ACI STRUCTURAL JOURNAL TECHNICAL PAPER

Title no. 92-S72

A report on research sponsored by the Reinforced Concrete Research Council

Effects of Epoxy Coating on Anchorage and Development of Welded Wire Fabric

by Stacy J. Bartoletti and James O. Jirsa

The effects of epoxy coating on anchorage and development of welded wire fabric were investigated. The program included weld shear tests, pullout tests of bars with and without cross wires, and slab tests with splices in the welded wire fabric. Slabs containing spliced fabric were cast with no coating on the welded wire fabric for comparison with slabs cast with coated fabric.

Keywords: anchorage (structural); coatings; splicing; welded wire fabric.

Welded wire fabric (WWF), which has been in use in the U.S. since the turn of the century, can be defined as a prefabricated reinforcement consisting of parallel series of cold-drawn or cold-rolled wires welded together in a rectangular grid. The intersecting longitudinal and transverse wires are electrically resistance-welded by a continuous automatic welder. Welded wire fabric may consist of plain wires, deformed wires, or combinations of both.[1] Until recently, epoxy-coated WWF was not used, but with the continuing concern about corrosion of reinforcing steel in concrete, coated WWF is now in use. Epoxy coating is typically applied electrostatically to the required thickness. It acts as a barrier between the corrosive environment and the steel.

The ACI Building Code (ACI 318-89)[2] stipulates that certain ASTM standards be met in the manufacture of wire reinforcement and WWF. The physical properties of wire reinforcement and WWF, as stipulated in the ASTM standards, are outlined in Table 1. The ASTM designation is also listed in Table 1. In addition to the material properties for wire reinforcement and WWF, ASTM A 884[3] also stipulates the allowable thickness of epoxy coating on wire reinforcement and WWF. A minimum of 7 mils (0.18 mm) and a maximum of 12 mils (0.31 mm) is allowed for reinforcement to be used in concrete.

ACI requirements for the development of welded deformed wire fabric and welded plain wire fabric in tension are found in ACI 318-89 Sections 12.7 and 12.8, respectively. Requirements for splices of welded deformed wire fabric and welded plain wire fabric in tension can be found in Sections 12.18 and 12.19, respectively. Concerning the development of welded deformed wire fabric in tension, Section 12.7.1 states that the modification factors in Sections 12.2.3 through 12.2.5 must be applied. The modification factor for epoxy-coated reinforcement given in Section 12.2.4.3 states that a modification factor of 1.5 should be used for epoxy-coated bars with a cover less than $3d_b$ or clear spacing between bars less than $6d_b$, and that a factor of 1.2 should be used for all other conditions with epoxy-coated bars. These values, based on the work of Treece and Jirsa[4] and Hamad, Jirsa, and d'Abreu[5], are a function of d_b, the nominal diameter of the bar or wire being developed. These modification factors are applied to epoxy-coated deformed WWF, even though all research used to develop Section 12.2.4.3 was conducted on reinforcing bars.

RESEARCH SIGNIFICANCE

Prior to this study, very limited testing had been conducted to determine the effects of epoxy coating on the anchorage

Table 1—Minimum physical properties for wire reinforcement and WWF

	Yield strength		Tensile strength		Weld shear strength/cross section area	
	psi	MPa	psi	MPa	psi	MPa
Plain wire reinforcement, A 82[8]	70,000	483	80,000	552	—	—
Deformed wire reinforcement, A 496[9]	75,000	517	85,000	586	—	—
Welded plain wire fabric, A 185[10]	65,000	448	75,000	517	35,000	241
Welded deformed wire fabric, A 497[11]	70,000	483	80,000	552	35,000	241

ACI Structural Journal, V. 92, No. 6, November-December 1995.
Received Jan. 9, 1995, and reviewed under Institute publication policies. Pertinent discussion will be published in the September-October 1996 *ACI Structural Journal* if received by May 1, 1996.

Stacy J. Bartoletti received his MS from the University of Texas in Austin. He is a structural designer with Degenkolb Engineers in San Francisco, California.

James O. Jirsa holds the Janet S. Cockrell Centennial Chair in Engineering at the University of Texas. He is a member of ACI Committees 318, Standard Building Code; 408, Bond and Development of Reinforcement; and 369, Seismic Repair and Rehabilitation.

and development of WWF. The data reported here provides information that indicates the effects of epoxy coating on development of WWF, and the results are used to suggest changes in design procedures and code requirements.

