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Structural Integrity Justification of a Rectangular Duct Under Large External Pressure

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ABSTRACT

This paper presents a methodology to justify the structural integrity of a 116" x 40" rectangular HVAC duct subjected to tornado-induced depressurization. Hand calculations are unable to demonstrate structural qualification per ASME AG-1 criteria. Based on these calculations, a significant number of additional reinforcing stiffeners would be required. As an alternative to this design upgrade, a finite element analysis (FEA) is performed to eliminate excess analysis conservatism by considering both material and geometrical nonlinearity.

The load-deflection relationship is determined using the elastic-plastic and large-deflection analysis capabilities of the ABAQUS computer code. The allowable collapse load based on the ASME Code, Section III, Appendix F for Level-D Service is much greater than the FEA computed collapse load. Confirmation of the HVAC duct structural adequacy of the duct is therefore possible without a design modification.

For comparative purposes, linear elastic and elastic-plastic, small-deflection FEA evaluations are also performed. A comparison of the results shows that the effects of large deflections are important considerations in evaluating the structural capability of HVAC ducts under large pressures.

1.0 INTRODUCTION

The consequences of tornado-induced depressurization on a large rectangular HVAC duct section represents a difficult problem to evaluate. Closed form solutions of duct panel sections based on traditional elastic plate and beam theory are often too conservative to enable verification of structural adequacy. To enable tractable analyses, simplifying assumptions are typically made which neglect the effects of membrane stiffness, structural stability, and stress redistribution.

Structural design criteria for HVAC duct are currently based on national Codes and Standards developed by the SMACNA[1,2] and ASME[3,4]. The ASME AG-1 design code considers dynamic pressure loads (DPD) resulting from a design basis accident, such as a tornado, to be classified as Service Level-D. AG-1 further stipulates (AA-4332.3) that Level-D design verification of linear-type systems is ensured through compliance with ASME Code, Section III.

This paper presents a methodology to verify the structural integrity of an existing 116" x 40" rectangular HVAC duct with angle stiffeners spaced 60" apart. The objective is to investigate the duct's structural adequacy which is challenged by an external pressure of 5.26"w.g. (0.19 psi).

Several different methods are illustrated which employ increasing levels of analytical complexity. Initially, hand calculations are used to compute the elastic bending stresses in the largest side panel and bordering angle stiffeners. This is followed by the determination of panel plastic collapse using a closed form solution that accounts for large deflection effects. Finally, a computerized non-linear finite element solution is obtained. For the sample duct evaluated, the computer solution was the only method that was able to successfully confirm the structural adequacy of this duct section.

2.0 DUCT CONFIGURATION

A sketch of the sample rectangular duct is shown in Fig. 1. The dimensions of the duct section including angle stiffeners are given below:

Duct width = 116"

Duct height = 40"

Duct panel gauge = 14
(0.0747" nominal thickness)

Duct stiffeners = two structural angles, 2" x 3" x 3/16" (welded back-to-back forming T-sections)

Stiffener spacing = 5'-0" (typ.)

Duct panel material = ASTM A-570
(hot rolled carbon steel sheet)

Duct stiffener material = ASTM A36

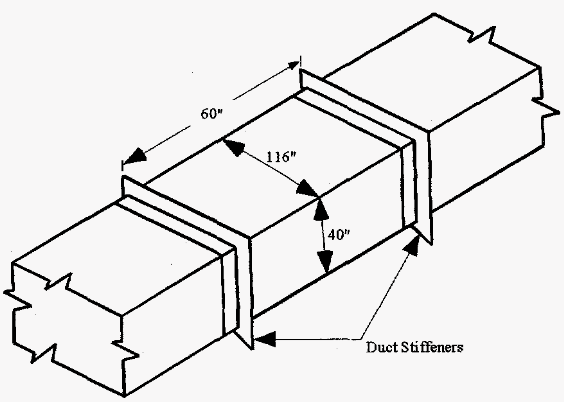

Figure 1. Typical Rectangular HVAC Duct Section

3.0 CLOSED FORM ANALYSIS

3.1 Linear Elastic Analysis

The duct panel bending stresses are computed using an analysis model based on a rectangular plate with two long edges fixed (at duct stiffeners) and two short edges simply supported (at duct corners). The plate maximum bending stress due to uniform pressure loading occurs at the center of the fixed edge and is equivalent to[5]

