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Influence of Stirrups on Overlap Splice Strength of Epoxy Coated Deformed Bars

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Abstract **– This paper reports the effect of transverse reinforcement on tensile reinforcement splice strength of epoxy coated reinforcing bars. Thirty six (36) full size beams of varying lengths and sectional dimensions with lap spliced bars in constant moment region were cast and tested in a four point bending system. The beams were cast with three high yield diameter bars, namely 16 mm, 20 mm and 28 mm. 8 mm and 10 mm diameter high yield stirrups were introduced over the lap in an attempt to study the effect of stirrups on bond performance of epoxy coated reinforcing bars. The ultimate moment from the tests were used to determine the stress developed in the steel rods. The ratios of the test bond stresses and bond stress values using the tensile reinforcement yield stress τ_t/τ_y were used for comparison of the parameter under investigation. Transverse reinforcement was found to increase the splice strength of epoxy coated reinforcing bars and the larger the diameter of stirrup the better the improvement of the bond efficiency.**

Keywords **– Bond efficiency, stress, transverse reinforcement, ultimate moment.**

Notations

A_s area of tension reinforcement;
A_{tr} area of transverse reinforcement;
a_v shear span;
b width of beam;
BS British Standard;
c minimum cover;
c_b thickness of bottom concrete cover;
c_s thickness of side concrete cover;
d effective depth of beam;
d_b diameter of bar;
$f^1{}_c$ cylinder strength of concrete;
f_{cm} mean cube strength;
f_s stress in steel;
f_y characteristics strength of reinforcement;
f_{yt} yield strength of transverse reinforcement;
k ratio of steel stress;
k_1 ratio of the average compressive stress to the characteristic cube strength f_{cu};
k_2 ratio of the depth of the centroid of the stress block to the neutral axis depth;
K_{tr} Transverse Reinforcement index $\left(K_{tr} = \frac{A_{tr} \cdot f_{yt}}{1500_{sn}}, \text{where } n - \text{number of legs}\right)$;
s maximum spacing of transverse reinforcement;
l length of beam;
l_s lap length;
l_d development length;
M_u ultimate test bending moment;
Q applied load;
τ_{BS} ultimate bond stress recommended in BS 811: 1997;
τ_{cal} theoretical bond stress;
τ_t test bond stress;
τ_y bond stress from tensile reinforcement yield strength;
x depth of neutral axis;
S with stirrup overlap;
WS without stirrup overlap;
ρ steel ratio, A_s/bd;
ϕ_e effective bar diameter;
ε_{cu} strain in concrete in compression;
ε_s strain in tension reinforcement;
β bond coefficient.

I. Introduction

Experimental research investigation has identified the factors that influence splice strength and analysis of the test data has resulted in empirical equations used in design practice. The American Concrete Institute (ACI) code for development length of tension bars is a typical example of this. The 2002 ACI code on bond is an improvement on the 1983, 1995 codes because the influence of various factors are accounted for in the basic equation of development length, based on experimental findings on the various parameters that influence bond strength. The Eurocode, [1], apart from known parameters influencing bond, the bond condition is also taken into consideration. The British code, [2], on bond is yet to take these factors into consideration. Instead emphasis is placed on factors which could be expected to increase useable bond capacity, namely a higher concrete strength, heavier shear links and larger concrete cover to reinforcement bars resulting in the Code being regarded as conservative.

The more the data generated, the clearer is the picture of the effect of the parameters and the more reliable is the empirical equation there from. Most of the parameters earlier investigated on bond resistance were carried out on uncoated bars. It is therefore desirable to investigate the influence of these parameters on coated bars as coating prevents adhesion between the concrete and steel bars which reduce bond resistance as reported by [3] and [4]. One of such parameters is transverse reinforcement. Coating, when applied on reinforcing bars to reduce corrosion, causes loss of strength. The bond resistance of coated reinforcing bars is reduced as coating alters the surface condition. Increased concrete cover has been found to improve bond strength of coated bars [5]. Waste aluminium and steel shreds have also been found to increase the cube and bond strength of concrete with uncoated bars [6]. The effect of transverse reinforcement on the behaviour of lap spliced steel in tension zone are reported in [7]. The parameters investigated include compressive strength, the lap splice length, the transverse reinforcement provided within the splice region and the shape of transverse steel provided around spliced bars. The results show that the displacement ductility increased, the mode of failure changed from splitting to flexural bond failure when the amount of transverse reinforcement increased. The presence of transverse reinforcement increased the ultimate load deflection and the displacement ductility. The effect of diameter of transverse reinforcement, its shape and distribution on the behaviour of R.C beams with tension lap splices confined with transverse reinforcement using 3 different types of concrete under pure bending was reported in [8]. This was compared with analytical study using 3-dimensional non-linear finite element analysis with finite element software *ABAQUS*. The analytical and experimental results were compared and contrasted. Good agreement was obtained. Will the use of stirrups improve bond strength of coated bars such as to nullify the effect of coating? The investigation reported herein was undertaken to answer this question as no information is available yet in literature on the effects of transverse reinforcement on splice strength of coated bars.

