Recommended Improvements to C303 Bar-Wrapped, Steel Cylinder Concrete Pressure Pipe

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ABSTRACT

AWWA C303 Bar-Wrapped Steel Cylinder Concrete Pipe has been compared and classified as cement mortar lined and coated AWWA C200 steel pipe due to similar design methods, manufacture processes, pipe stiffness, and in corrosion protection offered by cement mortar linings and coatings. While there are similarities between the two pipe products, the nature of the traditional bar-wrapped pipe manufacturing process limits some of the desirable key features available with C200 steel pipe. Though it is not the common industry practice, bar-wrapped pipe cylinders can be produced with helical complete penetration butt welds per C303, resulting in a number of significant improvements that mirror a number of advantageous characteristics of C200 steel pipe.

Roll grooved gasket joint configurations for a 54” bar-wrapped pipe were analyzed by Finite Element Analysis (FEA) and were also full scale tested by the University of Texas at Arlington (UTA). This paper will focus on presenting recommended improvements in C303 pipe that have been verified through the UTA research and also offer insight into how these improvements can add considerable value to the C303 pipe material.

INTRODUCTION

Bar-Wrapped Concrete Cylinder Pipe (bar-wrapped pipe) is produced per AWWA C303 (AWWA 2008a) in sizes of 10-inch through 72-inch and is designed per the AWWA M9 Concrete Pressure Pipe Design Manual (AWWA 2008b). Bar-wrapped pipe is typically manufactured with a steel cylinder, ranging in thicknesses of 16 gage to 8 gage, depending on the pipe diameter, with a helical full penetration butt weld or offset lap weld from coil steel. Steel joint rings, Carnegie bells and spigots in thickness of 10 gage up to 5/8-inch, are then fillet welded to the cylinders. Steel bar reinforcement is wrapped helically around the cylinder to provide the total area of steel, A_s, required to resist internal hoop stress. In areas of thrust and fittings, thicker cylinders and or double welded joint rings are provided to

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handle additional longitudinal stresses. Restrained joint methods include ID full fillet welds of "trimmed" Carnegie spigots, OD fillet welds utilizing filler bars and skip welds, or harnessed joints – see Figure 9-24 and 9-25 in the AWWA M9 Manual (AWWA 2008b). The cylinder is lined and coated with ¾-inch of cement mortar over the metal surfaces for corrosion protection. Allowable pipe lengths range from 24-ft to 40ft, and vary based on a manufacturer's capability. Fittings are manufactured and welded into pipe sections or shipped loose.

Bar-Wrapped AWWA C303 pipe has been compared and classified as cement mortar lined and coated AWWA C200 steel pipe (AWWA 2005) due to similar design methods, manufacture processes, pipe stiffness, and corrosion protection offered by the cement mortar lining and coatings (Arnaout 2005). While there are similarities between the two steel products, the nature of bar-wrapped pipe manufacturing limits some of the key desirable features available with C200 steel pipe. This paper will focus on recommended improvements to C303 pipe and how these improvements can add considerable value to the C303 pipe material. Additionally, pipe joint research conducted by the University of Texas at Arlington that included finite element analysis with full scale testing of a modified bar-wrapped pipe joint, trade named S303™, that verified the recommended joint improvements, is also presented.

CYLINDER FABRICATION IMPROVEMENTS

AWWA C303 allows both full penetration helical butt welds and offset lap welds per ASME Code Section VIII Figure UW 13.1 as detailed in Figure 1a and 1b, respectively.