$$\sigma = \frac{\beta \times q \times b^2}{t^2} = 67.7\,ksi \qquad \ldots(1)$$

where
a = 116 in. (long side of the panel)
b = 60 in. (short side of the panel)
t = 0.0747 in. (panel nominal thickness)
β = 0.4972 (factor dependent on value of a/b)
q = uniform load per unit area (pressure)
q = $W_t + W_d$ = 0.211 psi (duct top panel)
or
q = $W_t - W_d$ = 0.169 psi (duct bottom panel)
W_t = 0.19 psi (vacuum pressure corresponding to tornado event)
W_d = 0.0211 psi (equivalent panel pressure due to deadweight)
Note - pressure units conversion: 1"w.g. = 0.03611 psi

The panel bending stress due to deadweight effects is included in the above formulation. The linear elastic computed stress of 67.7 ksi exceeds the ASME AG-1 Code (AA-4300) allowable value of 25.3 ksi (ASTM A-570 @ 2.25S) for this Level-D Service condition.

The stiffener bending stress for fixed end stiffeners is computed using the following equation per SMACNA[2]:

$$\sigma_b = \frac{M}{Z} = \frac{q \times s^2}{10 \times Z} = 42.6\,ksi \qquad \ldots(2)$$

where
$q = C \times p \times \ell$ = 12.7 lb/in (load on stiffener)
s = 116 in. (panel width or length of stiffener)
ℓ = 60 in. (stiffener spacing)
p = 0.211 psi (top panel pressure including deadweight effects)
C = 1.0 for $\ell / s \leq 2.0$
Z = 0.401 in^3 (two stiffeners, 3"x2"x3/16" welded back-to-back)

The linear elastic computed stress of 42.6 ksi exceeds the ASME AG-1 Code (AA-4300) allowable value of 32.6 ksi (ASTM A-36 @ 2.25S) for this Level-D Service condition.

3.2 Large Deflection, Collapse Load

This analysis method is based on several simplifying assumptions whereby a panel is analytically modeled as a flat rectangular plate with simply supported edges and a uniform (pressure) load. The plate modulus of rupture is determined analytically by computing (approximately) the ultimate load corresponding to the breaking point and then applying a safety factor for evaluation purposes. Reference 5 (pg. 409) has solutions for several plate configurations but suggests that this analytical approach can be in error by as much as 30%. This computational uncertainty can be accounted for in the evaluation safety factor.

ASME AG-1, Section AA-4300 allows structural evaluation by limit analysis and collapse load determination. For Level-D Service structural criteria, ASME AG-1 refers to the ASME Code, Section III. ASME Code Section III, Division 1, Appendix F, Section F-1331 requires that the actual component load shall not exceed 90% of the predicted collapse load using elastic analysis methods. Consequently, the evaluation safety factor should be defined so as to account for both computational uncertainty and ASME Code margin, i.e., S.F.= 0.70 × 0.90 = 0.63.

The collapse uniform pressure load required to collapse the plate is[5]:

$$P_u = \frac{W_u}{a \times b} = \frac{\beta \times \sigma_y \times t^2}{a \times b} \qquad \ldots(3)$$

$$P_{allowable} = 0.63 \times P_u = 0.0773 psi \qquad \ldots(4)$$

where

W_u = collapse load, lb.

σ_y = 25.0 ksi (ASTM A-570 Gr. A)

t = 0.0747 in. (panel thickness)

β = 6.11 (factor dependent on value of b/a)

a = 116 in. (width of the duct panel)

b = 60 in. (stiffener spacing)

As indicated in Section 3.1 above, the actual total equivalent pressure on the top panel is 0.211 psi (including deadweight effects). This exceeds the ASME Code allowable uniform pressure load required to collapse the plate of 0.0773 psi.

The closed form solutions illustrated above are very conservative in their determination of duct panel lateral pressure load capability. Analysis using a computer is discussed in the section that follows.

4.0 FINITE ELEMENT ANALYSIS

4.1 Assumptions

The structural responses of adjacent duct sections are assumed to be identical based on symmetry. As a result, only a single duct section that is bounded by a pair of stiffeners is analyzed (Fig. 2). Symmetrical boundary conditions can be applied on the stiffeners at the two edges of the duct section.

The material properties of the stiffeners (ASTM A36) are assumed to be the same as those of the duct. The material stress strain characteristics are discussed in Appendix A.

