

# TEST PROGRAM FOR EVALUATING DESIGN METHOD AND STANDARD DESIGNS FOR PRECAST CONCRETE BOX CULVERTS WITH WELDED WIRE FABRIC REINFORCING

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This paper describes the results of a test program developed to verify the design method and the standard designs for precast concrete box culverts reinforced with welded wire fabric (1). The design equations used to calculate expected test results and the structural analysis used to determine test loads equivalent to design loads are included. The test results are evaluated by comparison with the required design and ultimate loads. The evaluations verify that the design method and the standard designs are adequate and result in satisfactory designs. The results also show that the equations for determining the maximum wire spacing for crack control are conservative.

•THIS REPORT summarizes the results of a test program developed to verify the design method and standard designs for precast concrete box culverts reinforced with welded wire fabric (1). The results are compared with test strengths calculated by using the proposed design method and with required equivalent design and ultimate loads for prototype culvert designs.

## NOTATION

These notations will be used throughout the paper:

- $a$  = distance between test loads = 0.25 Si;
- $a_n$  = depth of stress block in ultimate strength design for section  $n$ ;
- $A_s$  = area of reinforcing steel per unit width;
- AS1 = area of reinforcing steel per unit width in outside layer walls, and top and bottom slabs;
- AS2 = area of reinforcing steel per unit width in inside layer, top slab;
- AS3 = area of reinforcing steel per unit width in inside layer, bottom slab;
- $b$  = width of unit strip (12 in.);
- C-Len = length of outside steel in top and bottom slabs to theoretical cutoff point plus anchorage length;
- $C_1, C_2$  = constants in various equations;
- $d$  = depth from extreme compression fiber to centroid of tension reinforcement;
- $d_1, d_2, d_3$  = depth from extreme compression fiber to centroid of tension reinforcement at locations 1, 2, and 3 (Fig. 3, load arrangement);
- D-Load = total test load per ft of culvert divided by inside span, Si, in ft;
- D.T. = diagonal tension failure;
- F = flexural failure;

- $f'_c$  = compressive strength of concrete, psi;  
 $f_s$  = stress in reinforcement at service loads;  
 $f_{su}$  = ultimate tensile strength of reinforcing steel;  
 $f_y$  = yield strength of reinforcing steel;  
 $M_u$  = ultimate design moment;  
 $P_b$  = steel ratio,  $A_s/bd$ , for balanced ultimate flexural failure;  
 $P$  = load on test specimen;  
 $P_{cr}$  = total load on test specimen at first visible crack;  
 $P_{des}$  = total test load that produces structural behavior in test specimen equivalent to effect of design earth cover;  
 $P_u$  = ultimate test load;  
 $P_{u des}$  = total ultimate test load that is equivalent to required ultimate strength with design earth cover;  
 $P_{ult calc}$  = total load on test specimen calculated to cause ultimate diagonal tension failure;  
 $P_{ult test}$  = total load on test specimen in diagonal tension failure;  
 $P_{uf calc}$  = total load on test specimen calculated to cause ultimate flexural failure;  
 $P_{uf test}$  = total load on test specimen in ultimate flexural failure;  
 $P_{0.01 calc}$  = total load on test specimen calculated to cause 0.01-in. crack;  
 $P_{0.01 test}$  = total load on test specimen at 0.01-in. crack;  
 $s_g$  = spacing of longitudinal wires;  
 $S_i$  = span, between inside faces of side walls;  
 $t_b$  = distance from centroid of tension steel to outermost concrete tension fiber;  
 $W$  = weight of box culvert per unit width (12 in.); and  
 $w$  = uniformly distributed load on prototype culvert.

## DESIGN METHOD

The proposed design method (1) covers both ultimate strength and service load criteria. Standard culvert dimensions have been suggested (1), and a range of culvert strengths were obtained by varying the area of flexural reinforcement without the use of shear reinforcement.

The design method essentially follows the 1971 ACI code (2) and conforms to the 1972 Interim AASHTO specification (3) with two relatively minor deviations. At present the design method limits the maximum steel ratio to  $0.75 P_b$  instead of  $0.50 P_b$  as required (3); however, none of the standard designs presented (1) has steel in excess of  $0.50 P_b$ . The design method does not limit the maximum service load stress to 36,000 psi (3). Instead, it uses a crack control criterion to limit service load stress for reinforcing.

Crack widths are limited to 0.01 in. at the service or design load on the culvert. The required crack control is obtained by limiting the spacing of wires in the welded wire fabric reinforcing. For a maximum crack width of 0.01 in.:

$$f_{s0.01} \leq \frac{65}{\sqrt[3]{t_b^2 s_g}} + 5 \quad (1)$$

Stresses calculated with Eq. 1 are lower (i.e., more conservative) than would be obtained from a similar relation (2).

## TEST PROGRAM

The test program was designed to evaluate and verify the design method and standard designs that have been suggested (1).

### Test Specimens

Design requirements that were established for the test culverts are given in Table 1. Three sizes were selected to represent small, intermediate, and large spans and three

designs for each size were selected to represent the lowest, intermediate, and highest heights of cover. The highest height is at or just above the design limit of diagonal tension strength for the standard wall thickness and concrete strength. Because test loads can be related more easily to field design loads, which do not include a concentrated surface load, the standard designs without truck load are used for the comparison of test results with design loads.

The arrangement of reinforcing suggested for standard culvert designs and used for test specimens and the nomenclature used in this report are shown in Figure 1. Various dimensional parameters that determine the structural behavior of the test culverts were measured for each test specimen.

Note that, because of a clerical error prior to manufacture,  $2 \times 6-0.5/7$  fabric was called for instead of  $3 \times 6-0.5/7$  fabric for the exterior wall reinforcing of the  $6 \times 4 - 2A$  and the  $6 \times 4 - 2B$  specimens; this resulted in 50 percent excess outside reinforcing. Furthermore, 0.5 wire instead of 1.5 wire was furnished for the inside reinforcing of the top slab, which provided 17 percent excess inside reinforcing. The bottom slab has approximately the correct reinforcing, and this portion of the culvert governs its 0.01-in. crack strength and ultimate diagonal tension strengths—the two parameters that define the design limit of these culverts.

### Material Control Tests

Control tests were carried out to determine significant structural properties of steel and concrete materials in the specimens. Measured steel strengths were well in excess of the 75,000-psi minimum ultimate strength requirement (ASTM A185).

Concrete mixes were designed by the manufacturers to meet the nominal design compressive strength of 5,000 psi. Concrete compressive strengths in the actual specimens were measured by tests on both standard cylinders and cores cut from the wall of the culverts after the test. They were representative of average strengths expected for typical 5,000-psi design mixes in commercial precasting plants.