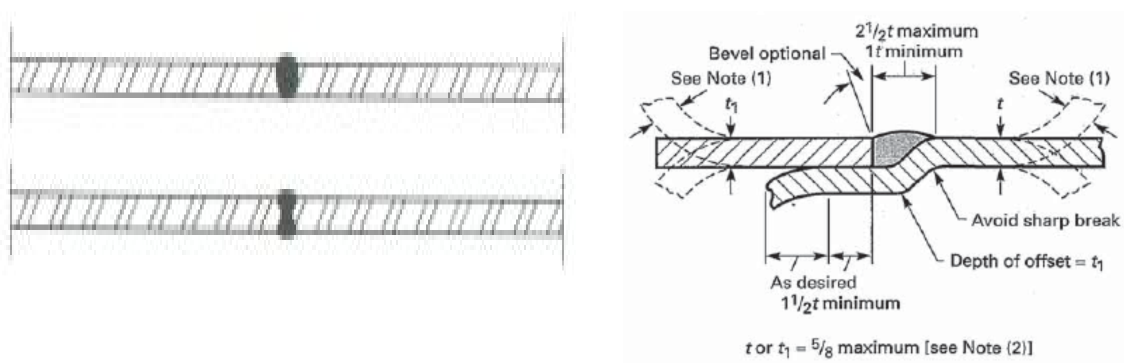


Figure 1a, b: Helical Butt Weld, Helical Offset Lap Weld (ASME 2007)

It is noteworthy that the "offset" component of the weld in Figure 1b results in a lower ASME joint efficiency of 0.65 instead of a 0.70 for a butt welded joint. From examination, the butt weld is a "stronger" joint capable of sustaining higher stress levels, with a higher factor of safety, in hoop, bending and tensile stresses. In addition, the offset lap weld does not allow for manufacture of a rolled groove joint, a widely specified gasket-joint for steel pipes of diameters of up to 78-inch. The two thickness of metal at the helical seams do not allow for a precise roll groove unless one thickness of metal is removed. This is one reason why Carnegie joint rings are the only real joint option for the offset lap welded cylinders. Butt welded cylinders can and are routinely roll grooved per AWWA C200. For these reasons, butt welded helical seams for bar-wrapped pipe cylinders are a recommended improvement.

<u>Hydrostatic Testing of the Cylinder</u>: AWWA C303 requires steel cylinders to be hydrostatically tested in the plant for water tightness (no leaks) of the helical pipe seam and joint ring welds. The test pressure is determined by Equation 1 and is variable depending on diameter and cylinder thickness.

$$P = \frac{2St}{D} = \frac{2(0.75 * s_y)t}{D} \qquad \textbf{Equation 1}$$

Where,

- P = minimum hydrostatic test pressure (psi)
- D = inside diameter of steel cylinder (in)
- S = pipe wall stress during test (psi), limited to 75% of specified minimum yield strength of steel which is 36,000 psi
- t = wall thickness (in)
- σ_y = specified minimum yield point of steel = 36,000 psi

It should be noted that test pressures are often less than project design pressures and are not a "proof of design" for the completed pipe structure as is provided with C200 steel pipe. However, thicker cylinders do require a higher test pressure providing a higher factor of safety as to the ability of the welded on joint rings and pipe cylinder welds to perform at design or transient pressures.

Table 1: Example Test Pressures for C303 Class 150 Cylinder Thickness Compared to Recommended Minimum 10 Gage Cylinder Thickness in S303 Class 150 Joint

Pipe Diameter (in)	C303 Cylinder		S303 Cylinder	
	Thickness (in)	Test Pressure (psi)	Thickness (in)	Test Pressure (psi)
24	0.075	158	0.135	288
36	0.090	130	0.135	193
48	0.105	115	0.135	147
72	0.164	121	0.184	135

JOINT IMPROVEMENTS

A key recommended improvement to AWWA C303 bar-wrapped pipe is the use of rolled groove gasket joint configuration in lieu of welded on joint rings. Joint rings depend on the essential welded connection between a relatively thin cylinder and a thicker joint ring, Figure 2. Welding of this joint ring is critical to the water tightness and service life of the bar-wrapped pipe itself. This is especially true if the joint will be field welded and/or harnessed to resist horizontal thrust. If a weld is made improperly but passes a hydrotest, there is the possibility that actual design pressure, transient events, pipe settlement causing bending or improper cylinder thickness by the laying of pipe out of sequence could be problematic. The use of a rolled groove gasket joint does not require welding to the cylinder and is integral to the pipe wall. The groove is precision rolled into the spigot end of the pipe by a controlled cold working method that has been used successfully since the 1960's (Rahman et. al 2011).

