AGENDA ITEM 650-1095

TITLE	Wind Girder Update
DATE	May 27, 2021
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PURPOSE	To update 650's approach for sizing wind girders
SOURCE	API 650-1074, Wind Update
REVISION	1
EFFECT	This item modernizes API 650's wind girder requirements and makes them rational and consistent.
RATIONALE	API 650's requirements for sizing wind girders have been pieced together over time without a holistic approach, leading to inconsistencies.
PROPOSAL	Make the changes shown below.

DISCUSSION:

1. Introduction

API 650 addresses two types of wind girders: top wind girders and intermediate wind girders. Their treatment in 650 is summarized in Table 1.

Table 1 Wind Girders in API 650

wind girder type	650 section	limit states checked	diameter *D* used for checks	tank types	participating shell length
top	5.9.5	flexural yielding (5.9.5.3)	if $D < 200'$ use *D*; if $D \geq 200'$ use 200' for *D*	open top	$16t$ (5.9.5.5)
		compression buckling (5.9.5.4)	only check if $D > 200$ ft		
intermediate	5.9.6	flexural yielding (5.9.6.6)	all	open top closed top	$0.424(Dt)^{1/2}$ (5.9.6.6.2)

Table 1 reveals several issues:

1) For the top girder, the 650 flexural yielding check is a function of diameter squared, but if the tank diameter exceeds 200 ft, 650 allows the top girder to be sized for a tank diameter of 200 ft. If the top girder flexural yielding equation of 650 is correct, then for a 300 ft diameter tank the top girder should be $(300/200)^2 = 2.25$ times larger than what 650 requires. Conversely, 650 requires that the intermediate girder size be based on the actual diameter of the tank, regardless of whether the diameter exceeds 200 ft.
2) 650 requires a buckling check on the top girder, but no buckling check on the intermediate girder.
3) The length of the shell considered to be part of the wind girder for intermediate girders differs from that for top girders.
4) By limiting the participating shell length, 650 includes a safeguard against local buckling for the shell component of wind girders, but not of any other components of wind girders.

5) 650 limits the yield strength used in its wind girder size requirement to 30 ksi regardless of the actual yield strength of the wind girder material. This is inconsistent with 650's approach to other tank components such as the shell.
6) 650 conservatively limits the extreme fiber stress in wind girders to the yield stress, using the elastic section modulus rather than the plastic section modulus of the wind girder.

These issues are more significant for large diameter tanks and tall tanks. Because such tanks are becoming more common, these issues are becoming more important.

The possible combinations of tank top (open or with a fixed roof) and intermediate wind girder (with or without) and their estimated frequency of occurrence in the US for tanks 50 ft diameter and greater are listed in Table 2.

Table 2 Tank Top and Intermediate Wind Girder Configurations

	intermediate wind girder	
fixed roof?	yes	no
yes	fixed roof and intermediate wind girder 5%	fixed roof and no intermediate wind girder 35%
no	open top, intermediate wind girder, and top wind girder 10%	open top and top wind girder 50%

This suggests that intermediate wind girders are relatively rare, totaling only 15% of all tanks, and top wind girders are frequent, used in 60% of all tanks. Wind girders (top, intermediate, or both) are used in 75% of all tanks, making them an important tank design consideration.

2. Wind Girder Loading

Background for agenda item 650-1074 provided detailed information on wind loads on tanks, and that information is used to determine the forces acting on wind girders in the discussion below.

MacDonald (1988) provided the wind pressure distribution for tanks with a height to diameter ratio H/D = 0.5, typical of a 100 ft diameter tank, as shown in Figure 1 and summarized in Table 3. Positive pressure acts inward on the shell, and negative pressure acts outward.

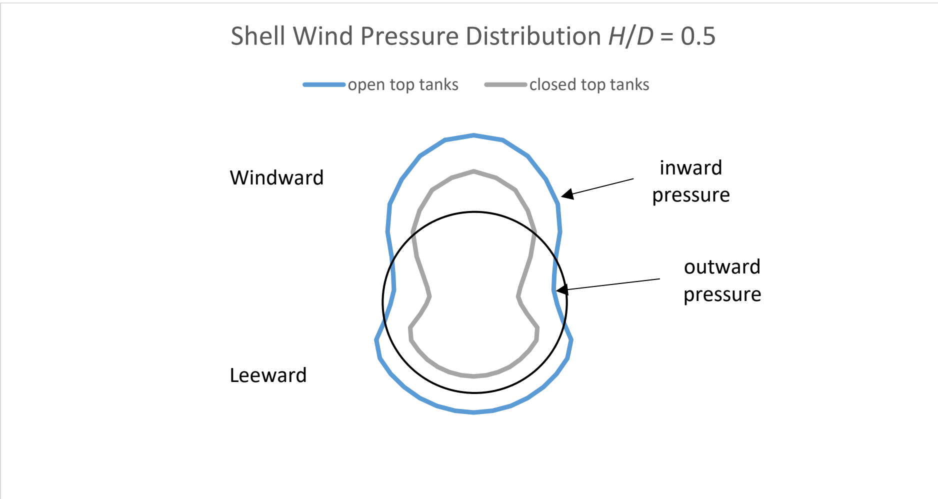

Figure 1 Plan View of Tank Shell Wind Pressure Coefficient C_p for Open and Closed Top Tanks

Table 3 Maximum External Shell Wind Pressure Coefficients, *H*/*D* = 0.5

tank top	external pressure coefficient C_p					
	windward	90° to wind	leeward	average radial	net horizontal	average on 15° windward
open	1.75	– 0.2	0.4	0.51	0.56	1.5
closed	1.0	– 1.0	– 0.4	– 0.26	0.55	0.8

MacDonald also showed that the wind pressure distribution around the tank circumference depends on the tank's height-to-diameter ratio *H*/*D*. As this ratio decreases (as the tank diameter increases, *H*/*D* decreases because tank height is typically about 50 ft for all tank diameters), the ovalizing effect of the wind decreases. This is because the outward suction of the wind at roughly 90° to the wind direction decreases in magnitude and extent as illustrated in Figure 2.

