BOND STRENGTH OF WELDED WIRE FABRIC IN CONCRETE BRIDGE DECKS

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ABSTRACT: The bond strength of welded wire fabric (WWF) in concrete bridge decks was investigated by testing 22 pullout specimens for bond strength up to their ultimate capacity. The pullout study showed that after the bond between longitudinal wires and concrete failed, the specimens resisted additional loads due to the anchorage effects of transverse wires and shear strength of welds. This increase in bond strength ranged from 16 to 771%, depending upon the type and arrangement of longitudinal and transverse wires. The transverse wires and shear strength of the weld, therefore, make large contributions to the bond strength of the welded wire fabric in concrete bridge decks.

INTRODUCTION

The bond strength of welded wire fabric (WWF) is an important structural property of WWF in the design of WWF-reinforced bridge decks. The objective of this study is to investigate the factors that affect the bonding strength of WWF in bridge decks. To investigate the effects of different factors on the bond strength of WWF-reinforced bridge decks, a literature review was carried out. The reviewed references included Atlas et al. (1962) and (1964); Donahey and Darwin (1982); Menzel (1952); Watstein and Mathey (1961); "Bond Stress—the State of the Art," by the American Concrete Institute, Committee 408 (1966); Ferguson et al. (1965); and Ferguson and Thompson (1962). These studies reported that the bond strength of WWF depends on concrete srength, size of longitudinal wires, size of transverse wires, and weld shear strength, which is affected by penetration depth at the welds. In addition, concrete slump, vibration of freshly poured concrete, and temperature can have some secondary effect on the bond strength.

A pullout experimental program and an analytical study were performed to investigate the bond strength of WWF in bridge decks. The factors that were considered in the pullout study included penetration and strength of welds between transverse and longitudinal wires; size of transverse wires; number of adjacent longitudinal wires; number of adjacent longitudinal wires, transverse wires, and weld strength; and using bundled longitudinal wires. The results of the pullout study are presented in the form of bond strength, and percent increase in bond strength due to the different factors.

EXPERIMENTAL PROGRAM

Test Specimens for Bond

To study the bond strength of WWF in bridge decks, a total of 22 pullout specimens were tested. They consisted of 14 specimens with US epoxy-coated WWF, and eight with German WWF. The WWF wires used in the specimens met ASTM standard specifications for deformed-steel welded wire fabric for concrete reinforcement (1986).

The dimensions and wire arrangements of the different pullout specimens are shown in Figs. 1 and 2. The specimens containing the U.S. WWF used D12 × D12 wires spaced 3 in. (76 mm) longitudinally and 4 in. (102 mm) laterally, i.e., 3 × 4 in. (76 × 102 mm); while those made from German WWF used D12 × D12 wires spaced at 4 × 4 in. (102 × 102 mm) with bundled longitudinal wires. For each specimen, the mechanical anchoring contribution of the wires due to the weld between the transverse and longitudinal wires on the bond strength was determined by breaking the bond between the concrete and the wires using an unbonding tape around the wires. The contribution of bonding of the transverse wire and the weld to the pullout strength was also studied by using a bonded transverse wire and an unbonded longitudinal wire. To reduce the effect of the compression zone near the supported surface of the specimens on the pullout results, the bond for the first 2 in. (51 mm) for the loaded end of the longitudinal wire for all the specimens was broken by taping.

The 22 pullout specimens were tested at an age of 28 days. Loading was applied at a rate of 10 lb/s (44.5 N/s). A dial gage was used to record the free-end slip of the protruding top end of the longitudinal wire. The loads at first slip of the top end of the longitudinal wire, and at failure of the pullout specimen were recorded. The load at first slip is the load at which the bond between the concrete and the wire completely breaks. In addition, control concrete cylinders were tested in compression according to the ASTM