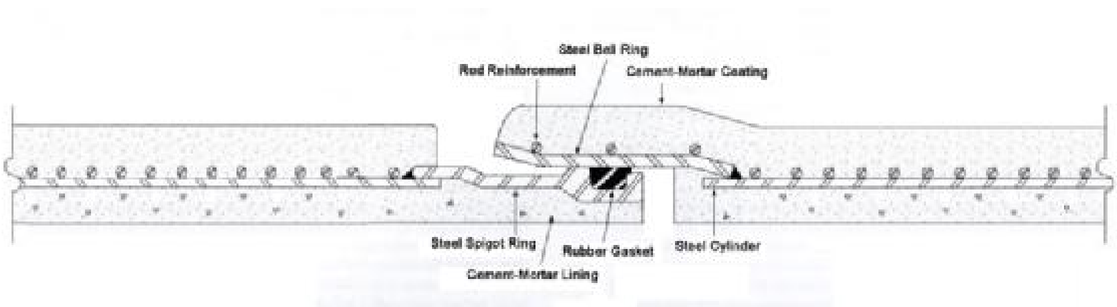


Figure 2: Cross-section of AWWA C303 Bar-wrapped Pipe Joint (not to scale)

The bell end of the pipe is swedged over a die for precise diameter control during the hydrostatic testing process. The AWWA C200 standard Section 4.13 is recommended for dimensions, quality control etc. as the rolled groove joint is not currently included in the C303 standard. The S303 joints are compatible with C303 joints and can be readily connected to both new and old C303 pipe. As stated previously, the offset lap weld of the helical seams does not allow the manufacture of a rolled groove and is a key reason this joint is not in C303. When combined with butt welded helical seams and a minimum 10 gage cylinder, the rolled groove joint is a proven non-restrained joint with a long history.

Since roll groove joints are not currently in the C303 and due to the fact that a section of the spigot can not be directly reinforced with bar, a research/testing program was initiated to verify the joint as acceptable for use on C303 bar-wrapped pipe. The rolled grooved joint will be referred to as the S303 joint and is detailed in Figure 3.

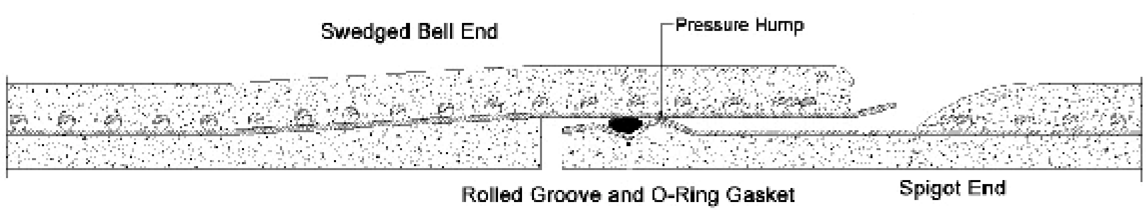


Figure 3: S303™ Rolled Groove Test Joint Profile (not to scale)

IMPROVED JOINT ANALYSIS AND TESTING

The University of Texas at Arlington was commissioned to verify the performance of the rolled groove joint on bar-wrapped pipe (UTA 2011). The goals of the research project as stated in the final research report follow:

"*As part of this validation process for the proposed improvements, two phases were carried out. First, a finite element model of the proposed configuration was developed to gain insight on the behavior of the proposed system. Second, a prototype of the spigot/bell assembly was fabricated and tested. The complete assembly, made of the bell and spigot sections, was tested to service pressure and* *subsequent failure in a hydrostatic tester in Northwest Pipe Company's Saginaw, Texas manufacturing facility."*

Finite Element analysis was performed by UTA to understand the behavior of the rolled groove spigot and bell of the S303 joint. Since an area between the bar reinforcement and the pressure hump, Figure 3, would be unreinforced, a model that predicted the influence of stiffness provided from the pressure hump and the bar wrap(s) was determined. An optimal stab depth and number of bar wraps on the spigot was determined by the FEA model. Figure 5 details the modeling of the cylinder and bar in both the spigot and bell ends. Figures 6a and 6b detail the anticipated Von Mises stresses at 150 psi and 225 psi, the working pressure and the transient pressure, respectively. To fully verify the model, full scale testing was necessary, and was performed by Principal Investigators Dr. Guillermo Ramirez, Ph.D., P.E., and Dr. Mohammed Najafi, Ph.D., P.E., both faculty members in the Dept. of Civil Engineering.