The steel angles are assumed to be uniformly fixed to the duct plates (continuous integral welds).

4.2 Methodology

Finite-element static stress analyses were performed by using the ABAQUS[6] computer program. Two finite element models were generated using the ABAQUS S4R 3-D shell elements - a full duct section model and a one-eighth duct section model. The one-eighth model takes advantage of the geometrical symmetry of the duct section. Figures 2 and 3 show the full and the one-eighth models together with their boundary conditions.

Three different types of analyses were performed for the external pressure load, i.e., (1) linear elastic analysis; (2) elastic-plastic, small deflection analysis; and (3) elastic-plastic, large deflection analysis.

For the case (2) and (3) nonlinear analyses, some difficulty was encountered in obtaining solution convergence. This difficulty was overcome by utilizing a combination of both direct and automatic time step selections to direct the iterative solutions. For example, near the point of predicted structural instability, the revised Riks method[6] was used to determine the corresponding applied load.

4.3 Summary of Analytical Results

4.3.1. Full Duct Section Model

The results of the linear elastic analysis indicate that the maximum von Mises stress due to the tornado-induced depressurization of 0.19 psi (5.26"w.g.) exceeds the AG-1 allowable of 25.3 ksi. This represents a very conservative solution since, in addition to assuming a linear stress-strain relationship, the bending moment reductions due to large rotations are neglected. The absence of membrane stiffness associated with large deflections also contributes to analysis conservatism.

The results of the elastic-plastic, small-deflection analysis also predicts that the maximum von Mises stress due to the tornado-induced depressurization of 0.19 psi (5.26"w.g.) exceeds the AG-1 criteria. This also represents a conservative solution because of the limitations of small deflection theory.

The results of the elastic-plastic, large-deflection analysis indicates that the maximum stress due to the tornado-induced depressurization of 0.19 psi (5.26"w.g.) is actually below the yield stress. The maximum von Mises stress was computed to be 14.4 ksi which is acceptable per the AG-1 criteria. The maximum deflection was computed to be about 1.0". Figure 4 is an illustration of the deformed shape (magnified) due to the applied external pressure.

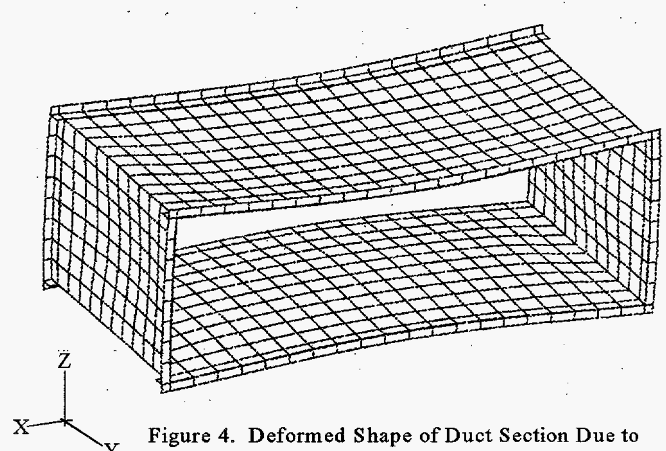

Figure 4. Deformed Shape of Duct Section Due to External Pressure of 5.26" w.g. (0.19 psi)

Figure 5 shows the load-deflection curves of the duct section as determined by the three types of analyses. The load is the applied uniform external pressure, whereas the deflection corresponds to the maximum duct deflection at the center of the bottom panel.

4.3.2 One-Eighth Duct Section Model

The stress distribution predicted by the one-eighth model due to the external pressure is the same as that for the full model. The load-deflection curve of the one-eighth model is shown in Fig. 5.

When the external pressure is below 0.3 psi, (8.3"w.g.) the load-deflection for the elastic-plastic, large-deflection analysis is approximately the same as that of the full model. However, the load-deflection curve deviates from that of the full-model with increasing external pressure. The one-eighth model is not able to predict the postbuckling mode identified by the full model, and thus, can not predict the collapse load accurately.

5.0 DETERMINATION OF COLLAPSE LOAD

Tornado-induced depressurization is classified as a Level D Service (Faulted) load (DPD) per ASME AG-1[3]. Accordingly, the acceptance criterion of collapse loads defined in the ASME Code, Section III, Appendix F[4] is applicable.