The major thrust of this investigation is to generate data on the influence of transverse reinforcement and hence contribute to knowledge and engineering practice on bond between concrete and coated steel reinforcement.

II. Research Significance

The research investigation was carried out with full sized beams; this is rather rare due to cost. The full sized beams gave more realistic results as expected in practice. The investigation provided solutions to practical problems on bond in reinforced concrete in the following ways:

a) new way of improving splice strength and efficiency of coated reinforcing steel was identified i. e. the use of transverse reinforcement with epoxy coated bars;
b) effects of transverse reinforcements on epoxy coated bars were established.

III. Test Programme

A. Test Beams

The test beams, thirty six in number, were all designed to fail in flexure, either by the yielding of steel bars or by the failure of the concrete in compression zone before the steel yields. Twelve beams were cast for the preliminary investigation and twenty four beams for the confirmatory tests. The beams were of three section sizes 300 mm × 230 mm; 300 mm × 200 mm and 300 mm × 180 mm. The main high yield bars, 16 mm, 20 mm and 28 mm were coated with epoxy. Nine beams had uncoated spliced bars and without stirrups. The stirrups 8 mm and 10 mm diameter were not coated because if the stirrups were coated before bending there is the likelihood of damage to the coating during bending. A lot of coating material is wasted on the other hand when stirrups were coated after bending. The effect of coating of stirrups on splice strength of coated bars was investigated by [9] later because if the stirrups were not coated, the effect of corrosion may manifest on the stirrups being the closest to the external surface of the beam and once the stirrups are attacked by corrosion it would extend to the main bars so additional investigation was carried out to know the effect of coating of stirrups on bond strength of lapped splice. Coating of stirrups was found to further reduce the bond resistance by 26 % and 17 % using the BS Code and the steel yield stress respectively. The length of the beam varied with bar diameters as 2.75 m, 2.90 m and 3.20 m respectively.

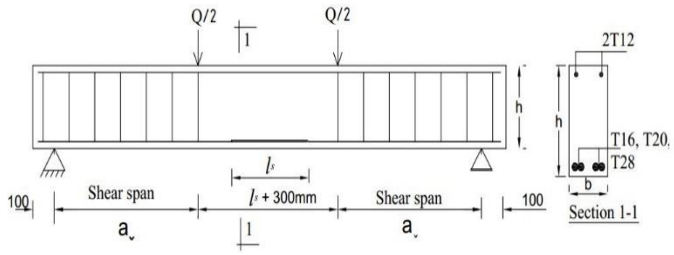

Fig. 1. Typical beam without stirrup overlap.

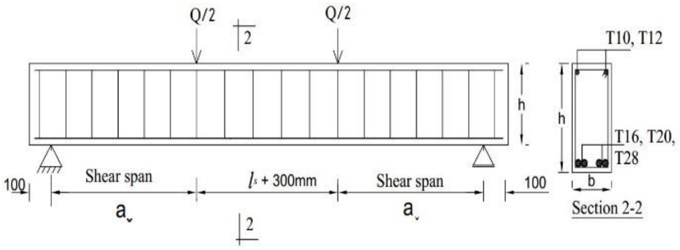

Fig. 2. Typical beam with stirrup overlap.

TABLE I
Beam Data (Uncoated)

Beam Name	*b*, mm	Tensile Reinforce-ment	A_s mm^2	Lap Length l_s + 300 mm	Shear Span a_v, mm	Beam Lengt, m
A-UR-10A	180	2T16	402	940	801	2.75
A-UR-10B	180	2T16	402	940	801	2.75
A-UR-10C	180	2T16	402	940	801	2.75
A-UR-11A	200	2T20	628	1100	795	2.90
A-UR-11B	200	2T20	628	1100	795	2.90
A-UR-11C	200	2T20	628	1100	795	2.90
A-UR-12A	230	2T28	1232	1420	783	3.20
A-UR-12B	230	2T28	1232	1420	783	3.20
A-UR-12C	230	2T28	1232	1420	783	3.20

UR – Uncoated Beam (Control).
Depth of the beam is 300 mm.
Side and bottom covers are 25 mm.
All the beams are without stirrups overlap.