### Test Procedure

The arrangement of loads used for test specimens is shown in Figure 2. It produces approximately the same ratio of positive moment (tension on the inside of the culvert) in the top and bottom slabs of the test specimen at midspan to shear at a distance  $d$  (out from the end of the haunch) as is produced by the uniformly distributed earth load on the top and bottom slabs of the buried culvert. These two structural parameters are the most significant parameters that govern the field strength of box culverts.

Test load was recorded at the occurrence of the first 0.01-in. crack, and ultimate failure and crack patterns were sketched for all specimens. After testing, the concrete covering the reinforcing was broken off at critical locations and the depth of cover measured.

### Test Results

Test results are given in Table 2 for each specimen. The insides of the top and bottom slabs are subject to tension over much of their length, and crack spacing was equal to or less than the 8-in. spacing of longitudinal wires. In many cases, there were 2 cracks per longitudinal wire space in the central region of maximum bending moment. The test load also causes tension in the outside of the side walls. No cracks were observed in the outside surface at the ends of the top and bottom slabs although tension existed.

## ANALYSIS OF TEST RESULTS

### Evaluation of Design Method for Limiting Crack Width

The 0.01-in. crack strengths obtained in the tests are compared with the corresponding calculated strengths for the test load arrangement, and they provide an evaluation and verification of the design method for limiting crack width. The load needed to

Table 1. Requirements for test culverts.

Culvert Size (ft × ft)	Wall Thick-ness (in.)	Design Earth Cover			Nominal Reinforcing Area			Distance Between Test Loads (in.)	P <sub>40.5</sub> <sup>b</sup> (lb/ft)	P <sub>6.40.5</sub> <sup>c</sup> (lb/ft)	Ultimate Load, Calculated Test <sup>d</sup>	
		Interstate Truck Load (ft)	No Truck Load <sup>e</sup> (ft)	Test Box Culvert Mark	AS1 (in. <sup>2</sup> /ft)	AS2 (in. <sup>2</sup> /ft)	AS3 (in. <sup>2</sup> /ft)				Flexural (lb/ft)	Diagonal Tension (lb/ft)
8×4	8	8	12	8×4-8A	0.301	0.301	0.301	24	7,110	11,950	13,400	20,800
	8	2	18	8×4-8B								
	8	18	21	8×4-2A	0.516	0.410	0.410	24	10,660	17,930	21,600	20,800
6×4	7	10	14	8×4-2B								
	7	2	21	8×4-18A	0.516	0.516	0.516	24	12,440	20,920	24,200	20,800
	7	22	24	8×4-18B								
4×4	5	4	12	6×4-10A	0.173	0.239	0.239	18	6,020	9,750	10,600	18,100
	5	18	20	6×4-10B								
	5	2	24	6×4-2A	0.273*	0.351*	0.325	18	9,030	14,620	16,100	18,100
4×4	5	4	12	6×4-2B								
	5	18	20	6×4-22A	0.295	0.410	0.410	18	10,320	16,700	19,100	18,100
	5	2	28	6×4-22B								
4×4	5	4	12	4×4-4A	0.135	0.135	0.135	12	3,090	5,470	7,100	12,200
	5	18	20	4×4-4B								
	5	2	24	4×4-18A	0.135	0.239	0.239	12	5,160	9,120	9,900	12,200
4×4	5	4	12	4×4-18B								
	5	18	20	4×4-2A	0.186	0.325	0.325	12	7,220	12,770	13,600	12,200
	5	2	28	4×4-2B								

<sup>a</sup>Used for design loading condition with unit weight of fill equal to 120 pcf.  
<sup>b</sup>Total test load that produces same midspan bending moment in test culvert as the design earth cover at 120 pcf produces in a buried culvert. The effect of side pressure equal to  $\frac{1}{2}$  the top pressure is included in determining the proper equivalent bending moment for test specimen. The bending moment in the test culvert is for loads and supports as arranged in Figure 2.  
<sup>c</sup>1.5 times the total weight of 120 pcf of earth cover (with no truck) between critical shear points located at distance d out from haunch.  
<sup>d</sup>Based on  $f_{cu} = 75,000$  psi and  $f'_c = 5,000$  psi.  
<sup>e</sup>0.410 in.<sup>2</sup>/ft actually provided because wrong style fabric called for.

Figure 1. Arrangement and nomenclature for standard box culverts.

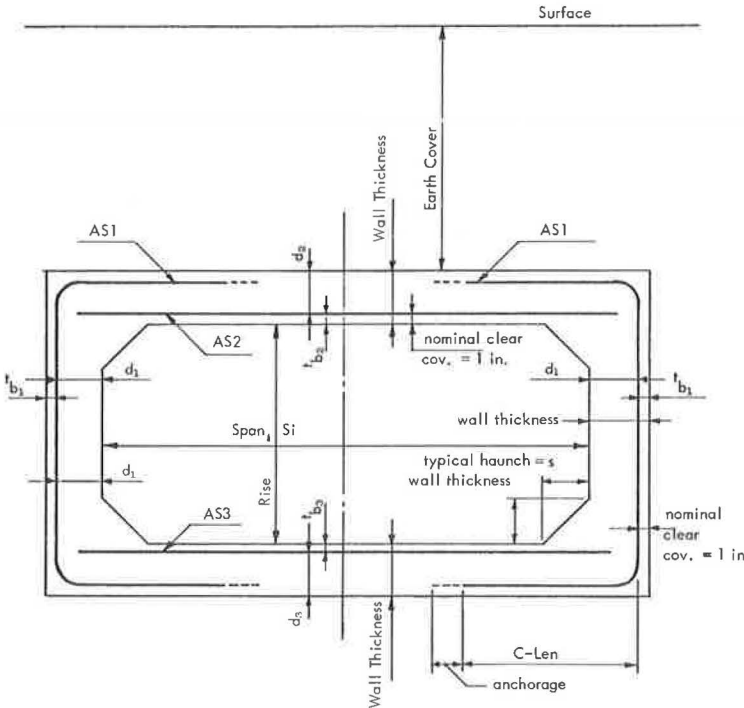




Figure 2. Test loading arrangement.

