PCCP DESIGN CHECK USING AWWA-C304 IN AN EXCEL SPREADSHEET

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Abstract

The manufacture of prestressed concrete cylinder pipe(PCCP) has been governed by AWWA C-301 for several decades. The pipe suppliers used either Method A or Method B to help the design engineer and the owner design and specify PCCP pipe for major water transmission and sewer force main projects. Numerous owners and design engineers began to question the validity of these over-simplified design curves in the appendices of AWWA C-301, particularly when the pipe intended to last forever or long time were falling apart. American Concrete Pressure Pipe Association(ACPPA) and its members responded to this criticism by developing a pair of new standards, namely AWWA C301 and C304, to address material properties and design methodology. The design steps involved in C304 are so complicated that ACPPA had an elaborate computer software developed to implement C304 for designers of this pipe. In most cases, the software was purchased primarily by the pipe manufacturers who belong to the ACPPA and either they would run design analyses for interested parties or ACPPA would sell a copy of the software for an enormous fee. The authors of this paper were experts on a number of lawsuits involving PCCP failures and came across the above problems. As part of the discovery phases for the members in the legal profession, the authors developed a simple spreadsheet based on C304-92 to check the structural adequacy of PCCP lines designed to the old C301-72 to C301-84 design standards rather efficiently. This paper provides an overview of this approach and a sample application of this spreadsheet for specific PCCP projects to illustrate the point that an adequate design methodology does not necessarily have to be complicated.

Introduction

For several decades, the design and manufacturing of Prestressed Concrete Cylinder Pipe (PCCP) has been in accordance with ANSI/AWWA C301 (American Water Works Association, 1972, 1984). Two distinct procedures designated as Method A and Method B governed the design of PCCP and were described in Appendices A and B of ANSI/AWWA C301. These methods are also known as Cubic Parabola Design Method and Stress Analysis Method, respectively. These procedures only limited concrete core tensile stress and used generic design values for all component material characteristics, and thus did not address material and environmental variations. The existence of two methods for the PCCP design caused confusion and the extremely simplified design curves raised questions on the validity of the design procedures. These procedures were replaced with the new PCCP standard C304-92. This new standard presents a unified design method for both types of PCCP, namely lined cylinder pipe (LCP) and Embedded Cylinder Pipe (ECP).

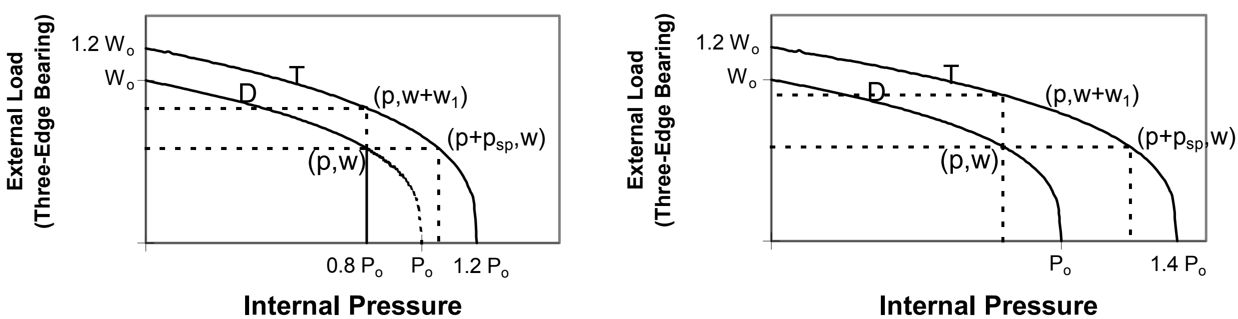
The methodology presented in AWWA C304-92 is based on a literature review of the state of art of prestressed concrete design, theoretical work by Zarghamee and Fok (1990), and on the analysis of hundreds of PCCP performance tests made over several years. The new standard presents simplified practical design equations developed by evaluating time related stress variations using computerized numerical integration procedures. The resulting design steps in the PCCP design methodology are so complex that an elaborate computer program was developed by ACPPA for use in the design of PCCP. As experts providing litigation assistance to clients, the authors have encountered a number of projects where the failed PCCP pipes were designed using the old C301-72 to C302-84 standards. To help the discovery process, the authors developed a simple spreadsheet to check the structural adequacy of the PCCP lines efficiently using the current design standard C304-92. An overview of this spreadsheet is presented in this paper.

