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Collapse Strength of Casing Subjected to Combined Load

Triaxial evaluation of wellbore loads is used extensively for casing and tubing string design and analysis. A triaxial based collapse strength method was recently adopted by the American Petroleum Institute (API), and an addendum issued to API Technical Report 5C3 (TR 5C3). The triaxial based collapse formula incorporates internal pressure and axial load into the calculation of casing and tubing collapse strengths. Casing and tubing that are subjected to combined loads have higher collapse strength than previous formulas would predict, permitting the use of thinner walled, or lower strength, pipe than formerly required.

API provides methods of calculating the collapse strength of casing and tubing. The fundamental collapse strength calculations contained in TR 5C3 are based on collapse strength given zero internal pressure and zero axial load. The industry recognized that collapse strength is a function of the triaxial stress (axial, radial, and tangential, or hoop) acting on the pipe, and consequently incorporated the effect of axial stress on collapse strength approximately 75 years ago. Later, API added a formula to 5C3 for calculating the effect of internal pressure on the collapse strength. API has recently changed the method in TR 5C3 for calculating the collapse strength of casing and tubing in the presence of internal pressure.

The TR 5C3 formula previously used to calculate the collapse strength in the presence of an axial load, Formula 42, is accepted practice; however, the previous TR 5C3 method for calculating the effect of internal pressure on collapse, Formula 43, had been applied much less extensively for several reasons.

1. Formula 43 assumes that collapse strength (for given do/t) is solely a function of yield. Collapse strength calculated using the Plastic and Transition formulas in TR 5C3 is a function of both the yield strength and elastic instability. Formula 43, based solely on yield strength, is therefore not accurate.
2. Collapse strength calculated using the Elastic formula in TR 5C3 is a function of elastic instability only. It is independent of yield strength and, again, Formula 43 is not accurate.
3. Formula 43 is based on uniform stress across the wall, producing increased error for thicker wall pipe. Application of Formula 43 to collapse strength that is calculated using the Yield formula in TR 5C3 is also not accurate.

An alternate, more accurate method of incorporating the triaxial effect of internal pressure on collapse strength has been adopted by API and incorporated into TR 5C3.

Triaxial Effects of Collapse

To accurately determine the simultaneous effects of axial stress and internal pressure on collapse strength, Formula 42 in TR 5C3 was recently modified. In addition, having a separate formula for calculating the effect of internal pressure became unnecessary, and Formula 43 was deleted. The new Formula 42 simultaneously accounts for the influences of axial stress and internal pressure on collapse strength. Formula 42 is re-written to produce the single triaxial based collapse strength formula:

$$f_{ycom} = \left\{\left[1 - 0.75\left((\sigma_a + p_i)/f_{ymn}\right)^2\right]^{1/2} - 0.5(\sigma_a + p_i)/f_{ymn}\right\} f_{ymn}$$

The combined loading equivalent grade is the equivalent yield strength in the presence of axial stress and internal pressure. The formula is developed from the Hencky-von Mises distortion energy theory of yield, disregarding the assumption that the internal pressure is zero. The single Formula 42 simultaneously accounts for collapse strength under axial stress and the effect of internal pressure. Note that one psi of internal pressure has the same impact on collapse strength as one psi of axial tension.

The graphical representation of the collapse strength of the triaxial performance envelope, in quadrants 3 and 4, is achieved by changing the axial load axis from applied load, a biaxial based performance envelope, to the applied load plus the product of the internal pressure and the pipe body cross-sectional area, a triaxial based performance envelope, as shown in Figure 1. The y-axis is the collapse strength under combined load - the differential pressure, $p_i - p_o$.

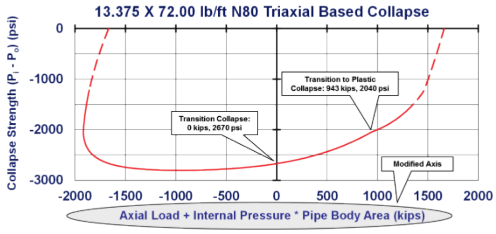

Figure 1: Quadrants 3 and 4 of triaxial performance envelope for 13-3/8 in. 72.00 lbf/ft N80.

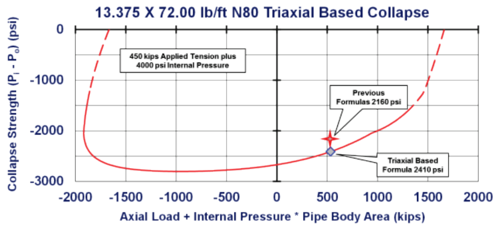

Figure 2: Collapse strength comparison of previous method and triaxial based collapse.

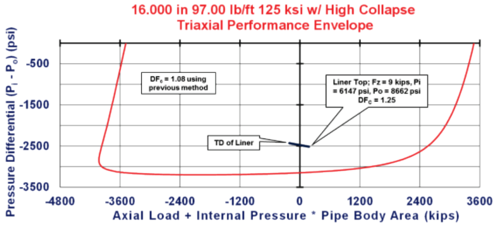

Figure 3: Triaxial based collapse with liner loads superimposed on the triaxial performance envelope.