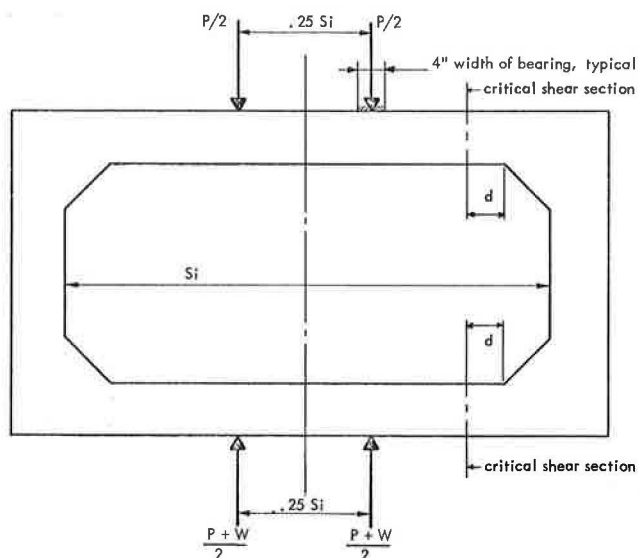


Table 2. Test results.

Box Culvert Mark	Design Earth Cover		Test for First Visible Crack Load		Test for 0.01-In. Crack Load			Test for Ultimate Load				Type of Failure Observed
	Interstate Truck Plus Earth Cover (ft)	No Truck (ft)			Top (lb/ft)	Bottom (lb/ft)	Minimum D-Load (psf)	Flexure		Diagonal Tension		
			P <sub>cr</sub> (lb/ft)	D-Load (psf)				P <sub>ult</sub> (lb/ft)	D-Load (psf)			
8x4-8A	8	12	5,500	690	9,250*	11,000	1,160	17,860	2,230			F
-8B			6,500	815	11,300*	13,000	1,420	17,230	2,150			F
-2A	2	18	6,000	750				29,690	3,710			F
-2B			7,000	880	12,300*	15,500	1,540			22,520	2,820	D.T.
-18A	18	21	7,500	940	13,000*	15,500	1,630			20,890	2,610	D.T.
-18B			7,000	880	15,000	13,500*	1,700			24,490	3,060	D.T.
6x4-10A	10	14	6,500	1,090		9,500*	1,590	16,100	2,660			F
-10B			6,800	1,135		9,500*	1,590	15,000	2,500			F
-2A	2	21	8,300	1,390		14,500*	2,430			19,400	3,230	D.T.
-2B			6,800	1,135		10,500*	1,760	25,250	4,210	25,250	4,210	F, D.T.
-22A	22	24	8,810	1,475		15,000*	2,510			25,680	4,280	D.T.
-22B			7,300	1,220	12,500*	14,500	2,090			21,150	3,530	D.T.
4x4-4A	4	12	5,300	1,335	6,700*	6,700*	1,690	8,980	2,245			F
-4B			4,300	1,085	6,000*	7,000	1,510	8,440	2,110			F
-18A	18	20	5,800	1,465	7,000*	7,000*	1,770	13,150	3,290			F
-18B			5,500	1,385	8,000*	8,500	2,010	13,170	3,290			F
-2A	2	28	5,000	1,265	7,800*	7,800*	1,980			14,080	3,520	D.T.
-2B			5,300	1,335	8,500*	8,500*	2,140	19,300	4,830			F

\*Lowest test 0.01-in. crack load.

produce a 0.01-in. crack in the top or bottom slab under the test load arrangement may be determined from the following equations, which are based on the maximum bending moments shown in Figure 3.

$$P_{0.01 \text{ calc}} = C_1 A_s d f_{s,0.01} - C_2 W \quad (2)$$

where

$C_1 = 139$  for  $4 \times 4$  culverts,  $107$  for  $6 \times 4$  culverts, and  $89$  for  $8 \times 4$  culverts and  $C_2 \approx 0.9$  for 0.01-in. crack in bottom slab and  $0.2$  for 0.01-in. crack in top slab,

or

$$f_{s,0.01} = \frac{65}{\sqrt[3]{t_b^2 s_g}} + 5 \quad (1)$$

or  $f_y$ , whichever is less.

Values for  $P_{0.01 \text{ calc}}$  were calculated for all test culverts by using Eqs. 1 and 2 and the actual measured values for wall thickness, concrete cover thickness, and steel area. Test and calculated 0.01-in. crack loads are given in Table 3.

For the entire 18 test specimens of the culvert test program, the average  $P_{0.01 \text{ test}}/P_{0.01 \text{ calc}} = 1.29$ . The coefficient of variation is 34 percent, and the standard deviation is 0.43. If the two specimens with the lowest steel areas for each size culvert are excluded from the statistical analysis, for the 12 remaining specimens the average  $P_{0.01 \text{ test}}/P_{0.01 \text{ calc}} = 1.08$ . The coefficient of variation is 14 percent, and the standard deviation is 0.15. Figure 4 graphically shows this comparison.

The test results show that the design equations give a low (i.e., very conservative) estimate of 0.01-in. crack strength for lightly reinforced culverts. This probably occurs because, for these structures, the 0.01-in. crack strength is not much greater than the first visible crack strength and the concrete flexural strength between cracks significantly reduces the average stress in the reinforcement. A similar phenomenon was observed in pipe tests (7), and the semiempirical equation for a 0.01-in. crack strength of pipe (7) contains a term reflecting the contribution of flexural concrete strength between cracks. This term is most significant for lightly reinforced pipe.

Excluding the lightly reinforced test specimens, the correlation between test and calculated 0.01-in. crack strength is good, and the coefficient of variation is typical of statistical variation for 0.01-in. crack strength obtained in many pipe tests (7, 8).

#### Evaluation of Design Methods for Ultimate Strength

The ultimate strengths that were obtained in the test culverts are compared with the corresponding calculated strengths in both flexure and diagonal tension for the test load arrangement. This provides an evaluation and verification of the design methods.

The ultimate flexural strength is determined by using two assumptions from the plastic theory of reinforced concrete behavior:

1. The critical flexural sections are underreinforced. At the sections of maximum bending moment, welded wire fabric reinforcing can be stressed to its ultimate tensile strength without failure of concrete in compression.

2. The ductility of the underreinforced sections of maximum bending moment with welded wire fabric reinforcing causes flexural failure to occur by tensile rupture of the steel reinforcing at one or more sections of maximum bending moment. This occurs only after plastic hinges have formed at the sections of maximum bending moment at the bottom midspan and sidewall exteriors, or top midspan and sidewall exteriors. The shear and bending moment diagrams are shown in Figure 5 for the test load arrangement.

The first assumption is the standard basis for calculating ultimate bending strength (2, 3) except that, for welded wire fabric reinforcing, the ultimate strength of the steel

Figure 3. Load, shear, and bending moment diagrams for test load.