Review of PCCP Design Methodologies

In a prestressed concrete pipe, the concrete core and the steel cylinder act as primary load carrying components. The purpose of prestressing the core is to maintain compressive stresses in the concrete core under normal working conditions, as concrete is weak in tension.

Method A

The Cubic Parabola Design Method specified in the Appendix A of the C301 standard is generally known as "Method A". This method is based on: 1) W_o, which is nine tenths of the three-edge bearing test load that causes incipient cracking; and 2) the theoretical hydrostatic pressure P_o that relieves the residual compression in the concrete core due to



a) Lined Cylinder Pipe b) Embedded Cylinder Pipe

Figure 1: Design and Transient Capacity Curves for Lined and Embedded Cylinder Pipe using Cubic Parabola Design Method (Appendix A, AWWA C301-84)

prestressing. The allowable combinations of three-edge bearing load and internal pressure were determined by a cubic parabola, passing through W_o and P_o, as defined by the following equation:

$$w = W_o \left(\frac{P_o - p}{P_o} \right)^{\frac{1}{3}}.$$

Where

$$W_o = 0.9 W_{3-edge}$$

$$P_o = \frac{f_{cr}}{6D_y} \left[A_c + n_r \left(A_s + A_y \right) \right]$$

$$f_{cr} = f_{ci} \left[\frac{A_c + n_r \left(A_s + A_y \right)}{A_c + n_r \left(A_s + A_y \right) \left(1 + C_r \right)} \right]$$

$$f_{ci} = \frac{A_s f_{sg} \left(1 - R_1 - R_2 \right)}{A_c + n_i \left(A_s + A_y \right)}$$

where, R_1 and R_2 are relaxation factors; C_r is shrinkage strain; f_{cr} is final prestress in the core; f_{ci} is the initial prestress in the core; P_o is the internal pressure required to overcome all compression in the core concrete, exclusive of the effect of external load; W_o is nine tenths of the three-edge bearing load producing incipient cracking in the core, with no internal pressure; p is the maximum design pressure in combination with three-edge bearing load w; and w is the maximum three-edge bearing load, equivalent to dead load, in combination with design pressure p. All other variables are as given in AWWA C-304. Design (D) and transient (T) capacity curves resulting from the Cubic Parabola Design Method is shown in Figure 1 for both embedded-cylinder and lined-cylinder pipes.

Method B

The Stress Analysis Design Method outlined in the Appendix B of AWWA Standard C301 is also known as 'Method B'. This procedure is based on limiting the maximum combined net tensile stress in pipe under static external load and internal pressure to a value equal to $7.5\sqrt{f_i'}$, where f_i' is the specified 28-day compressive strength of the concrete. This concept is illustrated in Figure 2 and the resulting design curve is defined by the following equation:

$$p = \left(f_{cr} + 7.5\sqrt{f_c'} \pm \frac{M}{S} \pm \frac{F}{A_t} \right) \frac{A_t}{12R_v}$$

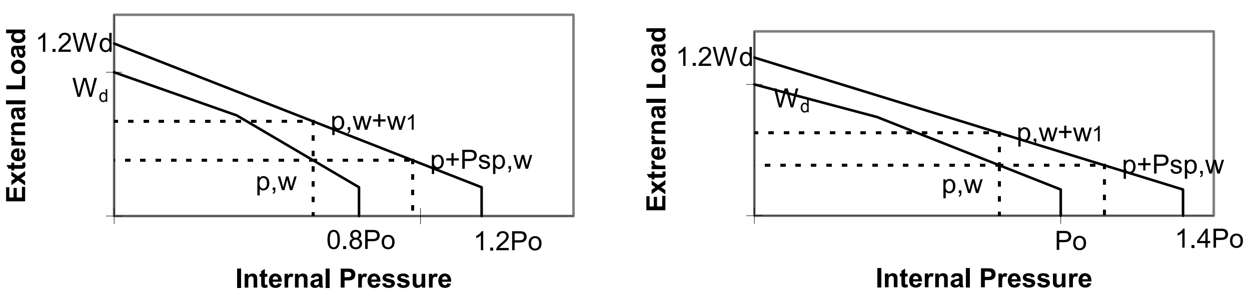
where, p is maximum design pressure in combination with field dead-load; w, not to exceed 0.8 P_o for lined-cylinder pipe or P_o for embedded-cylinder pipe; f_{cr} is resultant induced compression; M is total moment in the pipe section due to pipe weight, water weight, and external static load; and F is total thrust in the pipe section due to pipe weight, water weight, and external static load; S is section modulus of the control pipe section based on the total pipe wall at the crown and invert sections and on the prestressing wire and core only at the side section; A_t = transformed cross-sectional area of the control section based on the total pipe wall at the crown and invert sections and on the prestressing wire and core only at the side section; and R_v = outside radius of the steel cylinder. The design (D) and transient (T) capacity curves resulting from the Stress Analysis Design Method are shown in Figure 2 for lined-cylinder and embedded-cylinder pipes.

