Span Limits for Elevated Temperature Piping

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Pipe deflection due to self-weight quite often governs in the determination of the spacing between supports. Methods are readily available for calculation of elastic deflection of the pipe. However, such methods are not available for calculation of long-term deflection due to creep, which can be many times the initial elastic deflection for pipe operating in the creep regime of the material. Closed-form solutions for simple span conditions are presented which can be used by the analyst to develop charts for specific applications. These solutions provide insights into the problem of establishing span limits for elevated temperature pipe. [S0094-9930(00)01101-X]

Introduction

While pipe deflection is not limited by ASME B31.1 or B31.3, it quite often governs support spacing of pipe. While the pipe may be strong enough to span between supports, excessive sag is generally considered undesirable for several reasons, including the fact that personnel tend to lose confidence in the design of piping exhibiting large deflection. A general rule of thumb in design of process piping is to limit the deflection to 1/2 in. (13 mm).

While calculating the deflection of piping that behaves elastically is relatively trivial, determining the deflection of pipe operating well into the creep regime for the material of construction poses problems for the designer. Span tables, piping stress analysis programs, and generally available design methods only consider the elastic deflection of pipe. While creep deflection, over time, can be dramatically more than the initial elastic deflection, simplified methods to determine the development of the pipe sag over time are not available. Various approaches have been considered, such as limiting the allowable sustained longitudinal stress at elevated temperatures to something less than the code allowable stress. Note that this is essential to prevent excessive creep deflection at very high temperatures.

In developing the design basis for stainless steel pipe to operate at temperatures up to 1800°F (980°C) for the Marble Hill Nuclear Reactor Pressure Vessel Annealing Demonstration Project, it was apparent that accumulation of creep deflection required consideration in establishing the maximum permissible span between pipe supports. To establish these limits, closed-form integrals to calculate creep deflection of pipe spans were developed, which could readily be solved on available math software, such as MathCad. These integrals, and their derivation, are provided in the Appendix. They are based on a steady-state creep law, Norton, where creep strain rate is equal to a constant times stress to the power of n. The exponent n depends on material and temperature, but a value of about 6 can be expected for high-temperature austenitic stainless steel.

Creep Deflection Equations

Creep deflection under bending was calculated per Finnie and Heller [1] as follows. The same basic assumptions as in elastic beam analysis were made (e.g., shear deformation neglected, plane sections remain plane, and small displacement). It is also assumed that the creep rate in tension and compression, at the same stress level, is the same.

The Norton creep equation is assumed, as follows:

$$\varepsilon_c = B\sigma^n t \tag{1}$$

The stress in a beam section redistributes due to creep because of the sensitivity of creep rate to stress. The stress on the outer fiber of a beam under steady-state creep condition may be calculated as follows:

$$\sigma_{y1} = \frac{Mh}{2I_c} \tag{2}$$

The outer fiber strain in a beam is proportional to the radius of curvature, as follows:

$$\varepsilon_{y1} = \frac{y_1}{\rho} \tag{3}$$

Combining Eqs. (1), (2), and (3), results in the following equation:

$$\left[\frac{Mh}{2I_c}\right]^n = \frac{y_1}{\rho B t} \tag{4}$$

The inverse of the radius of curvature can be replaced with the second derivative of deflection, d^2y/dx^2. The resulting equation is integrated twice to calculate deflection, with appropriate inclusion of constants of integration and due consideration to changes in direction of curvature.

Equations are provided in the Appendix for three conditions: simply supported beam, cantilever beam, and beam with fixed ends.

Discussion

The evaluations provided insights into the problem of establishing allowable spans for high-temperature piping. One very interesting finding at very high temperatures was that the allowable span was relatively insensitive to the allowable deflection and the constant B in the creep equation, within reasonable limits. It is the sensitivity of creep rate to stress, and, in turn, the sensitivity of stress to span length, that dominates the creep deflection problem. Considering that stress is proportional to the span length to the second power, and assuming that creep strain rate is proportional to stress to, say, the sixth power, knowing that deflection is proportional to strain, we find that creep deflection rate is highly sensitive to span length.