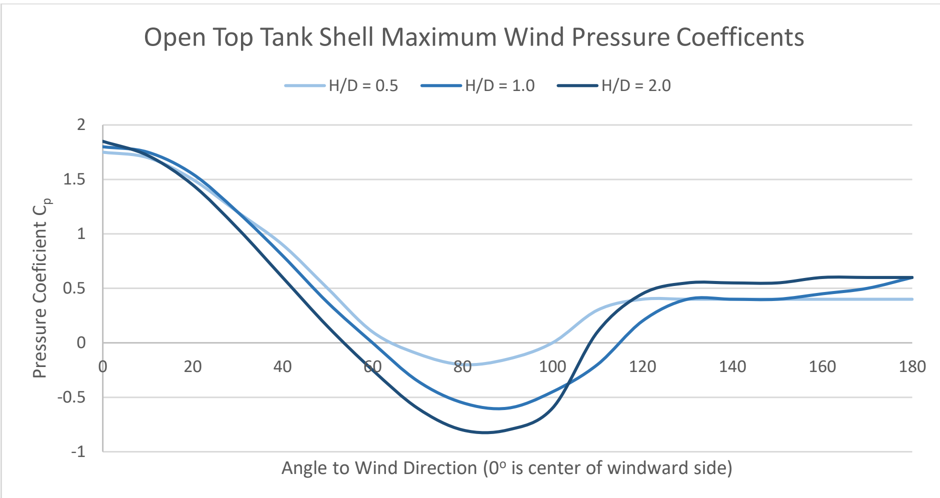

Figure 2 Open Top Shell Wind Pressure Related to *H/D*

Typical open top API 650 tanks have *H/D* ratios that vary from approximately 1 (a 50 ft diameter 48 ft tall tank) to 0.2 (a 300 ft diameter 48 ft tall tank). A 200 ft diameter 48 ft tall tank has *H/D* = 0.24, which is less than the smallest *H/D* ratio investigated by MacDonald. Although MacDonald did not investigate tanks with *H/D* ratios less than 0.5, his data suggest that as the *H/D* ratio decreases, the extent and magnitude of the suction portion of the shell perpendicular to the wind decrease. Decreased suction produces decreased ovalizing effect and decreased flexure in the wind girder. Regardless of the *H/D* ratio, however, the windward and leeward wind pressure coefficients remain approximately the same at about 1.8 and 0.4 (both inward), respectively.

Wind pressure also varies over the tank height, as shown in Figure 3 based on MacDonald's study. The average wind pressure on the top ½ of the shell is approximately 93% of the maximum wind pressure.

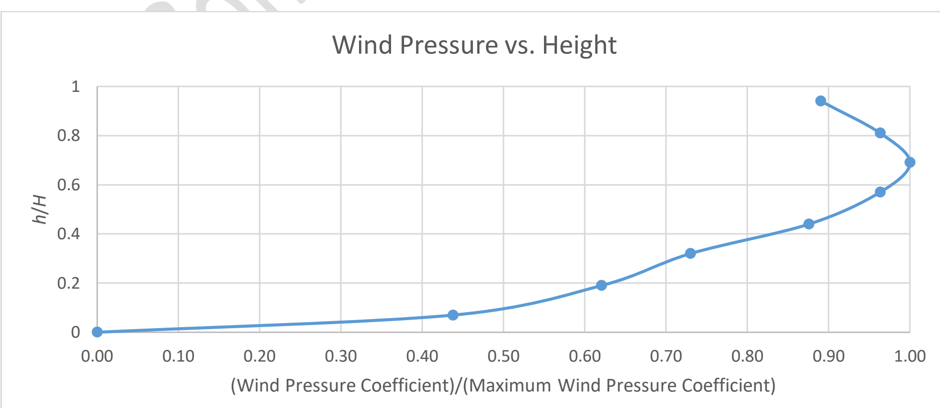

Figure 3 Wind Pressure vs Height on an Open Top Tank Shell

Agenda item 650-1074 updated API 650 to ASCE 7-16 giving a shell horizontal wind pressure P_{WS} of 11 psf for the 120 mph reference wind speed based on a drag force coefficient C_f of 0.65. The drag force coefficient from MacDonald's results in Table 3 is 0.56 at the shell elevation where the wind pressure was a maximum. Over the top half of the tank, the average pressure was 93% of the maximum. Therefore, the average pressure on the top half of the shell is 80% of P_{WS} (= 0.56(0.93)/0.65)). Given the conservative determination of the shell wind pressure, using the average shell pressure to determine the wind girder forces is reasonable.

Wind, because it acts as a pressure, acts perpendicular to the tank shell. Therefore, wind girders are ring beams with transverse distributed loads. These distributed loads can cause moments, shears, and axial forces in the girders.

3. Wind Girder Forces

Moments, shears, and axial forces in a circular ring can be determined by combining cases that have been solved using Castigliano's second theorem. Many such cases are tabulated in Roark's Table 17. Agenda item 650-1063 used this approach, combining Roark case 8 for a uniform lateral pressure and case 20 for tangential shear as shown in Figure 4:

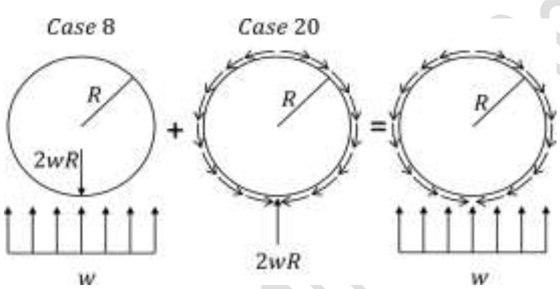

Figure 4 Forces in a Circular Ring from Uniform Load

The resulting maximum moment M in the wind girder due to a uniform horizontal distributed load w over the tank diameter D is

$$M = 0.14wR^2$$

Figure 5 shows the moment in the ring using this method for a 100 ft diameter, 48 ft tall tank with 11 psf shell wind pressure.