OBJECTIVE AND SCOPE

The objective of this investigation was to determine the effects of epoxy coating on anchorage and development of WWF. The test program included weld shear tests, pullout tests, and slab tests with splices of WWF. Weld shear tests and pullout tests were conducted to evaluate the anchorage provided by bond along the wire and by the weld of the transverse wire. Slab tests were conducted to examine the differences in lap splice strengths between slabs reinforced with coated and uncoated WWF. The sizes of WWF used in this investigation were 4 x 8 (W4 x W4), 4 x 8 (D4 x D4), 4 x 16 (W20 x W10), 4 x 16 (D20 x D10), 2 x 8 (W20 x W11), and 2 x 8 (D20 x D11).

EXPERIMENTAL PROGRAM

Weld shear tests

Weld shear tests were conducted on coated and uncoated 4 x 16 (W20 x W10) and 4 x 16 (D20 x D10) WWF to determine the weld shear strength of the weld between the longitudinal and transverse wires. A number of weld shear tests were also conducted on WWF with Size 4 longitudinal wires. In each of these cases, it was found that fracture occurred in the wire before shearing of the weld. For this reason, only a few weld shear tests on the WWF with Size 4 longitudinal wires were conducted.

Fig. 1 shows how a typical sheet of WWF was divided into weld shear specimens and pullout specimens. Test procedures and the dimensions of the test specimens followed the requirements of ASTM A 497. A weld shear test apparatus was constructed according to ASTM specifications. Each of the test specimens was tested to failure to determine the shear strength of the weld. The tests were run at a constant rate of stress, and the ultimate shear strength was recorded. Only the load was monitored.

Pullout tests

A total of 31 pullout tests were conducted. Twenty-seven pullout tests were conducted on coated and uncoated 4 x 16 (W20 x W10) and 4 x 16 (D20 x D10) WWF, and four tests were conducted on coated and uncoated D20 wires. Both pullout and weld shear tests were conducted on specimens taken from the same longitudinal wire. Bond along the longitudinal wire was eliminated in some pullout tests so that anchorage was provided entirely by the transverse wire and weld. This was accomplished by placing a plastic sleeve around the longitudinal wire before casting the specimen in concrete. All specimens were cast in a 10-in.-(25.4-cm-) square by 12-in.-(30.5- cm-) long concrete block. Free and loaded-end slip were recorded at selected load increments until the peak load was reached. The peak load was reached when the weld on the transverse wire fractured, or the longitudinal wire failed in bond when no transverse wire was present.

One-way slab tests

Dimensions and reinforcement—A total of 12 one-way slabs were tested to determine the influence of epoxy coating on splice strength and crack widths for the various configurations of WWF used in this investigation. The notation used for the slab specimens (Table 2) designates the presence of epoxy coating (C for coated and U for uncoated wires) and the type of WWF (W for plain and D for deformed wires).

Slab thickness for all tests was 6 in. (15.3 cm). The length of all slabs was 13 ft (3.96m), but the width varied. The

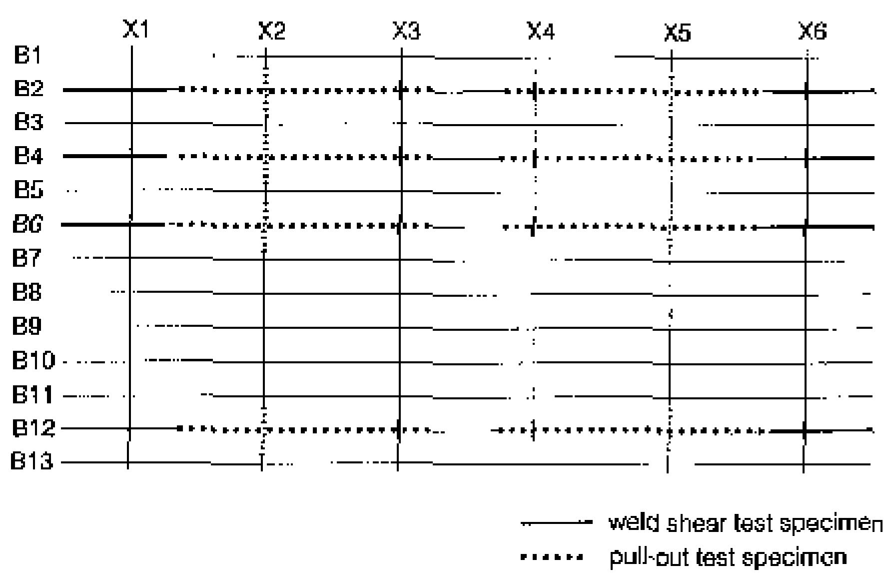

Fig. 1—Welded wire fabric divided into weld shear and pullout specimens

Table 2—Reinforcement ratio for slab specimens

Specimen number	Spacing between longitudinal bars		Size and spacing of transverse bars			Number of longitudinal wires	Area of longitudinal reinforcement		Reinforcement ratio
	in.	cm	size	in.	cm		in.2	mm2	
UW4-1, CW4-1	4	10.2	W4	8	20.3	6	0.24	155	0.00167
UD4-1, CD4-1			D4	8	20.3				
UW20-1, CW20-1	4	10.2	W10	16	40.6	13	2.6	1680	0.00803
UD20-1, CD20-1			D10	16	40.6				
UW20-2, CW20-2	2	5.1	W11	8	20.3	11	2.2	1420	0.0153
UD20-2, CD20-2			D11	8	20.3				

