = 36.25 ft	in.	Normal	0	2
Support movement in Y - direction at X = 76.5 ft	in.	Normal	0	2
Support movement in Z - direction at X = 76.5 ft	in.	Normal	0	2

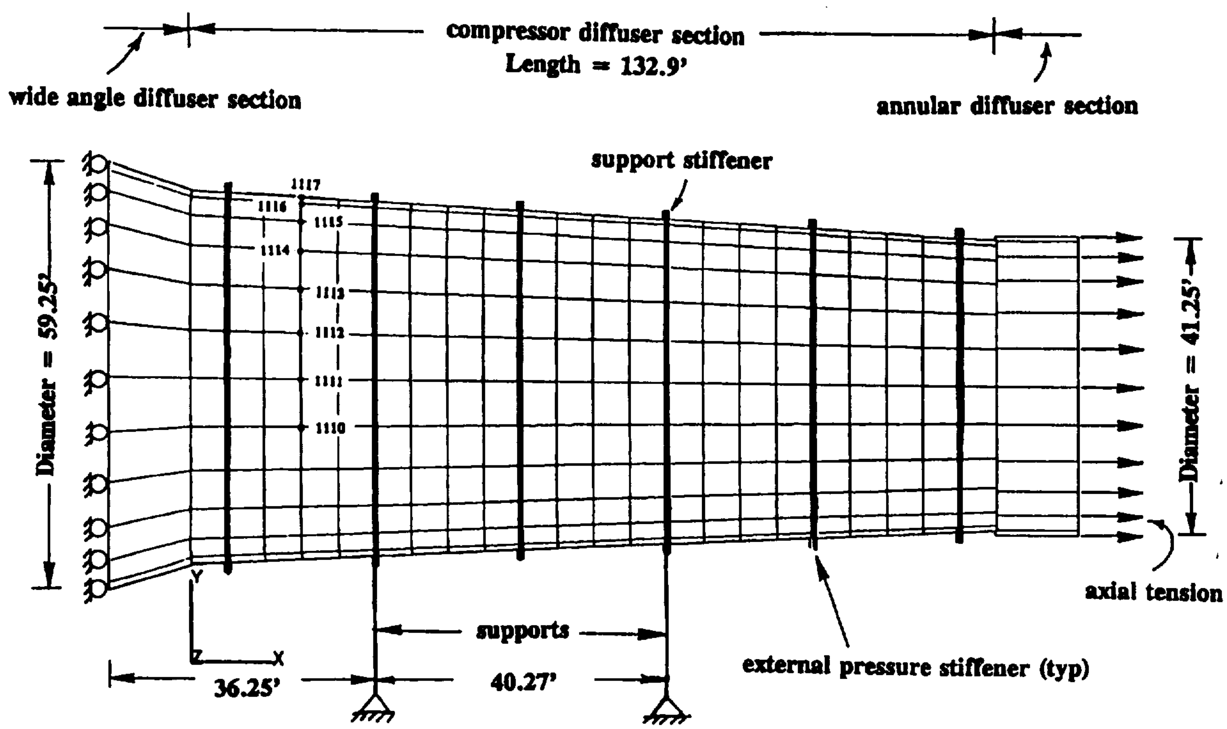

Figure 1.—National Wind Tunnel - critical section and components.

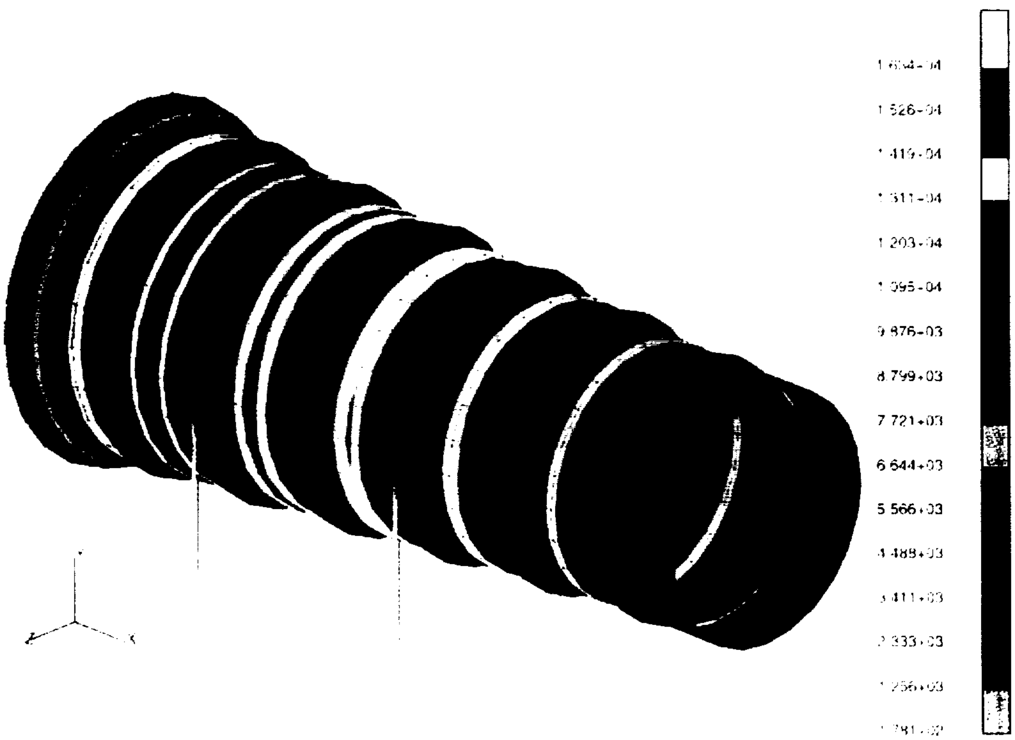

Figure 2.—Mean von-Mises stresses, psi.

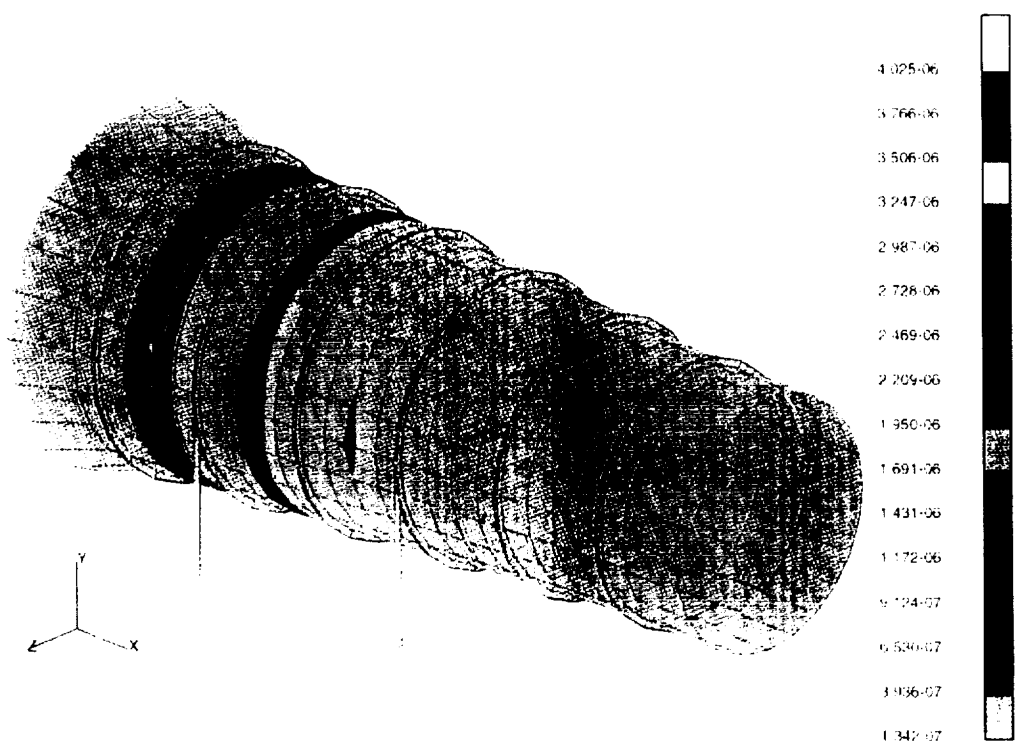

Figure 3.—Probability of failure contours - von-Mises failure criteria.