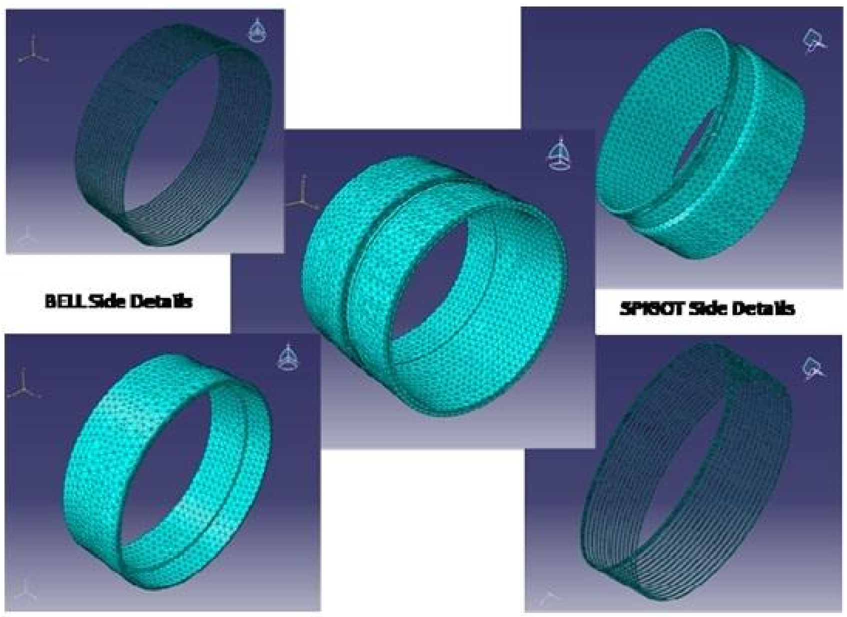
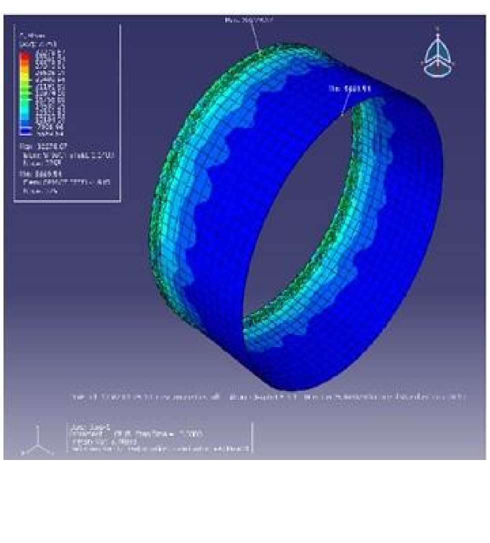


Figure 5: Finite Element Model Details for S303 Joint



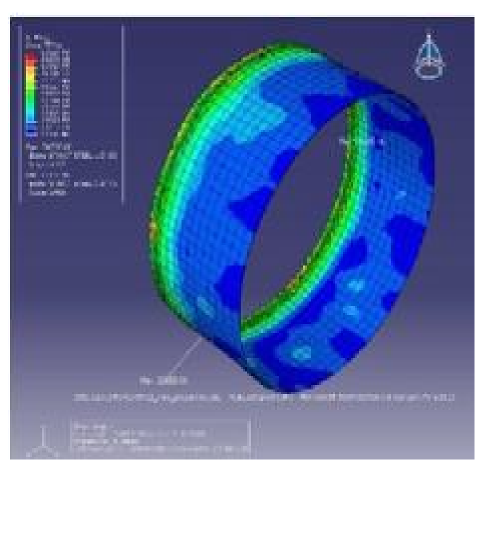


Figure 6a, b: Von Mises Stresses on Spigot End at 150 psi, at 225 psi

Full scale verification tests were conducted on a 54-inch Class 150 joint at a selected stab depth and at a 1-inch pull to reflect the worst case scenario of an angularly deflected joint in the field. The test stand consisted of two 20-ft sections of 54-inch bar-wrapped pipe, Figures 7a and 7b.