Creep deflection goes up exponentially with span length, so that beyond a given length, at least at relatively high temperatures, deflection is unacceptable, and below that length, deflection is not particularly significant. Figure 1 shows the creep deflection of a simply supported Schedule 10S 304L stainless steel line, assuming 30 lb/ft. (44 kg/m) steel and insulation weight with vapor as the contents, as a function of length at 1500°F (815°C) and for a duration of 1000 h. One can see that, between span lengths of 17

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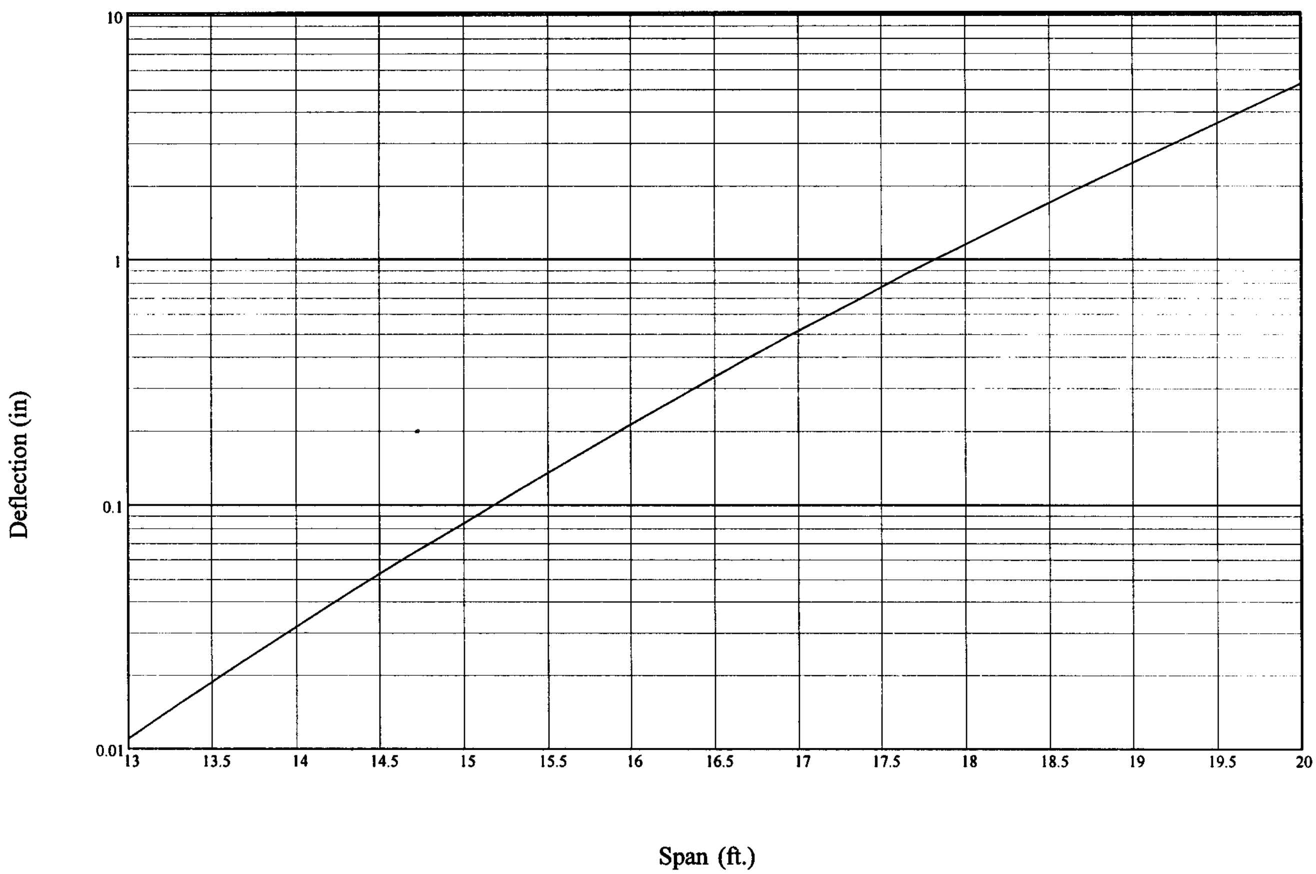