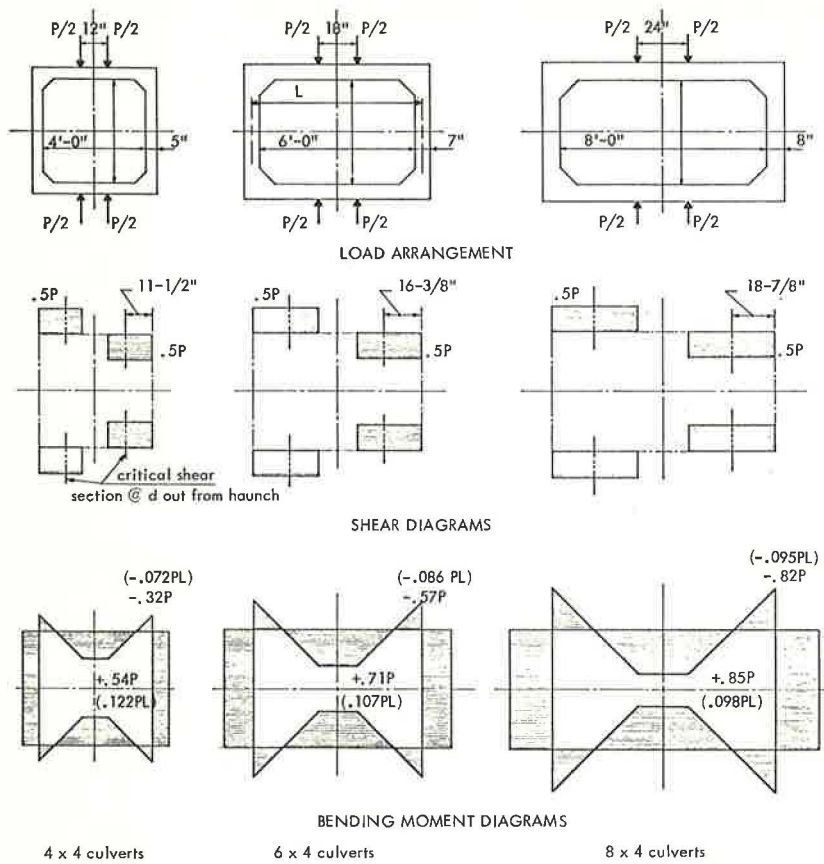


Table 3. Comparison of test and calculated 0.01-in. crack strengths.

Box Culvert Mark	Test		Calculated				
	$P_{0.01 \text{ test}}$ (lb/ft)	$f_{s0.01}^*$ (ksi)	Top $P_{0.01 \text{ calc}}$ (lb/ft)	$f_{s0.01}^*$ (ksi)	Bottom $P_{0.01 \text{ calc}}$ (lb/ft)	$f_{s0.01}^*$ (ksi)	$\frac{P_{0.01 \text{ test}}}{P_{0.01 \text{ calc}}}$
8x4-8A	9,250 T <sup>c</sup>	54.6	7,840	46.7	6,570	49.4	1.18
-8B	11,300 T	62.5	9,430	52.7	6,400	49.4	1.19
-2A	14,000 B <sup>2</sup>	61.8	10,540	43.9	10,950	50.3	1.29
-2B	12,300 T	48.6	12,360	48.8	9,410	46.2	1.00
-18A	13,000 T	41.8	15,650	50.0	12,550	47.2	0.83
-18B	13,500 B	50.1	13,940	45.9	13,442	50.0	1.00
6x4-10A	9,500 B	71.4	8,743	54.8	5,830	48.2	1.62
-10B	9,500 B	69.9	7,640	49.7	6,220	49.7	1.53
-2A	14,500 B	73.9	14,900	54.4	10,640	56.4	1.36
-2B	10,500 B	55.8	11,610	45.4	10,640	56.4	0.99
-22A	15,000 B	61.1	14,410	53.8	12,510	52.1	1.20
-22B	12,500 T	49.4	11,090	44.0	12,510	52.1	1.13
4x4-4A	6,700 B	97.0 <sup>d</sup>	2,760	41.8	2,740	47.2	2.45
-4B	6,000 T	87.9 <sup>d</sup>	2,700	41.3	2,020	41.8	2.22
-18A	7,000 B	56.5	6,220	49.8	7,770	62.0	0.90
-18B	8,000 T	59.7	7,090	53.1	5,740	51.3	1.13
-2A	7,800 B	51.6	6,690	40.4	6,940	46.6	1.12
-2B	8,500 B	52.0	6,600	41.3	8,380	51.4	1.01

\*Test  $f_{s0.01}$  is the calculated reinforcing stress in the top or bottom slab, whichever governs, for the test 0.01-in. crack load.

<sup>b</sup>Calculated  $f_{s0.01}$  is the reinforcing stress (Eq. 2) that determines  $P_{0.01 \text{ calc}}$ .

<sup>c</sup>T = top and B = bottom. They denote slab location where first 0.01 in. crack occurred.

<sup>d</sup>Yield strength of wire equals 78.5 ksi.

Figure 4. Comparison of test and calculated 0.01-in. crack strengths.