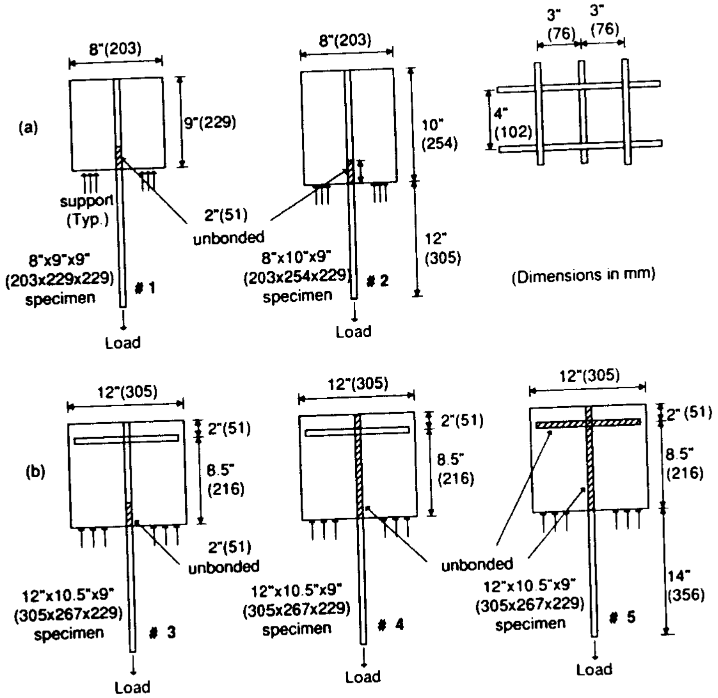

FIG. 1. Pullout Specimen from 3 × 4 in. (76 × 102 mm) U.S. Welded Wire Fabric

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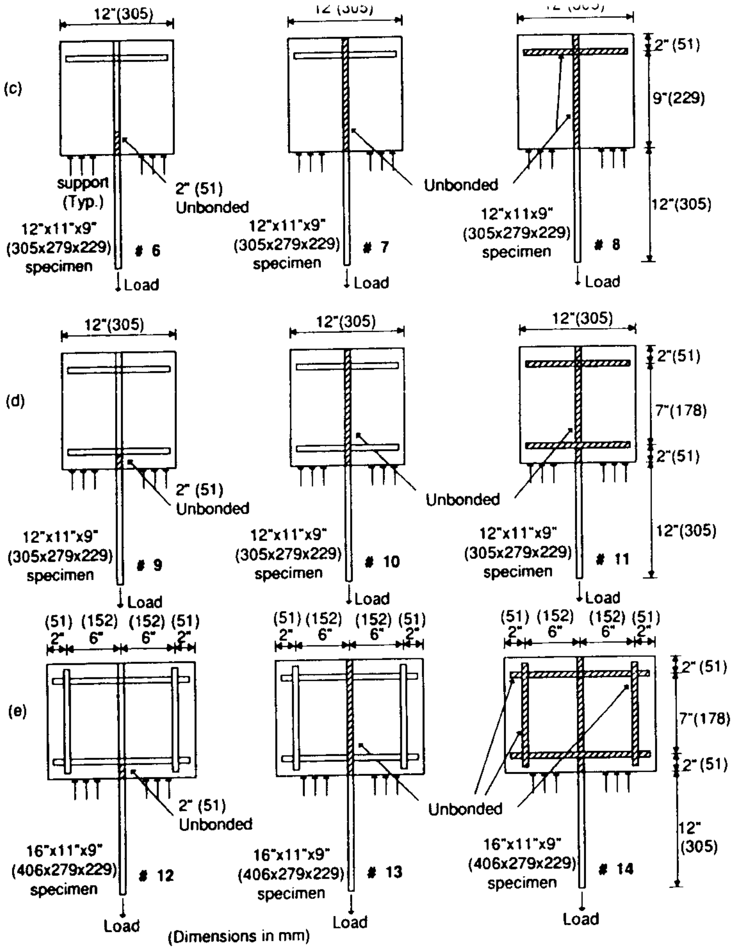

FIG. 1. *Continued*

specifications (*Test method for compressive* 1986), which resulted in an average concrete compression strength of 4,627 psi (31.91 MPa) with a standard deviation of 347 psi (2.39 MPa). Other concrete control cylinders were tested in tension according to the ASTM specifications (*Test method for splitting* 1986), which resulted in an average splitting strength of 600 psi (4.14 MPa) with a standard deviation of 24 psi (0.17 MPa).