TABLE II
BEAM DATA (COATED)

Beam Name	**Beam Type**	***b*, mm**	**Tensile Reinforcement**	**A_s, mm^2**	**Lap Length. l_s + 300 mm**	**Stirrup Diameter & Type**	**Shear Span a_v, mm**	**Beam Length *l*, m**
A-E-1A	WS	180	2T16	402	940	–	801	2.75
A-E-1B	WS	180	2T16	402	940	–	801	2.75
A-E-1C	WS	180	2T16	402	940	–	801	2.75
A-E-2A	WS	200	2T20	628	1100	–	795	2.90
A-E-2B	WS	200	2T20	628	1100	–	795	2.90
A-E-2C	WS	200	2T20	628	1100	–	795	2.90
A-E-3A	WS	230	2T28	1232	1420	–	783	3.20
A-E-3B	WS	230	2T28	1232	1420	–	783	3.20
A-E-3C	WS	230	2T28	1232	1420	–	783	3.20
B-E-1A	S	180	2T16	402	940	T8	777	2.70
B-E-1B	S	180	2T16	402	940	T8	775	2.70
B-E-1C	S	180	2T16	402	940	T8	775	2.70
B-E-2A	S	200	2T20	628	1100	T8	771	2.85
B-E2B	S	200	2T20	628	1100	T8	770	2.90
B-E-2C	S	200	2T20	628	1100	T8	770	2.90
B-E-3A	S	230	2T28	1232	1420	T8	760	3.15
B-E-3B	S	230	2T28	1232	1420	T8	760	3.20
B-E-3C	S	230	2T28	1232	1420	T8	760	3.20
B-E-4A	S	180	2T16	402	940	T10	771	2.70
B-E-4B	S	180	2T16	402	940	T10	775	2.70
B-E-4C	S	180	2T16	402	940	T10	775	2.70
B-E-5A	S	200	2T20	628	1100	T10	765	2.85
B-E-5B	S	200	2T20	628	1100	T10	770	2.90
B-E-5C	S	200	2T20	628	1100	T10	770	2.90
B-E-6A	S	230	2T28	1232	1420	T10	753	3.15
B-E-6B	S	230	2T28	1232	1420	T10	760	3.20
B-E-6C	S	230	2T28	1232	1420	T10	760	3.20

Details of the arrangement of steel are in Fig. 1 and Fig. 2 and can generally be grouped in two: beams without transverse reinforcement, series A and beams with transverse reinforcement overlap, series B, the beam data are in Table I and Table II. The spacing of the stirrups varied between 130 mm and 140 mm in the preliminary tests while a constant spacing of 140 mm was used in the confirmatory tests.

Lapped bars in contact, and lapped bars spaced apart have been reported to give satisfactory bond performance by [10]. In this investigation the contact arrangement was adopted because this is the most probable on construction sites. The loading points were 150 mm from the lap ends thereby making the distance between the point loads to be l_s + 300 mm. The ultimate anchorage bond length recommended in [11] was used.

$$l_s = \frac{0.87 f_y \phi}{4\beta\sqrt{f_{cu}}}. \quad (1)$$

Failure mode in flexure is strongly dependent on the shear-span/effective depth ratio (a_v/d). Based on reported experimental studies in [12] the failure pattern to ensure flexural failure was used. a_v/d was taken as 3.

Three different sizes were designed for the width of the beam, these are 180 mm, 200 mm and 230 mm. The sizes were a function of the diameter of the main bar.

The depth of all beams was 300 mm while the length is a function of lap length and shear span, thus length:

$$l = l_s + 300\text{ mm} + 2a_v + 200\text{ mm}. \quad (2)$$

B. Preparation and Application of Coating Material

Coating material was sprayed on the steel rods, Fig. 3. This was in an attempt to make the coating thickness as uniform as possible and to limit the film thickness to approximately 0.025 cm or less.

Epoxy Zinc Rich is in two parts. Part A, the base and Part B, the hardener. The parts were measured out by volume in ratio 3:1, as recommended in the manufacturer's manual and the two parts were thoroughly mixed together in a container. Thinner was added until the mixture was light enough to pass through the nozzle of a conventional spraying gun. The lengths of the reinforcements to be coated were marked out. The mixture was then sprayed, in one coat, on the marked portions of the reinforcements and allowed to dry in the shade, with no direct exposure to sunshine.

IV. Manufacture and Test Procedure of Cubes and Beams

The concrete used for the investigation was concrete Class 35 (C35) ready mix with targeted mean cube strength of 35 N/mm^2. The wooden beam moulds were oiled, for easy removal of the concrete beams. The reinforcement cages were put in the mould and concrete spacers were placed at intervals in various locations, bottom and sides. The ready mixed concrete was poured from a rotating mixer and vibrated in the mould with poker vibrator. The concrete beams were initially covered with nylon to prevent a rapid evaporation of the mixing water. After demoulding; the beams were placed on wooden joists in the storage area and cured by wetting at intervals for over seven (7) days.