specimens with Size 20 longitudinal wires spaced at 4 in. (10.2 cm) were 4 ft 6 in. (1.37 m) wide; those with Size 4 longitudinal wires spaced at 4 in. (10.2 cm), and Size 20 longitudinal wires spaced at 2 in. (5.1 cm), were 2-ft-(0.61-m)-wide. Different widths permitted casting of more slabs at the same time without major alterations to the forms. The WWF was placed in the top of the slab with a nominal $^3/_4$-in. (19.1-mm) clear cover. A lap splice between two sheets of WWF was centered longitudinally in the slab. Table 2 lists the number of longitudinal wires, total area of longitudinal reinforcement, and the reinforcement ratio for each slab.

Slabs were constructed in pairs, with each containing identical reinforcement and lap splices. The only difference between the specimens in a pair was epoxy-coated WWF in one and uncoated WWF in the other. The epoxy was applied commercially on all specimens except those with 2-in. (5.1-cm) spacing between the longitudinal bars (CW20-2, CD20-2), where the epoxy was applied in the laboratory using a brush. This was done to reduce fabrication and shipping time. The commercially coated WWF was fusion bonded.

Epoxy coating thickness measurements were taken using a thickness gage. The average thickness of all coated WWF fell within the ASTM A884 requirements of 7 to 12 mils (0.18 to 0.31 mm), except CW20-2, which was coated by hand (2.2 mils), and CD4-1 (average thickness 15 percent greater than the maximum allowed by ASTM A 884). The differences for CW20-2 were considered acceptable because it was desired to break adhesive bond between the wire and the concrete rather than to provide corrosion protection. On the deformed wire, a thicker coating will tend to fill in the indentations on the deformed wires and consequently reduce the bond strength so the tests provide a conservative condition.

Lap splices used in the slab specimens were generally shorter than those required by ACI 318-89. It was desired to test lap splices shorter than those required by ACI so that failures could be observed and a comparison between the epoxy-coated and uncoated WWF could be made with failure occurring before the wires reached yield. Fig. 2 through 4 detail the lap splices used for each pair of slabs. Also shown are the minimum lap splices required by ACI 318-89, using f_y = 60 ksi (414 MPa) and f_c' = 3500 psi (24.1 MPa). In the calculation of the minimum ACI requirements, only the modification factor for epoxy-coated reinforcement was considered.

Slab test setup and procedures—A diagram of the testing apparatus used to test the slab specimens is shown in Fig. 5. The slabs were loaded 6 in. (15.3 cm) from each end. A constant negative moment region of 5 ft (1.52 m) was used for the slabs constructed with coated and uncoated 2 x 8 (W20 x W11) and 2 x 8 (D20 x D11) WWF, while all other slabs were tested with a 6-ft. (1.83-m) constant negative moment region. Load was applied to each end of the slab through a pair of hydraulic rams and distributed to the slab through a reaction beam placed between the slab and the hydraulic rams.

Slab vertical deflections were measured at load points and at the midpoint of the slab, as shown in Fig. 5. Deflections were taken at load increments chosen so that approximately 15 to 20 readings were obtained for each specimen. In addition to deflection measurements, cracks were marked at each load increment and measured at selected load increments. The slab specimens were either tested to failure or to yield-