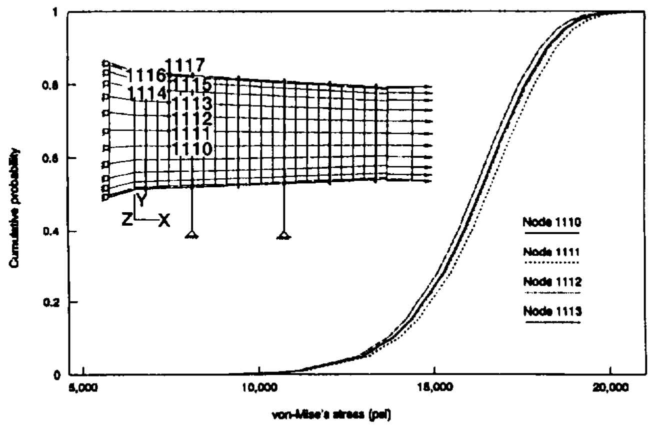

Figure 4a.—Cumulative distribution of function of von–Mises stresses at critical nodes.

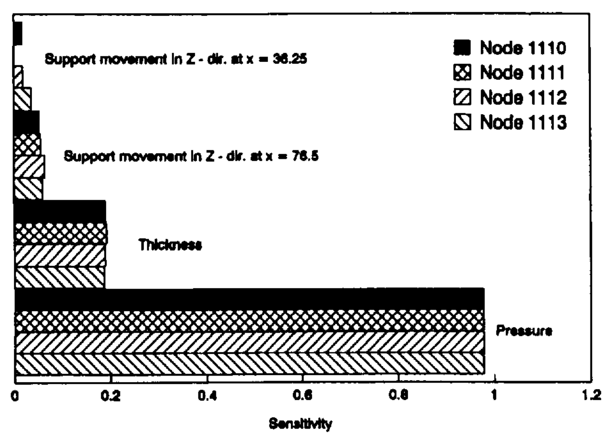

Figure 4b.—Sensitivity of the von–Mises stresses to the random variables at critical nodes at 0.9999 reliability.

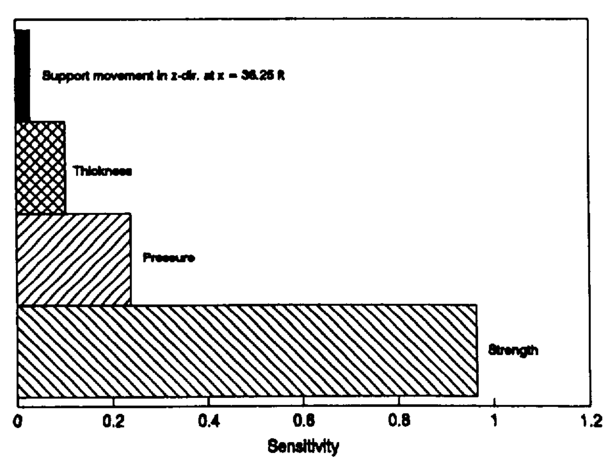

Figure 5.—Sensitivity of the failure probability to the random variables at node 1111.

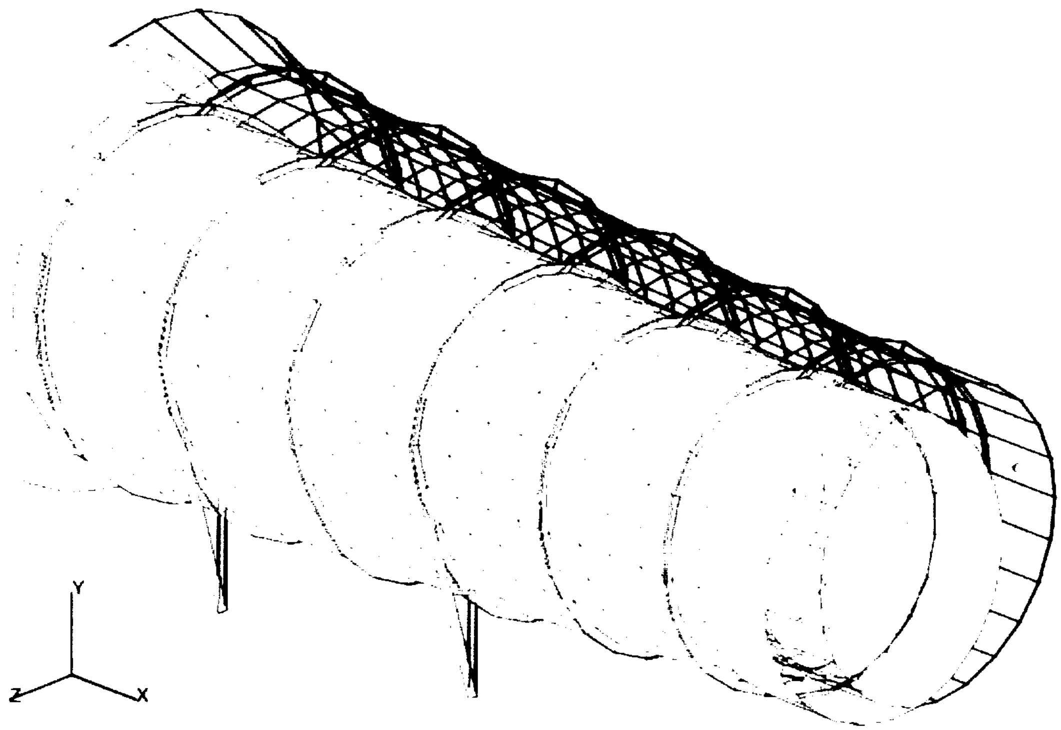

Figure 6.—Vibration mode shape 1 - frequency = 1.29 cps.