A. Compressive Strength Test of Concrete Cubes

The aim of the test was to determine the strength of concrete in the beams and check that the compressive strength reached at least the targeted value of 35 N/mm^2. Six, 150 mm × 150 mm × 150 mm cubes were cast with each batch of concrete and the average strength of the six cubes is the compressive strength of the concrete for the batch.

The cubes were weighed on Avery weighing machine, 50 kg capacity and tested in the Avery Universal Testing Machine of 100 000 kg capacity. The strength achieved at test is in Table III.

B. Bond Beam Test

The test was aimed at determining the ultimate failure load, failure mode and crack patterns in the beams. The beams were tested in a third point loading arrangement with an I steel section used as the spreader joist in a 100 000 kg capacity Avery Universal Testing Machine. Failure mode in beams with stirrup is summarized thus: as the load was gradually applied, initial vertical cracks appeared at the lap ends followed by similar cracks at the point loads. Vertical cracks appeared along the stirrups which widened and increased in number as the load increased. Faint cracks appeared at the shear zones. The cracks at the lap ends progressed towards the compression zone. Horizontal cracks suddenly appeared within the lap, followed by subtle failure of the beam.

Fig. 3. Epoxy coated test rods.

TABLE III
BEAM AND STRENGTH ACHIEVED

Beam Name	Cube Strength, N/mm^2	Beam Name	Cube Strength, N/mm^2	Beam Name	Cube Strength, N/mm^2
Preliminary		**Confirmatory**			
B-E-2A B-E-5A	35.06	B-E-5B	30.44	A-E-2B A-E-1C A-E-3B	37.90
B-E-1A B-E-3A	33.28	B-E-3B B-E-5C B-E-1B	37.88	A-E-2C A-E-3C A-E-1B	36.98
B-E-6A B-E-4A	28.60	B-E-1C B-E-4B B-E-4C	33.12	A-UR-10B A-UR-11B A-UR-12B	36.47
A-E-1A A-E-3A A-E-2A	31.09	B-E-2B B-E-2C B-E-6B	30.51	A-UR-10C A-UR-11C A-UR-12C	34.44
A-UR-10A A-UR-11A A-UR-12A	34.67	B-E-3C B-E-6C	35.33	–	

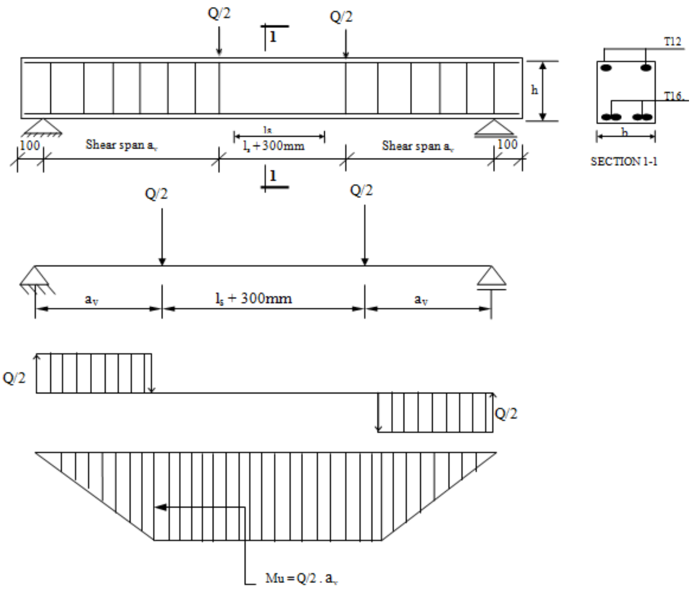

Fig. 4. Shear force and bending moment diagrams.

Horizontal cracks were later seen along the lapped bars and the stirrups on the underside of the beam. In beams without stirrups, vertical cracks appeared first at the lap ends (in some cases at the point loads first). Cracks at the lap ends progressed to the compression zone. After, horizontal crack appeared along the lapped splice which preceded the sudden and violent failure of the beam. In most cases the cover slab on the underside of the beam split and dropped off or with pronounced cracks along the reinforcements over lap and across the beam at the lap ends. The failure mode and load were noted and analysed below.

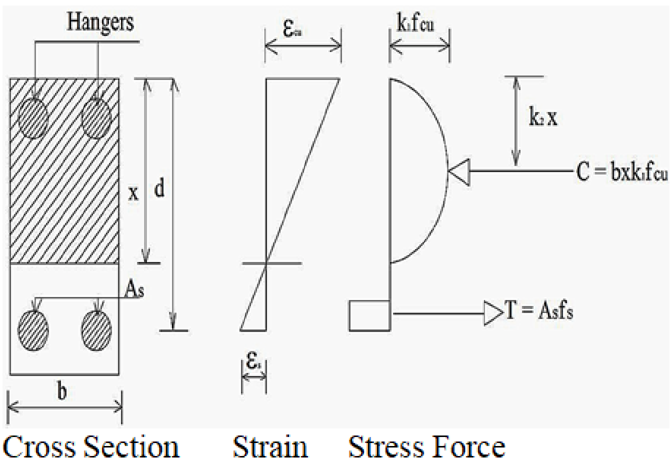

Fig. 5. Strain and stress distribution at failure.