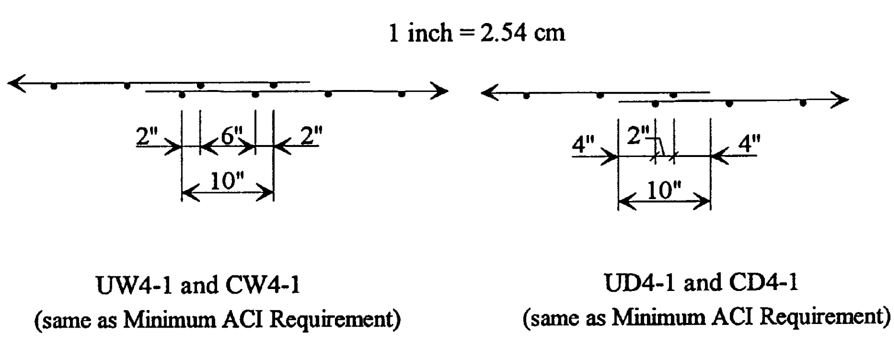

Fig. 2—Splice details for 4 x 8 (W4 x W4) and 4 x 8 (D4 x D4) welded wire fabric

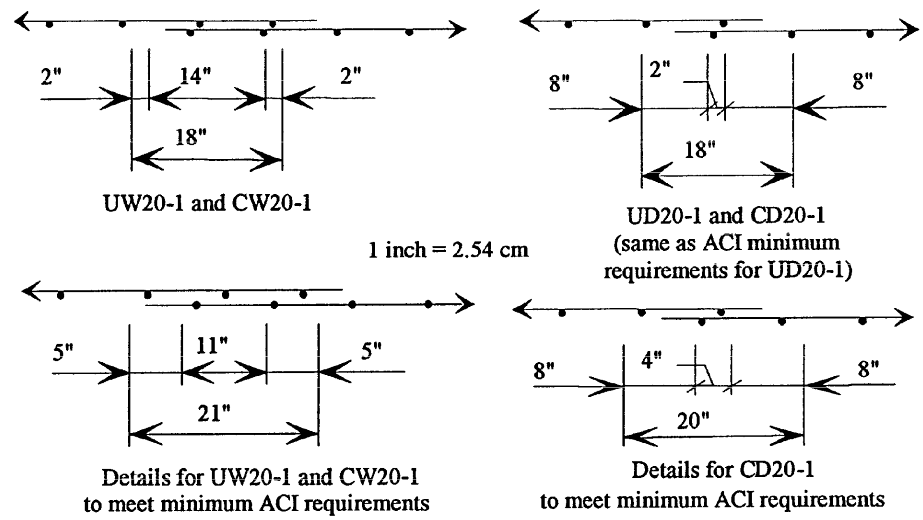

Fig. 3—Splice details for 4 x 16 (W20 x W10) and 4 x 16 (D20 x D10) WWF

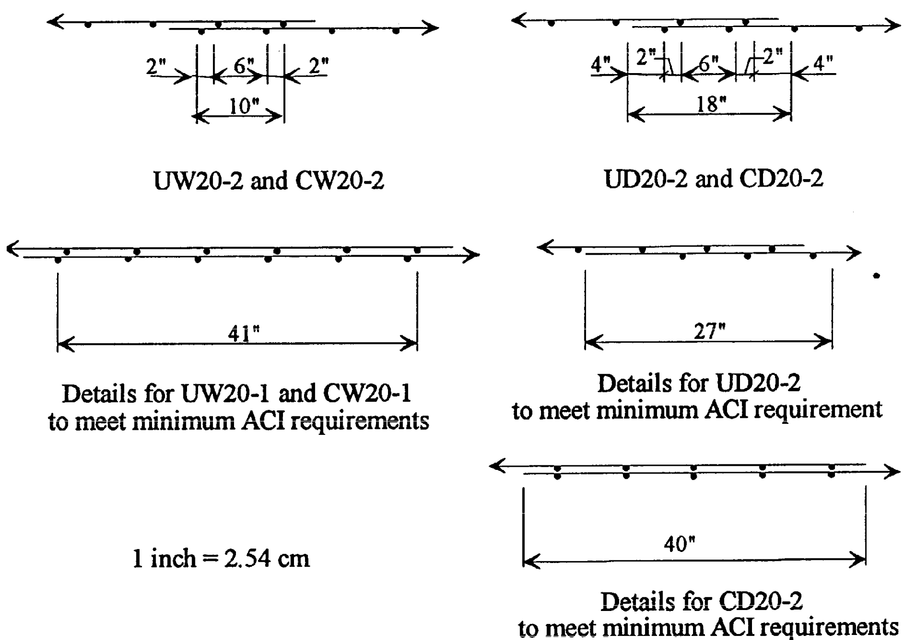

Fig. 4—Splice details for 2 x 8 (W20 x W11) and 2 x 8 (D20 x D11) WWF

ing of the longitudinal wires, as determined by a markedly reduced slope on the load-versus- deflection curve.

Material properties—All slabs and pullout specimens were cast using the same concrete mix design. A maximum coarse aggregate size of $^3/_4$ in. (19.1 mm) and a water-to-cement ratio of 0.72 were used. Specimens were generally tested at about 28 days after casting, at concrete strengths ranging from 3510 to 4590 psi (24.2 to 31.6 MPa).