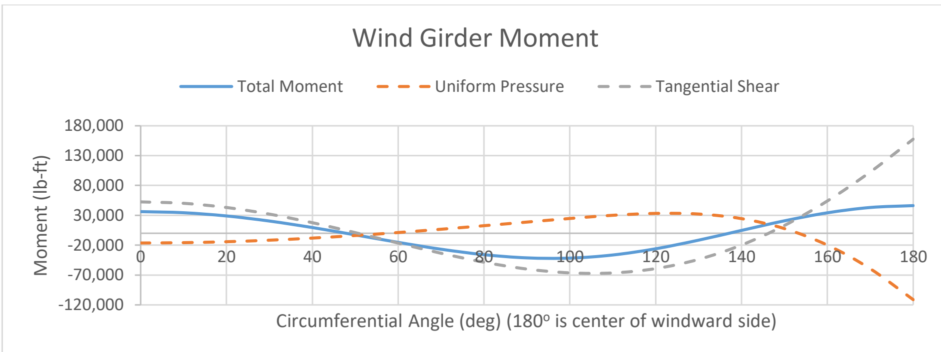

Figure 5 Moment in a Circular Ring from a Uniform Projected Wind Pressure

The moment thus calculated varies in sign around the circumference as shown in Figure 5, causing compression at the outside of the wind girder in some points on the circumference (approximately the portion 40° to either side of the wind direction on the windward side and 40° to either side of the wind direction on the leeward side) and tension at the outside of the wind girder in the areas around 90° to the wind direction.

Tank shells are typically constructed of 8 ft tall courses of decreasing thickness toward the top of the shell. The shell of open top tanks is stiffened against buckling from wind pressure at its top by the top wind girder and at its bottom by the tank bottom. The wind girder supports the shell against buckling in the top half of the transformed shell's height and the bottom supports the shell against buckling in the bottom half of the transformed shell's height. The transformed shell height H_{tr} given in 5.9.6.2 is the height of a shell with the minimum shell thickness t_{min} that has the same buckling strength as the actual shell:

$$H_{tr} = \sum W_{tr} = \sum_{i=1} W_i \left(\frac{t_{\min}}{t_i} \right)^{2.5}$$

shell buckling is resisted by:

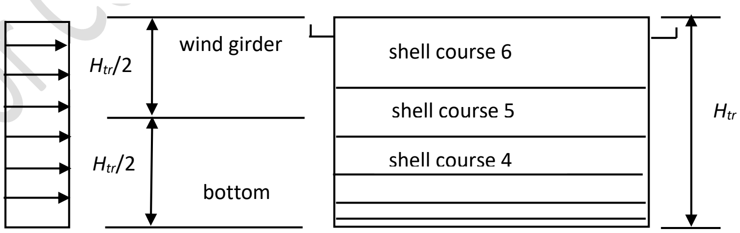

Figure 6 Shell Buckling Resistance Over the Shell Height

The transformed shell height is always less than the actual shell height since the transformed height of shell courses thicker than the minimum shell thickness is less than their actual height. For example, for a 200 ft diameter 48 ft tall tank designed for a product specific gravity of 0.8, the transformed shell height is 18.22 ft.

API 650 current provisions assume that the top ¼ of the actual shell height H equals ½ the transformed shell height, in which case $w = P_{WS}H/4$. Expressing the tank radius $R = D/2$, the moment acting on the wind girder is

$$M = 0.14wR^2 = 0.14(P_{WS}\,H/4)(D/2)^2 = 0.00877P_{WS}HD^2$$

This moment is used to determine the section modulus required by API 650 Section 5.9.5.3 by limiting the bending stress it causes (M/S) to the yield strength F_y of the wind girder. This estimate of the moment in the wind girder is approximate because it assumes that one half of the transformed shell equals one quarter of the actual shell height for all tanks. For a 200 ft diameter tank, one half of the transformed shell height is (18.22 ft)/2 = 9.11 ft, which is only 19% of the actual shell height rather than 25%.

The wind girder size that results from the current 650 requirement is within 14% of H. C. Boardman's estimate in an unpublished paper dated September 23, 1929. Boardman based his estimate on an inward pressure on 60^o of the windward side and an outward wind pressure on the rest of the shell. Boardman attempted to make a more accurate estimate of the wind distribution than a uniform pressure, proposing that $M = 0.01P_{WS}HD^2$ but noted that "This formula has not been derived …, but at least its form has been shown to be logical". Because the wind distribution Boardman used differs from more recent findings and the fact that he did not derive a formula but rather estimated one, the Boardman approach is quite approximate.

Using half of the transformed shell height instead of one quarter of the actual tank height to determine the tributary height of the shell supported by the wind girder, the maximum moment in the wind girder is

$$M = 0.14wR^2 = 0.14(P_{WS}\,H_{tr}/2)(D/2)^2 = 0.0175P_{WS}H_{tr}D^2$$

The required section modulus S with a safety factor of Ω and a yield strength of F_y is

$$S = M\Omega/F_y$$

Substituting the moment above

$$S = 0.0175P_{WS}H_{tr}D^2\Omega/F_y$$

The approximation that the wind girder supports the top ¼ of the shell height is reasonably accurate for tanks less than 200 ft in diameter, but overly conservative for tank diameters over 200 ft. For large tanks, the thickness of the lower shell courses is much greater than the minimum shell thickness, and the transformed shell height is small. By eliminating this approximation, the arbitrary rule that wind girders for tanks over 200 ft in diameter need not be larger than the wind girder size for a 200 ft diameter tank can be eliminated without requiring significantly larger wind girders. Figure 7 compares wind girders using the current and proposed rules.