V. Analysis and Discussion of Test Results

A. Ultimate Test Moment

The ultimate moment for each beam was obtained by applying the principles of statics. The lapped splice is in the constant moment region.

From Fig. 4, the ultimate moment at the point load is:

$$M_u = \frac{Q}{2}(a_v). \tag{3}$$

Applying the equilibrium condition in Fig. 5.

$$k_1 f_{cm} b x = A_s f_s. \tag{4}$$

Taking moment about the compressive force, the ultimate moment of resistance is:

$$M_u = A_s f_s (d - k_2 x), \tag{5}$$

from where:

$$\frac{M_u}{bd^2} = l f_s - \frac{k_2}{k_1}\frac{(l f_s)^2}{f_{cm}}. \tag{6}$$

TABLE IV

Characteristics of Hognestad et-al' Stress Block

S/N	f_{cm}, N/mm^2	k_1	k_2	ε_{cu}
Preliminary				
1.	35.06	0.586	0.451	0.0033
2.	33.28	0.598	0.453	0.0034
3.	28.60	0.626	0.61	0.0035
4.	31.09	0.611	0.457	0.0034
5.	34.67	0.591	0.449	0.0034
Confirmatory				
6.	30.44	0.614	0.457	0.0034
7.	33.12	0.598	0.455	0.0034
8.	30.51	0.616	0.459	0.0034
9.	35.33	0.583	0.45	0.0033
10.	37.90	0.575	0.450	0.0034
11.	36.98	0.578	0.449	0.0033
12.	34.44	0.594	0.454	0.0034
13.	36.47	0.581	0.450	0.0033

The properties of the concrete stress block are expressed in terms of the characteristic ratio k_1 and k_2. Stress block by Hognestad in [12] and universally accepted was used. Based on the mean cube strength, various values of k_1 and k_2 and ε_{cu} are tabulated in Table IV. The quadratic equation in (6) was solved yielding two values of f_s, one of which was always unreasonable because it is not practicable. The reasonable value was the stress developed in the steel.

B. Test Bond Stress, τ_t

The bond strength is the average stress along the length of the splice. It was calculated as the force developed in the bar divided by the product of the splice length and the nominal perimeter of the bar. From equilibrium:

$$A_s f_s = \tau_t \pi \phi_e l_s, \tag{7}$$

from where:

$$\tau_t = \frac{f_s \phi_e}{4 l_s}. \tag{8}$$

The steel stress developed in each beam determined from equation (6) was substituted in equation (8) to obtain τ_t.

C. Theoretical Bond Stress, τ_{cal}

The theoretical bond stress τ_{cal}, was determined from a semi-empirical statistical regression equation developed in [13].

These expressions were converted to SI units and modified for use of coated bars with mean concrete cube strength (f_{cm}) by [14] to give:

$$\tau_{cal} = \left(0.09 + 0.24\frac{c}{d_b} + 3.9\frac{d_b}{l_s}\right)\sqrt{f_{cm}}; \quad (9)$$

$$\tau_{cal} = \left(0.09 + 0.24\frac{c}{d_b} + 3.9\frac{d_b}{l_s} + \frac{0.022 A_{tr} f_{yt}}{s d_b}\right)\sqrt{f_{cm}}. \quad (10)$$

The bond strength equation in (9) and (10) proposed in [13] have been widely discussed, [15] accepted and used as reference by various researchers since it was published.

Thus, the bond strength equation proposed in [13] was adopted as the formula for theoretical bond stress, [13] adopted theoretical bond stress equation formed the basis of the bond strength equation in the 1995 and 2002 American Concrete Institute (ACI) codes [16].

D. Bond Stress Using BS 8110's Recommendation, τ_{BS}

The British Standard's, [2] recommended bond stress was also used to calculate the bond efficiency:

$$\tau_{BS} = \beta\sqrt{f_{cm}}, \quad (11)$$

with the factor β, taken as 0.5 because deformed bars were use in tension (BS 8110: Clause 3.12.8.4).

E. Bond Stress using the Yield Stress of Tensile Reinforcement, τ_y

The bond stress using the yield stress of tensile reinforcement, τ_y, was calculated with equation (8) but using the yield stress of the reinforcing bars from Table V:

$$\tau_y = \frac{f_y \phi_e}{4 l_s}. \quad (12)$$

VI. DISCUSSION OF TEST RESULTS

Influence of Transverse Reinforcement on Splice Strength of Epoxy Coated Bars

Previous research findings have shown that bond strength of coated bars is reduced when compared to uncoated bars, [10], [14], [17]. Stirrups have been found to increase bond strength of uncoated bars [18], [19].