EXPERIMENTAL RESULTS

Weld shear tests

The results for the weld shear specimens taken from each sheet of WWF exhibited different strengths along different longitudinal wires. This can be attributed to the manufacturing process, where each weld across the width of a sheet is performed by a different automatic electric resistance welder. Specimens taken from welded plain wire fabric showed much less variation in weld shear strength along a longitudinal wire than did the specimens taken from welded deformed wire fabric. The average percent difference in the maximum and minimum weld shear strengths along a longitudinal wire, when compared to the minimum ASTM weld shear strength of 7000 lbs (31.1 kN), was 9.3 percent for welded plain wire fabric and 18.1 percent for welded deformed wire fabric.

Only one of the average weld shear strengths along a longitudinal wire did not exceed the minimum ASTM requirement of 7000 lb (31.1 kN). However, the sheet of WWF met ASTM standards that require the average of four tests representing the entire width of the sheet of WWF must exceed the minimum weld shear value. Average values calculated for a particular longitudinal wire do not represent the entire width of a sheet of WWF. The average shear strength was

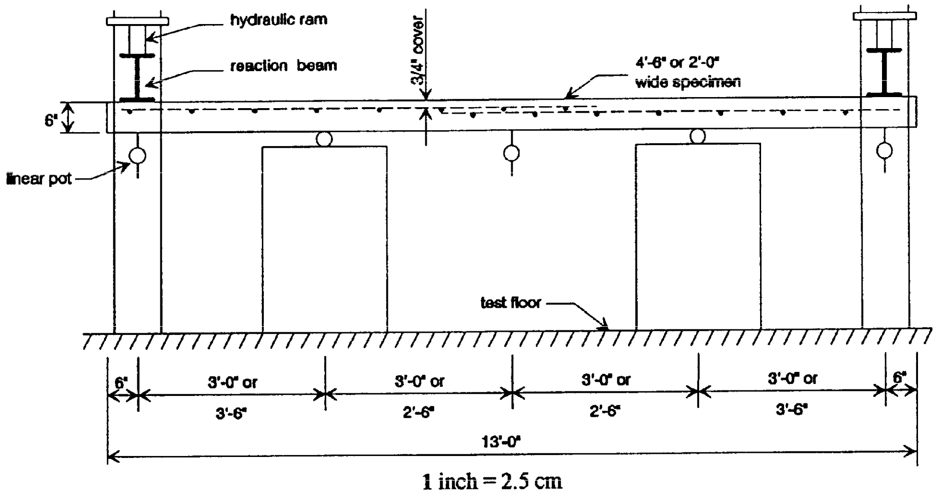

Fig. 5—Slab specimen testing apparatus

8420 lb (37.5 kN) for W20 x W10 welds and 7700 lb (34.3 kN) for D20 x D10 welds.

Pullout tests

Pullout specimens were compared on the basis of loaded-end and free-end slip measurements at various applied load-to-average weld shear strength ratios, where the average weld shear strength was determined from the same longitudinal wire used for the pullout specimens. With this comparison, the effect of variation in weld shear strength between different longitudinal wires in the same sheet of WWF could be minimized. Results from these comparisons gave an indication of the effect of epoxy coating on anchorage and development of the WWF.

Results from the pullout tests conducted on specimens with no bond along the longitudinal wire showed that, for both plain and deformed wires, the average slip for the uncoated specimens was consistently larger than the slip for the coated specimens. However, there was considerable scatter in the data. Loaded and free-end slip values showed the same trends at various applied load-to-average weld shear strength values. From these results, it can be concluded that epoxy coating on the transverse wire does not detrimentally affect the weld shear performance of either welded plain wire fabric or welded deformed wire fabric.

Results from the pullout tests conducted on specimens with a 4-in. (10.2-cm) bond length along the longitudinal wire showed that, for both plain and deformed wires, the average slip for the uncoated specimens was generally greater than or equal to the slip for the coated specimens. As in the tests with no bond along the longitudinal bar, the scatter was large and made it difficult to determine clear trends.

Four pullout specimens were constructed with deformed wires, a 4-in. (10.2-cm) bond length, and no cross wire. From the results obtained with these specimens, it was found that the largest difference between the uncoated and coated average free-end slip was 0.003 in. (0.076 mm) at a load of 10,000 lbs (44.5 kN). At this load, the average slip for the coated wires was 10 percent higher than the average slip for the uncoated wires, but the differences in slip were so small that epoxy coating on the longitudinal wire did not significantly alter the performance of deformed WWF.

