Evaluation of the ultimate pressure capacity of rectangular HVAC ducts for nuclear power plants

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ABSTRACT

This paper presents an analytical design method and its correlation with test results for HVAC ducts for nuclear power plants.

Load combinations include positive and negative pressure loads which are generated due to normal plant operation and/or postulated accident conditions.

Simple formulae for the design of rectangular HVAC ducts are presented. Lower bound values of duct sheet, and stiffener ultimate loads are derived, and correlated with recent test results. Analytically predicted ultimate pressures are also compared with other available duct test data.

1 INTRODUCTION

There is an absence of generally accepted structural design criteria for Category I HVAC ducts of welded construction for Nuclear Power Plants. The American Iron and Steel Institute (AISI) "Specification for the Design of Cold-Formed Steel Structural Members" of 1968, with supplements of 1971, was adopted to be the governing code for the design of such ducts. Design of ducts to the AISI code, however, often result in ducts which are too heavy or have sheet thicknesses and stiffener frames which are heavier than those required by stress, stability, and/or structural integrity considerations only.

In order to improve the economy of HVAC duct design, Bechtel Power Corporation made use of the testing provision of the AISI code and conducted two sets of test, one in 1974 and the other in 1976 for ducts used in actual nuclear plant projects (Bechtel 1974a, 1976b). While other HVAC duct test results which have been published in the literature have not included or considered pressure loads, both Bechtel test series included pressure loading, either positive or negative. The test results indicated that negative (vacuum) pressure loads are especially critical and may control the design of the duct. The Bechtel tests also demonstrated that it is possible to increase the duct width and height to sheet- thickness ratios beyond the limits (500 and 200, respectively) set by the AISI code and still be able to achieve safe design of the duct.

Subsequent to the completion of the last HVAC duct test program, a new analytical method was developed for a more rational design of Category I rectangular HVAC ducts. The method which is to be presented in this paper correlates well with the results of both test series and provides the basis for a more rational design of rectangular HVAC ducts.

2 DESCRIPTION OF TESTS

The Bechtel Test Program (Bechtel 1974a, 1976b) involved rectangular HVAC ducts from 24" x 24" to 96" x 48" "flow area" with equal angle stiffener frames up to L3x3x1/4 spaced from two to four feet, and with duct width to thickness ratios up to 1600. The loading included dead, concentrated live load, simulated equivalent-static seismic load, and/or pressure load. All tests were continued to and beyond ultimate, until failure in the sense of loss of the duct's structural integrity occurred. Failure was, in all the tests, caused by the negative pressure load.

Two distinct failure modes were observed:

(a) Duct panel sheet buckling or "corner-crippling," and

(b) Duct stiffener frame buckling

Duct beam mode corner buckling is a third possible failure mode, which may occur in long span and/or heavily loaded ducts. This mode is not pressure induced, and it was not observed in any of the tests.

The analytical procedure to be described in Section 3 was based on these observed failure mechanisms, which may be described qualitatively as follows:

Duct Sheet Buckling or Corner Crippling (See Figure 1)

In this failure mode, the sheet failed while the stiffeners remained intact.

Initially, the sheets responded to the pressure by bending into a concave shape. As the pressure increased, the sheet strain gauge readings revealed that membrane tension normal to the sheet edges developed throughout the sheet. These membrane tensile forces pulled the weakest sheet corner inward causing it to "cripple" or buckle, with a subsequent breaching of the duct's air-tightness and a final cave-in.

Duct Stiffener Frame Buckling (See Figure 2)

From the tests where this failure mode occurred, the stiffener frames were observed to start yielding at the corners and at the mid-spans and subsequently buckled while the sheets remained elastic.

The duct panel sheets transmit the uniform pressure load to the stiffener frames, mainly by bending. Plastic hinges formed first at the four corners and later at the center of the long members.

Duct Beam Mode Buckling (See Figure 3)

The post sheet buckling ultimate strength of the duct is derived based on the assumed four corners effective duct cross-section.

Failure occur when corner reach yield rather than "buckling" due to the AISI stiffener frame spacing limitation.

Summary of test results with indication of governing failure modes are listed (Bechtel 1976b).

3 ANALYTICAL METHOD

3.1 Duct Sheet Response Mode

The response to a static negative pressure load of a typical thin, rectangular duct panel sheet with rigid vertical supports at the four corners and restrained rotationally, and in-plane translationally at all four edges may be calculated based on the large deflection bending theory of plates. The following assumptions are made for the analysis:

1) The initial shape of the panel is flat;

2) The deflected shape of the loaded panel may, at initiation of yield, be described geometrically by an elliptic paraboloid;

3) The membrane forces at initiation of yieldlines along the edges are constant throughout the panel;

4) All panel edges are fully restrained rotationally and translationally (in-plane) up to, and at initiation of yield.