The beam data and test results are shown in Tables I, II, VI, and VII, Figures 6 and 7 respectively. Three beams were cast for each bar diameter and the average values were plotted. Theoretically, the last term in equation (10) is to reflect the effect of stirrups.

If τ_{cal} is used as denominator in the bond ratio expression, undue advantage would be given to beams with stirrups, because a higher value of τ_{cal} would result and this would lead to a lower bond ratio for beams with stirrups.

TABLE V

TENSILE TEST RESULTS

Bar Size, mm	Yield Stress, N/mm^2	Ultimate Stress, N/mm^2	Elongation, %
Y8	594.270	851.790	13.000
Y8	554.660	831.980	13.540
Y8	574.470	851.790	12.000
AVRG	574.470	845.190	12.830
Y10	510.260	621.960	12.500
Y10	528.030	649.880	14.500
Y10	533.110	653.690	15.000
Y10	514.070	634.650	14.500
AVRG	521.370	640.045	14.125
Y12	515.380	660.740	16.500
Y12	524.190	665.150	15.500
Y12	528.590	662.510	17.500
Y12	519.780	653.690	15.500
AVRG	521.985	660.523	16.250
Y16	549.980	661.460	16.500
Y16	535.110	624.340	14.000
Y16	512.820	629.250	14.500
AVRG	532.640	638.340	15.000
Y20	523.250	624.730	15.000
Y20	523.250	631.070	16.000
Y20	545.450	637.420	17.500
AVRG	530.650	631.070	16.170
Y28	599.260	679.580	15.000
Y28	577.650	700.620	15.000
Y28	566.320	666.640	16.000
AVRG	581.080	682.280	15.330

Bond efficiency was therefore investigated with τ_t/τ_{BS} and τ_t/τ_y, the findings are similar, but the percentage increase in bond efficiency is lower in τ_t/τ_y than when τ_t/τ_{BS} was used, this may not be unconnected with the fact that τ_{BS} is empirical. The ratio τ_t/τ_{BS} was used for the comparison because it is the least influenced by compromises.

TABLE VI

BEAM TEST RESULTS (UNCOATED)

Beam Name	f_{cm}, N/mm^2	M_u, kN·m	f_s, N/mm^2	τ_t, N/mm^2	τ_{cal}, N/mm^2	τ_{BS}, N/mm^2	τ_y	$\frac{\tau_y}{\tau_{cal}}$	$\frac{\tau_t}{\tau_{BS}}$	$\frac{\tau_t}{\tau_{cal}}A$	$\frac{\tau_t}{\tau_{BS}}A$	$\frac{\tau_t}{\tau_y}A$	**Failure Mode**
A-UR-10A	34.67	54.07	561.53	3.51	3.31	2.94	3.33	1.06	1.19				Splitting
A-UR-10B	36.47	55.27	573.31	3.58	3.40	3.02	3.33	1.05	1.19	1.07	1. 22	1.07	Splitting
A-UR-10C	34.44	52.27	576.65	3.60	3.30	2.93	3.33	1.09	1.28				Splitting
A-UR-11A	34.67	61.17	473.92	2.96	2.87	2.94	3.32	1.03	1.01				Splitting
A-UR-11B	36.47	82.28	555.30	3.47	2.94	3.02	3.32	1.17	1.20	1.14	1.13	1.00	Splitting
A-UR-11C	34.44	79.10	556.86	3.48	2.86	2.93	3.32	1.22	1.19				Splitting
A-UR-12A	34.67	115.49	450.41	2.82	2.37	2.94	3.63	0.98	0.96				Splitting
A-UR-12B	36.46	129.20	519.40	3.25	2.43	3.02	3.63	1.23	1.08	1.12	0.90	0.83	Splitting
A-UR-12C	34.44	119.41	473.43	2.96	2.36	2.93	3.63	1.14	1.01				Compression

TABLE VII

BEAM TEST RESULTS (COATED)