To account for post-buckling behavior in the determination of duct collapse load, it is necessary to use the full model. The resulting load-deflection curve is shown in Fig. 6. The allowable collapse load according to the ASME Code is 13.2"w.g. (0.477 psi) and is shown in the figure along with the expected external pressure corresponding to the magnitude of tornado-induced depressurization, 5.26"w.g. (0.19 psi).

6.0 CONCLUSIONS

Conclusions from the present analysis are as follows:

1. The allowable collapse load was determined to be 13.2"w.g. (0.477 psi) based on ASME Code, Section III, Appendix F for Level D (Faulted) Service[4]. The anticipated maximum external pressure in this duct section during the tornado is 5.26"w.g. (0.19 psi) which is well within the structural capability of this duct.

2. The maximum von Mises stress in the duct is 14.4 ksi, which is much less than what is permitted by AG-1 for this material (25.3 ksi). The maximum deflection was computed to be about 1.0 inch.

3. Based on several linear and nonlinear analyses performed, it was concluded that the effects of large deflections and large rotations are important considerations for this type of evaluation.

7.0 REFERENCES

1. HVAC Duct Construction Standards, Metal and Flexible, SMACNA, 1985.
2. Rectangular Industrial Duct Construction Standards, SMACNA, 1980.
3. ASME AG-1-1994, Code on Nuclear Air and Gas Treatment,/w AG-1a-1996 Addenda, ASME.
4. ASME Boiler & Pressure Vessel Code, Section III, Appendix F, 1995.
5. Roark, R. J. and Young, W.C., Formulas for Stress and Strain, 5th Ed., McGraw-Hill, 1975.
6. ABAQUS/Standard User's Manual, Vol. II and III, version 5.6.
7. Shigley, J. E. and Mitchell, L. D., Mechanical Engineering Design, 4th Ed., McGraw-Hill, 1983.
8. ASTM A570-75, Standard Specification for Hot-Rolled Carbon Steel Sheet, and Strip, Structural Quality, ASTM, 1975.

-APPENDIX A-

Material Properties of ASTM A-570[8]

The inelastic material properties needed for the analysis are derived in the following.

The nominal yield stress and Young's modulus of ASTM A-570 steel are:

$$\sigma_{ny} = 25{,}000\,psi$$

$$E = 29 \times 10^{6}\,psi$$

The nominal tensile strength and its corresponding nominal strain are:

$$\sigma_{nu} = 45{,}000\,psi$$

$$\varepsilon_{nu} = 0.27\,in/in$$

The relationship between nominal stress and nominal strain is:

$$\sigma_n = E\varepsilon_n \qquad \ldots(A1)$$

where σ_n = nominal stress

ε_n = nominal strain
E = Young's modulus

The true stress-true strain relation is[7]:

$$\sigma_t = K\varepsilon_t^n \qquad \ldots(A2)$$

where σ_t = true stress

K = strength coefficient
ε_t = true strain
n = strain-hardening exponent

The true stress can be expressed in terms of the nominal stress and nominal strain as follows[7]:

$$\sigma_t = \sigma_n(1+\varepsilon_n) \qquad \ldots(A3)$$

Furthermore, the true strain can be expressed in terms of nominal strain as follows[7]:

$$\varepsilon_t = \ln(1+\varepsilon_n) \qquad \ldots(A4)$$

Using Equations (A1) through (A4), the following values of the strength coefficient, K, and strain-hardening exponent, n, are determined from the values of σ_{ny}, σ_{nu}, ε_{nu}, and K:

$$K = 70{,}500\, psi$$

$$n = 0.1468$$

Consequently, the formula for the true stress - true strain of A570 Grade A steel is:

$$\sigma_t = 70{,}500\, \varepsilon_t^{0.1468} \qquad \ldots(A5)$$

Figure A1 shows the plot of the true stress - true strain curve based on equation A5.