Figure 7a, b: Test Stand with Assembled Joint

One joint had a spigot section with a S303 rolled groove gasket and the other joint had a swedged bell end, Figure 8. It should be noted that swedging of the bell provides greater consistency of construction of a gasketed joint than expanding the bell with a hydraulic expander. Acceptance criteria for the joint included no leakage or deformation at 150 psi working, 180 psi test or 225 psi transient pressure. The joint was also required to be water tight to 300 psi which represents a factor of safety of 2 over working pressure.

Figure 8: Swedged Bell and Spigot w/ Rolled Groove Prior to Assembly

The prototype was instrumented for measurement of strains at the spigot end in the joint area and overall external deformation during the testing, Figure 9. Internal strains in the metal pipe were measured by means of resistance bonded strain rosettes in a rectangular pattern. The external deformations were recorded using a cable displacement transducer placed in three locations around the perimeter, one on each springline of the pipe and one at the top. In addition to deformation data, Acoustic Emission (AE) sensors were placed externally in the spigot wrap to monitor leakage and indications of damage during the pressurization progression.

Figure 9: Strain Measurement Instrumentation Attached to Prototype

All criteria were satisfactorily met and the test was stopped at 437 psi when the pump could no longer provide the needed pressure. It should be noted that the joint still did not leak when the test was terminated at 437 psi.

The conclusion from the UTA research project report states:

> "*The joint performed successfully at the acceptance criteria levels of design pressure equal to 150 psi, transient pressure equal to 225 psi and 300 psi test pressure which represents a factor of safety of 2 over design pressure. As such, it is concluded that the S303 Bar-wrapped pipe joint has excellent performance and met test specifications*."

Recommended Joint Restraint Improvement: Another recommended improvement is the use of expanded single lap weld slip joints when joint restraint is needed, Figure 10. The weld bell is simply formed by expanding the bell end of the joint in a hydraulic expander. There is limited preparation required for the spigot end and field cut spigot ends are acceptable for use. The use of a hydraulic expander is appropriate for lap weld ends as the tolerances are greater than for in a rolled groove gasket joint; which are swedged over a die. Butt welded cylinders with expanded weld bells have a track history of highly successful installations on steel pipe. Harnessed joints depend on mechanical means and exacting installation to function and as such involve more risk than a welded joint. Lap welded joints transmit full thrust loads through the integral bell without structural concerns of the joint ring, mechanical harness assemblies or attachment of the joint ring to the thin cylinders.

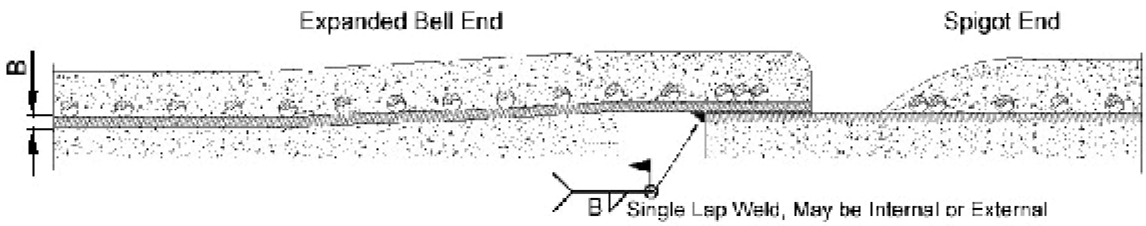


Figure 10: Restrained Single Lap Weld S303™ Joint Geometry (not to scale)