PCCP Design using C304 Standard

The current design methods for buried PCCP under internal pressure defined in the C304-92 standard includes the effects of working, transient, and field-test load, and internal pressure combinations. The new standard uses appropriate design values for component material characteristics as summarized in Table 1 and uses limit states design criteria. The limit state design criteria limit circumferential thrust and bending moment resulting from internal pressure, external loads, pipe weight, and fluid weight. Also, the design criteria assures that the state of prestress and safety margins for adequate strength will be maintained even if the pipe is subjected to abnormal conditions that may cause visible cracking. The design procedure consists of the following three limit-states criteria: 1) Serviceability Limit State; 2) Elastic Limit State; and 3) Strength Limit State.

Serviceability limit-states criteria ensure the performance of the pipe under service loads by precluding the microcracking from occurring in the core and by controlling microcracking in the coating under working loads and pressures. Also it is intended that the criteria preclude visible cracking from occurring in the core and the coating under working plus transient loads and pressures. The serviceability limit state criteria include 1) Core-crack control; 2) Radial tension control; 3) Coating-crack control; 4) Core-compression control; and 5) Maximum pressure.

Elastic limit states criteria define the onset of material non-linearity. The criteria limit combined working plus transient loads and pressures so that if cracks develop in a prestressed pipe under the transient condition, the pipe response will be elastic and damage or loss of prestress will not occur. The elastic limit state criteria include 1) Wire-stress control; and 2) Steel-cylinder stress control.



a) Lined Cylinder Pipe

b) Embedded Cylinder Pipe

Figure 2: Design and Transient Capacity Curves for Lined and Embedded Cylinder Pipe using Stress Analysis Design Method (Appendix B, AWWA C301-84)

Strength limit states are defined to provide safety and to protect the pipe under extreme loads. The criteria protect the pipe against yielding of the prestressing wire, crushing of the concrete core under external load, and tensile failure of the wire under internal pressure. Safety factors are applied to loads and pressures that produce the strength limit states. The strength limit state criteria include 1) Wire yield-strength control; 2) Core compressive-strength control; 3) Burst-pressure control; and 4) Coating bond-strength control.

The three limit state criteria described above determine the allowable combinations of internal pressure, external loads, pipe weight, and fluid weight to assure adequate serviceability of the pipe under working plus transient design loads and pressures. The load factors to be used in the design for differing loading conditions are summarized in Table 2 for both embedded and lined cylinder pipes. Table 3 provides a summary of different limit state conditions and associated loading conditions for both type of pipes.