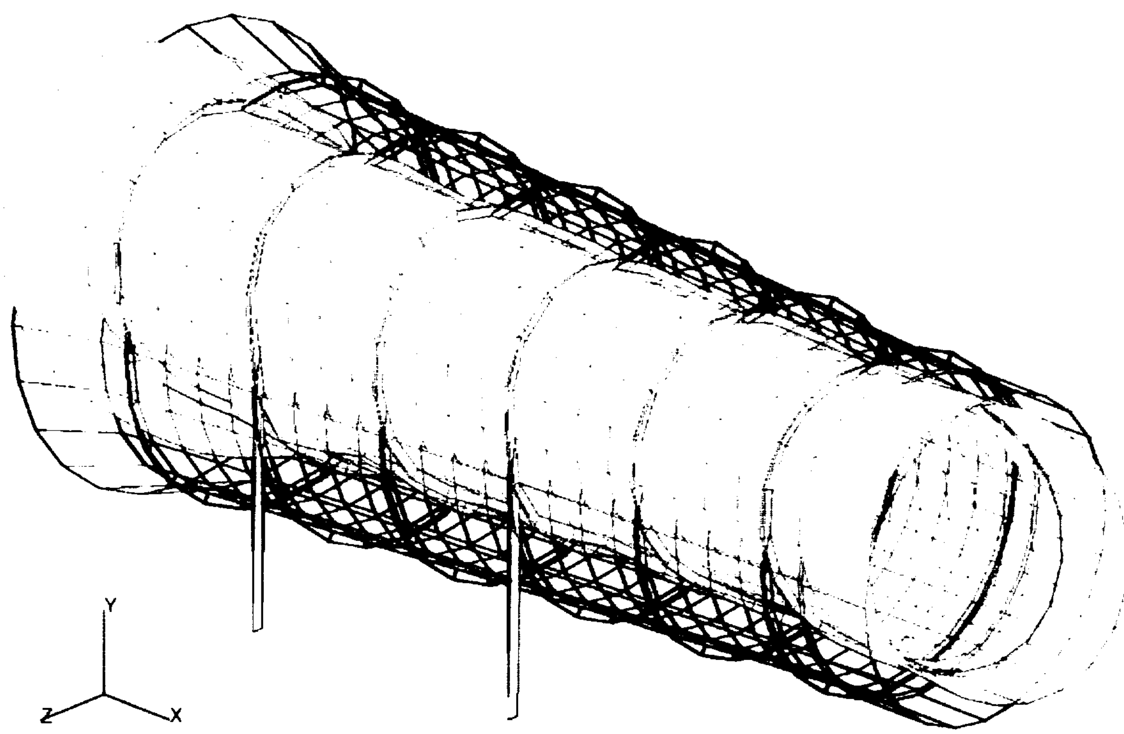

Figure 7.—Vibration mode shape 2 - frequency = 3.58 cps.

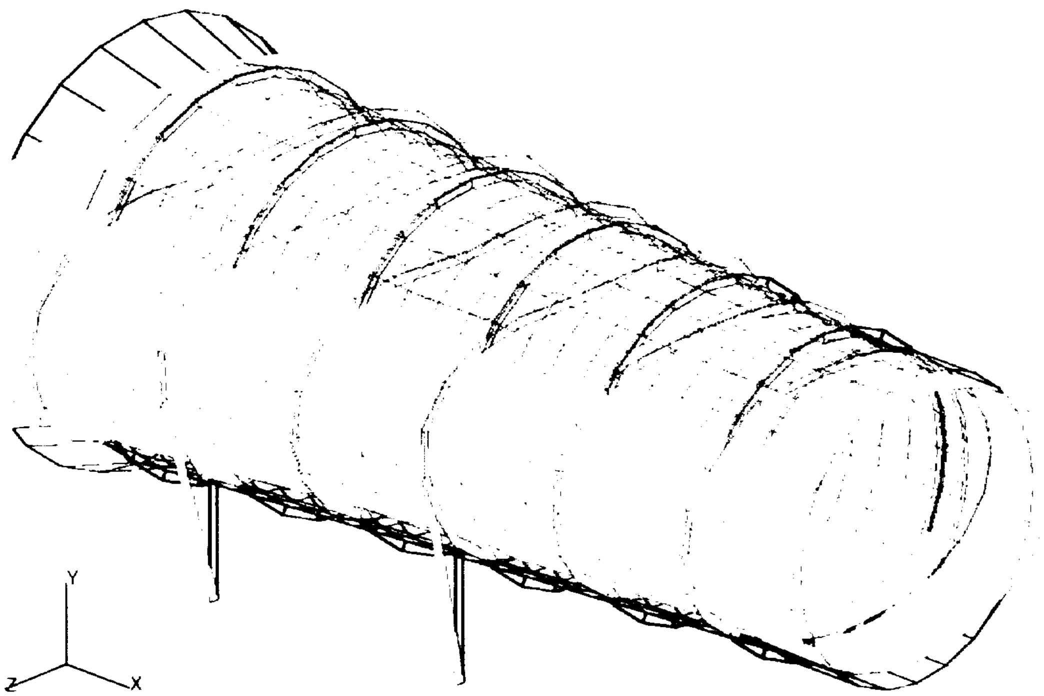

Figure 8.—Vibration mode shape 3 - frequency = 3.61 cps.

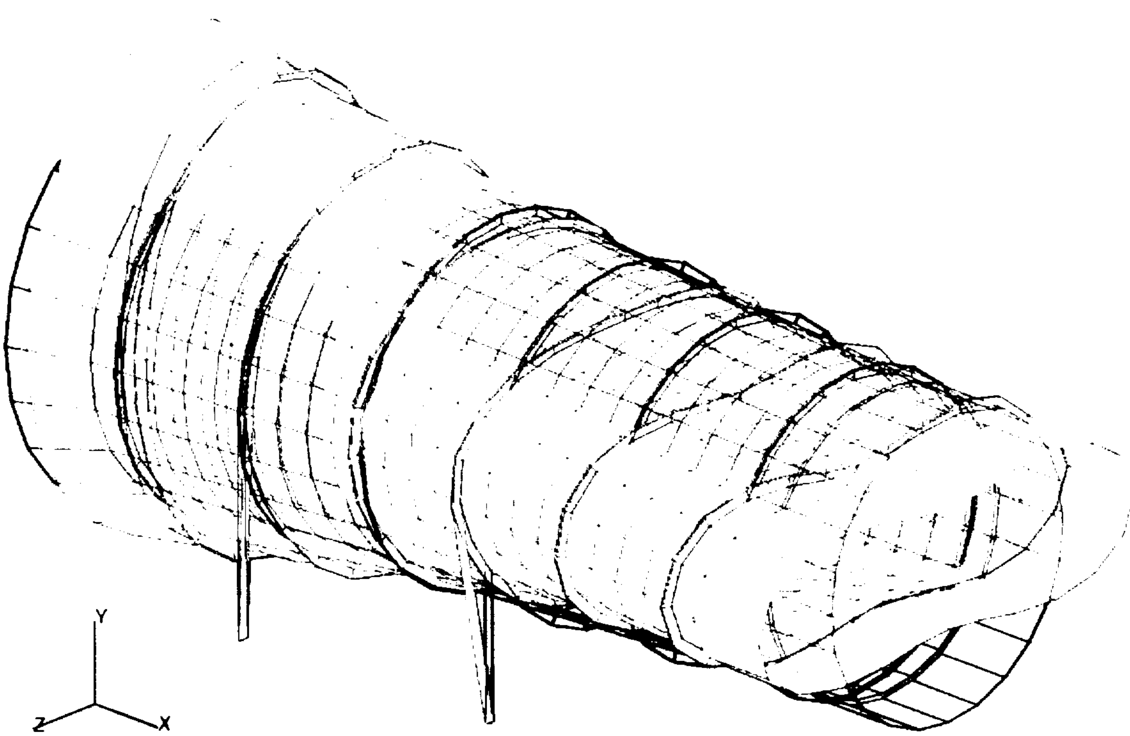

Figure 9.—Vibration mode shape 4 - frequency = 7.012 cps.

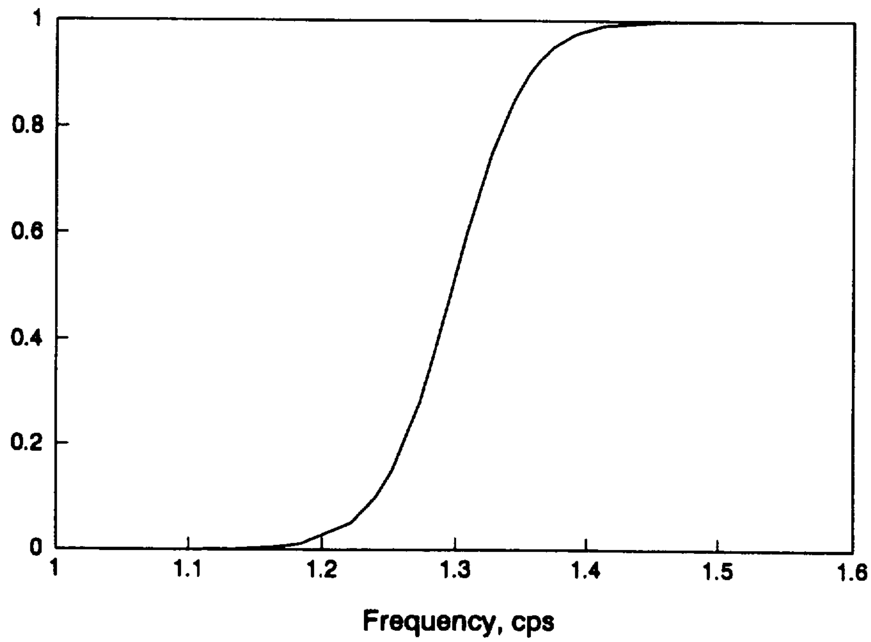

Figure 10a.—Cumulative distribution function of the first natural frequency.