One-way slab tests

Results of the slab tests are presented in terms of load-deflection relationships. Fig. 6 through 8 show plots of the ratio of the test moment to the ultimate moment capacity versus an equivalent beam center span deflection for the 12 one-way slab tests. The equivalent beam center span deflection was determined by adding the measured center span deflection to the average of the two end span deflections. The resulting slab deflection represents an element simply supported at the ends. The ultimate moment capacity for each of the slabs was calculated according to ACI 318 flexural provisions using the concrete strength at the time of testing and the measured yield strength of the wire as defined by ACI 318-89.

In Fig. 6 through 8, the two specimens compared were identical, except that one was constructed with uncoated WWF and one with coated WWF. As can be seen in Fig. 8, Specimens UW20-2, CW20-2, UD20-2, and CD20-2 failed before reaching the yield strength of the longitudinal wires. The failure occurred in the splice region by splitting of the concrete between the outer transverse wires in the lap and by pulling out the longitudinal wires extending beyond the last transverse wire.

Results from the one-way slab tests can be used to support the conclusions developed from the pullout tests. Slabs UW4-1, CW4-1, UD4-1, CD4-1, UW20-1, CW20-1, UD20-1, and CD20-1 were all able to develop the full yield strength of the longitudinal wires before a splice failure occurred. In fact, none of these slabs failed in the splice region, and the tests were concluded because it was apparent that the longitudinal wires were yielding. As can be seen in Fig. 6 and 7, each pair of coated and uncoated slabs behaved nearly identically under load. This reinforces the conclusion that there is no difference in anchorage characteristics between epoxy-coated and uncoated WWF.

Slabs UW20-2, CW20-2, UD20-2, and CD20-2, which failed in the splice region prior to reaching the yield strength of the slabs, can be used to examine the effects of epoxy coating on the anchorage and development of WWF when a

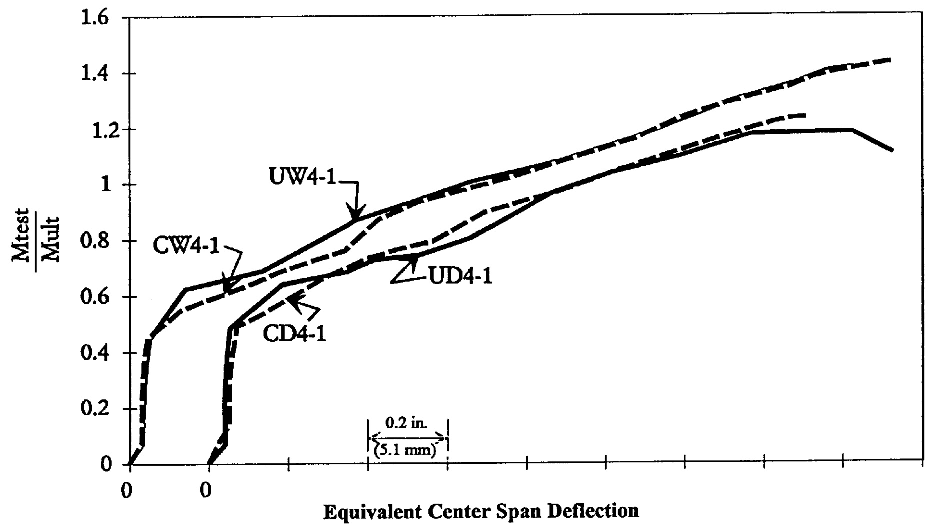

Fig. 6—One-way slabs with W4 and D4 longitudinal wires

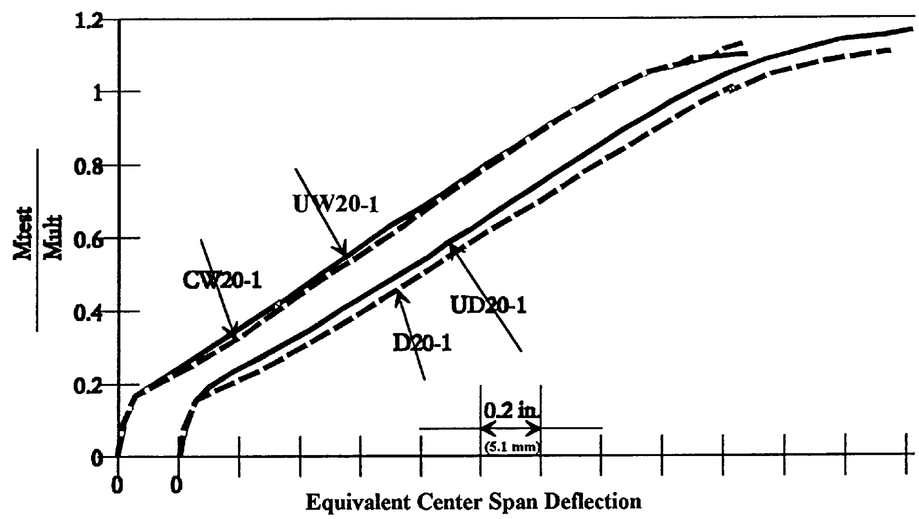

Fig. 7—One-way slabs with W20 and D20 longitudinal wires at 4-in. (10.2-cm)