Fig. 1 Creep deflection of simply supported beam at 1000 h versus span (1500°F)

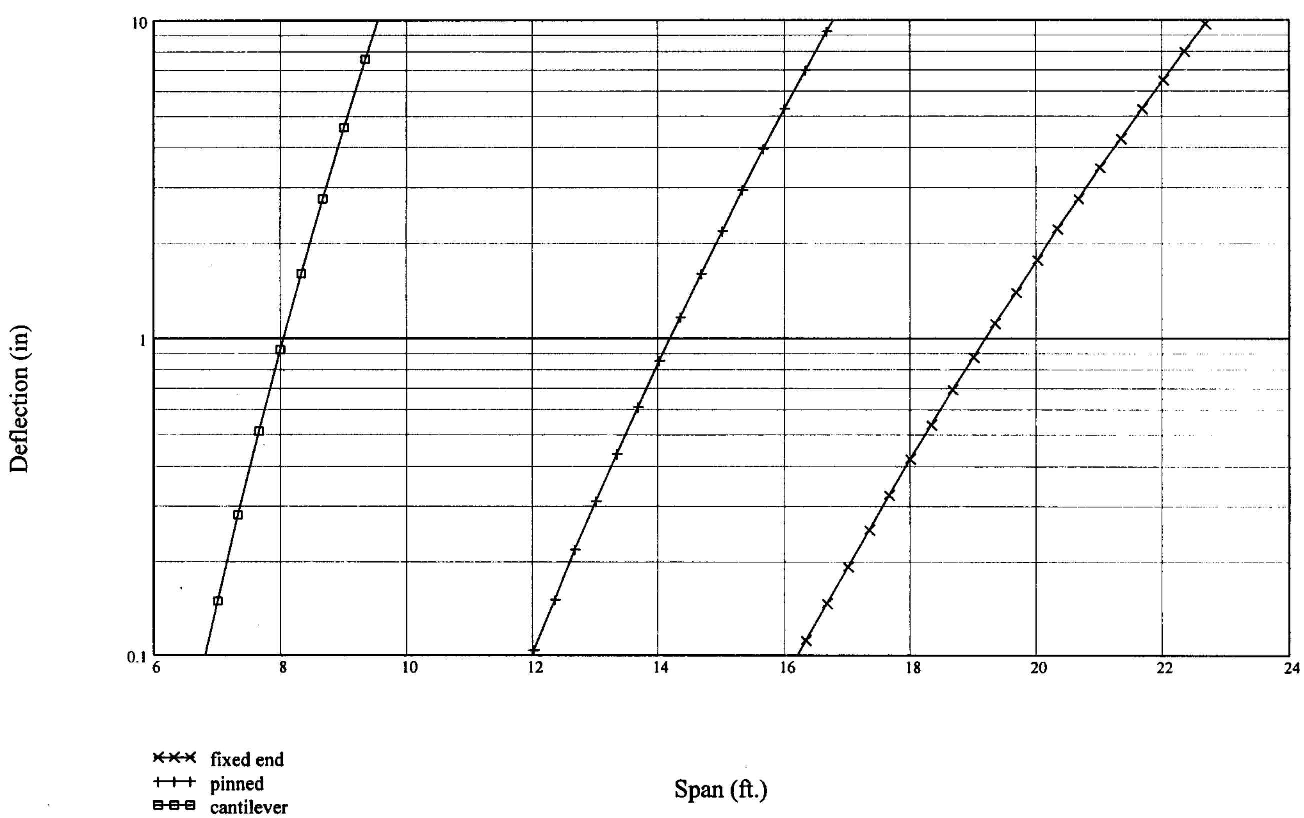

Fig. 2 Creep deflection versus span length at 1000 h for different restraint conditions (1600°F)