From these assumptions, the panel deflected shape under pressure in a right-handed cartesian coordinate system (shown on Figure 4) has the following equation:

$$W = W_m + W_b \qquad \text{Eq. (1)}$$

where W, the panel displacement at the point (x, y) consists of a "membrane component" W_m and a "bending component" W_b which are:

$$W_m = \left[1-K_1\left(\frac{x}{a}\right)^2-K_2\left(\frac{y}{c}\right)^2\right](W_o); \qquad \text{Eq. (2)}$$

$$W_b = \left\{A\left[\cosh(ux)-\cosh\left(\frac{ua}{2}\right)\right]+B\left[\cosh(vy)-\cosh\left(\frac{vc}{2}\right)\right]\right\}(W_o); \qquad \text{Eq. (3)}$$

and where

a = width of duct

c = spacing of the stiffener frames

W_o = panel displacement normal to the panel at the center (0,0)

and u, v, K_1, K_2, A, and B are coefficients which can be determined from the panel-boundary conditions and elastic properties.

This assumed panel deflected shape satisfies all the panel boundary conditions, and the following basic differential equilibrium equation for the bending of a thin plate under the combined action of a uniform lateral pressure load (q) and membrane ("in-plane") forces (N_x, N_y, N_{xy}).

$$W''''+2W''^{\cdot\cdot}+W^{\cdot\cdot\cdot\cdot}=\frac{1}{D}\left[q+N_xW''+N_yW^{\cdot\cdot}+2N_{xy}W'^{\cdot}\right]; \qquad \text{Eq. (4)}$$

where D is the bending rigidity of the panel sheet and prime signifies differentiation with respect to x and "dot" differentiation with respect to y.

The additional requirements of in-plane translational restraints, i.e., that the distance between stiffener frames and between the duct corners remains constant prior to and up to yield, lead to relations Eqs. (5) and (6) between panel membrane forces N and curvatures ρ_x and ρ_y. The bending moments along the panel edges may also be expressed in terms of the membrane forces and center curvatures, as Eqs. (7) and (8):

$$N_x = \frac{1}{24}(Et)\left(\frac{a}{\rho_x}\right)^2; \qquad \text{Eq. (5)}$$

$$N_y = \frac{1}{24}(Et)\left(\frac{c}{\rho_y}\right)^2; \qquad \text{Eq. (6)}$$

$$M_x = \frac{1}{2}\left(\frac{a}{\rho_x}\right)\left[(N_x)(D)\right]^{1/2}; \qquad \text{Eq. (7)}$$

$$M_y = \frac{1}{2}\left(\frac{c}{\rho_y}\right)\left[(N_y)(D)\right]^{1/2}; \qquad \text{Eq. (8)}$$

t is the thickness of the panel sheet.
The membrane-bending interaction along the panel edges at yield are:

$$\frac{N_x}{N_{ux}} + \frac{M_x}{M_{ux}} = 1 \qquad \text{Eq. (9)}$$

$$\frac{N_y}{N_{uy}} + \frac{M_y}{M_{uy}} = 1 \qquad \text{Eq. (10)}$$

Where N_{ux}, N_{uy} and M_{ux}, M_{uy} are the membrane and the bending yield capacities of the duct panel sheets in the x and y direction, respectively. Eqs. (9) and (10) when combined with Eqs. (5), (6), (7), and (8) lead to the expression Eq. (11) for the lower bound critical pressure which initiates the sheet corner crippling mode of failure and to the expression for the panel center displacement at yield Eq. (12):

$$q = 0.40\,(f_y)\left(\frac{f_y}{E}\right)^{1/2}(t)\left(\frac{1}{a} + \frac{1}{c}\right); \qquad \text{Eq. (11)}$$

$$W_o = 0.26\left(\frac{f_y}{E}\right)^{1/2}(a+c); \qquad \text{Eq. (12)}$$

the pertinent expressions for the panel strain fields are derivable from Eqs. (11) and (12) and the strain-displacement relations.

The quantity, q determined from Eq. (11), is the pressure load which causes the formation of yieldlines along the panel edges and initiates the subsequent large membrane forces which lead to duct corner crippling at the ultimate load. Thus, the actual ultimate load will be larger than the pressure load determined from Eq. (11). The calculated q value may be considered as an estimate of the lower bound value of the duct ultimate load governed by the corner crippling mode of failure.