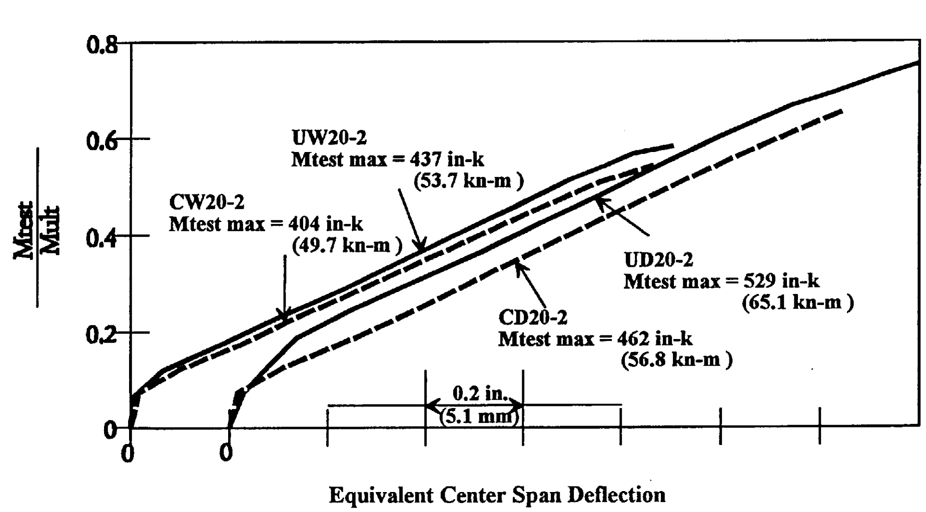

Fig. 8—One-way slabs with W20 and D20 longitudinal wires at 2-in. (5.1-cm) spacing

failure occurs in the splice region. The other slab specimens did not reach a splice failure, so the maximum development strength was not reached.

Fig. 8 shows the ratio of test moment-to-ultimate moment capacity versus the equivalent center span deflection for Slabs UW20-2 and CW20-2. Both of these slabs behaved nearly the same, with only a 7.5 percent difference in their maximum strengths. After failure, the average cover on the longitudinal wires was measured and found to be 7/16 in. (11.1 mm) for Slab UW20-2 and $^1/_2$ in. (12.7 mm) for Slab CW20-2. The low cover may have resulted in a reduction in strength of both specimens, but they had nearly identical cover.

Fig. 8 also shows the ratio of the test moment-to-ultimate moment capacity versus the equivalent center span deflection for Slabs UD20-2 and CD20-2. As can be seen in this figure, Slab CD20-2 has approximately 15 percent larger deflections for each test moment-to-ultimate moment capacity ratio above the cracking load. Even though the deflections were larger for CD20-2, the difference was small, and the stiffness of the two slabs appeared to be the same. Slab UD20-2 reached a 13 percent higher maximum moment than Slab CD20-2, but this can be accounted for by differences in average cover between the two slabs. Average cover for Specimen UD20-2 was 11/16 in. (17.5 mm), while that for CD20-2 was $^1/_2$ in. (12.7 mm). Using an equation proposed by Jirsa, Lutz, and Gergely,[6] the additional $^3/_{16}$-in. (4.8-mm) cover resulted in a 20 percent increase in the bond stress, which may explain why Slab CD20-2 failed at a lower moment than Slab UD20-2.

Test results from Slabs UW20-2, CW20-2, UD20-2, and CD20-2 again indicate that there is no clear trend showing that epoxy coating has a detrimental effect on the development and anchorage of WWF.

Effects of epoxy coating on the bond of WWF were also evaluated using cracking patterns for the one-way slab specimens. At each steel stress, there appears to be a very close correlation between average crack spacing and maximum crack width between the coated and uncoated slabs reinforced with either welded plain wire fabric or welded deformed wire fabric. One aspect of the crack data that should be pointed out is the difference in cracking characteristics between the slabs reinforced with welded plain wire fabric and those reinforced with welded deformed wire fabric. Welded deformed wire fabric tended to have smaller maximum cracks because better bond along the deformed bar reduced the average crack spacing. The slabs reinforced with welded plain wire fabric showed wider cracks spaced further apart.