Test Specimens for Weld Shear Strength

The shear strength of welds was measured by testing nine specimens, using a weld tester in accordance with ASTM specifications (*Steel, welded wire fabric, plain* 1986). The specifications require an average shear stress not less than 35,000 psi (241.3 MPa). The dimensions of the nine test specimens made from U.S. epoxy-coated WWF and the respective weld properties are shown in Table 1.

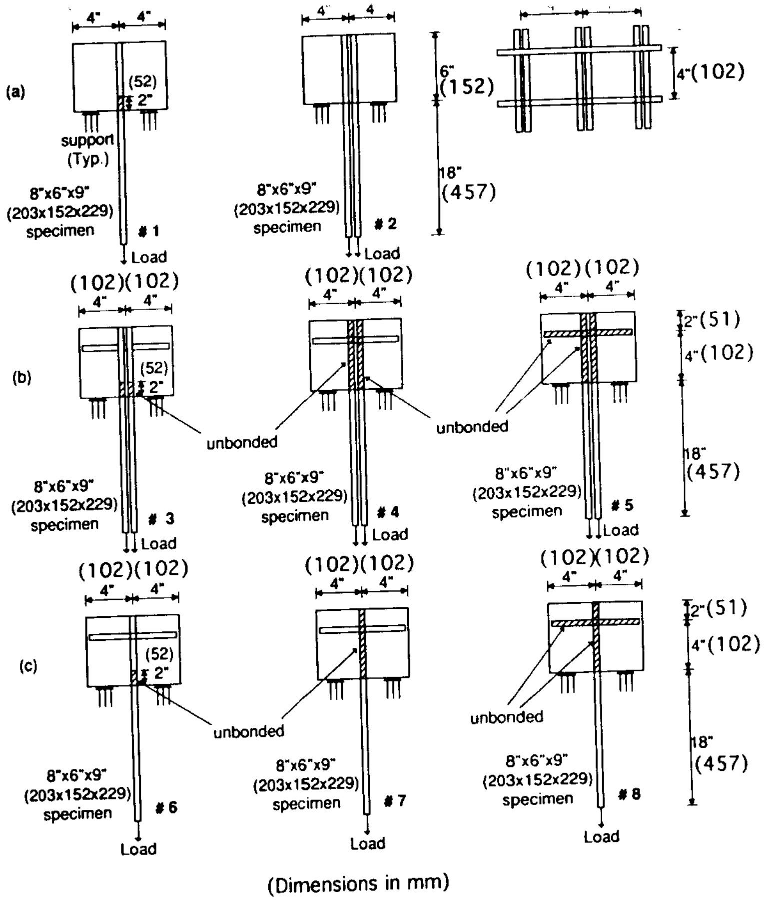

FIG. 2. **Pullout Specimen from 4 × 4 in. (102 × 102 mm) German Welded Wire Fabric**

ANALYSIS

Bond is defined as the adhesion between the reinforcement and the surrounding concrete. Thus, a bond failure is caused by a failure in this adhesion, giving an ultimate bond strength (Perry et al. 1966; Mirza et al. 1979; Ferguson et al. 1965). The stresses in a longitudinal wire of WWF embedded in concrete were calculated at the first-slip load and the ultimate failure load. The stresses in the longitudinal wires were calculated as

$$\sigma = \frac{P}{A_b} \tag{1}$$

where σ = stress in a longitudinal wire; P = applied load; and A_b = cross-sectional area of the longitudinal wire. The calculated values are shown in columns (6) and (7) of Tables 2 and 3 for the U.S. and German WWF specimens. The ultimate bond stress can be obtained by dividing the load