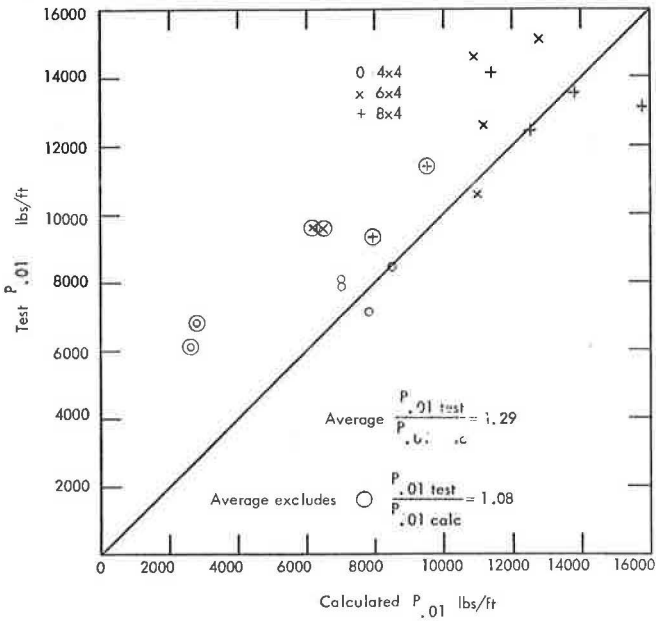
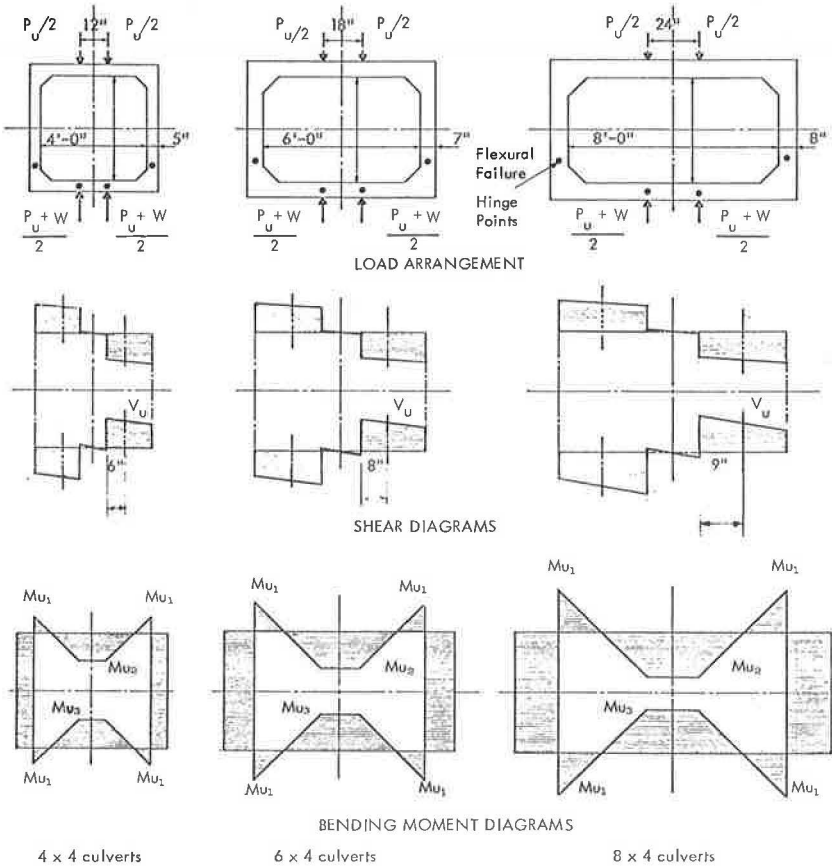


Figure 5. Load, shear, and bending moment diagrams for ultimate test load.





is used instead of the yield strength. This assumption is confirmed by the tensile rupture of reinforcing attained in the box culvert test specimens that failed in flexure. It is also confirmed by the results of many pipe tests (7). The ultimate tensile strength is used only for comparison of calculated and measured strengths in the test program and is not used for design of standard culverts. The more conservative yield strength is used as the maximum reinforcing strength for ultimate strength design of the standard box culverts.

The second assumption is based on the observed behavior of pipe that is reinforced with welded wire fabric and that fails in flexure (6, 7, 8). Some of the box culverts that failed in flexure showed the same behavior, namely, rupture or near rupture of both inner reinforcing at the midspan and outer reinforcing at sidewall locations at the time of failure.

The load to produce ultimate flexural failure for the test load arrangement is determined from the following equations, which are based on the ultimate flexural theory and the assumptions explained above.

$$P_{uf \text{ calc}} = \frac{4(M_{us} + M_{ul})}{(0.75 S_i + 2)} - C_s W \quad (3)$$

$$M_{un} = A_{sn} f_{sun} (d_n - a_n/2) \quad (4)$$

$$a_n = \frac{f_{sun} A_{sn}}{10.2 f_c} \quad (5)$$

Calculate for sections with  $n = 3$  and  $1$ , or  $2$  and  $1$  of Figure 1 (i.e., use of values of  $A_{s1}$ ,  $f_{su1}$ ,  $d_1$ , and  $a_1$  for section 1) where  $C \approx 0.9$  for bottom slab failure and  $0.2$  for top slab failure.

Values for  $P_{uf \text{ calc}}$  were calculated for all test culverts by using Eqs. 3, 4, and 5 and the actual measured values for wall thickness, concrete cover thickness, steel area, steel ultimate tensile strength, and concrete ultimate compressive strength (based on cores). Test and calculated ultimate flexural loads are given in Table 4 for culverts that failed in flexure, and Figure 6 graphically shows this comparison.

For the 10 test specimens that failed in flexure, the average  $P_{uf \text{ test}}/P_{uf \text{ calc}} = 1.03$ . The coefficient of variation and the standard deviation are both 6 percent.

The load calculated to produce ultimate diagonal tension (shear) failure for the test load arrangement is determined from the following equation:

$$P_{udt \text{ calc}} = 48 d_n f_c - C_4 W \quad (6)$$

where  $C_4 \approx 0.9$  for bottom slab failure and  $0.2$  for top slab failure.

Values for  $P_{udt \text{ calc}}$  were calculated (by using Eq. 5) for (a) all test culverts, (b) actual measured values for wall thickness, (c) cover thickness, and (d) concrete compressive strength. Test and calculated ultimate diagonal tension loads are compared in Table 4 for culverts that failed in diagonal tension, and Figure 7 graphically shows this comparison.

For the 8 test specimens that failed in diagonal tension, the average  $P_{udt \text{ test}}/P_{udt \text{ calc}} = 1.02$ . The coefficient of variation and the standard deviation are both 12 percent. Both comparisons (tested and calculated for flexure and shear failure) show excellent correlations and are typical of other pipe tests (7, 8).

### Evaluation of Standard Box Culvert Designs

The test results may be used for a direct evaluation of standard culvert designs (1) by determining the test loads that represent the equivalent design earth load in the test arrangement and the required ultimate test load in the test arrangement.

Shear and bending moment diagrams are shown in Figure 8 for uniformly distributed vertical pressure on the top slab and reaction on the bottom slab and are shown in Figure 9 for a uniformly distributed lateral load on each side equal to  $1/3$  the vertical

Table 4. Comparison of test and calculated ultimate strengths.