DESIGN CONSIDERATIONS

Design requirements in ACI 318-89 for the development of welded deformed wire fabric in tension require that basic development length, defined in Section 12.7, be multiplied by modification factors from Sections 12.2.3 through 12.2.5. The modification factor for epoxy-coated reinforcement is given in Section 12.2.4.3. Section 12.2.4.3 states that a modification factor of either 1.5 or 1.2 be used for bars, depending on the amount of cover and clear spacing. Tests conducted in conjunction with this investigation have indicated that epoxy-coated welded wire fabric has essentially the same anchorage and development strength as uncoated welded wire fabric. It is recommended that a modification factor of 1.0 be applied to epoxy-coated WWF, which can be accomplished by adding the following statement to ACI 318-89 Section 12.2.4.3:

"Welded wire fabric with cross wires within the development length and with cross wires lapped by at least 2 in. (5 cm) 1.0"

In addition to this requirement, it is suggested that the following paragraph be added to Commentary R12.2.4.3:

"When welded wire fabric is used for reinforcement, the cross wires provide anchorage to the wire being developed, and tests indicate that epoxy coating does not influence the development or splice strength."

The stipulation is that a factor of 1.0 can be used for WWF only when cross wires are present within the development length. The development of epoxy-coated wire was not considered directly in this study. A number of pullout tests using epoxy-coated and uncoated wires were conducted as part of this experimental program and by Schmitt and Darwin,[7] but the data was insufficient to make a recommendation regarding the effects of epoxy coating on the development of deformed wire.

To specifically include deformed wire in the ACI 318 requirements for epoxy-coated reinforcement, and to eliminate confusion about the modification factor for epoxy-coated deformed wire, it is suggested that the first statement in ACI 318-89 Section 12.2.4.3 be modified to include deformed wire as follows:

"Bars *and deformed wires* with cover less than $3d_b$ or clear spacing between bars less than $6d_b$ 1.5"

To clarify the provisions in ACI 318-89 for epoxy-coated WWF, it would be desirable to include an additional statement to Commentaries R12.7 and R12.8 as follows:

"Tests have indicated that epoxy-coated welded wire fabric has essentially the same development and splice strength as uncoated welded wire fabric. Therefore, an epoxy coating factor of 1.0 is included for the development or splice length of epoxy-coated welded wire fabric with cross wires within the development or splice length."

Sections 12.7 and 12.8 define the required development length for welded deformed wire fabric and welded plain wire fabric, respectively. Development of epoxy-coated welded deformed wire fabric is covered explicitly, since Section 12.7 requires the use of the modification factors in Sections 12.2.3 through 12.2.5. For welded deformed wire fabric, the statement previously given may not be necessary for Commentary R12.7, but it is desirable. Since the use of the modification factors in Sections 12.2.3 through 12.2.5 is not required for development length of welded plain wire fabric, the user is not given any direction in Section 12.8 about how epoxy coating affects development length of welded plain wire fabric. For the case of welded plain wire fabric, it is desirable to include the previous statement in Commentary R12.8 so that it is specifically stated that no modification in development length needs to be made for epoxy coating.

CONCLUSIONS

From the experimental program carried out in conjunction with this investigation, it can be concluded that epoxy coating has little or no effect on the development and anchorage of welded plain wire fabric and welded deformed wire fabric. This conclusion is based on a series of pullout tests and one-way slab tests conducted on epoxy-coated and uncoated welded plain wire fabric and welded deformed wire fabric. Load-versus-deflection curves for both types of tests showed that epoxy coating did not have a detrimental effect on the development and anchorage of WWF. In addition, the one-way slab tests demonstrated that there is no significant difference in cracking behavior of slabs reinforced with epoxy-coated and uncoated WWF, although there was a significant difference in cracking behavior between slabs reinforced with welded plain wire fabric and welded deformed wire fabric.

Current ACI 318 requirements for development of epoxy-coated reinforcement are based on results from tests with deformed bars. From results obtained in this investigation, a change is recommended for ACI Code provisions for development of epoxy-coated WWF. The development length of WWF does not need to be modified (increased) to account for effects of epoxy coating because anchorage is provided by cross wires.

ACKNOWLEDGMENTS

The support provided by the Reinforced Concrete Research Council and the Wire Reinforcement Institute under RCRC Project 58 is gratefully acknowledged. The assistance of Task Committee 58, especially Chairman R. A. Ramsey, was instrumental in bringing the project to fruition. Other members of Task Committee 58 are D. P. Gustafson, J. F. McDermott, R. G. Smith, R. N. White, R. H. Wildt, and P. Zia. The work was conducted in the Ferguson Structural Engineering Laboratory. The authors express their appreciation to the staff and students in the laboratory who helped with the many details that made the project a success. The study was conducted by Mr. Bartoletti as part of his requirements for the MS degree.

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