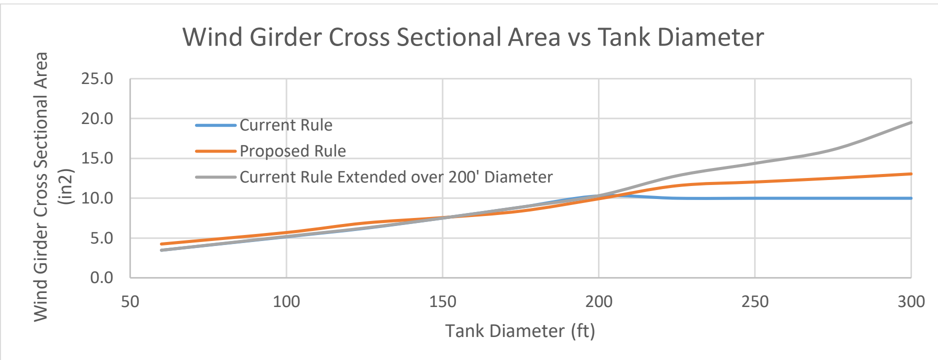

Figure 7 Wind Girder Size by Current and Proposed Rules

4. Limit States for Wind Girders

Axial compression in wind girders may cause global buckling, local buckling, or yielding. Flexure may cause yielding or local buckling but not lateral-torsional buckling because wind girders are continuously laterally braced by the shell. The limit states of axial compression global buckling, flexural yielding, and local buckling are addressed below.

4.1 Axial Compression

The buckling strength of a stiffened cylinder subjected to uniform external pressure is addressed in the SSRC Guide. Figure 11 compares the actual wind pressure distribution with a uniform inward pressure. For H/D = 0.5, the average inward pressure coefficient reported by MacDonald was 0.51, which is 81% of the 0.63 coefficient used to determine the shell pressure. For an 11 psf horizontal projected pressure, then, the average inward pressure is 9 psf. Conservatively overlooking this difference, let's use the SSRC buckling strength to check the accuracy of the current API 650 check on wind girder axial compression buckling.

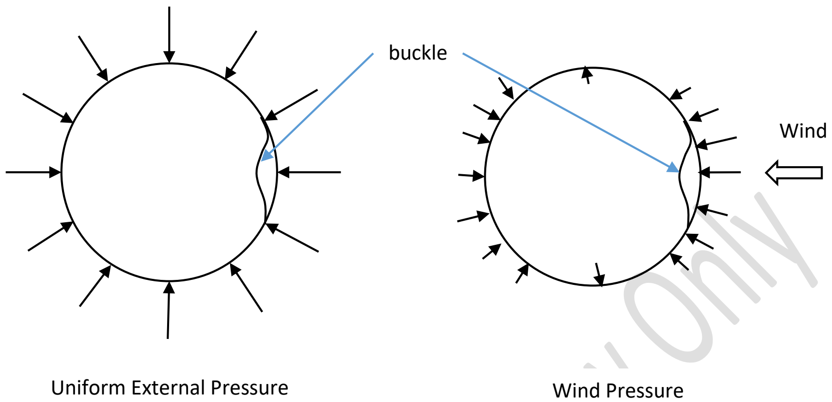

Figure 11 Pressure Distributions on a Tank Cross Section

For a ring-stiffened cylinder, the SSRC Guide Section 14.4.2 gives the uniform external pressure *P* over the circumference of the shell causing elastic buckling as

$$P = \frac{2E}{D/t}\frac{\lambda^4}{\left(n^2+(\lambda/2)^2-1\right)\left(n^2+\lambda^2\right)^2}+\frac{8EI\left(n^2-1\right)}{LD^3}$$

where
I = the moment of inertia of the ring stiffener
n = number of buckling lobes
L = distance between stiffeners
H = cylinder height
$\lambda = \pi D/(2H)$
D = cylinder diameter
t = cylinder thickness
E = modulus of elasticity

The first term is the contribution to the buckling strength from the shell, and the second term is the contribution to the buckling strength from the stiffener. The second term is also the Levy formula for buckling of a circular ring under uniform external pressure. The number of buckles *n* is determined iteratively as the one producing the smallest buckling pressure.

In 650's 12th edition, a buckling check was added for top wind girders in Section 5.9.5.4. This check applied the net horizontal wind pressure as a uniform inward pressure on the shell, ignored the shell contribution to the ring strength, and postulated only two buckling lobes (*n* = 2), the most conservative approach. For *H* and *D* in ft, the 5.9.5.4 check thus results:

$$\Omega P = \frac{8EI\left(n^2-1\right)}{HD^3} = \frac{8EI\left(2^2-1\right)}{HD^3} = \frac{24EI}{HD^3}$$

$$I = \frac{\Omega PHD^3}{24E} = \frac{(1.6)(11\ \text{lb}/\text{ft}^2)HD^3}{24(E\ \text{lb}/\text{in}^2)}(144\ \text{in}^2/\text{ft}^2) = \frac{106HD^3}{E}$$

Table 4 provides the accurate buckling strength for wind girders sized for the yield limit state currently in 650 Section 5.9.5.1. It shows that the wind girder size required by 650 for the yield limit state is much greater than that required for buckling. For example, for an open top 50 ft diameter tank, the buckling pressure is 792 psf, over 70 times greater than the wind shell pressure of 11 psf for a design wind speed of 120 mph. For a 300 ft diameter tank, the buckling pressure is 1320 psf, or 120 times the wind shell pressure. Even assuming the peak pressure for open top tanks acts around the shell's entire circumference, giving a wind pressure of 1.75/0.51 = 3.4 times the average inward pressure, wind girders sized for the limit state of yielding will not buckle. Therefore, a wind girder buckling check is unnecessary, and this ballot proposes to remove this check from 650.