Table 2: Load and pressure factors for Lined and Embedded Cylinder Pipes

Loading Conditions	Loads and Pressures (ECP)							Loads and Pressures (LCP)						
	We	Wp	Wf	Wt	Pw	Pt	Pft	We	Wp	Wf	Wt	Pw	Pt	Pft
Working Loads and Pressure Combinations														
W1	1.00	1.00	1.00	-	1.00	-	-	1.00	1.00	1.00	-	1.00	-	-
W2	1.00	1.00	1.00	-	-	-	-	1.00	1.00	1.00	-	-	-	-
FW1	1.25	1.00	1.00	-	-	-	-	-	-	-	-	-	-	-
Working Load Plus Transient Load and Pressure Combinations														
WT1	1.00	1.00	1.00	-	1.00	1.00	-	1.00	1.00	1.00	-	1.00	1.00	-
WT2	1.00	1.00	1.00	1.00	1.00	-	-	1.00	1.00	1.00	1.00	1.00	-	-
WT3	1.00	1.00	1.00	1.00	-	-	-	1.00	1.00	1.00	1.00	-	-	-
FWT1	1.10	1.10	1.10	-	1.10	1.10	-	1.20	1.20	1.20	-	1.20	1.20	-
FWT2	1.10	1.10	1.10	1.10	1.10	-	-	1.20	1.20	1.20	1.20	1.20	-	-
FWT3	1.30	1.30	1.30	-	1.30	1.30	-	1.40	1.40	1.40	-	1.40	1.40	-
FWT4	1.30	1.30	1.30	1.30	1.30	-	-	1.40	1.40	1.40	1.40	1.40	-	-
FWT5	1.60	1.60	1.60	2.00	-	-	-	1.60	1.60	1.60	2.00	-	-	-
FWT6	-	-	-	-	1.60	2.00	-	-	-	-	-	1.60	2.00	-
Field-Test Condition														
FT1	1.10	1.10	1.10	-	-	-	1.10	1.10	1.10	1.10	-	-	-	1.10
FT2	1.21	1.21	1.21	-	-	-	1.21	1.32	1.32	1.32	-	-	-	1.32

Spreadsheet Implementation

With increasing availability of faster computers and powerful spreadsheet software, problems with increasing complexity are being solved utilizing the spreadsheets. Although, the need for programming the complex equations are not eliminated, the ease with which the problems are modeled and differing model situations are analyzed is remarkable. One of the strengths of this approach is that the computations are being performed even while the data is being entered and the model is being manipulated. Overall, this distributed computing resulting in a higher apparent speed, with which the calculations are performed, better than that of a conventional stand-alone program.

With the ease of post-processing, report generation within a spreadsheet and the flexibility of modeling, the spreadsheet programming is attractive for problems that can be programmed within a spreadsheet. With programming languages and numerical tools linked with spreadsheet programs, the range of problems that can be analyzed within a spreadsheet is very wide.

The PCCP design problem presented here has been implemented in an EXCEL spreadsheet. Use of macros, written in Visual Basic has been kept to an absolute minimum with the equations embedded in the cells. By protecting the cells that contain equations, the interface between the user is kept only to the necessary user input. A sample input-sheet is shown in the Figure 3.

Table 3: Limit States and load combinations for Embedded and Lined cylinder pipes

Location	Purpose (To Preclude)	Load Combination	Criteria - ECP	Criteria - LCP
Serviceability Limit State				
Full Pipe	core decompression	W1	Internal working pressure	Internal working pressure
Circumference	coating cracking	WT1	Internal working pressure	Internal working pressure
Invert/Crown	onset of core microcracking	W1	Inside core tensile strain	Inside core tensile strain
		FW1	Inner core-to-cylinder radial tension	-
	onset of core visible cracking	WT1, WT2, FT1	Inside core tensile strain	Inside core tensile strain
		WT3	Inside core tensile strain	-
Springline	onset of core microcracking & to control microcracking of coating	WT1	Outer core tensile Strain & outer coating Tensile strain	Outer core tensile Strain & outer coating Tensile strain
	coating visible cracking	WT1, WT2, FT1	Outer core tensile strain & outer coating tensile strain	Outer core tensile strain & outer coating tensile strain
	core compression	W2	Inner core compression	Inner core compression
		WT3	Inner core compression	Inner core compression
Elastic Limit State				
Invert/Crown	exceeding limit stress in steel cylinder	WT1, WT2, FT1	Cylinder stress Reaching yield	-
		WT3	Onset of tension in Cylinder	-
Springline	exceeding wire limit stress & maintain core compression stress below 0.75 fc'	FWT1, FWT2, FT2	Wire stress limit & Core compression	Wire stress limit & Core compression
Strength Limit State				
Springline	wire yielding	FWT3, FWT4	Wire stress limit	Wire stress limit
	core crushing	FWT5	Ultimate moment	Ultimate moment
Burst pressure	to prevent burst failure	FWT6	Internal pressure is less than burst pressure	Internal pressure is less than burst pressure

The present implementation offers a larger window on the computations performed each step has been reproduced in the spreadsheet. However, this increased visibility of the data (i.e., results) is often confusing and overwhelming to an inexperienced user. In such a situation, increasing the variables in the Visual Basic macros can reduce the visibility of the data or select sheets can be hidden from the user keeping the similar programming style. Table 4 shows the computed design variables for the above example. Also, Table 5 shows a typical calculation summary for the serviceability conditions at invert/crown and the results show that the design satisfies inside core micro-cracking, inside core visible cracking, and inside core-to-cylinder radial tension.