Beam Name	f_{cm}, N/mm^2	M_u, kN·m	f_s, N/mm^2	τ_t, N/mm^2	τ_{cal}, N/mm^2	τ_{BS}, N/mm^2	τ_y	$\frac{\tau_y}{\tau_{cal}}$	$\frac{\tau_t}{\tau_{BS}}$	$\frac{\tau_t}{\tau_y}$	$\frac{\tau_t}{\tau_{cal}}A$	$\frac{\tau_t}{\tau_{BS}}A$	$\frac{\tau_t}{\tau_y}A$	**Failure Mode**
A-E-1A	31.09	62.64	370.98	2.32	3.14	2.79	3.33	0.74	0.93	0.70				Splitting
A-E-1B	36.98	72.25	471.98	2.94	3.42	3.04	3.33	0.86	0.97	0.88	0.91	1.03	0.91	Splitting
A-E-1C	37.90	85.07	589.58	3.86	3.46	3.08	3.33	1.12	1.25	1.16				Splitting
A-E-2A	31.09	88.40	430.12	2.69	2.72	2.79	3.32	0.99	0.96	0.81				Splitting
A-E-2B	37.90	113.45	539.32	3.37	3.00	3.08	3.32	1.12	1.26	1.01	1.10	1.01	0.89	Splitting
A-E-2C	36.98	92.38	452.16	2.83	2.96	3.04	3.32	0.95	0.91	0.85				Splitting
A-E-3A	31.09	125.44	384.79	3.37	2.46	2.79	3.63	1.07	0.86	0.93				Splitting
A-E-3B	37.90	142.86	452.73	2.83	2.47	3.08	3.63	1.14	0.92	0.78	1.04	0.84	0.78	Splitting
A-E-3C	36.98	122.70	358.61	2.24	2.44	3.04	3.63	0.92	0.74	0.62				Splitting
B-E-1A	33.28	54.39	591.43	3.69	5.13	2.88	3.33	0.58	1.23	1.11				Splitting
B-E-1B	37.88	56.33	595.39	3.72	4.86	3.08	3.33	0.77	1.21	1.12	0.73	1.25	1.11	Splitting
B-E-1C	33.12	56.19	590.48	3.69	5.11	2.88	3.33	0.72	1.31	1.11				Splitting
B-E-2A	35.06	69.30	475.14	2.97	3.70	2.96	3.32	0.57	1.00	0.89				Splitting
B-E-2B	30.51	76.23	543.56	3.40	3.07	2.76	3.32	0.92	1.23	1.02	0.92	1.07	0.98	Splitting
B-E-2C	30.51	76.62	546.94	3.42	3.27	2.76	3.32	0.92	1.24	1.03				Splitting
B-E-3A	33.28	114.76	452.58	2.83	3.07	2.88	3.63	0.92	0.98	0.78				Splitting
B-E-3B	37.88	126.16	496.60	3.10	3.27	3.08	3.63	0.95	1.00	0.85	0.93	0.99	0.81	Splitting
B-E-3C	35.33	119.32	470.21	2.94	3.16	2.97	3.63	0.93	0.99	0.81				Splitting
B-E-4A	28.60	52.62	590.99	3.69	3.99	2.67	3.33	0.93	1.39	1.11				Splitting
B-E-4B	33.12	56.85	599.90	3.75	4.32	2.88	3.33	0.82	1.23	1.13	0.72	1.32	1.12	Splitting
B-E-4C	33.12	56.96	599.84	3.75	5.28	2.88	3.33	0.71	1.30	1.13				Splitting
B-E-5A	35.06	80.33	565.99	3.54	4.57	2.96	3.32	0.81	1.19	1.07				Splitting
B-E-5B	30.44	85.47	584.96	3.62	4.08	2.76	3.32	0.89	1.31	1.09	0.85	1.26	1.08	Splitting
B-E-5C	37.88	82.78	579.29	3.62	4.55	3.08	3.32	0.80	1.18	1.09				Splitting
B-E-6A	28.60	110.31	568.38	3.55	3.88	2.67	3.63	0.92	1.33	0.98				Compression
B-E-6B	30.51	124.64	526.63	3.29	3.34	2.67	3.63	0.99	1.19	0.91	0.98	1.18	0.95	Shear
B-E-6C	35.33	133.76	553.20	3.46	3.59	2.97	3.63	0.96	1.16	0.95				Splitting

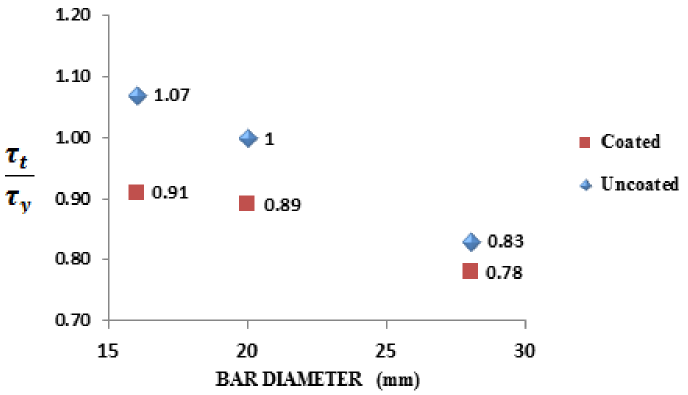

Fig. 6. Effect of coating on overlap splice strength.