Box Culvert Mark	Flexural Failure			Diagonal Tension Failure		
	$P_{uf\ test}$ (lb/ft)	$P_{uf\ calc}$ (lb/ft)	$\frac{P_{uf\ test}}{P_{uf\ calc}}$	$P_{dt\ test}$ (lb/ft)	$P_{dt\ calc}$ (lb/ft)	$\frac{P_{dt\ test}}{P_{dt\ calc}}$
8x4-8A	17,860	16,050	1.11		34,430*	
-8B	17,230	15,780	1.09		21,582	
-2A	29,690	28,200	1.05		20,120	
-2B		27,750		22,520	21,520	1.05
-18A		31,800		20,890	21,590	0.97
-18B		31,830		24,490	22,860	1.07
6x4-10A	16,100	15,380	1.05		22,170	
-10B	15,000	15,390	0.98		23,360	
-2A		28,690		19,400	23,420	0.83
-2B		28,990		25,250	23,950	1.05
-22A		26,690		25,680	21,260	1.21
-22B		26,700		21,150	23,530	0.90
4x4-4A	8,980	9,800	0.92		14,900	
-4B	8,440	9,011	0.94		14,260	
-18A	13,150	12,680	1.04		16,350	
-18B	13,170	12,730	1.03		14,670	
-2A		17,290		14,080	12,790	1.10
-2B	19,300	18,510	1.04		14,670	

\*Abnormal core strength causes high calculated results.

Figure 6. Comparison of test and calculated ultimate flexural strengths.

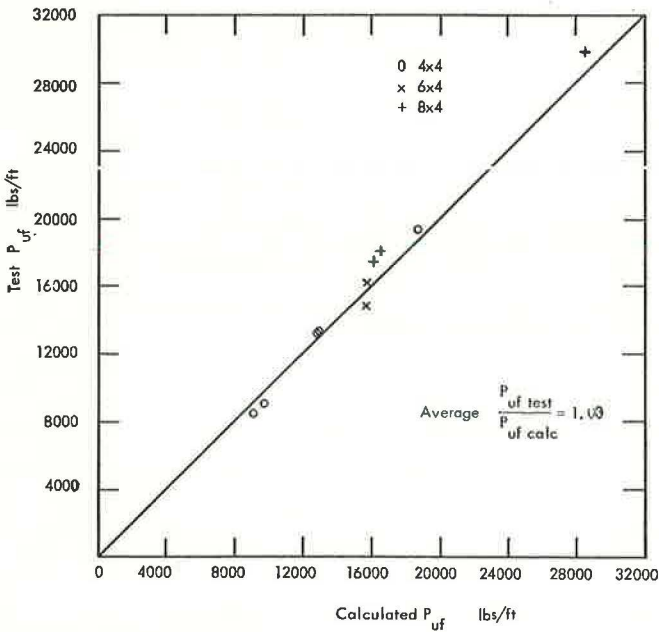


Figure 7. Comparison of test and calculated ultimate diagonal tension strengths.

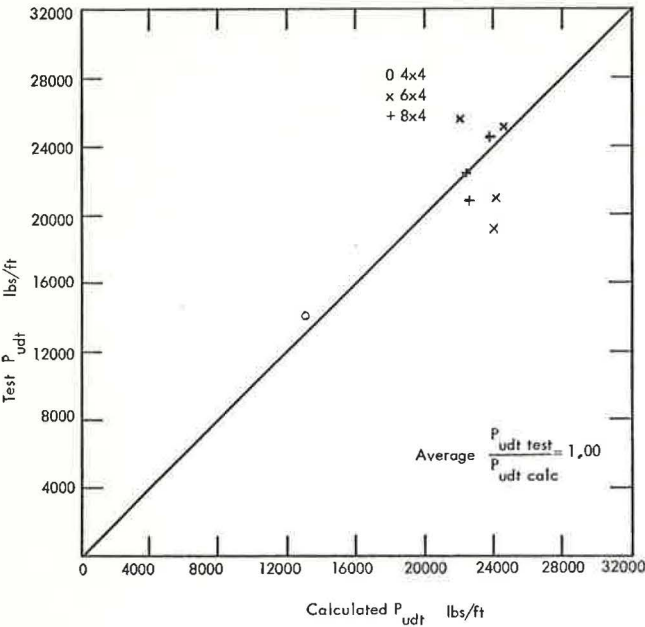


Figure 8. Load, shear, and bending moment for culvert subjected to uniform vertical earth load.

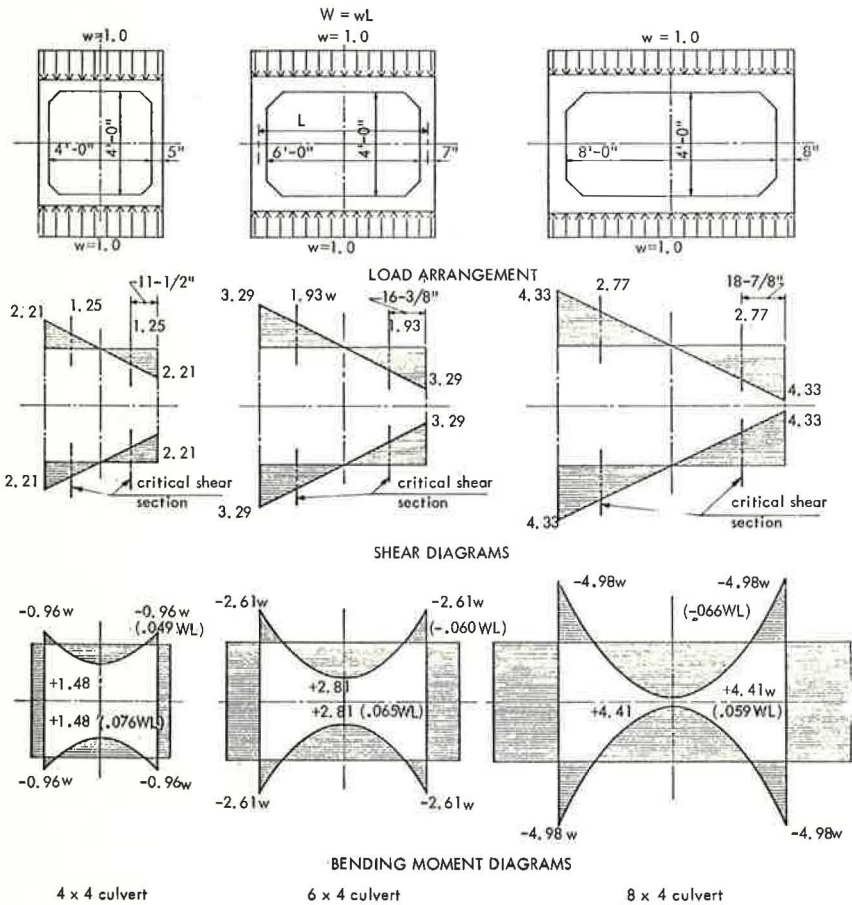


Figure 9. Load, shear, and bending moment for culvert subjected to uniform lateral earth load.