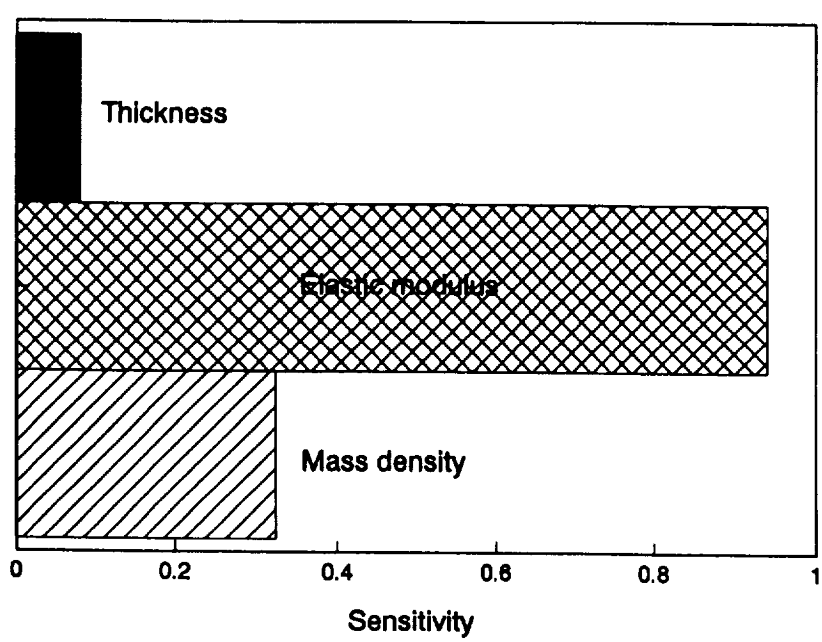

Figure 10b.—Sensitivity of the first natural frequency to the random variables at 0.9999 reliability.

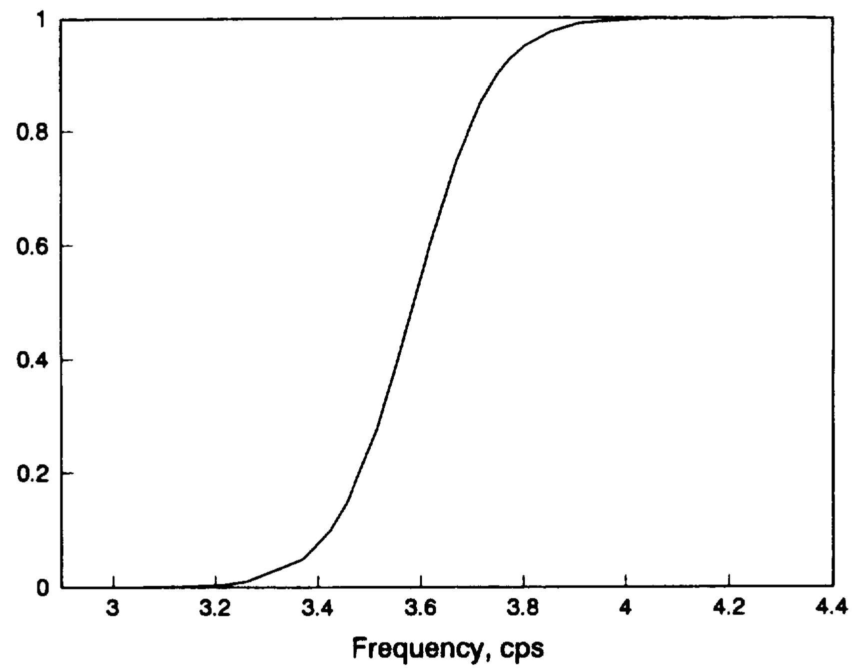

Figure 11a.—Cumulative distribution function of the second natural frequency.

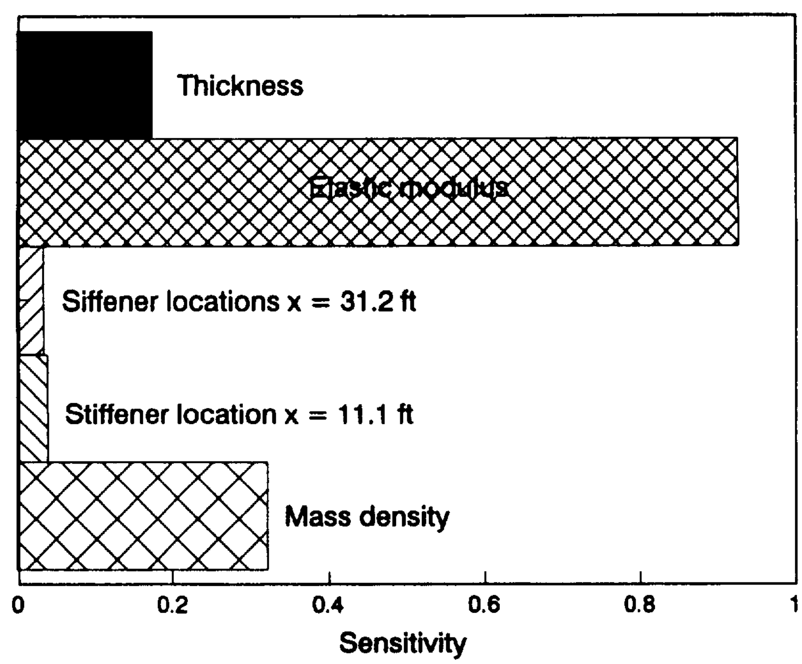

Figure 11b.—Sensitivity of the second natural frequency to the random variables at 0.9999 reliability.

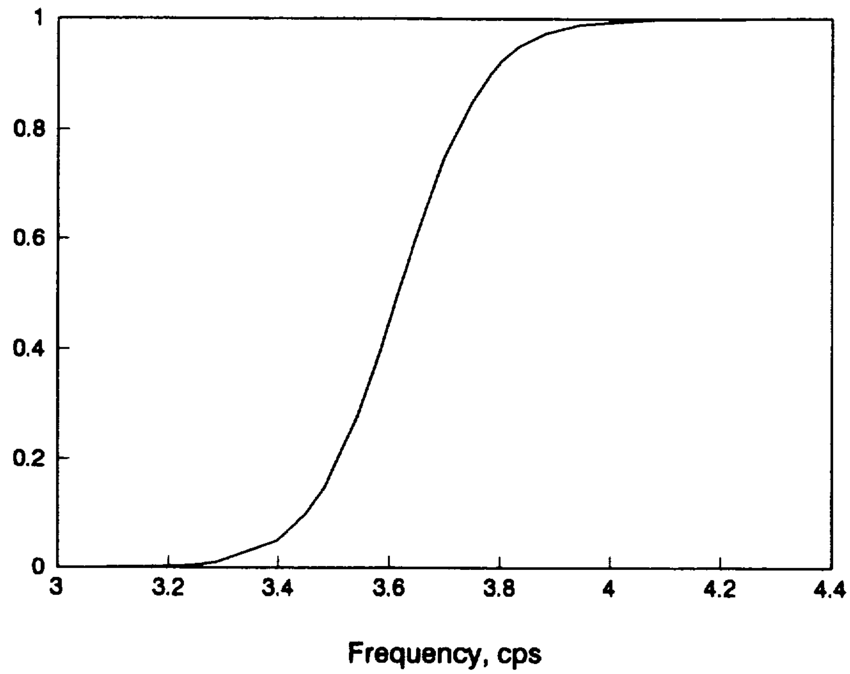

Figure 12a.—Cumulative distribution function of the third natural frequency.