TABLE 1. Weld Shear Test Specimen Dimensions for U.S. Epoxy-Coated Welded Wire Fabric

Specimen number (1)	Weight lb (g) (2)	Length in. (mm)			Calculated diameter in. (mm) (6)	Thickness[c] at weld in. (mm) (7)	Penetration[d] in. (mm) (8)	Reduction in diameter (%) (9)
		A[a] (3)	B[b] (4)	Total (5)				
1	0.4583 (207.9)	5.556 (141)	7.502 (191)	13.058 (332)	0.3968 (10.1)	0.734 (18.6)	0.0596 (1.51)	7.51
2	0.4636 (210.3)	5.640 (143)	7.510 (191)	13.150 (334)	0.3977 (10.1)	0.701 (17.8)	0.0944 (2.40)	11.87
3	0.4475 (203.0)	5.446 (138)	7.250 (184)	12.696 (322)	0.3977 (10.1)	0.706 (17.9)	0.0894 (2.27)	11.24
4	0.4522 (205.1)	5.565 (141)	7.259 (184)	12.824 (325)	0.3977 (10.1)	0.736 (18.7)	0.0594 (1.51)	7.47
5	0.4489 (203.6)	5.230 (133)	7.494 (190)	12.724 (323)	0.3978 (10.1)	0.689 (17.5)	0.1066 (2.71)	13.40
6	0.4700 (213.2)	5.875 (149)	7.499 (190)	13.374 (339)	0.3971 (10.1)	0.683 (17.3)	0.1112 (2.82)	14.00
7	0.4466 (202.6)	5.104 (130)	7.547 (192)	12.651 (322)	0.3980 (10.1)	0.756 (19.2)	0.0400 (1.02)	5.03
8	0.4471 (202.8)	5.345 (136)	7.286 (185)	12.631 (321)	0.3985 (10.1)	0.707 (18.0)	0.0900 (2.29)	11.29
9	0.4478 (203.1)	5.195 (132)	7.550 (192)	12.745 (324)	0.3970 (10.1)	0.677 (17.2)	0.1170 (2.97)	14.74

[a] Longitudinal wire.

[b] Transverse wire.

[c] Thickness at weld which is the average of four readings.

[d] Penetration which is the difference between the diameter of the two wires before welding and the thickness at the weld.

at first slip of the longitudinal wire by the bonded nominal surface area of the reinforcing steel as follows:

$$\mu_b = \frac{P_s}{\pi D_b L_d}; \qquad \text{for single bars} \tag{2a}$$

and

$$\mu_b = \frac{P_s}{\pi(2D_b)L_d}; \qquad \text{for bundle of two bars} \tag{2b}$$

where μ_b = bond stress capacity; P_s = pullout load at first slip of the longitudinal wire; D_b = nominal diameter of the longitudinal wire; L_d = effective embedded length or development length. The ultimate bond stress can also be found in terms of the stress at first slip of the longitudinal wire using

$$\mu_b = \frac{f_s A_b}{\pi D_b L_d} = \frac{f_s D_b}{4L_d} \tag{3}$$

where f_s = longitudinal wire stress at first slip of the free-end; and A_b = cross-sectional area of the longitudinal wire.

TABLE 2. Pullout Test Results for 3 × 4 In. (76 × 102 mm) U.S. Welded Wire Fabric