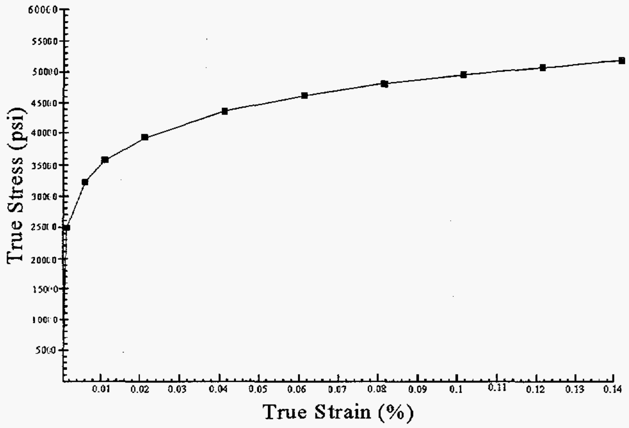

Figure A.1 True Stress vs. True Strain for ASTM A570, Grade A Steel

In performing elastic-plastic analysis, the ABAQUS computer program[6] requires material property data in the form of true stresses and corresponding plastic strains. True plastic strains can be calculated from the true total strains and true stresses by using the following equation:

$$\varepsilon_t^{pl} = \varepsilon_t - \frac{\sigma_t}{E} \qquad \ldots(A6)$$

The plastic strain data for the duct material (ASTM A-570, ASTM A-36) is tabulated in Table A1 below.

Table A1. Material Plastic Strain Data

True Stress (psi)	True Plastic Strain (in/in)
25,000	0.0
32,390	0.00388
35,860	0.00876
39,700	0.01863
43,950	0.03848
46,650	0.05839
48,660	0.07832
50,280	0.09827
51,640	0.1182
52,830	0.1382

Acknowledgments

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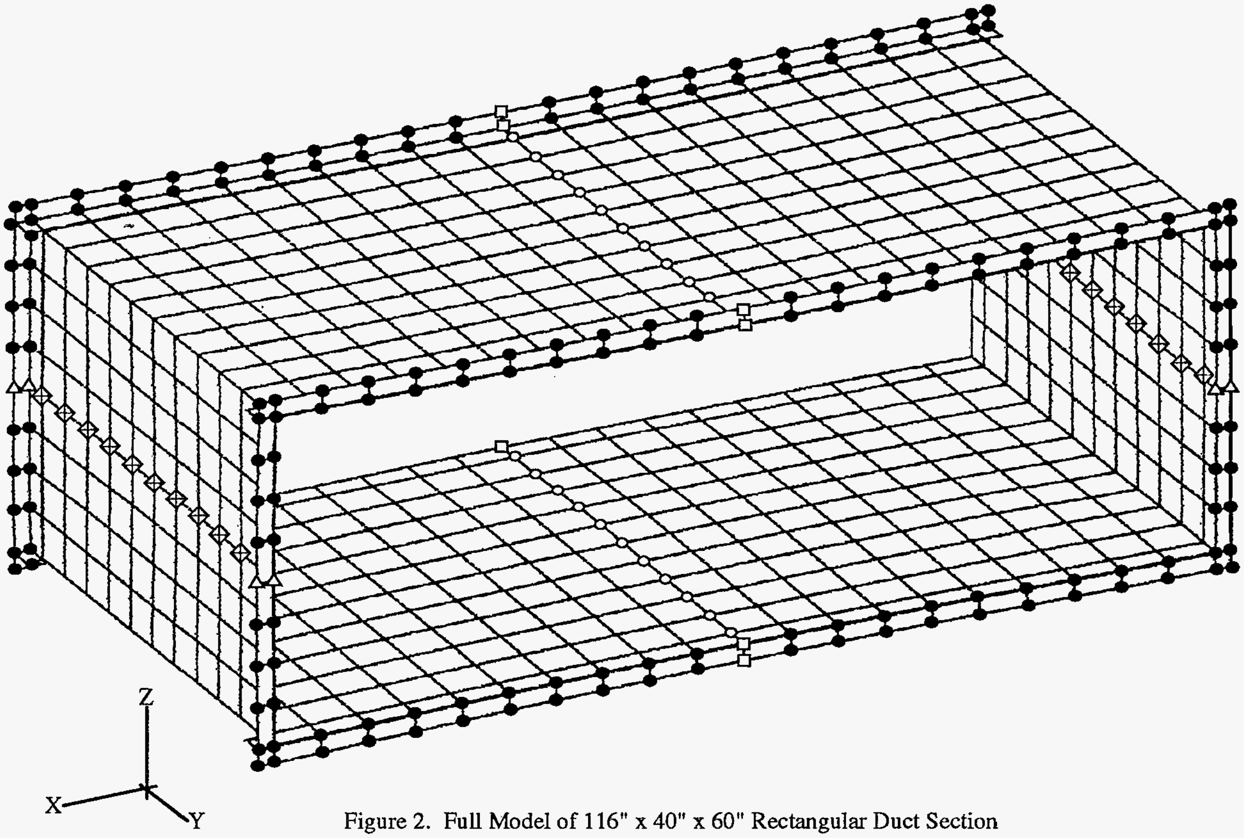