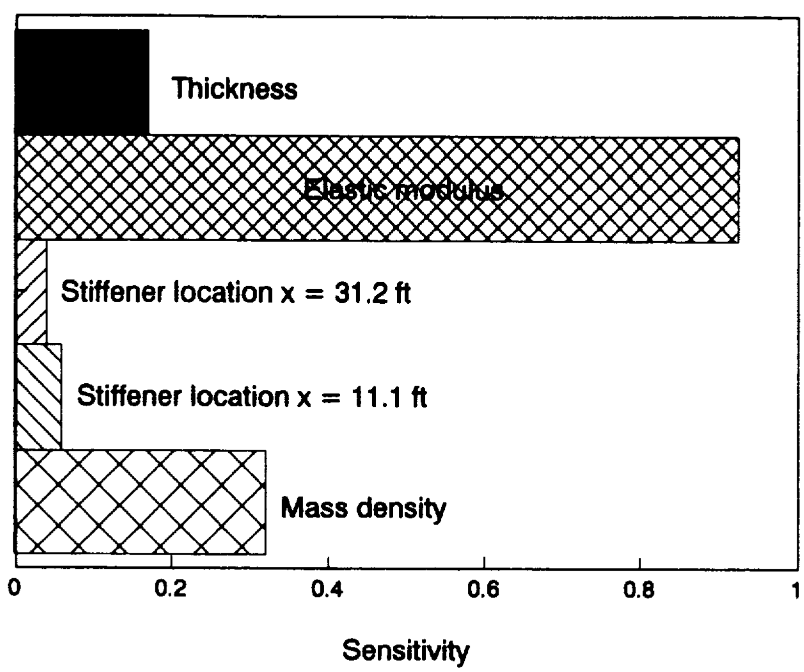

Figure 12b.—Sensitivity of the third natural frequency to the random variables at 0.9999 reliability.

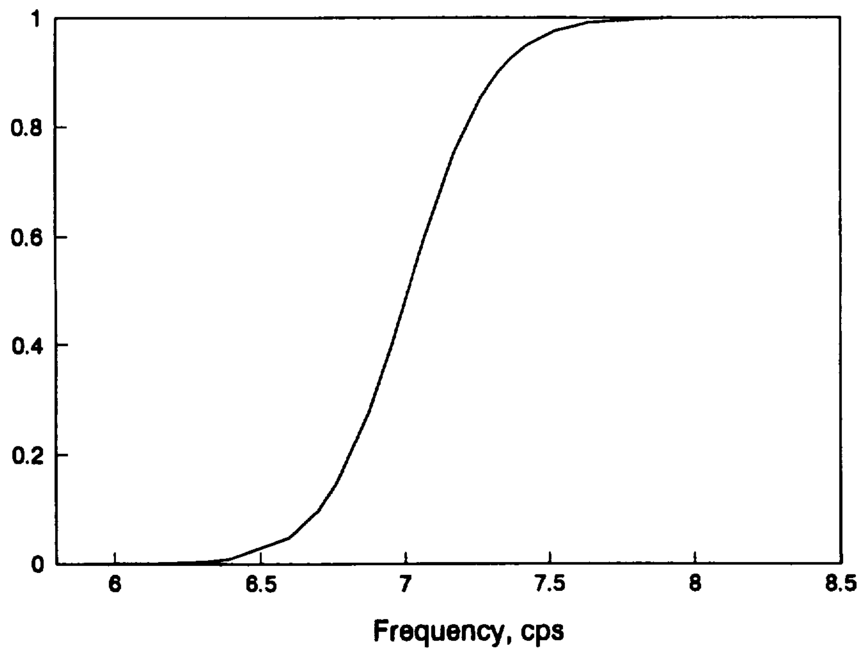

Figure 13a.—Cumulative distribution function of the fourth natural frequency.

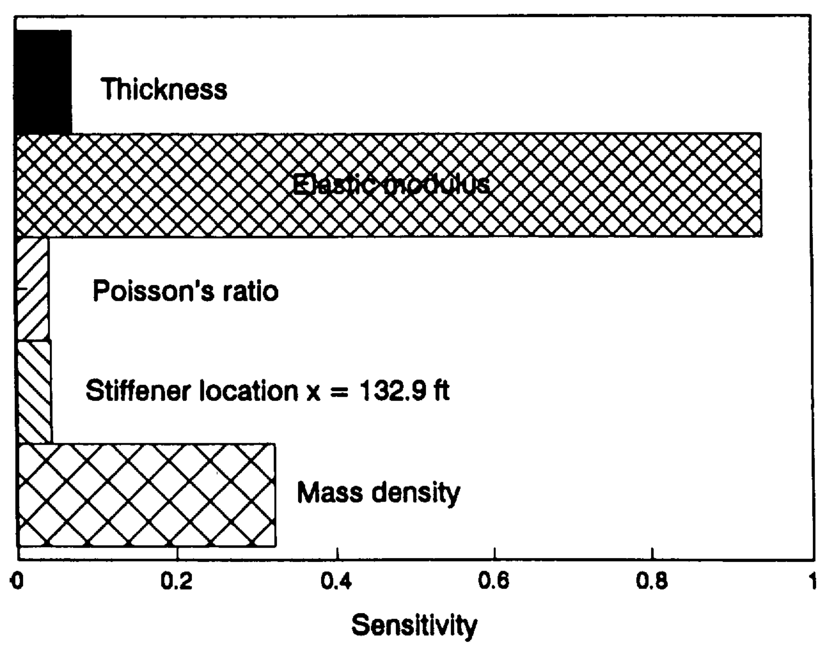

Figure 13b.—Sensitivity of the fourth natural frequency to the random variables at 0.9999 reliability.