3.2 Duct Stiffener Response Mode

The derivation for analysis of stiffener response disregards the axial loading in the stiffener, which is low for as long as the panel remains in the elastic range, and before large membrane forces develop. The beneficial effects of counting a portion of the attached panels which deform with the stiffener have also been neglected.

The plastic moments at the center are assumed to reach the capacity of the stiffener, $(f_y)(Z)$, but only 50% of capacity at the corners, since the stiffener is not completely fixed at the corners. This assumption is agreeable with the available test results. A calculation based on yield line theory leads to the following formula for the critical pressure (q) which causes duct stiffener buckling:

$$q = \frac{18(f_y)(Z)}{(a)^3(\alpha)}; \quad \text{where} \qquad \text{Eq. (13)}$$

$$\alpha = -\frac{a}{c} + \left[3+\left(\frac{a}{c}\right)^2\right]^{1/2};..\text{for}...a \le c;$$

and

$$q = \frac{36(f_y)(Z)}{(a)^2(c)\left(3-\left(\frac{c\alpha}{a}\right)^2\right)}; \qquad \text{Eq. (14)}$$

$$\alpha = -\frac{c}{a} + \left[3+\left(\frac{c}{a}\right)^2\right]^{1/2};..\text{for}..a > c;$$

3.3 Duct Beam Mode Response

The duct beam mode ultimate strength capacities based on the assumed four corners effective cross section are:

$$F_{ux} = 256(t)^2(fy); \; M_{uy} = 128(t)^2(b)(fy); \; M_{uz} = 128(t)^2(a)(fy);$$

$$M_{ux} = 0.183\left(\frac{t}{c}\right)(ab)(a+b)(fy), \; V_{uy} = 0.183\left(\frac{t}{c}\right)(b)^2(fy)$$

$$V_{uz} = 0.183\left(\frac{t}{c}\right)(a)^2(fy)$$

4 CORRELATION WITH TESTS

Two sources of test data on the ultimate pressure capacity for rectangular ducts are available (Bechtel 1974a, 1976b). Comparison with the ultimate pressure loads obtained analytically in Section 3 show good agreement considering the following variability:

(1) The measured thickness of the test panel deviated by up to 10% from the specified thickness.

(2) The panels were assumed initially flat, while some of the test panels were initially deflected inward or outward up to 1/4".

(3) Non-uniform membrane stress distribution existed in the test panels.

(4) Some of the test frames exhibited premature failure due to failure of the corner welds before the center plastic hinges were developed.

4.1 Sheet Response Mode

The analytically predicted lower bound value of the duct ultimate pressure for the sheet failure mode from Eq. (11) was lower than the actual measured ultimate pressures for all available duct tests. The measured ultimate pressures have a mean or average value of (q_s) about 25% above the analytically predicted lower bound pressure from Eq. (11). The largest deviations from the average value was +25% and -15%.

The tests indicated that yielding occurs along the panel edges only and not at the center of the panels, which is in agreement with the analysis. Interior yielding was not observed in any of the tests where strain data were recorded. The center region of the panel sheets exhibited almost pure membrane behavior. The HVAC duct ultimate pressure were proportional to the duct sheet thickness as predicted by the calculation.

4.2 Stiffener Response Mode

The test ultimate pressures for ducts which failed by stiffener buckling ranged from 90% and 111% of the pressures (q_F) calculated by the method described in Section 3.

The assumed distribution of panel pressure reactions is conservative considering that the panels remain elastic during stiffener bending.

In some of the tests, the stiffener frame corner welds failed when only 50 to 60% of full plastic frame corner bending capacity had been reached. The calculation assumed frame corner capacity at 50% of full capacity.

4.3 Beam Mode Response

This mode was not observed at any of the tests.

5 PROPOSED DUCT ANALYSIS METHOD

The duct system should be designed and analyzed for all applicable load cases and their corresponding allowables.

The following linear interaction equations should be satisfied for the load case at the section being considered, using applicable factor of safety (F.S.):

$$\frac{Fx}{Fux} + \frac{My}{Muy} + \frac{Mz}{Muz} + \frac{Mx}{Mux} + \frac{Vy}{Vuy} + \frac{Vz}{Vuz} + \frac{P}{q_S} \leq \frac{1}{(F.S)}; \qquad \text{Eq. (15)}$$

$$\frac{P}{q_F} \leq \frac{1}{(F.S)} \qquad \text{Eq. (16)}$$

For duct sheet and stiffener respectively.