Figure 2. Full Model of 116" x 40" x 60" Rectangular Duct Section

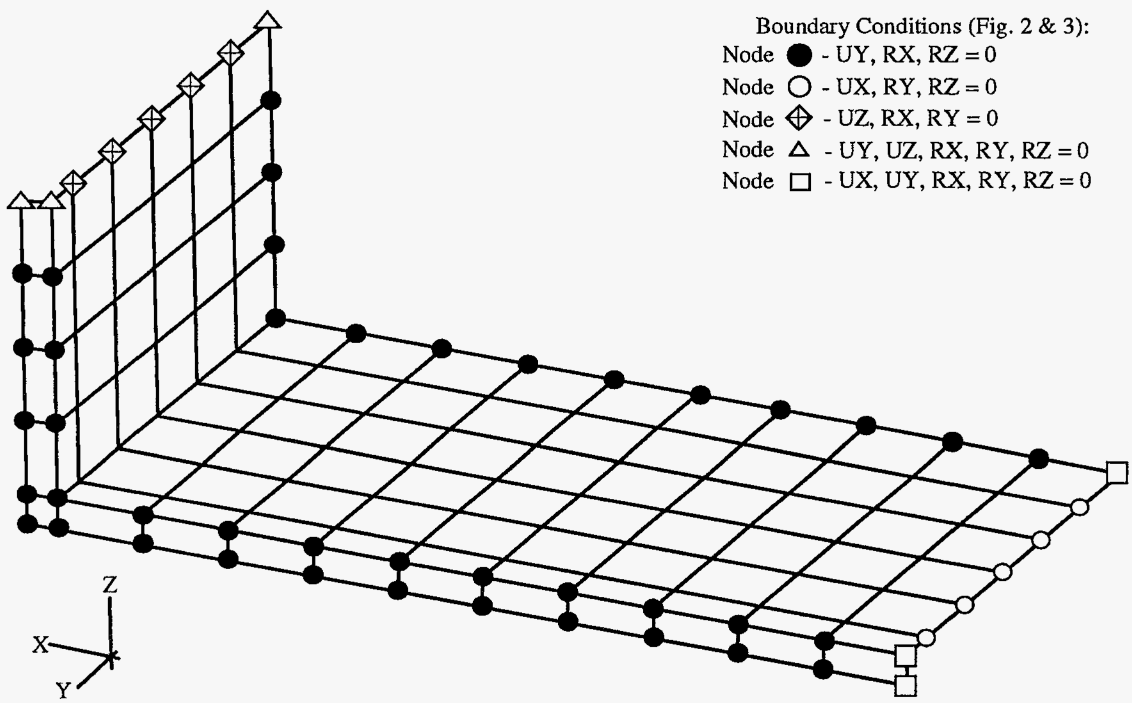

Figure 3. One-Eighth Model of 116" x 40" x 60" Rectangular Duct Section