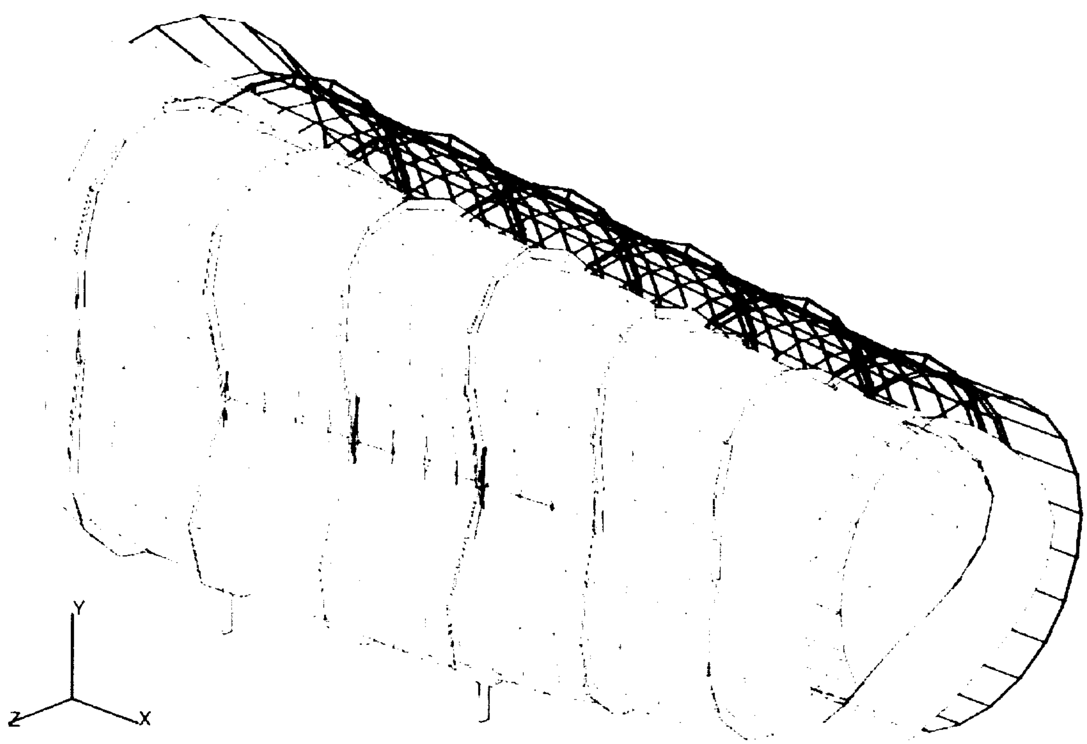

Figure 14.—Buckled mode shape - critical pressure = 13.15 atm. external.

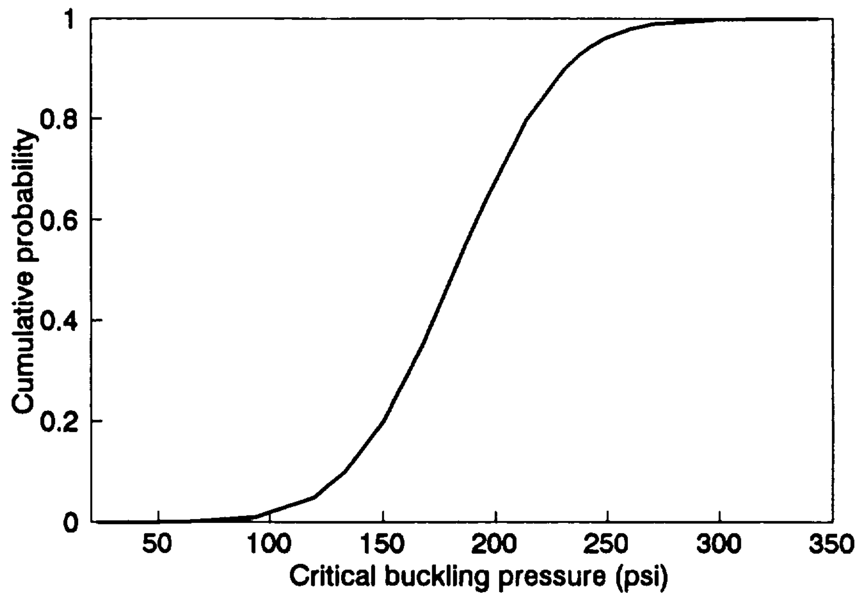

Figure 15a.—Cumulative distribution function of the critical buckling pressure (external).

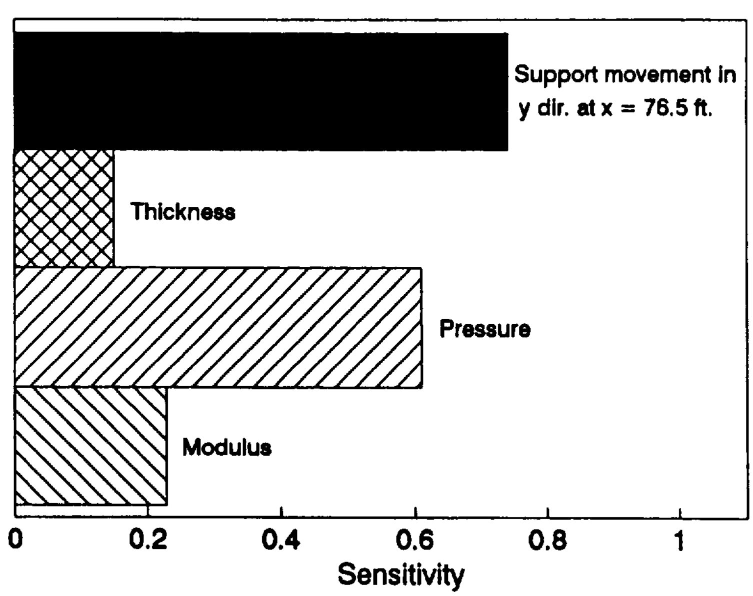

Figure 15b.—Sensitivity of the critical buckling pressure to the random variables at 0.9999 reliability.

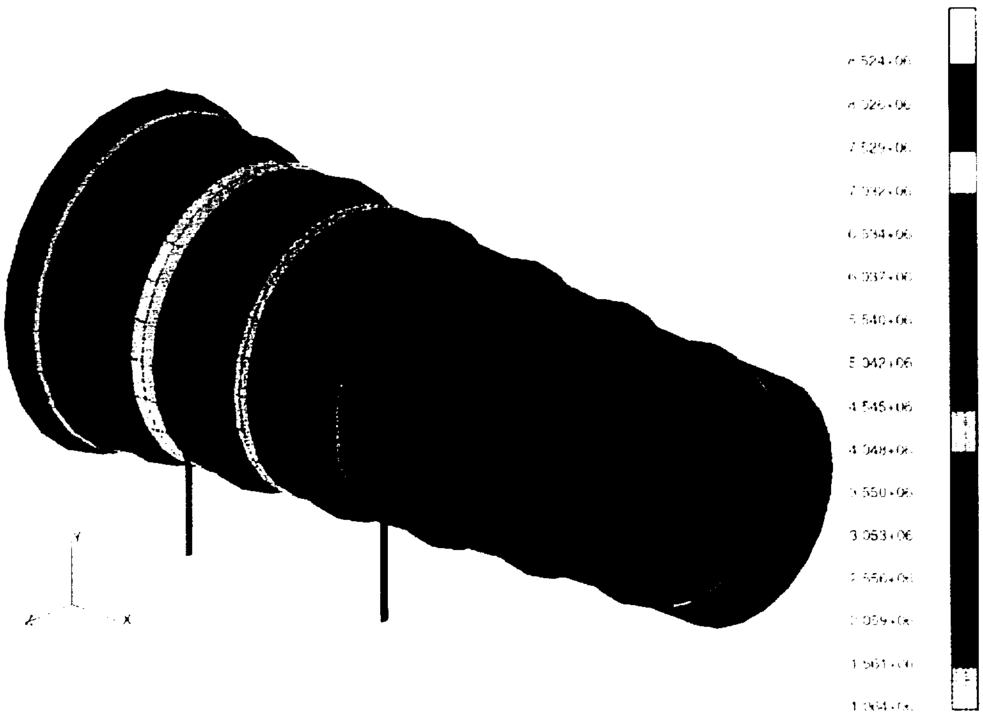

Figure 16.—Fatigue life contours for 0.9999 reliability.