Table 4 Buckling Strength of Ring-Stiffened Cylindrical Shells Subjected to Uniform External Pressure

tank diameter	D	ft	50	100	150	200	300
shell height	H	ft	48	48	48	48	48
minimum shell thickness	t_{min}	in.	0.250	0.250	0.312	0.312	0.375
shell thickness assumed	t	in.	0.250	0.250	0.312	0.312	0.375
number of buckles	n	-	7	8	10	11	14
distance from shell to wind girder centroid	c	in.	4.0	9.0	16.0	20.0	20.0
API 650 wind girder section modulus	S	in^3	12	48	108	192	192
wind girder moment of inertia = Sc	I	in^4	48	432	1728	3840	3840
shell pressure resistance	p_s	lb/ft^2	189	523	492	525	389
shell portion of pressure resistance	p_s/P	-	0.24	0.36	0.22	0.21	0.29
ring pressure resistance	p_r	lb/ft^2	602	914	1,701	1,933	931
ring portion of pressure resistance	p_r/P	-	0.76	0.64	0.78	0.79	0.71
total pressure resistance	P	lb/ft^2	792	1,437	2,193	2,458	1,320

4.2 Flexure
The Roark approach detailed in Section 3 above shows that the wind girder experiences much greater stresses from flexure than from axial force. The strength of flexural members is the least of the strengths for lateral-torsional buckling (LTB), yielding, and local buckling. Because the shell is assumed to provide a continuous lateral brace to the wind girder, LTB needs no further consideration. Yielding and local buckling are considered below.

4.2.1 Yielding
API 650 currently sets the flexural strength M of the wind girder as $S_{min} F_y$, where S_{min} is the minimum elastic modulus of the wind girder about its vertical neutral axis and F_y is the yield stress. The AISC *Specification for Structural Steel Buildings* Section F12 prescribes this approach for the yield strength of unsymmetric shapes other than angles but notes this "can be overly conservative".

The yield strength can be as great as ZF_y, where Z is the plastic section modulus, since the flexural strength is not reached until all material on both sides of the neutral axis has yielded, rather than only the extreme fiber. For the wind girder shapes in API 650 Figure 5-24, Z/S ranges from 1.14 to 1.80, and for detail e, the formed plate, Z/S is about 1.3. To avoid yielding at service loads, the strength increase above initial yield is usually limited to 1.5 or 1.6. To be conservative for cases where the wind girder is unsymmetric about its plastic axis, this ballot proposes to use the elastic section modulus S rather than the plastic section modulus Z to determine the flexural yield strength of the wind girder.

Using the equation for the moment in the wind girder, the required section modulus S is

$$S = \Omega M/F_y = 0.0175\Omega P_{WS}H_{tr}D^2/F_y$$

The wind girder's required section modulus was first expressed as a function of variables other than the tank height and diameter in 650's 12th edition. To get the same wind girder section moduli as before, the yield strength used to determine the wind girder size was limited to 30 ksi. Today, the typical yield strength for mild carbon steel is 50 ksi. Limiting strength of components to an arbitrary number is inconsistent with 650's approach for other tank components such as the shell. For 36 ksi yield strength steel, for example, it introduces a conservatism of 20%. Therefore, this ballot proposes to use the actual yield strength of the wind girder material to determine the wind girder's yield strength.

4.2.2 Local Buckling

Local buckling strength is a function of the slenderness (b/t ratio) of the wind girder elements. API 650 only addresses local buckling of the shell (by limiting the shell's contribution to the wind girder to 16t, which is approximately $0.56\sqrt{\left(\frac{E}{F_y}\right)}$, roughly in the middle of AISC's non-compact range for I-shape beam flanges). The length of the shell that API 650 includes on each side of a stiffener (in 5.9.7.6.2, adjusted for consistent units) is $0.424(Dt)^{.5}$ for intermediate wind girders, Annex V tank stiffeners for external pressure, and tank top compression rings for internal pressure, but 16t only for top wind girders for open top tanks. The SSRC *Guide* Section 14.4.2 gives the participating length of the shell as $0.55(Dt)^{.5}$, because the parameter θ is greater than 2 for API 650 tanks. API 650 is inconsistent and conservative, especially on large diameter tanks, because the 16t rule neglects the effect of tank diameter. Therefore, this ballot proposes to change the shell contribution below the wind girder from 16t to $0.424(Dt)^{0.5}$.

API 650 does not address the local buckling strength of other elements of wind girders, which can be unconservative. Therefore, this ballot addresses local buckling by limiting the slenderness of:

a) Webs stiffened at both edges to $5.7(E/F_y)^{0.5}$, which is 163 for F_y = 36 ksi. This is the AISC *Specification* Table B4.1b case 19 limit on web slenderness for rectangular tubes, above which the strength of the section must be reduced below $F_y S$. The largest web slenderness currently shown in API Table 5-24 detail e is 40"/0.25" = 160, so typical details shown in 650 have not violated the proposed limit of 163.
b) Flanges stiffened on one edge to $1.0(E/F_y)^{0.5}$, which is 29 for F_y = 36 ksi. This is the AISC *Specification* Table B4.1b case 10 non-compact to slender limit on flanges of I-shapes, channels, and tees. A limit of 29t on the effective length of the shell acting with the stiffener is about twice the current 650 top wind girder limit of 16t.

c) Webs stiffened on one edge to $1.52(E/F_y)^{0.5}$, which is 43*t* for F_y = 36 ksi. This is the AISC *Specification* Table B4.1b case 14 non-compact to slender limit on stems of tees in flexure.

5. Intermediate Wind Girders

Currently, API 650's required section modulus for the intermediate wind girder uses the same expression as for the top wind girder but uses the shell height above the intermediate wind girder rather than the full shell height in the required section modulus expression. This approach is inaccurate because it neglects the demand placed on the intermediate wind girder due to the tributary area of the shell below the intermediate wind girder.