Specimen number (1)	Diameter in. (mm) (2)	Penetration in. (mm) (3)	Load at first slip lb (N) (4)	Load at failure lb (N) (5)	Stress at first slip psi (MPa) (6)	Stress at failure psi (MPa) (7)	Order of failure modes (8)
1	0.395 (10.03)	0.091 (2.31)	6,000 (26,688)	8,150 (36,251)	48,940 (377)	66,476 (458)	Bond
2	0.396 (10.06)	0.091 (2.31)	7,500 (33,360)	8,800 (39,142)	60,877 (420)	71,778 (495)	Bond
3	0.396 (10.06)	0.106 (2.69)	7,900 (35,139)	12,900 (57,379)	64,019 (441)	104,538 (721)	Wire fracture
4	0.395 (10.03)	0.110 (2.79)	1,800 (8,006)	7,500 (33,360)	14,730 (102)	61,375 (423)	Bond, weld
5	0.397 (10.08)	0.105 (2.67)	1,000 (4,448)	6,450 (28,690)	8,078 (56)	52,100 (359)	Bond, weld
6	0.397 (10.08)	0.090 (2.29)	8,500 (37,808)	9,850 (43,813)	68,826 (475)	79,757 (550)	Bond, wire fracture
7	0.395 (10.03)	0.092 (2.34)	2,500 (11,120)	9,250 (41,144)	20,358 (140)	75,326 (519)	Bond, wire fracture
8	0.396 (10.06)	0.096 (2.44)	1,800 (8,006)	8,650 (38,475)	14,634 (101)	70,325 (485)	Bond, wire fracture
9	0.398 (10.11)	0.111 (2.82)	None	12,200 (54,266)	None	98,071 (676)	Wire fracture
10	0.395 (10.03)	0.103 (2.62)	3,500 (15,568)	10,500 (46,704)	28,548 (197)	85,644 (591)	Bond, weld
11	0.396 (10.06)	0.113 (2.87)	2,500 (11,120)	10,950 (48,706)	20,259 (140)	88,736 (612)	Bond, wire fracture
12	0.397 (10.08)	0.098 (2.49)	None	12,900 (57,379)	None	104,453 (720)	Wire fracture
13	0.397 (10.08)	0.091 (2.31)	5,500 (24,464)	9,300 (41,366)	44,355 (306)	75,000 (517)	Bond, wire fracture
14	0.396 (10.06)	0.101 (2.57)	4,000 (17,792)	11,850 (52,709)	32,520 (224)	96,341 (664)	Bond, wire fracture

The ultimate bond stresses in this study were calculated using (2), and are listed in Tables 4 and 5. In addition, an equivalent stress at failure of the pullout specimen was calculated using (2) by substituting the pullout load at failure for the pullout load at first slip. The equivalent bond stress shows the contribution of the deformation of the wires; the number and size of transverse wire; the weld shear strength; or the number of adjacent longitudinal wires. This contribution was indicated by the percent increase in bond stress after the adhesion between the reinforcement and the surrounding concrete had failed. Thus, the percent increase in bond stress is given by

$$\text{Percent increase in bond stress} = \frac{\mu_f - \mu_b}{\mu_b} \times 100 \tag{4}$$

where μ_f = equivalent bond stress at failure; μ_b = ultimate bond stress capacity or bond stress at first slip of the free end of the longitudinal wire. The percent-increase values are shown in column (6) of Tables 4 and 5.

TABLE 3. Pullout Test Results for 4 × 4 in. (102 × 102 mm) German Welded Wire Fabric

Specimen number (1)	Diameter in. (mm) (2)	Penetration in. (mm) (3)	Load at first slip lb (N) (4)	Load at failure lb (N) (5)	Stress at first slip psi (MPa) (6)	Stress at failure psi (MPa) (7)	Order of failure modes (8)
1	0.475 (12.07)	0.056 (1.42)	4,500 (20,016)	14,000 (62,272)	25,381 (175)	78,962 (544)	Bond
2	0.475 (12.07)	0.065 (1.65)	None	11,000 (48,928)	None	31,038 (214)	Concrete crushing
3	0.475 (12.07)	0.049 (1.24)	12,900 (57,379)	17,300 (76,950)	36,369 (251)	48,774 (336)	Bond, concrete crushing
4	0.475 (12.07)	0.087 (2.21)	5,500 (24,464)	14,200 (63,162)	15,524 (107)	40,079 (276)	Bond, concrete crushing
5	0.475 (12.07)	0.039 (0.99)	4,000 (17,792)	10,550 (46,926)	11,280 (78)	29,752 (205)	Bond, concrete crushing
6	0.475 (12.07)	0.046 (1.17)	5,500 (24,464)	14,800 (65,830)	31,056 (214)	83,569 (576)	Bond, concrete crushing
7	0.475 (12.07)	0.059 (1.50)	1,200 (5,338)	10,450 (46,482)	6,772 (47)	58,973 (407)	Bond, weld
8	0.475 (12.07)	0.050 (1.27)	950 (4,226)	6,800 (30,246)	5,364 (37)	38,396 (265)	Bond, concrete crushing