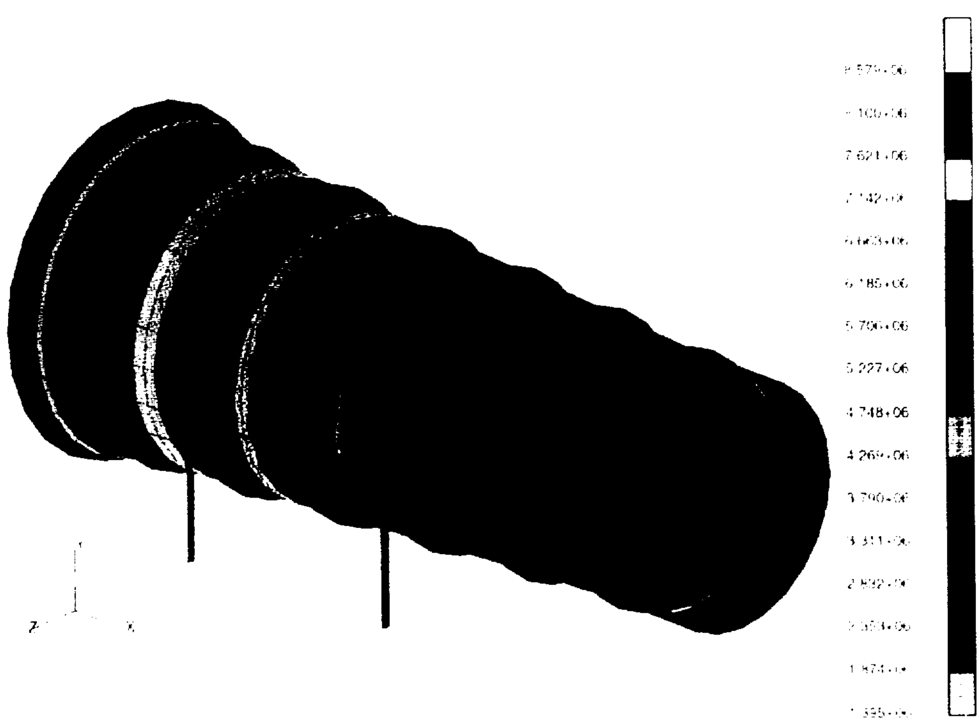

Figure 17.—Fatigue life contours for 0.999 reliability.

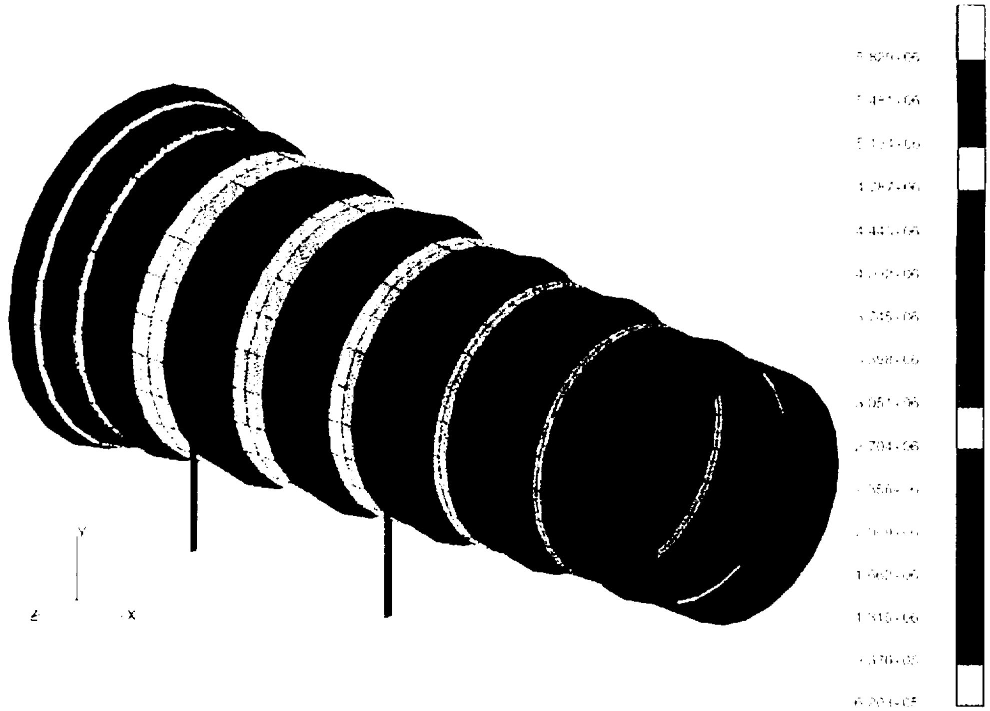

Figure 20.—Weld fatigue life contours for 0.999 reliability.

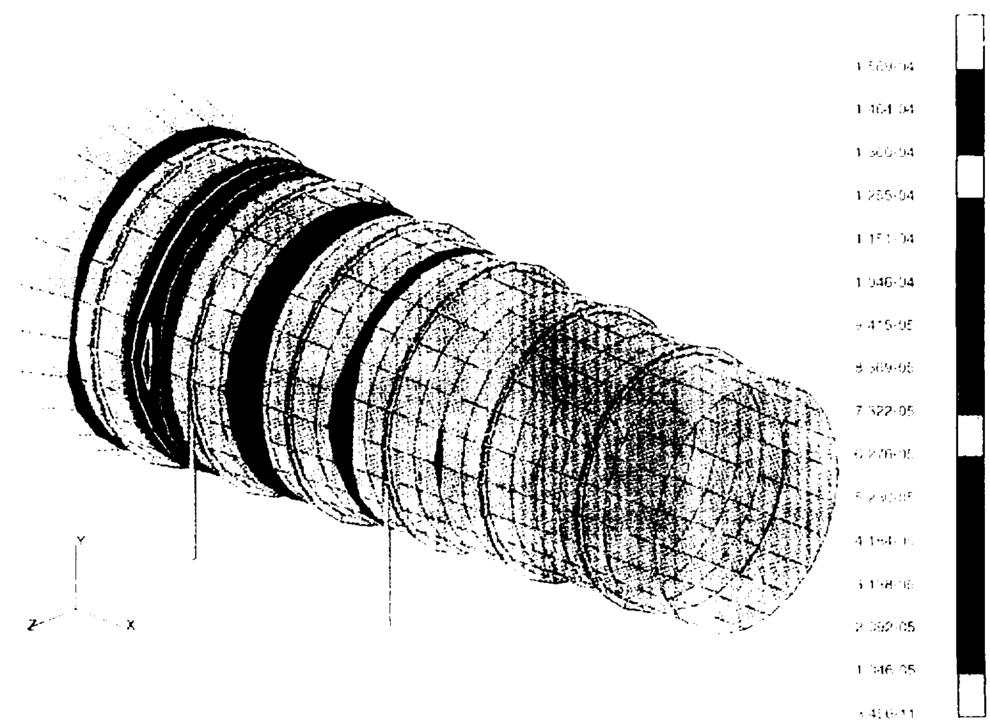

Figure 21.—Probability of failure contours under 125% proof load.