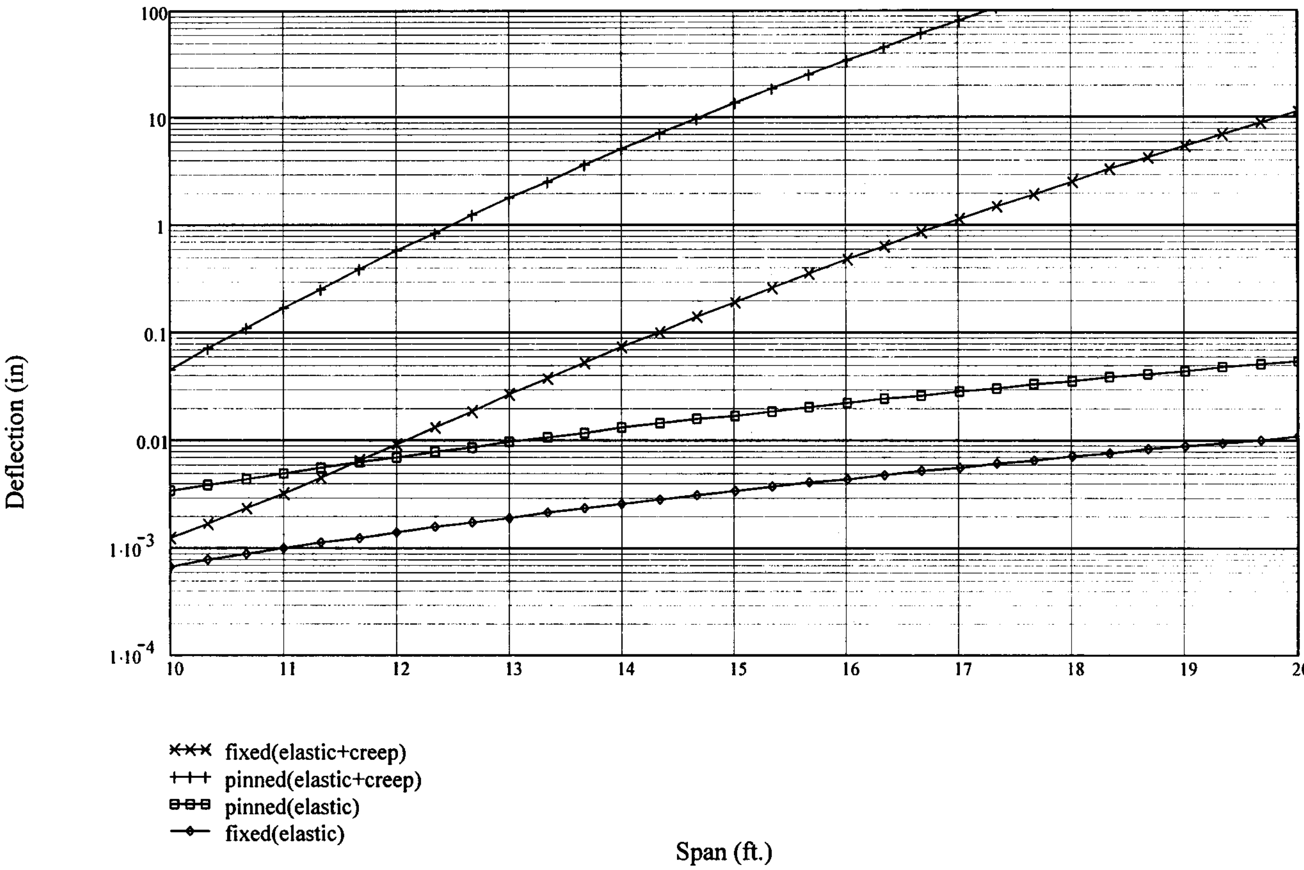

Fig. 3 Comparison of creep and elastic deflection of beams at 100,000 h versus span length for pinned and fixed restraint (1500°F)

and 18 ft (5.2 and 5.5 m), the deflection increases from 1/2 in. (13 mm) to over 1 in. (25 mm). At 16 ft (4.9 m), the deflection is about 0.2 in. (5 mm). Material properties for 304L are from Swindeman [2,3].

Figure 2 shows deflection as a function of span length, temperature, and end restraint condition. These curves are based on 304L material. The duration for the charts is 1000 h and the temperature is 1600°F (870°C). They are for a specific application; they are provided to illustrate the effect of span length and support condition on deflection. The project for which this work was done used dual stamped material, so that the L-grade material properties were appropriate to evaluate the elevated temperature material properties of the material.