TEST RESULTS AND COMMENT

Bond

The diameter, cross-sectional area, penetration depth, load at first slip of the wires, and the load at failure for both the 3 × 4 in. (76 × 102 mm) U.S. WWF and the 4 × 4 in. (102 × 102 mm) German WWF are shown in Tables 2 and 3, respectively. For each specimen, the mode of failure is shown in column (8) of the corresponding tables. The following modes of failures were observed: (1) Bond failure; (2) bond failure followed by weld failure; (3) bond failure followed by fracture of the reinforcement; (4) bond failure followed by crushing the concrete; (5) crushing the concrete; (6) fracture of the reinforcement; and (7) crushing of concrete.

For the 3 × 4 in. (76 × 102 mm) U.S. WWF, the ultimate bond stress is shown in Table 4, and ranges from 691 to 758 psi (4.8 to 5.2 MPa) for the pullout specimens having bonded longitudinal wires. However, the specimens with unbonded longitudinal wires had a strength ranging from 94 to 490 psi (0.6 to 3.4 MPa) due to the presence of the transverse wires, the shear strength of the weld, or the presence of the adjacent longitudinal wires. After the initial slip of the longitudinal wires, the pullout specimens resisted an additional load due to the wires' deformed surfaces, the anchoring effect of the transverse wires, the weld shear strength, the adjacent longitudinal wires, or a combination of these factors. This increase in bond strength ranges from 16 to 545% as shown in Table 4.

The bond stresses for the 4 × 4 in. (102 × 102 mm) German WWF are shown in Table 5. It ranges from 754 to 1,080 psi (5.2 to 7.4 MPa) for pullout specimens having bonded longitudinal wires. For specimens having unbonded longitudinal wires, the bond stresses range from 159 to 461 psi (1.1 to 3.2 MPa), due to the anchoring effect of the transverse wires, and the weld shear strength. Two German WWF specimens, i.e., specimens 3 and 6, with bundled wires, had bond strengths of 1,080 and 922 psi (7.4 to 6.4 MPa), respectively. The increased bond stress can be attributed to the existence of the transverse wires, which added to the rigidity of the pullout specimens and the resistance of the longitudinal wire to slippage. Due to the wires' protruding deformation pattern and the larger diameter of the German WWF wires, almost all the German specimens failed by bond, followed by crushing of the concrete. The percent increase in bond stress, after the initial slippage of the longitudinal wires, ranges from 34 to 771%. This increase is due to the anchoring effect of the transverse wires, and the shear strength of the welds.

TABLE 4. Bond Strength for Pullout Specimen Using 3 × 4 in. (76 × 102 mm) U.S. Welded Wire Fabric