Intermediate wind girders support the shell against buckling over a portion of the transformed shell height. Because the intermediate wind girder might not be located at the mid-height of the transformed shell, this ballot expresses the required section modulus of the intermediate wind girder as:

$$S = 0.0175 \Omega P_{WS} (H_{tra} + H_{trb}) D^2 / F_y$$

where

H_{tra} = transformed height of the shell between the intermediate wind girder and the next wind girder above or for fixed roof tanks, the top of the shell

H_{trb} = transformed height of the shell between the intermediate wind girder and the next wind girder below or the tank bottom

This expression of the required section modulus allows for the rare case of multiple intermediate wind girders.

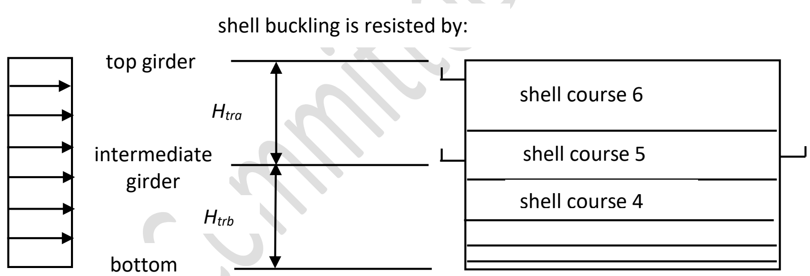

Figure 8 Tank with an Intermediate Wind Girder

6. Example

Diameter 60 ft
Shell Height 48 ft; 6 – 8 ft tall courses
ASCE 7-10 wind velocity 150 mph

In the API 650 13th edition, if ASCE 7-10 has a wind speed of 150 mph for the site, 5.2.1.k gives the design wind speed as *V* = (0.78)150 = 117 mph and the shell wind pressure is

P_{ws} = (18.6 psf)(117/120)^2 = 17.7 psf

In the ballot, the wind speed comes from the ASCE 7-16 wind speed map, which is essentially the same as the ASCE 7-10 wind map, so the design wind speed is 150 mph and the shell wind pressure is

$P_{ws} = P_{WSR}\ (V/V_r)^2$ = (11 psf)(150/120)^2 = 17.2 psf

These shell pressures are the same except for the difference introduced by round off.

The shell thickness for the fluid load, assuming F_y = 30,000 psi, F_u = 55,000 psi, and G = 0.8, gives the first shell course thickness t_1 = 0.326" and the second shell course thickness t_2 = 0.270", and all other courses t = 0.25". This results in a transformed shell height of 42.7 ft.

The maximum unstiffened transformed shell height using the 13th edition is

$H_1 = 600{,}000t(t/D)^{1.5}\ (36/P_{wd})$
$P_{wd} = 31(117/120)^2 + 5 = 34.5$ psf
$H_1 = 600{,}000(0.25)(0.25/60)^{1.5}(36/34.5) = 42.1$ ft

The maximum unstiffened transformed shell height using the ballot is

$H_{trmax} = 2.1Et^{2.5}/[1.6P_{ws}D^{1.5}] = 2.1(29{,}000{,}000)0.25^{2.5}/[1.6(17.2)(720)^{1.5}](12\text{ in/ft}) = 43.0$ ft

These maximum unstiffened transformed shell heights computed by the 13th edition and the ballot are the same; the only difference is introduced by roundoff in the coefficients in the equations such as 600,000.

Because the maximum height of the transformed shell (43.0 ft) is greater than the transformed shell height (42.7 ft), no intermediate wind girder is needed.

The wind girder required section modulus by the 13th edition is

$S = 1.5H\,D^2/[0.5F_y]\ (P_{wd}/36) = 1.5(40)60^2/[0.5(30{,}000)]\ (34.5/36) = 13.8\text{ in}^3$

The wind girder's required section modulus by the ballot is

$S = 0.0175H_{tr}\Omega\ P_{ws}D^2/F_y = 0.0175(34.7)17.2(1.6)60^2/30{,}000(12\text{ in/ft}) = 24.1\text{ in}^3$

The wind girder section modulus required by the ballot is more than that required by the 13th edition. However, the actual additional cost is relatively small. In this case, the 13th edition requires Figure 5.24 Detail d with 2 – 4 x 3 x 3/8 angles with a total cross sectional area of 5.0 in^2 and total weight of (5.0)60(12)π(0.283) = 3180 lb. The ballot requires 2 – 6 x 4 x 3/8 angles with a total cross sectional area of 7.2 in^2 and total weight of (3.6)60(12)π(0.283) = 4620 lb. The additional cost is about $720. If 36 ksi yield strength steel were used, the difference would be less, and is less as the diameter increases.

References

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3. American Petroleum Institute (2020), API Standard 650, *Welded Tanks for Oil Storage*, 13th ed., API, Washington, DC.
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5. MacDonald, P.A., et al (1988), Wind Loads on Circular Storage Bins, Silos and Tanks: I. Point Pressure Measurements on Isolated Structures, *Journal of Wind Engineering and Industrial Aerodynamics*, Amsterdam.
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PROPOSED CHANGES *Note: existing text below reflects changes passed in agenda item 650-1074*

5.9 Top and Intermediate Stiffening Rings (Wind Girders)

5.9.1 General *(unchanged)*

5.9.2 Maximum Height of Unstiffened Shells

The maximum transformed height H_{trmax} of unstiffened shells between stiffening rings, tank bottom, or fixed roof is

$$H_{trmax} = \frac{2.1Et^{2.5}}{P_{WS}\Omega D^{1.5}}$$

where

E is the modulus of elasticity of the shell at the maximum design temperature (see Tables M.1a and M.1b)

t is the nominal thickness of the thinnest shell course in the portion of the unstiffened shell under consideration without corrosion allowance (unless noted otherwise on the Data Sheet, Line 9)