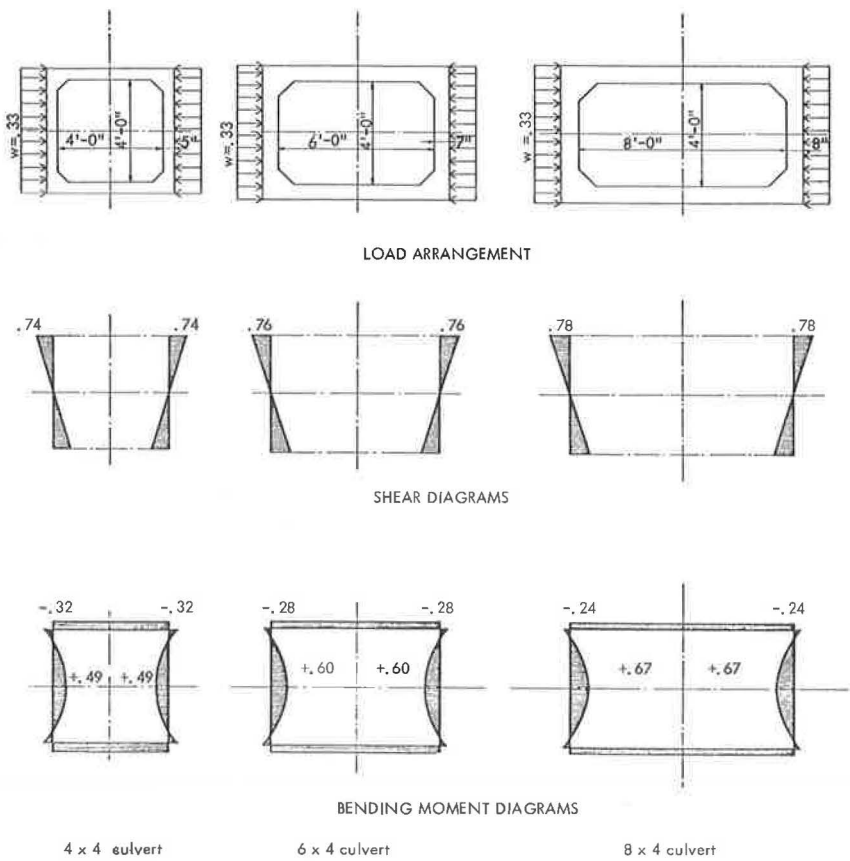


Table 5. Comparison of test and design loads.

Box Culvert Mark	Design Earth Cover		Minimum Calculated Ultimate Load <sup>d</sup>							Type of Failure Observed					
	Interstate Truck Load (ft)	No Truck Load <sup>a</sup> (ft)	P <sub>test</sub> <sup>b</sup> (lb/ft)	P <sub>0.01 test</sub> (lb/ft)	$\frac{P_{test}}{P_{0.01 test}}$	P <sub>0.5 test</sub> <sup>c</sup> (lb/ft)	P <sub>0.9 test</sub> (lb/ft)	$\frac{P_{0.5 test}}{P_{0.9 test}}$	P <sub>ult calc</sub> (lb/ft)		P <sub>ult test</sub> (lb/ft)	$\frac{P_{ult test}}{P_{ult calc}}$	P <sub>cr</sub> (lb/ft)	$\frac{P_{cr}}{P_{test}}$	
8x4-8A -8B -2A -2B	8	12	7,110	9,300	1.31	11,950	18,000	1.51	13,400	20,800	F	1.34	—	5,500	0.77
				11,300	1.59		17,400	1.46			1.30	—	6,500	0.91	
	2	18	10,660	14,000	1.31	17,930	30,000	1.67	21,600	20,800	F	1.39	—	6,000	0.56
				12,300	1.15		22,800	1.27			D.T.	—	1.10	7,000	0.66
-18A -18B	18	21	12,440	13,000	1.05	20,920	21,000	1.00	24,200	20,800	D.T.	—	1.01	7,500	0.60
				13,500	1.08		24,800	1.19			D.T.	—	1.19	7,000	0.56
	10	14	6,020	9,500	1.58	9,750	16,100	1.65	10,600	18,100	F	1.52	—	6,500	1.08
				9,500	1.58		15,000	1.54			F	1.42	—	6,800	1.13
6x4-10A -10B -2A -2B -22A -22B	2	21	9,030	14,500	1.61	14,620	19,500	1.33	16,100	18,100	F, D.T.	—	1.07	8,300	0.92
				10,500	1.16		25,500	1.74			F, D.T.	—	1.41	6,800	0.75
	22	24	10,320	15,000	1.45	16,700	25,800	1.54	19,100	18,100	D.T.	—	1.43	8,800	0.85
				12,500	1.21		21,400	1.28			D.T.	—	1.18	7,300	0.71
4x4-4A -4B -18A -18B -2A -2B	4	12	3,090	6,800	2.20	5,470	9,100	1.66	7,100	12,200	F	1.28	—	5,300	1.71
				6,000	1.94		8,600	1.57			F	1.21	—	4,300	1.39
	18	20	5,160	7,000	1.36	9,120	13,200	1.45	9,900	12,200	F	1.33	—	5,800	1.12
				8,000	1.55		13,200	1.45			F	1.33	—	5,500	1.07
Average	2	28	7,220	7,800	1.08	12,770	14,200	1.11	13,600	12,200	D.T.	—	1.16	5,000	0.69
				8,500	1.18		19,500	1.53			F	1.43	—	5,300	0.73
					1.41			1.44			1.36	1.19			

<sup>a</sup>Used for design loading condition with unit weight of fill equal to 120 pcf.

<sup>b</sup>Total test load that produces the same midspan bending moment in the test culvert as the design earth fill height produces in a buried culvert. Load from design fill height is taken as the weight of a column of 120 pcf earth having same width as culvert. The effect of side pressure equal to  $\frac{1}{3}$  the

top pressure is included in determining the proper equivalent bending moment for test specimen. The bending moment in the test culvert is for loads and supports as arranged in Figure 2.

<sup>c</sup>1.5 times the total weight of 120 pcf earth cover (with no truck) between critical shear points located at distance  $d$  out from haunch.

<sup>d</sup>Based on  $f_{cu} = 75,000$  psi and  $f'_c = 5,000$  psi.



pressure. The midspan bending moments in Figure 3 for test loads and in Figures 8 and 9 for field loads are equated to obtain the test load, which is equivalent to the design earth fill height.