Figure 3: Input Screen for the PCCP Design spreadsheet

Type of Pipe LCP

Units English

Data From Purchaser		Data from Pipe Manufacturer		Design Values	
Inside diameter of the Pipe, in.	72	Outside diameter of the steel cylinder, in.	75.5	Design modulus of elasticity of prestressing wire, psi	28000000
Fluid Unit Weight, lb/ft^3	62.4	Thickness of the steel cylinder, in.	0.0598	Unit weight of prestressing wire, lb/ft^3	489
External Dead Load, lb/ft	6000	Diameter of the prestressing wire, in.	0.192	Unit weight of concrete, lb/ft^3	145
External surcharge load, lb/ft	0	Class of Prestressing wire (II/III)	252000	Design 28-day compressive strength of core concrete, psi	5500
External Transient Load, lb/ft	0	Number of layers of prestressing wire (1/2/3)	1	Design 28-day compressive strength of mortar, psi	5500
Internal Working Pressure, psi	150	Coating thickness over the prestressing wire, in.	0	Unit weight of mortar, lb/ft^3	140
Internal Transient Pressure, psi	60	Coating thickness between layers of prestressing wire, in.	0	Design modulus of elasticity of cylinder, psi.	30000000
Internal Field-test Pressure, psi	180	Concrete 28-day compressive strength, psi	5500	Tensile yield strength of steel cylinder, psi	33000
Time Period of Exposure to outdoor environment (days) if more than 270 days	270	Concrete modulus of elasticity multiplier (if less than 0.9)	0.9	Design tensile strength of steel cylinder at pipe burst, psi	45000
Time Period of Exposure of Pipe to Burial environment before water filling (days) if more than 90 days	90	Concrete creep-factor multiplier (if greater than 1.1)	1.1	minimum tensile strength of wire, psi	40000
Relative humidity of the outdoor environment	70	Concrete shrinkage strain multiplier (if greater than 1.1)	1.1	Height of Earth Cover, ft	5.5
		Prestressing wire intrinsic relaxation multiplier (if greater than 1.1)	1.1		

Summary

The paper presents a novel and an efficient spreadsheet program to check the design of PCCP using AWWA C304-92 standard. Owners of PCCP pipelines would find this approach extremely useful, as the material properties of the pipe, ground conditions, and loading on their pipelines vary during the life of the project. As part of the periodic inspection and maintenance program, this design check could be done effectively to determine the structural health of the pipeline, rather than let the pipeline blow up with absolutely no warning. The approach of using spreadsheet programming to perform PCCP design check in a computer is flexible, simpler, and efficient.

Table 4: Computed design variables for a sample problem

Core		**Cylinder**		**Wire**		**Concrete**		**Mortar**	
D_i	*72*	t_y	*0.0598*	d_s	*0.192*	f_c'	*5500*	f_m'	*5500*
D_y	*75.5*	f_{yy}	*33000*	f_{su}	*252000*	γ_c	*145*	γ_m	*140*
h_c	**5.5**	f_{yy}^*	*45000*	f_{sg}	*189000*	E_c	*3840887*	E_m	*4E+06*
Steel cylinder and concrete		E_y	*3E+07*	E_s	*28000000*	n	*7.28998*	m	*0.9484*
A_y	*0.718*	h_{ci}	*1.69*	f_{sy}	*214200*	n'	*7.81069*	f_{tm}'	*519.13*
A_c	*65.28*	d_y	*1.72*	λ_s	*0.017455*	f_t'	*519.134*	ε_{tm}'	*0.0001*
Coating:		λ_y	*0.31*	ε_{sg}	*0.00675*	ε_t'	*0.00014*	ε_{km}'	*0.0011*
h_m	*0.94*			ε_{sy}	*0.00765*	ε_k'	*0.00149*		
λ_m	*0.0856*			γ_s	*489*				
R	*39.22*								
Environ ment		PH	*70%*	t_1	*270 days*	t_2	*90 days*		
Pressures:		**Earth Load and Fluid Weight:**		**Earth Load (bedding: 90° Olander):**		**Pipe weight (bedding: 15° Olander)**		**Fluid weight (bedding:90° Olander)**	
P_w	*150*	γ_f	*62.4*	C_{m1e}	0.1247	C_{m1p}	0.2157	C_{m1f}	0.1208
P_t	*60*	W_e	*6000*	C_{m2e}	0.0885	C_{m2p}	0.1016	C_{m2f}	0.0878
P_{ft}	*180*	W_t	*0*	C_{n1e}	0.3255	C_{n1p}	0.1029	C_{n1f}	-0.2703
		W_f	*1764.3*	C_{n2e}	0.5386	C_{n2p}	0.3026	C_{n2f}	-0.0617