P_{WS} is the shell design wind pressure (see 5.2.1[k])

Ω is the safety factor = 1.6

D is the nominal tank diameter

NOTE 1 This formula is for tanks with open tops or closed tops and is based on R. V. McGrath's "Stability of API Standard 650 Tank Shells" for the buckling strength of the shell[21] with a 0.8 factor to account for tank out-of-roundness. The uniform external buckling pressure is

$$p = 2.1E\left(\frac{t}{D}\right)^{2.5}\left(\frac{D}{H}\right)$$

The transformed height of unstiffened shell between stiffening rings, tank bottom, or fixed roof shall not exceed H_{trmax} and is

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$$H_{tr} = \sum_{i=1} W_i \left(\frac{t_{unif}}{t_i} \right)^{2.5}$$

where, for the portion of the unstiffened shell for which the transformed height is being determined

W_i is the actual width of each shell course
t_{unif} is the nominal thickness of the thinnest shell course
t_i is the nominal thickness of each shell course

5.9.2 Types of Stiffening Rings *move to 5.9.3.1*

5.9.3 Restrictions on Stiffening Rings

5.9.2 3.1 Types of Stiffening Rings
Stiffening rings may be made of structural sections, formed plate sections, sections built up by welding, or combinations of such types of sections assembled by welding. The outer periphery of stiffening rings may be circular or polygonal (see Figure 5.24).

5.9.3.2 Minimum Size *use text from 5.9.3.1*

5.9.3.3 Drainage *use text from 5.9.3.2*

5.9.3.4 Weld Locations *use text from 5.9.3.3*

5.9.4 Supports for Stiffening Rings *(unchanged)*

5.9.5 Top Wind Girders

5.9.5.1 Location *(text unchanged)*

5.9.5.2 Top Angle *(text unchanged)*

5.9.5.3 Section Modulus
The section modulus *S* of the top wind girder shall equal or exceed:

$$S = \frac{0.00877 P_{WS} \Omega H D^2}{F_y} \quad S = \frac{0.0175 P_{WS} \Omega H_{tr} D^2}{F_y}$$

where
P_{WS} is the shell design wind pressure (see 5.2.1[k])
Ω is the safety factor = 1.6
D is the nominal tank diameter (for tanks in excess of 61 m (200 ft) diameter, the diameter shall be considered to be 61 m (200 ft) when determining the section modulus);
H_{tr} is the transformed height of the tank shell between the top of the tank and the bottom of the tank, or, if an intermediate wind girder is present, the first intermediate wind girder below the top of the tank (see 5.9.6.2)
F_y is the lesser of the minimum yield strength of the shell and wind girder at the maximum design temperature or 210 MPa (30 ksi), whichever is less.

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5.9.5.4 Slenderness Limits

The slenderness (width-to-thickness ratio) of the elements of wind girders shall not exceed the following limits, where E is the modulus of elasticity of the element and F_y is the yield strength, each at the maximum design temperature.

For elements in flexure (webs) stiffened at both edges, $5.70(E/F_y)^{0.5}$

For elements in flexure (webs) stiffened at one edge, $1.52(E/F_y)^{0.5}$

For elements in compression (flanges), $1.0(E/F_y)^{0.5}$

~~For tanks larger than 61 m (200 ft) in diameter, an additional check for the minimum required moment of inertia for the top stiffening ring shall be performed. The required minimum moment of inertia of the stiffening ring shall be determined by the following equations:~~

~~In SI units:~~

$$I = 3583\ H_2\ D^3\ (V/190)^2\ /E$$

~~where~~
~~I is the required minimum moment of inertia (cm^4);~~
~~D is the nominal diameter of the tank, in meters (m);~~
~~H_2 is the height of the tank shell (m), including any freeboard provided above the maximum filling height as a guide for a floating roof;~~
~~E is the modulus of elasticity (MPa) at maximum design temperature;~~
~~V is the design wind speed (3-sec gust) (km/h) (see 5.2.1[k]).~~

~~In USC units:~~

$$I = 108\ H_2\ D^3\ (V/120)^2\ /E$$

~~where~~
~~I is the required minimum moment of inertia (in.^{4});~~
~~D is the nominal diameter of the tank, in meters (ft);~~
~~H_2 is the height of the tank shell (ft), including any freeboard provided above the maximum filling height as a guide for a floating roof,~~
~~E is the modulus of elasticity (psi) at maximum design temperature;~~
~~V is the design wind speed (3-sec gust) (mph) (see 5.2.1[k]).~~

5.9.5.5 Shell Contribution

The section modulus of the wind girder shall include the stiffening ring and a portion of the tank shell within a distance of
a) $0.424(Dt)^{0.5}$ below the point of attachment of the stiffening ring to the shell, and
b) $0.56t(E/F_y)^{1/2}$ above the point of attachment of the stiffening ring to the shell, where F_y is the minimum specified yield strength of the shell, E is the modulus of elasticity of the shell, each at the maximum design temperature, and t is the as-built shell thickness (see Figure 5.24)

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The section modulus of the stiffening ring shall be based on the properties of the applied members and may include a portion of the tank shell for a distance of 16*t* below and, if applicable, above the shell-ring attachment where *t* is the as-built shell thickness, unless otherwise specified. When curb angles are attached to the top edge of the shell ring by butt-welding, this distance shall be reduced by the width of the vertical leg of the angle (see Figure 5.24 and Table 5.a19 and Table 5.19b).