Specimen number (1)	Diameter in. (mm) (2)	L_d in. (mm) (3)	μ_b psi (MPa) (4)	μ_f psi (MPa) (5)	Increase in bond stress (%) (6)	Cause of percent increase (7)
1	0.395 (10.03)	7 (177.8)	691 (4.76)	938 (6.47)	36	Wire deformation
2	0.396 (10.06)	8 (203.2)	753 (5.19)	884 (6.10)	17	Wire deformation
3	0.396 (10.06)	8.5 (215.9)	746 (5.14)	1218 (8.40)	63	Wire deformation and transverse wire
4	0.395 (10.03)	8.5 (215.9)	171 (1.18)	713 (4.92)	317	Transverse wire and weld shear strength
5	0.397 (10.08)	8.5 (215.9)	94 (0.65)	606 (4.18)	545	Weld shear strength
6	0.397 (10.08)	9 (228.6)	758 (5.23)	878 (6.05)	16	Wire deformation and transverse wire
7	0.395 (10.03)	9 (228.6)	224 (1.54)	829 (5.72)	270	Transverse wire
8	0.396 (10.06)	9 (228.6)	161 (1.11)	774 (5.34)	381	Weld shear strength
9	0.398 (10.11)	9 (228.6)	None	1084 (7.47)	None	—
10	0.395 (10.03)	9 (228.6)	313 (2.16)	939 (6.47)	200	Transverse wire and weld shear strength
11	0.396 (10.06)	9 (228.6)	223 (1.54)	977 (6.74)	338	Weld shear strength
12	0.397 (10.08)	9 (228.6)	None	1150 (7.93)	None	—
13	0.397 (10.08)	9 (228.6)	490 (3.38)	829 (5.72)	69	Transverse wire and weld shear strength
14	0.396 (10.06)	9 (228.6)	357 (2.46)	1058 (7.29)	196	Weld shear strength

Note: L_d = effective embedded length or development length; μ_b = bond strength; and μ_f = equivalent bond stress capacity.

The bond strength, therefore, varied greatly among the investigated cases. Fig. 3 shows the ratio of the load at first slip of the pullout specimens to the load at first slip of a single wire. The figure shows that the pullout

TABLE 5. Bond Strength for Pullout Specimen Using 4 × 4 in. (102 × 102 mm) German Welded Wire Fabric

Specimen number (1)	Diameter in. (mm) (2)	L_d in. (mm) (3)	μ_b psi (MPa) (4)	μ_f psi (MPa) (5)	Increase in bond stress (%) (6)	Cause of percent increase (7)
1	0.475 (12.07)	4 (102)	754 (5.20)	2345 (16.17)	211	Wire deformation
2	0.475 (12.07)	4 (102)	None	922 (6.36)	None	Wire deformation
3	0.475 (12.07)	4 (102)	1080 (7.45)	1449 (9.99)	34	Wire deformation and transverse wire
4	0.475 (12.07)	4 (102)	461 (3.18)	1190 (8.21)	158	Transverse wire and weld shear strength
5	0.475 (12.07)	4 (102)	335 (2.31)	884 (6.10)	164	Weld shear strength
6	0.475 (12.07)	4 (102)	922 (6.36)	2481 (17.11)	169	Wire deformation and transverse wire
7	0.475 (12.07)	4 (102)	201 (1.39)	1750 (12.07)	771	Transverse wire
8	0.475 (12.07)	4 (102)	159 (1.10)	1140 (7.86)	617	Weld shear strength

Note: L_d = effective embedded length or development length; μ_b = bond strength; and μ_f = equivalent bond stress capacity.

strength increases due to the contributions of adjacent elements of the wire fabric, indicated by the increase in the pullout strength from left to right [A to E for 3× 4 in. (76 × 102 mm) U.S. WWF, and A to D for 4 × 4 in. (102 × 102 mm) German WWF in Fig. 3]. Since the bond strength increases as the number of adjacent elements increases, it is reasonable to project that when the number of elements increases (the case of a wide mesh), failure is not expected to be in bond but in one of the other failure modes including case 3 in Fig. 3, where the bond is eliminated.

Shear Strength of Welds

A total of nine specimens were used for the weld shear test. The diameters and weld penetrations for the specimens are shown in columns (6) and (8) of Table 1, respectively. The diameter was used to calculate the weld shear stress while the weld penetration provides an indication of the achieved weld level. The average penetration and percent reduction in diameter were 0.0853 in. (2.17 mm) and 10.7% with a standard deviation of 0.0265 in. (0.67 mm) and 3.34%, respectively.

The tested specimens passed the ASTM requirement of an average shear stress of at least 35,000 psi (241 MPa). The ratio of weld shear stress to the ASTM limit is shown in column (5) of Table 6, and ranges from 1.29 to 2.29. Comparing the weld penetrations in Table 1 with the weld shear loads in Table 6, it can be observed that the weld shear load increases with the increase in penetration.