References

American Water Works Association, (1992), "AWWA Standard for Design of Prestressed Concrete Cylinder Pipe- AWWA C304-92", AWWA.

American Water Works Association, (1992), "AWWA Standard for Prestressed Concrete Pressure Pipe, Steel-Cylinder Type, for water and other liquids- AWWA C301-92", AWWA.

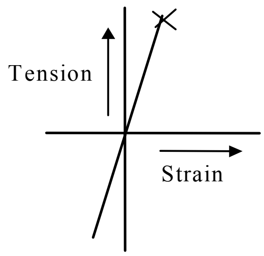
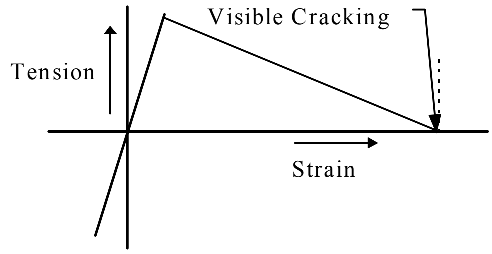
American Water Works Association, (1984), "AWWA Standard for Prestressed Concrete Pressure Pipe, Steel-Cylinder Type, for water and other liquids- AWWA C301-84", AWWA.

Zarghamee, M. S. and Fok, F. L.(1990), "Analysis of Prestressed Concrete Pipe Under Combined Loads," ASCE Journal of Structural Engineering, Vol. 116, No. 7, p 2022-2039.

Table 5: Typical calculation summary for Serviceability conditions at Invert/Crown

	WT1	WT2	FT1	W1	FW1	WT3
P	210.0	150.0	198.0	150.0	0.0	0.0
M_1	51693.7	51693.7	56863.1	51693.7	59030.0	51693.7
N_1	93483.7	66303.7	87883.1	66303.7	-2134.5	-1646.3
ν	10.0	10.0	10.0	10.0	10.0	10.0
ν_2	1.7	-0.1	1.2	-0.1	-1.7	-1.7
k	0.7	0.4	0.6	0.4	-0.3	-0.3
t_t	1.4	2.4	1.6	2.4	2.4	2.5
t_s	2.4	-0.3	1.9	-0.3	-3.9	-4.4
λ	0.7	-5.6	0.9	-5.6	-0.4	-0.4
"=>" m	0.3655	0.5926	0.3999	0.5926	0.9484	0.9484
	2.9959	3.0857	3.0098	3.0857	3.2160	3.2160
ε_{mm}	-0.0003	-0.0002	-0.0003	-0.0002	0.0000	0.0000
"=>" m	0.3655	0.5926	0.3999	0.5926	0.9484	0.9484
Strains						
ε_{ci}	0.00036	0.00012	0.00030	0.00012	-0.00009	-0.00010
Δ_{ey}	0.00020	0.00002	0.00015	0.00002	-0.00019	-0.00019
eco	0.00015	0.00019	0.00017	0.00019	0.00040	0.00039
Des	0.00016	0.00020	0.00018	0.00020	0.00041	0.00040
emm	-0.00007	-0.00005	-0.00006	-0.00005	0.00016	0.00015
emo	-0.00003	-0.00002	-0.00002	-0.00002	0.00019	0.00018
Stresses						
"=> " m	0.9	0.9	0.9	0.9	0.9	0.9
fci	431.8	452.9	456.4	452.9	-339.6	-384.9
Dfy	6044.2	620.6	4589.7	620.6	-5614.9	-5755.5
fcy	493.7	79.5	512.3	79.5	-718.9	-736.9
fco	586.0	741.3	641.4	741.2	1552.3	1510.3
Dfs	4524.1	5555.7	4903.4	5555.6	11470.4	11153.2
fms	-386.8	-252.5	-337.4	-252.6	516.9	475.7
fmm	-258.8	-175.3	-221.8	-175.3	595.3	548.4
fmo	-98.1	-78.3	-76.5	-78.3	693.8	639.8
Internal Forces						
F'ci	-49440.4	-81919.5	-54704.3	-81921.8	-80672.9	-86929.8
F"ci	31092.6	65805.2	38430.8	65804.4	-55915.3	-68800.9
Fci	-18347.8	-5669.2	-16273.5	-5668.8	-3138.8	-4344.8
Fy	-3983.1	-388.3	-2925.9	-388.3	3513.4	3601.4
Fco	5727.9	15183.7	7591.8	15183.6	65571.3	66887.1
Fs	2774.6	3281.7	2961.1	3281.6	6188.7	6032.8
F'm	-2371.1	-1539.1	-2074.3	-1539.1	2808.2	2583.2
F"m	-554.5	-442.7	-432.5	-442.8	3921.5	3616.4
Fm	-2925.5	-1981.8	-2506.8	-1981.9	6729.7	6199.6
ΣF	0.0	0.0	0.0	0.0	0.0	0.0
Internal Moments						
Mci	72266.3	24409.5	67675.1	24408.1	13514.5	18707.1
My	15437.9	1505.2	11340.6	1505.0	-13617.5	-13958.6
Mco	-3660.1	-18736.4	-5720.9	-18736.4	-160176.4	-170990.7
Mm	-811.9	-571.0	-682.3	-571.1	2698.4	2487.1
ΣM	nearly zero	nearly zero	nearly zero	nearly zero	nearly zero	nearly zero