Figure 3 shows a chart for 304L Schedule 20S pipe with 20 lb/ft (29 kg/m) insulation and a duration of 100,000 h, about 10 yr, for elastic and creep deflection as well as for elastic deflection only. Included on the chart are results based on simply supported and fixed supports. Note that the allowable span length based on allowable stress considerations only, per ASME B31.3, is about 16 ft (4.9 m) for simply supported and 23 ft (7 m) for fixed supports. The allowable span length, based on 1/2 in. (13 mm) permissible **elastic deflection** and a simply supported condition, would be 31 ft (9.4 m). It is obvious that these span lengths based on these conventional criteria would result in excessive long-term deflection for this elevated temperature pipe.

Conclusion

Creep deflection must be considered in determining allowable span lengths for elevated temperature piping. Equations are provided herein with which span tables can be developed for specific applications.

Nomenclature

B = constant in creep equation
h = outside diameter of pipe
I = moment of inertia of pipe
I_c = fictitious moment of inertia used to calculate outer fiber stress for creeping beam
K = constant
L = beam length
M = bending moment
n = stress exponent in creep equation
r_o = outside radius of pipe
r_i = inside radius of pipe
t = time
w = weight of pipe and contents per unit length
x = dimension along beam length
y = beam deflection
y'_0 = end slope of deflected beam
y_1 = extreme fiber distance from neutral axis
y_f = beam deflection at inflection point
y'_f = slope of deflection at inflection point
ε_c = creep strain
ε_{y1} = outer fiber strain
Γ = gamma function
ρ = radius of curvature of beam
σ = stress
σ_{y1} = outer fiber stress in beam

Appendix

The equations for calculating creep deflection of pipe, based on simply supported, cantilever, and fixed-end conditions, follow:

$$I_c = I \cdot \frac{8}{\left(3+\frac{1}{n}\right)\cdot\sqrt{\pi}} \cdot \frac{1-\left(\frac{r_i}{r_o}\right)^{3+1/n}}{1-\left(\frac{r_i}{r_o}\right)^4} \cdot \frac{\Gamma\left(1+\frac{1}{2\cdot n}\right)}{\Gamma\left(1.5+\frac{1}{2\cdot n}\right)}$$

(from Finnie and Heller [1] for hollow cylinder)

$$K = \frac{2\cdot B\cdot t}{h}\cdot\left(\frac{h}{2\cdot I_c}\right)^n\cdot\left(\frac{w}{2}\right)^n$$

Simply Supported

- slope at support

$$y_0' = K\cdot\int_0^{L/2}|(L\cdot x - x^2)^n|dx$$

$$y = \int_0^{L/2}\left[y_0' + K\cdot\int_0^x|(X\cdot L - X^2)^n|dX\right]dx$$

Cantilever

- end slope

$$y_0' = K\cdot\int_0^L (x^2)^n dx$$

- closed-form solution

$$y = \frac{2\cdot B\cdot t}{h}\cdot\left(\frac{h}{2\cdot I_c}\right)^n\cdot\left[\frac{w\cdot L^2}{2}\right]^n\cdot\frac{L^2}{2\cdot(n+1)}$$

Fix End Beam

- slope at inflection point

$$y_f' = -K\cdot\int_0^s|[6\cdot L\cdot x - L^2 - 6\cdot x^2]^n|dx$$

- deflection at inflection point

$$y_f' = \int_0^s\left[y_f' - K\cdot\int_0^x|[6\cdot L\cdot X - L^2 - 6\cdot X^2]^n|dX\right]dx$$

- deflection at midspan

$$y = y_f + \int_s^{L/2}\left[y_f' - K\cdot\int_s^x|(6\cdot L\cdot X - L^2 - 6\cdot X^2)^n|dX\right]dx$$

References

[1] Finnie, I., and Heller, W. R., 1959, *Creep of Engineering Materials*, McGraw-Hill, New York, NY.

[2] Swindeman, R. W., 1995, ''Compilation of Materials Data Base for Very High Temperature,'' PVRC 94-07, 1/18/95 draft report.

[3] Swindeman, R. W., 1996, personal communication with Dr. Swindeman; additional plots from reference database.