INTERNAL PRESSURE DESIGN

The difference between the operating energy grade line and the low point in the pipeline normally determines working pressure**, P_w.** Surge or transient pressure**, P_t,** adds a surge or transient allowance. Design pressure, **P,** then becomes **$P = P_w + P_t$**. The AWWA M11 Steel Pipe Design Manual (AWWA 2004) and the M9 Manual for Concrete Pressure Pipe both utilize the same principles and the Barlow Hoop Tension formula for pipe wall design. For steel pipe and fittings used with bar-wrapped pipe wall thickness**, t,** determination is shown in Equation 2. Equation 3 details the calculation for steel thickness**, t**, for working pressure only. Equation 4 details the required steel only wall thickness**, t**, when checking for **$P = P_w + P_t$** or transient pressure**.**

$$t = \frac{PD}{2S}$$ **Equation 2**

$$t = \frac{P_w D}{2(0.5 * s_y)}$$ **Equation 3**

Design Stress (S) is limited to 50% of the specified minimum yield strength of steel

$$t = \frac{(P_w + P_t)D}{2(0.75 * s_y)}$$ **Equation 4**

Design Stress (S) is limited to 75% of the specified minimum yield strength of steel

Where,

P	= pressure (psi)
D	= outside diameter of steel cylinder (in)
S	= design stress (psi)
t	= wall thickness (in)
P_w	= working pressure condition
(P_w+P_t)	= transient pressure or surge pressure condition
σ_y	= *specified minimum* yield strength

Bar-wrapped pipe also utilizes the Barlow Hoop Tension Formula per Manual M9 and calculates the total cross section, A_s, required from the combination of the thickness of the steel cylinder and the mild steel bar-wrapped pipe (but not for fittings). The required steel cross-section (A_s) is computed per lineal foot or 12 inches of pipe in lieu of per inch of pipe as for steel pipe. The rewritten Equation 1 with the conversion from inch to feet then becomes:

$$A_s = \frac{6PD}{S}$$ **Equation 5**

Equation 5 determines A_s required for Working Pressure (P_w) and Equation 6 determines the A_s required for Surge or Transient Pressure of (P_w + P_t). The greatest A_s controls design for internal pressure similar to Equations 2 and 3.

$$A_s = \frac{6P_wD}{S}$$ **Equation 6**

Design Stress (S) is limited to 50% of the *specified minimum* yield strength of steel but can not exceed 18,000 psi per M9 to protect cement-mortar coating from damage. Hence Bar-wrapped pipe is limited to steel with a 36,000 psi *specified minimum* yield.

$$A_s = \frac{6(P_w + P_t)D}{S}$$ **Equation 7**

Design Stress (S) is limited to 75% of the *specified minimum* yield strength of steel but can not exceed 27,000 psi per M9.

Where,

A_s = total cross-sectional steel area (in^2/ft)
D = inside diameter of steel cylinder(in)
S = design stress (psi)
P_w = working pressure condition
(P_w+P_t) = transient pressure or surge pressure condition
σ_y = *specified minimum* yield strength

Once A_s is determined, C303 provides minimum nominal cylinder thicknesses for bar-wrapped pipe as shown in Table 2 below (taken from AWWA C303). As an example 48" pipe can be supplied with a *nominal* 0.105-inch thickness

Table 2: Minimum Nominal Cylinder Pipe Thicknesses (AWWA 2008b) Note: Plate thickness for fittings is found on Table 4 of the C303 Standard

Pipe Diameter Range		Minimum Cylinder Thickness		
in.	*(mm)*	*gauge*	*in.*	*(mm)*
10–21	(250–530)	16	(0.060)	(1.5)
24–33	(610–840)	14	(0.075)	(1.9)
36–39	(910–990)	13	(0.090)	(2.3)
42–48	(1,100–1,200)	12	(0.105)	(2.7)
51–66	(1,300–1,680)	10	(0.135)	(3.4)
69–72	(1,750–1,830)	8	(0.164)	(4.2)

Once a cylinder thickness (t) is chosen, C303 allows the area of the bar reinforcement to be no greater than 60 percent of the total area of circumferential reinforcement required. C303 describes varying bar diameters and spacing of bar to arrive at the required bar reinforcement. *An area of improvement for bar-wrapped pipe design is to limit the A_s contribution from the bar to 40% in lieu of 60% of total A_s required.* This requires a thicker cylinder in many cases but does not increase the total A_s or amount of steel required per lineal foot for 36" Class 150 and greater. Rationale for this improvement of increasing the A_s from the cylinder to 60% of Total A_s and a minimum of 10 gage in all cases:

- § Hydraulic thrust or transient pressures are resisted by welding or harnessing sections of pipe to develop the required longitudinal restraint. Thin cylinders often do not have the ability to resist the longitudinal stresses developed as proper design requires restrained sections to have thicker cylinders and or double weld joint rings to the cylinders. This can be problematic if specific sections are installed out of sequence. Increasing the A_s of the cylinder will increase the ability of pipe to resist these stresses as bar reinforcement does not assist in dealing with longitudinal stress.
- § Welding of joint rings to thicker cylinders is less problematic as welding is simpler and the welded connection has higher strength due to the thicker cylinder or weld.
- § Thicker cylinder provides a higher factor of safety in hoop tension against the damage from unexpected transient or surge pressures.
- § Better able to field tap or field modify. 10 gage cylinders are more robust making welding much easier than on thin cylinders. Tapping saddles can be easily welded to the pipe cylinder and field modifications during installation can simpler.
- § Thicker cylinders have higher impact or puncture resistance and are less susceptible to overall damage.
- § Thicker cylinders should provide longer service life when considering corrosion.
- § Thicker cylinders allow for deflection limits used for C200 cement mortar coated pipe
- § Thicker cylinders provide more beam strength which aid with uneven bedding or pipe settlement at bell holes etc.
- § Added beam strength also allows for pipe lengths up to 50-ft as shown in Table 3. A comparison between the 50' joint lengths of S303 and a widely used bar-wrapped pipe, B303 in 40' lengths, manufactured by a national manufacturer, is presented.

Table 3: Beam Strength Comparison Between S303 and B303

Es = 29000 ksi
f'c = 4500 psi
Ec = 3824 ksi
T_w = 1.1 in
T_L = 0.75 in
ε_{lim} = 1.3E-04 cracking strain

Two point symmetrical Lift

Pipe Designation	Nominal Diameter (in)	Pipe Weight in (lbs/ft)	Pipe Thickness (in)	Pipe Length (ft)	Module n (Es/Ec)	I of Steel Pipe	I of Liner	I of Wrap	I TOTAL	Pipe OD (in)	Strap Location from end (ft)	Negative Strain in Wrap	Positive Strain in Wrap	% of limit Static	Criteria	% of limit Dynamic	Criteria
B303-36	36	283	0.090	40	7.6	14237.6	14618.2	25815.2	54671.0	39.9	15.0	3.6E-05	-1.1E-05	28%	PASS	55%	PASS
B303-42	42	341	0.105	40	7.6	25828.9	23010.7	39814.4	88654.0	46.0	15.0	3.1E-05	-9.5E-06	24%	PASS	47%	PASS
B303-48	48	419	0.105	40	7.6	38025.4	34122.8	58033.7	130182.0	52.0	15.0	3E-05	-9E-06	22%	PASS	45%	PASS
B303-54	54	478	0.135	40	7.6	68981.3	48336.3	81360.2	198677.8	58.0	15.0	2.5E-05	-7.5E-06	19%	PASS	37%	PASS
B303-60	60	555	0.135	40	7.6	93793.1	66032.8	109910.7	269736.6	64.0	15.0	2.3E-05	-7.1E-06	18%	PASS	35%	PASS
B303-66	66	636	0.135	40	7.6	123937.8	87594.1	144463.0	355995.0	70.0	15.0	2.2E-05	-6.7E-06	17%	PASS	34%	PASS
B303-72	72	705	0.164	40	7.6	195727.4	113401.9	186034.5	495163.7	76.1	15.0	1.9E-05	-5.8E-06	15%	PASS	29%	PASS