6 CONCLUSIONS

Based on the results of two independent HVAC duct test series reported herein and the new analytical methods proposed in this paper which closely predict the test results, the following conclusions may be made:

(1) A relaxation of the limitations imposed by the AISI code on HVAC duct design is warranted

(2) The new analytical method as proposed herein involving simple formulae for sizing rectangular HVAC duct sheet panels and stiffener frames are suitable for an optimum and cost-effective design of the ducts and stiffeners with equal or consistent safety factors against the ultimate capacity governed by either the duct sheet corner crippling mode or the stiffener frame buckling mode.

7 REFERENCES

Bechtel Power Corporation, 1974a, "Reactor Building Cool Air Supply Ducts, Testing and Evaluation," for Arkanasas Power & Light Co., Arkansas Nuclear One, Unit 1.

Bechtel Power Corporation, 1976b, "Report on Testing of HVAC Duct Specimens for the Philadelphia Electric Co., Limerick Generating Station, Units 1 and 2," Vols. 1 and 2, BPC, San Francisco, CA.

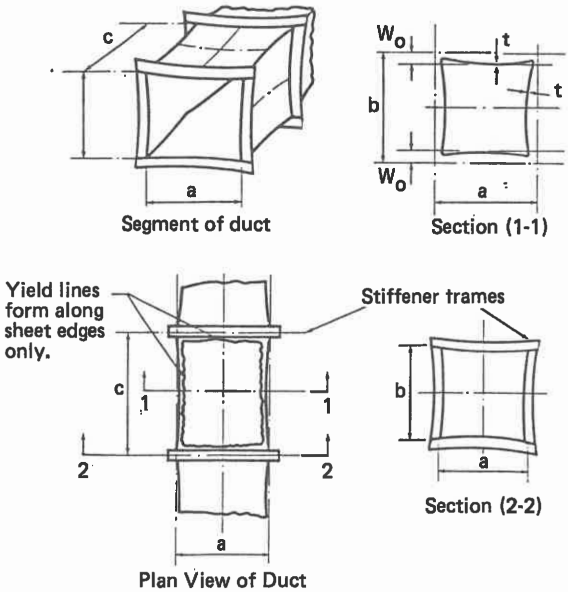

Figure 1 Response in the Duct Panel Sheet Corner Crippling Mode

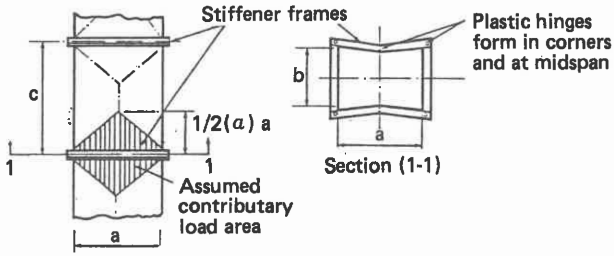

Figure 2 Response in the Duct Stiffener Frame Buckling Mode

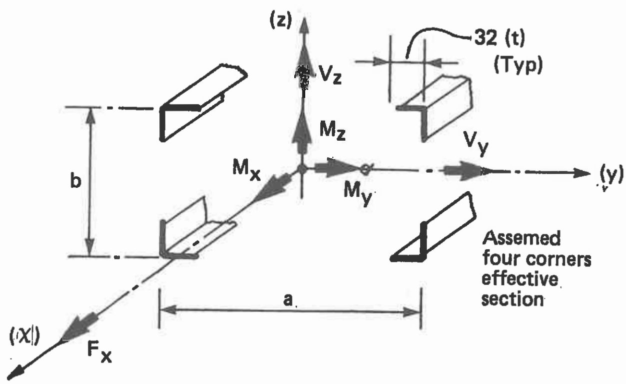

Figure 3 Duct Beam Mode Response

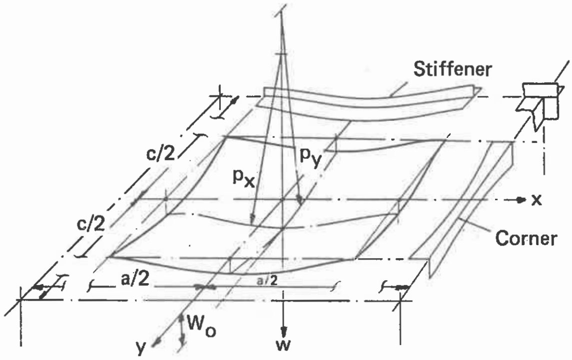

Figure 4 Deflected Shape of Duct Panel Sheet