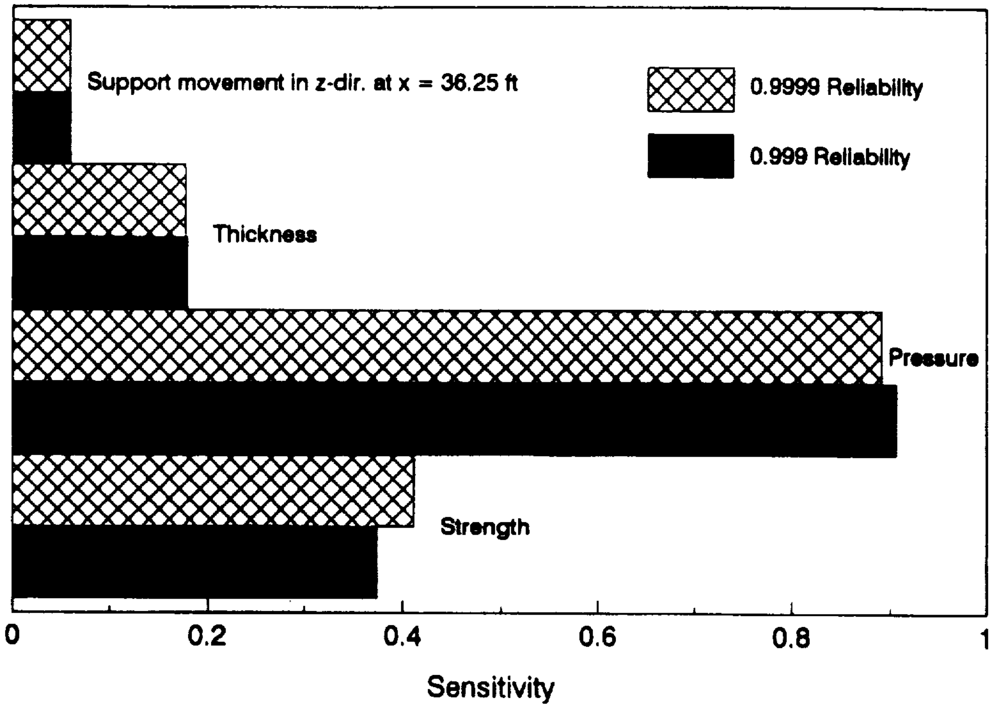

Figure 18.—Sensitivity of the fatigue life to the random variables at node 1111.

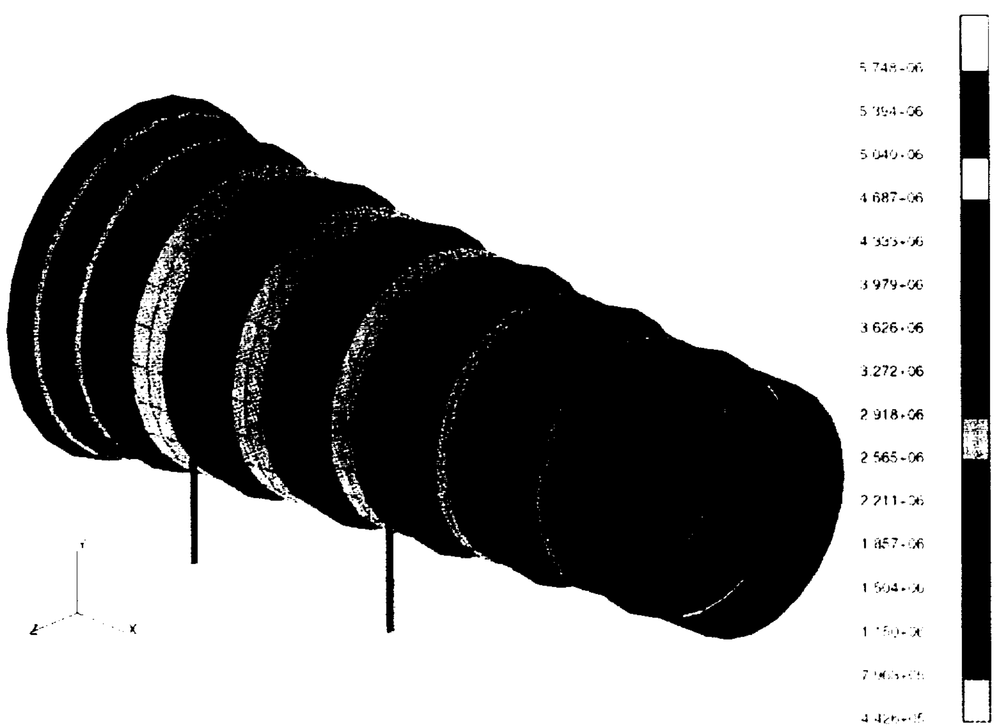

Figure 19.—Weld fatigue life contours for 0.9999 reliability.

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13. ABSTRACT ***(Maximum 200 words)***

A preliminary probabilistic structural assessment of the critical section of National Wind Tunnel (NWT) is performed using NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) computer code. Thereby, the capabilities of NESSUS code have been demonstrated to address reliability issues of the NWT. Uncertainties in the geometry, material properties, loads and stiffener location on the NWT are considered to perform the reliability assessment. Probabilistic stress, frequency, buckling, fatigue and proof load analyses are performed. These analyses cover the major global and some local design requirements. Based on the assumed uncertainties, the results reveal the assurance of minimum 0.999 reliability for the NWT. Preliminary life prediction analysis results show that the life of the NWT is governed by the fatigue of welds. Also, reliability based proof test assessment is performed.

14. SUBJECT TERMS
Cumulative probability distribution function; Scatter; Probability of failure; Sensitivity; Proof load; Frequency; Critical buckling load; Fatigue life

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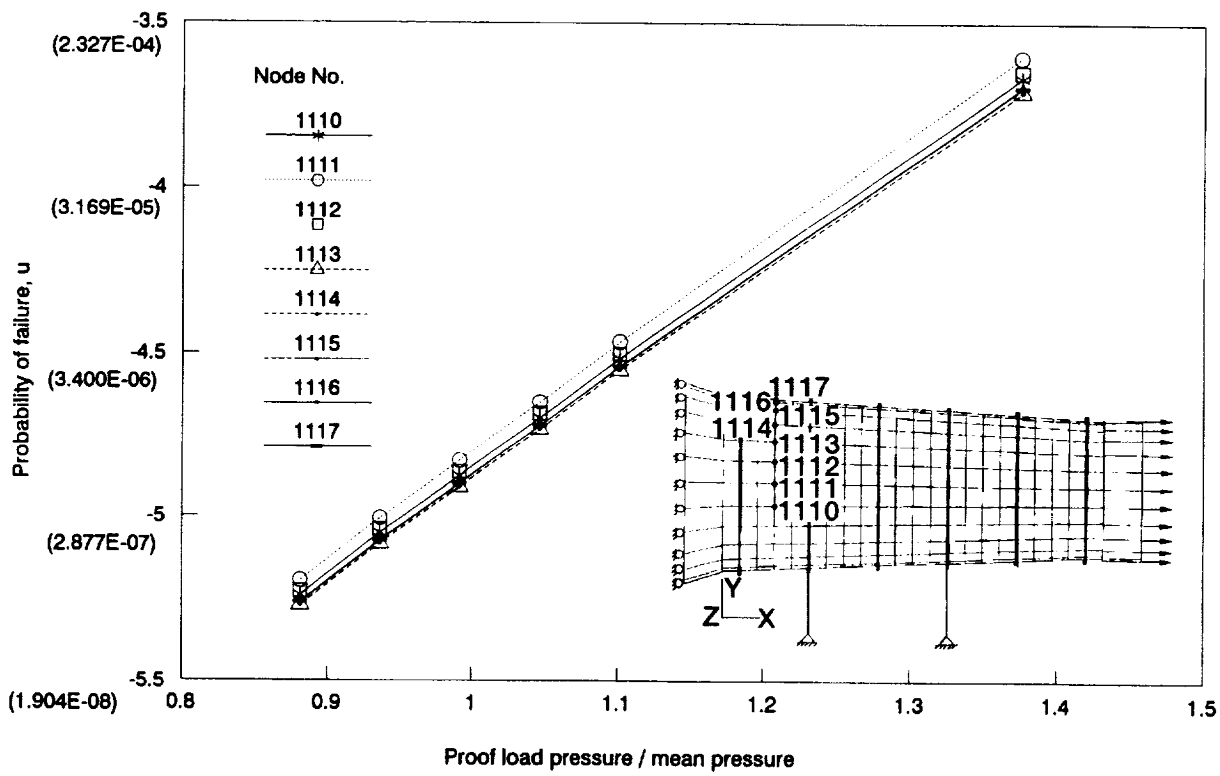

Figure 22.—Reliability based design chart for proof load (u – probability in standard unit normal space. Numbers in parenthesis represent actual probability).