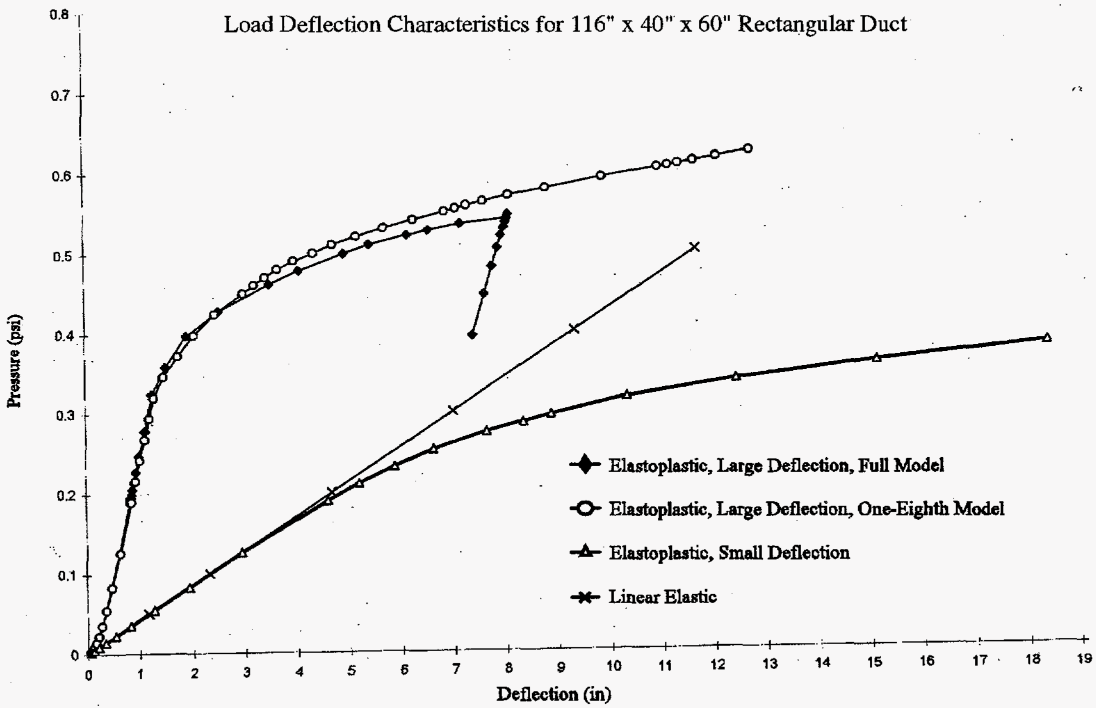

Figure 5. Load Deflection Curves for Various Analysis Cases

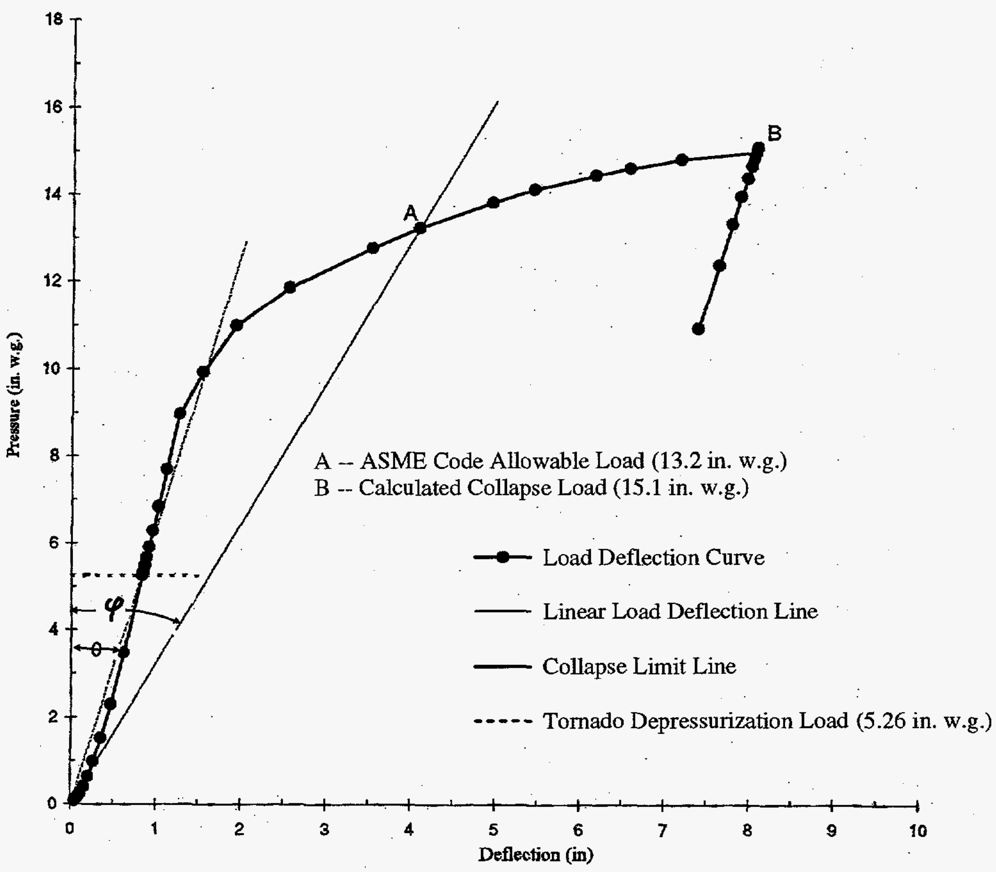

Figure 6. Determination of Allowable Collapse Load