Table 1:Differences in component properties between new and old design standards

<table>
<tr><th>Old PCCP Design Methods
(ANSI/AWWA C301-84)</th><th>New PCCP Design Standard
(AWWA C304-92)</th></tr>
<tr><td>Stress/Strain Diagram for Mortar/Concrete
</td><td>Stress/Strain Diagram for Mortar/Concrete
</td></tr>
<tr><td>Creep and Shrinkage factor for Cast Pipe = 2.0
Factors for Coating or Inner and Outer Core were not separated</td><td>Creep Factor Formula is:
$$\phi = \frac{(h_{co} + h_m)\phi_{com} - h_m\phi_m + h_{ci}\phi_{ci}}{h_{ci} + h_{co}}$$
Shrinkage Factor Formula is:
$$s = \frac{(h_{co} + h_m)s_{com} - h_m s_m + h_{ci}s_{ci}}{h_{ci} + h_{co}}$$
The effect of volume-to-surface ratios and relative humidity exposures is included</td></tr>
<tr><td>Limits stresses/strains in the concrete core</td><td>Limits stresses/strains in all component materials (concrete core, mortar coating, steel cylinder, and prestressing wire to preclude cracking or yielding</td></tr>
<tr><td>Steel Modulus
Wire Modulus, $E_s = 28 \times 10^6$ psi
Cylinder Modulus, $E_y = 28 \times 10^6$ psi</td><td>Steel Modulus
Wire Modulus, $E_s = 28 \times 10^6$ psi
Cylinder Modulus, $E_y = 30 \times 10^6$ psi</td></tr>
<tr><td>Cast concrete initial modular ratio, $n_i = 7$</td><td>Cast concrete initial modular ratio
$$n_i = 109(f'_c)^{-0.3}$$
$$n'_i = 117(f'_c)^{-0.3}$$
(Prime indicates ratio to cylinder steel)</td></tr>
<tr><td>Resultant Modular ratio, $n_r = 6$</td><td>Resultant modular ratio
$$n_r = 93(f'_c)^{-0.3}$$
$$n'_r = 99(f'_c)^{-0.3}$$
(Prime indicates ratio to cylinder steel)</td></tr>
<tr><td>Wire relaxation loss = 5 %</td><td>Wire relaxation loss
Cast concrete : $R = 0.111 - 3.5\frac{A_s}{A_c}$
Spun concrete : $R = 0.13 - 3.1\frac{A_s}{A_c}$</td></tr>
<tr><td>Pipes were designed using generic material characteristics without requiring material testing</td><td>All component materials used in each pipe factory are tested. If a characteristic of available material does not meet or exceed the default characteristic assumed in design, then the actual material characteristics are used in design.</td></tr>
</table>