Table 5.19a—Section Moduli (cm^3) of Stiffening-Ring Sections on Tank Shells (SI)

Table 5.19b—Section Moduli ($in.^3$) of Stiffening-Ring Sections on Tank Shells (USC)

5.9.5.6 Top Wind Girders as Walkways *(unchanged)*

5.9.5.7 Stair Openings *(text unchanged)*

5.9.6 Intermediate Wind Girders

5.9.6.1 The maximum height H_{max} of the unstiffened shell shall be determined as:

$$H_{max} = \frac{2.1Et^{2.5}}{P_{WS}\Omega D^{1.5}}$$

where
E is the modulus of elasticity of the shell at the maximum design temperature (see Tables M.1a and M.1b)
t is the nominal thickness of the thinnest shell course without corrosion allowance (unless noted otherwise on the Data Sheet, Line 9)
P_{WS} is the shell design wind pressure (see 5.2.1[k])
Ω is the safety factor = 1.6
D is the nominal tank diameter

NOTE 1 This formula is for tanks with open tops or closed tops and is based on R. V. McGrath's "Stability of API Standard 650 Tank Shells" for the buckling strength of the shell[21] with a 0.8 factor to account for tank out-of-roundness. The uniform external buckling pressure is

$$p = 2.1E\left(\frac{t}{D}\right)^{2.5}\left(\frac{D}{H}\right)$$

5.9.6.2 After the maximum height of the unstiffened shell, H_1, has been determined, the height of the transformed shell shall be calculated as follows:

a) With the following equation, change the actual width of each shell course into a transposed width of each shell course having the top shell thickness:

where
W_{tr} is the transposed width of each shell course, in millimeters (inches);

~~W is the actual width of each shell course, in millimeters (inches);~~

~~$t_{uniform}$ is the nominal thickness, unless otherwise specified, of the thinnest shell course, in millimeters (inches);~~

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~~t_{actual} is the nominal thickness, unless otherwise specified, of the shell course for which the transposed width is being calculated, in millimeters (inches).~~

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~~b) Add the transposed widths of the courses. The sum of the transposed widths of the courses will give the height of the transformed shell.~~

~~**5.9.6.3** If the height of the transformed shell is greater than the maximum height H_{max}, an intermediate wind girder is required.~~

~~**5.9.6.3.1** For equal stability above and below the intermediate wind girder, the girder should be located at the mid- height of the transformed shell. The location of the girder on the actual shell should be at the same course and same relative position as the location of the girder on the transformed shell, using the thickness relationship in 5.9.6.2.~~

~~**5.9.6.3.2** Other locations for the girder may be used, provided the height of unstiffened shell on the transformed shell does not exceed H_1 (see 5.9.6.5).~~

~~**5.9.6.4** If half the height of the transformed shell exceeds the maximum height H_1, a second intermediate girder shall be used to reduce the height of unstiffened shell to a height less than the maximum.~~

5.9.6.~~5~~ 1 Location

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Intermediate wind girders shall not be attached to the shell within 150 mm (6 in.) of a horizontal joint of the shell. ~~When the preliminary location of a girder is within 150 mm (6 in.) of a horizontal joint, the girder shall preferably be located 150 mm (6 in.) below the joint; however, the maximum unstiffened shell height shall not be exceeded.~~

5.9.6.~~6~~ 2 Section Modulus

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The section modulus S_{wg} of an intermediate wind girder shall equal or exceed:

$$S_{wg} = \frac{0.00877 P_{WS} \Omega h_1 D^2}{F_y} \quad \frac{0.0175 P_{WS} \Omega (H_{tra} + H_{trb}) D^2}{F_y}$$

where

D	is the nominal tank diameter
P_{WS}	is the shell design wind pressure (see 5.2.1[k])
Ω	is the safety factor = 1.6
H_{tra}	is the transformed height of the shell between the intermediate stiffener and the next stiffener above it, or, for fixed roof tanks, the top of the shell (see 5.9.6.2)

~~h_1~~ H_{trb} ~~is the vertical distance between the intermediate wind girder and the top angle of the shell or the top wind girder of an open-top tank;~~is the transformed height of the shell between the intermediate stiffener and the tank bottom, or the next stiffener below it, whichever is less (see 5.9.6.2)

F_y is the lesser of the minimum yield strength of the shell and the intermediate wind girder at the maximum design temperature ~~or 210 MPa (30 ksi), whichever is less~~.

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The width-to-thickness ratio of the elements of the wind girder shall not exceed the limits given in 5.9.5.2. The participating portion of the shell shall include a length $0.424(Dt)^{0.5}$ above and below the point of attachment of the wind girder to the shell.

~~**5.9.6.6.1** Where the use of a transformed shell permits the intermediate wind girder to be located at a height that is less than H_{max} calculated by the formula in 5.9.6.1, the spacing to the mid-height of the transformed shell, transposed to the height of the actual shell, may be substituted for h_1 in the calculation for the minimum section modulus if the girder is attached at the transposed location.~~

~~**5.9.6.6.2** The section modulus of the intermediate wind girder shall be based on the properties of the attached members and may include a portion of the tank shell for a distance above and below the attachment to the shell, in mm (in.), of:~~

~~In SI units:~~

~~$13.4(Dt)^{0.5}$~~

~~where~~

~~D is the nominal tank diameter, in meters;~~

~~t is the nominal shell thickness, unless otherwise specified, at the attachment, in millimeters.~~

~~In USC units:~~

~~$1.47(Dt)^{0.5}$~~

~~where~~

~~D is the nominal tank diameter, in feet;~~

~~t is the nominal shell thickness, unless otherwise specified, at the attachment, in inches.~~

5.9.6.~~7~~3 Stair Openings

An opening for a stairway in an intermediate wind girder is unnecessary when the intermediate wind girder extends no more than 150 mm (6 in.) from the outside of the shell and the nominal stairway width is at least 710 mm (28 in.). For greater outward extensions of a wind girder, the stairway shall be increased in width to provide a minimum clearance of 450 mm (18 in.) between the outside of the wind girder and the handrail of the stairway, subject to the Purchaser's approval. If an opening is necessary, it may be designed in a manner similar to that specified in 5.9.5.~~5~~7 for a top wind girder with the exception that only a 560 mm (22 in.) width through the wind girder need be provided.