Two point symmetrical Lift

Pipe Designation	Nominal Diameter (in)	Pipe Weight in (lbs/ft)	Pipe Thickness (in)	Pipe Length (ft)	Module n (Ec/Es)	I of Steel Pipe	I of Liner	I of Wrap	I TOTAL	Pipe OD (in)	Strap Location from end (ft)	Negative Strain in Wrap	Positive Strain in Wrap	% of limit Static	Criteria	% of limit Dynamic	Criteria
S303-36	36	289	0.135	50	7.6	21433.2	14618.2	25995.2	62046.6	40.0	20.0	5.9E-05	-2.6E-05	44%	PASS	89%	PASS
S303-42	42	341	0.135	50	7.6	33405.3	23010.7	39976.6	96392.6	46.0	20.0	5.1E-05	-2.2E-05	39%	PASS	78%	PASS
S303-48	48	418	0.135	50	7.6	49167.1	34122.8	58242.2	141532.1	52.0	20.0	4.8E-05	-2.1E-05	37%	PASS	73%	PASS
S303-54	54	478	0.135	50	7.6	69239.6	48336.3	81364.5	198940.4	58.0	20.0	4.4E-05	-1.9E-05	33%	PASS	67%	PASS
S303-60	60	555	0.154	50	7.6	107493.3	66032.8	110115.3	283641.4	64.1	20.0	3.9E-05	-1.7E-05	30%	PASS	60%	PASS
S303-66	66	635	0.169	50	7.6	155967.0	87594.1	144897.5	388458.6	70.1	20.0	3.6E-05	-1.6E-05	27%	PASS	55%	PASS
S303-72	72	704	0.185	50	7.6	220437.6	113401.9	186341.4	520180.9	76.1	20.0	3.2E-05	-1.4E-05	25%	PASS	49%	PASS

EXTERNAL LOAD DESIGN

The M9 Design Manual (AWWA 2008b) is used for external load design of C303 pipe. The original deflection limits for C303 pipe were set at D^2/4000 for pipe up to 42" diameter (largest diameter in the standard at the time). Since then diameters have increased to 72" but the deflection limit has not changed despite the acknowledged fact that the larger diameters are truly more "flexible" than the smaller diameters. The M11 utilizes a deflection limit of 2% for cement mortar lined and coated steel pipe. (Arnaout 2005) It is appropriate for the thicker cylinder S303 pipe material to also utilize the C200 deflection limit of 2%.

As with all flexible pipes the contribution from the soil stiffness is the most significant component in limiting overall deflection under load. This is especially true for S303 sizes 48" and larger. Hence while thicker cylinders are advantageous and allow for deflection limit of 2%, external load design is greatly influenced by the E' value or soil stiffness.

CONCLUSION

A number of key improvements to the AWWA C303 bar-wrapped pipe product have been proposed in the paper. The recommended improvements, except for the rolled groove joint configuration, are already included or permitted either in the C303 Standard or in the M9 Design Manual and can be simply covered in project specifications. The rolled groove joint configuration or S303™ joint is not currently in the C303 standard. The S303 joint would use the applicable sections of the C200 Section 4.13 for all manufacturing and quality control needs. Likely reasoning that roll groove joints are not currently in the C303 standard is the fact that the roll groove can not be manufactured on the traditional offset welded seam cylinders and the fact that light gage cylinders are allowed and widely used. To demonstrate the viability of the S303 joint on bar-wrapped pipe, an extensive research and testing program was conducted by the University of Texas at Arlington. The full scale physical tests on 54-inch bar-wrapped pipe with rolled groove joint were successful. The joint met all established industry acceptance criteria. The successful physical test corroborated the model obtained from Finite Element Analysis.

Recommended Improvements include:

1. Use of helical full penetration butt welds for the fabrication of all cylinders.
2. Use of roll groove gasket configuration for non restrained joints. Specify by referencing C200 Standard Section 4.13
3. Use of lap weld slip joint configuration for restrained joints
4. Internal pressure design which utilizes a minimum of 60% of the contribution of the cylinder to the Total A_s requirement. Minimum cylinder thickness of 10 gage.
5. Utilize deflection limit of 2% for the thicker S303 bar-wrapped pipe cylinders in all diameters
6. Allow up to 50' joint lengths with the thicker S303 bar-wrapped pipe cylinders.
7. Lastly, it is the recommendation of this group that since S303 bar wrapped pipe is most closely aligned with and would be more widely accepted as a flexible pipe, that the AWWA C303 standard be moved to the Steel Pipe Standards. Several papers have brought to light the similarities between Bar-Wrap and Steel Pipe.

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