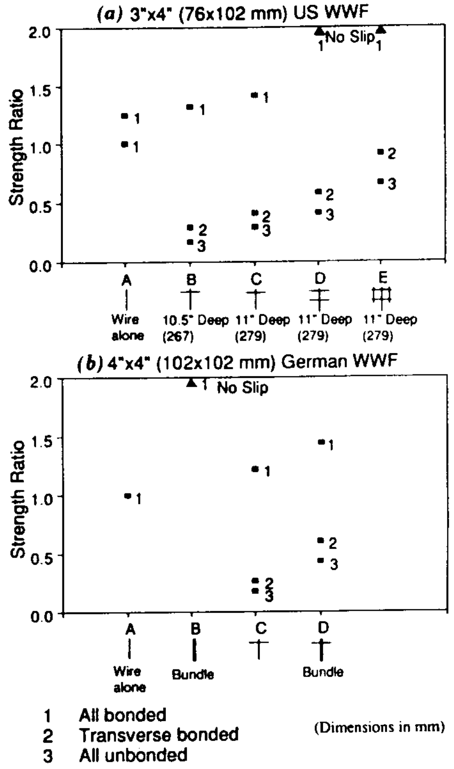

FIG. 3. Ratio of First Slip Load of Pullout Specimen to First Slip of Single Wire

SUMMARY AND CONCLUSIONS

The bond strength of welded wire fabric in concrete bridge decks was investigated by testing 22 pullout specimens for bond strength up to their ultimate capacity. Based on the experimental and analytical study of pullout specimens, the following can be concluded:

The pullout capacity of the WWF depends mainly on the bond strength between the WWF longitudinal wires, the anchorage effects of the transverse wires, and the shear strength of welds between the transverse and longitudinal wires. After the first slippage of the longitudinal wires, the load is resisted only by the transverse wires and the welds between the transverse and longitudinal wires.

The contribution of the adjacent longitudinal wires to the pullout resistance was very small, possibly because of the confining effect of surrounding concrete stiffness of transverse wires.

The majority of the pullout specimens failed by bond between the wires and concrete. Failures by splitting or crushing of concrete were the second most frequent type of failure.

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TABLE 6. Weld Shear Test Results for U.S. Epoxy-Coated Welded Wire Fabric

Specimen number (1)	Weld-shear load lb (N) (2)	Area of longitudinal wire, A_b, sq-in.^{2} (mm^2) (3)	Longitudinal-wire failure stress [column 2/ column 3] psi (MPa) (4)	Ratio of failure stress to ASTM requirement of 35,000 psi (241 MPa) (5)
1	5,750 (25,576)	0.124 (80.0)	46,483 (321)	1.33
2	8,690 (38,653)	0.124 (80.0)	69,968 (482)	2.00
3	7,200 (32,026)	0.124 (80.0)	57,971 (400)	1.66
4	6,000 (26,688)	0.124 (80.0)	48,309 (333)	1.38
5	8,520 (37,897)	0.124 (80.0)	68,544 (473)	1.96
6	9,360 (41,633)	0.124 (80.0)	75,606 (521)	2.16
7	5,620 (24,998)	0.124 (80.0)	45,177 (312)	1.29
8	7,600 (33,805)	0.125 (80.0)	60,946 (420)	1.74
9	9,920 (44,124)	0.124 (80.0)	80,129 (552)	2.29

APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A = length of longitudinal wire;
A_b = cross-sectional area of longitudinal wire;
B = length of transverse wire;
D_b = nominal diameter of longitudinal wire;
f_s = longitudinal wire stess at first slip;
L_d = effective embedded length or development length;
P = applied load;
P_s = pullout load at first slip of longitudinal wire;
μ_b = bond stress capacity or bond stress at first slip of longitudinal wire;
μ_f = equivalent bond stress at failure; and
σ = stress in longitudinal wire.