Design earth fill heights and  $P_{des}$  are given in Table 5 for each test culvert. These equivalent design loads are compared with  $P_{0.01\ test}$  in the table. The average  $P_{0.01\ test}/P_{des} = 1.41$ . All test culverts exhibited a higher test 0.01-in. crack load than the test load that produces the same maximum slab bending moment as the design earth fill height. A graphical comparison of  $P_{0.01}$  and  $P_{des}$  is shown in Figure 10.

The required minimum ultimate load for the design earth fill height is the test load that equals 1.5 times the weight of a column of 120-pcf earth extending between the critical shear sections on each side of the top slab. The critical shear section is at distance  $d$  into the slab from the edge of the haunch on each side. The spacing of test loads (Fig. 2) was established to obtain the same ratio of midspan positive moment to shear at the critical section in the test specimen as the ratio that occurs in a similar buried culvert. The moment in the buried culvert is the slab midspan positive moment caused by uniform vertical loads only. Thus, the ultimate load for design earth fill height produces both the same shear at a critical section  $d$  out from the haunches and the same midspan positive moment in the test culvert as 1.5 times the design earth fill height produces in the buried culvert (not accounting for the effect of side pressure).

Test loads equivalent to  $P_{u\ des}$  are given in Table 5 for each test culvert and compared with  $P_{u\ test}$ . The average  $P_{u\ test}/P_{u\ des} = 1.44$ . All test culverts had a higher test ultimate load than the required  $P_{u\ des}$ . A comparison of  $P_{u\ test}$  and  $P_{u\ des}$  is graphically shown in Figure 11.

## CONCLUSIONS

The test program results verify that the proposed design method provides satisfactory designs for precast concrete box culverts within the range of earth fill heights and culvert dimensions used for standard designs (1). They also provide a direct verification of the adequacy of nine standard designs, which cover the range of strength and dimensions of proposed standard designs.

The results show that there is additional reserve ultimate strength capacity of at least 15 percent above the 1.5 ultimate strength load factor used for standard designs that are governed by flexural ultimate strength. This is because the ultimate tensile strength of the steel is developed before flexural failure occurs. Because the standard designs with welded wire fabric reinforcing are based on a maximum steel stress equal to the 65,000-psi minimum yield strength of the wire and the wire has a specified minimum ultimate tensile strength of 75,000 psi, the additional ultimate flexural capacity of the culverts is at least the ratio of these strengths times the design ultimate flexural capacity.

This additional reserve capacity is not available for those designs near the upper end of the design fill heights because their strength is governed by diagonal tension failure; however, the test results show that the proposed design method provides the 1.5 specified load factor.

The test results also show that the proposed equations for determining the maximum wire spacing for crack control give increasingly conservative results as reinforcing reduced toward the low end of the range of proposed heights of earth fill. This occurs because, for these designs, the tensile strength of the concrete between cracks contributes a significant resistance to flexural deformation between cracks and reduces the crack width. However, for more heavily reinforced designs, the contribution of concrete tensile strength between cracks is much less significant. From a practical point of view, the design method already shows that wire spacing is not a critical parameter in lightly reinforced designs; therefore, the conservatism does not result in a penalty in practical design. Further research would probably show that a modified 0.01-in. crack equation for pipe (7, 8), which takes into account tensile resistance of concrete between cracks, would probably provide a better correlation of test and calculated 0.01-in. crack strength. However, such a development is not necessary for practical design of box culverts.

Figure 10. Comparison of test loads and design loads.

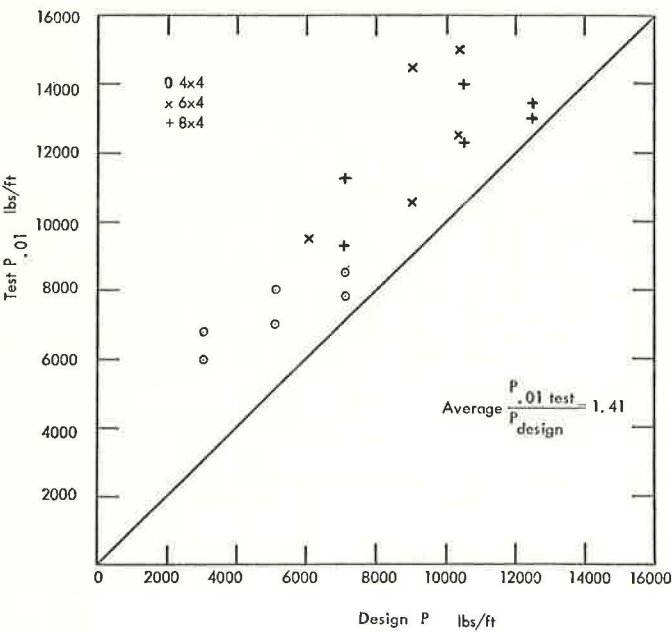
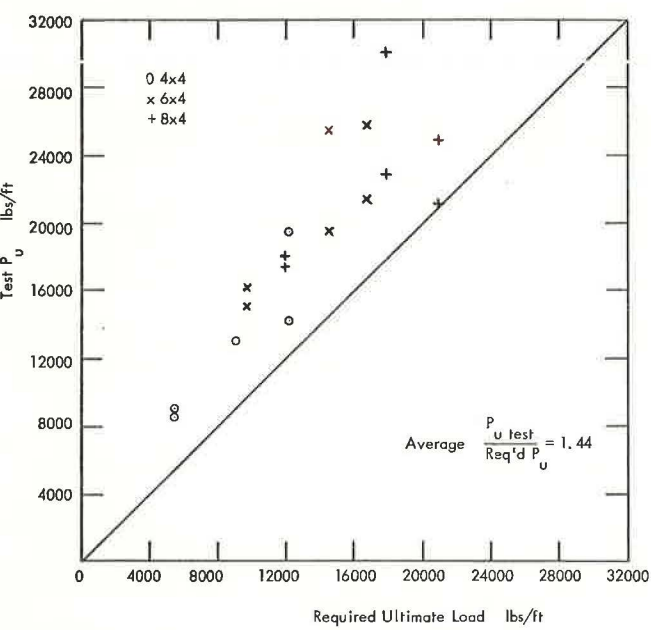


Figure 11. Comparison of test loads and required ultimate load.



Both the ultimate strength and crack control design methods proposed (1) for box culvert design are based on the current ACI code for reinforced concrete design, which is widely accepted without verification of specific applications by tests.

#### ACKNOWLEDGMENTS

This research was supported by the American Concrete Pipe Association. The contributions of the Wire Reinforcement Institute, Concrete Pipe Products Company, Inc., Gifford-Hill Pipe Company, Hydro Conduit Corporation, and Armco Steel Company are also recognized.

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