Collapse Strength of Casing Subjected to Combined Load

Example 1

For 13-3/8 in., 72.00 lbf/ft N80 (body yield strength equals 1,661 kips) casing with an applied load of 450 kips tension, plus internal pressure of 4,000 psi, we can calculate the reduced collapse strength. From the previous TR 5C3 Formulas 42 and 43, the collapse strength at 450 kips is calculated first:

$$f_{yax} = \left\{\left[1 - 0.75\left(\frac{450}{1661}\right)^2\right]^{\frac{1}{2}} - 0.5 * \frac{450}{1661}\right\}80$$
$$= 66.9\ ksi$$

and the collapse strength (P_c) reduced for 450 kips tension is 2,470 psi. The effect of internal pressure is then calculated:

$$p_{ci} = 2470 + \left(1 - 2 * \frac{0.514}{13.375}\right)4000$$
$$= 6163\ psi$$

The differential pressure (collapse strength) available is:

$$\Delta p = 6163 - 4000 = 2163\ psi\ (2160\ psi)$$

The 4,000 psi internal pressure reduces the collapse strength at 450 kips tension from 2,470 psi to 2,160 psi, a 13% reduction. Using the new triaxial based collapse strength method (stress and pressure in ksi and load in kips):

$$f_{ycom} = \left\{\left[1 - 0.75\left(\frac{\left(\frac{450}{20.768} + 4.000\right)}{80}\right)^2\right]^{\frac{1}{2}} - \frac{0.5\left(\frac{450}{20.768} + 4.000\right)}{80}\right\}80$$
$$= 64.0\ psi$$

Calculating the collapse strength for 13-3/8 in. 72.00 lbf/ft casing with a yield strength of 64.0 ksi produces a value of 2,410 psi. The 4,000 psi internal pressure reduces the collapse strength at 450 kips tension from 2,470 psi to 2,410 psi, a less than 3% reduction, using the new formula. The difference in collapse strengths between the previous method and the triaxial collapse method recently adopted is depicted in Figure 2.

Example 2

Wells drilled in deep water frequently use large diameter liners with deep setting depths. One such 16 in., 97.00 lbf/ft (0.575 in. specified wall thickness) 125 ksi drilling liner with high collapse strength was set with the liner hanger at 11,500 ft and the bottom of the string at 17,000 ft. The most severe collapse load case showed the string could be subjected to external pressure of 8,662 psi and 6,147 psi internal pressure at the top of the liner. The applied axial load at the liner top was calculated to be 9 kips tension at a temperature of 100°F.

The collapse design factor is first determined using the previous formulas. The collapse strength at 9 kips tension is 3,150 psi, which is the manufacturer's collapse strength for the 16 in. casing. The effect of internal pressure is then calculated:

$$p_{ci} = 3150 + \left(1 - 2 * \frac{0.575}{16}\right) * 6147$$
$$= 8855\ psi$$

The collapse strength, p_o - p_i, available is:

$$\Delta p = 8855 - 6147 = 2708\ psi$$

And the design factor in collapse is:

$$DF_c = 2710/2515 = 1.08$$

Using the new formula for determining the effect of internal pressure on collapse strength, the combined loading equivalent grade is calculated:

$$f_{ycom} = \left\{\left[1 - 0.75\left((9/27.84 + 6.147)/125\right)^2\right]^{1/2} - 0.5(9/27.84 + 6.147)/125\right\}125$$
$$= 121.6\ psi$$

Using Annex F of TR 5C3 to calculate the collapse strength at 121.6 ksi, and increasing the strength by the ratio of the manufacturer's high collapse rating of 3,150 psi to the Annex F value, the collapse strength at 121.6 ksi is 3,140 psi and the design factor for collapse is 1.25, which is 16% higher than calculated using the previous formulas.

Wellbore loads on the string can be superimposed on the pipe body performance plot to provide a graphical method of evaluating loads. Loads are commonly generated using commercially available software.

At strategic depths, the internal pressure, external pressure, axial load, and temperature are calculated for the selected load cases. Figure 3 shows quadrants 3 and 4 of the triaxial-based performance envelope for the pipe body with the loads on the liner superimposed on the plot. For loads in quadrants 3 and 4, the external pressure differential is plotted on the Y-axis, and the axial load, plus the product of internal pressure and pipe body area, are plotted on the X-axis for each depth. The plot permits the load, including the presence of internal pressure, for collapse loads at any depth to be evaluated relative to the pipe body performance.

Conclusions

The effect of internal pressure on collapse strength has been incorporated into the previous biaxial-based, collapse strength formula to create a triaxial-based, collapse strength formula using the relationship of axial load, internal pressure, and external pressure. Using this new formula for casing and tubing, permits the use of thinner walled, or lower strength, pipe than formerly required.

Wellbore loads can be incorporated into a graphical method for triaxial evaluation.

Nomenclature

DF_c	design factor in collapse
d_o	specified outside diameter (OD) L, inches
f_{yax}	the equivalent yield strength for collapse, m/Lt², psi
f_{ycom}	the combined loading equivalent grade, m/Lt², psi
f_{ymn}	the specified minimum yield strength, m/Lt², psi
p_c	collapse strength, m/Lt², psi
p_{ci}	collapse strength in the presence of internal pressure, m/Lt², psi
p_i	internal pressure, m/Lt², psi
p_o	external pressure, m/Lt², psi
t	specified wall thickness, L, inches
σ_a	axial stress excluding bending, m/Lt², psi

References

1. API TR 5C3, Technical Report on Equations and Calculations for Casing, Tubing, and Line Pipe Used as Casing or Tubing; and Performance Properties Tables for Casing and Tubing, First Edition, December 2008, Washington, DC, API.

2. Addendum. October 2015. ANSI/API Technical Report 5C3/ISO 10400:2007, Technical Report on Equations and Calculations for Casing, Tubing, and Line Pipe Used as Casing or Tubing; and Performance Properties Tables for Casing and Tubing, Washington, DC, API.