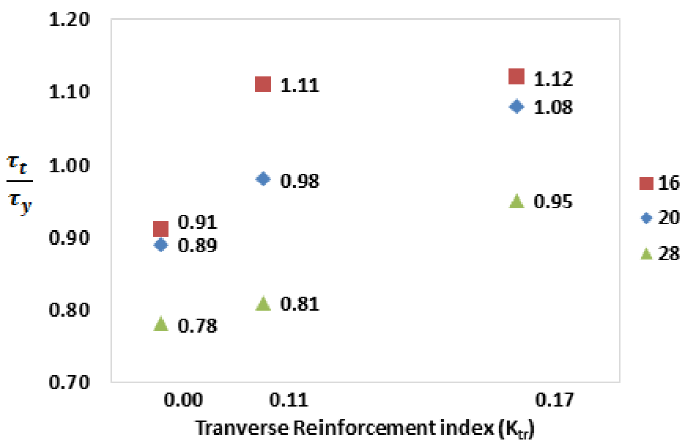

Fig. 7. Effect of stirrup on bond efficiency of epoxy coated bars.

The beam data and results of uncoated bars are in Tables I and V and Fig. 6. The results were used to benchmark or test the validity of bond efficiency, τ_t/τ_y in bond parameter investigations. A comparison of epoxy coated, and uncoated bars as tensile reinforcements showed that bond efficiency of beams with coated bars are reduced when compared to beams with uncoated reinforcing bars. This is a generally known fact which is corroborated by the use of test bond stress, τ_t. The reductions in bond efficiency are 14.95 %, 11.00 %, and 6.00 % for 16 mm, 20 mm, and 28 mm diameter high yield bars respectively, Fig. 6.

For 16 mm high yield bars, the bond efficiency of beams with 8 mm stirrups increased by 22.0 % (21.4 %) over beam without transverse reinforcements, while beams with 10 mm stirrups had a 0.89 % (5.60 %) increase in bond efficiency over beam with 8 mm stirrups.

Beams with 20 mm high yield bars with 8 mm stirrups had a 10.1 % (5.9 %) increase in bond efficiency over beam without transverse reinforcement. With 10 mm diameter stirrups the bond efficiency τ_t/τ_y is increased by 10.2 % (17.8 %) over beams with 8 mm diameter stirrups. Beams with 28 mm diameter high yield bars with 8 mm diameter stirrups had 3.85 % (17.90 %) increase in bond efficiency over beams without stirrup while beams with 10 mm diameter stirrups had 17.3 % (19.2 %) increase in bond efficiency than in beams with 8 mm stirrups, Fig. 7. Values in bracket were obtained when τ_t/τ_{BS} was also used to study the parameter under investigation. It would be observed that though there are increases in bond efficiency due to stirrups, the increase is neither consistent nor regular.

From Fig. 7, it is found that stirrups improved the bond efficiency of epoxy coated bars. This corroborates the results obtained for uncoated bars which were earlier mentioned. The provision of transverse reinforcements (stirrups) adds to the tensile capacity of the plane resisting splitting and increases the overall splice strength. Splitting occurred in splices with transverse reinforcements, but the reinforcements (stirrups) restrain splitting and reduce the tendency for sudden brittle failures. The overall strength of a splice with transverse reinforcement is regarded as the strength of a plain splice together with the strength contributed by the transverse steel, i.e. $\tau = \tau_c + \tau_{tr}$.

The strength contributed by the transverse steel τ_{tr} has been shown by [17] to depend on the splice length and the amount of transverse steel. The tensile capacity of the transverse reinforcement depends on its yield strength, f_{yt}.

The higher experimental values of bond strength obtained in beams with transverse reinforcement are in line with the higher theoretical values of bond strength in beams with transverse reinforcement for uncoated bars. The surrounding stirrups do not only increase the splice strength but also made the splice failure gradual with fully visible cracks, Fig. 8. The failure was neither sudden nor violent as in beams without stirrups.

Fig. 8: Crack patterns in beam B-E-1B (beam with transverse reinforcement).

VII. Conclusion

Based on the test results and the analysis of test data it can be concluded that:

1. Stirrups increase the splice strength and efficiency of **epoxy coated** reinforcing bars. 8 mm and 10 mm diameter stirrups increased bond efficiency by 22.0 % and 23.1 % respectively when compared with beams without stirrups, for 16 mm high yield main bars.
2. Increase in bond efficiency of beams with transverse reinforcement is enhanced with larger stirrup diameter. For example, in beams with 20 mm diameter main bars, 10 mm diameter stirrups gave an improvement in bond efficiency of 10.2 % over beams with 8 mm diameter stirrups.
3. The increase in bond strength due to transverse reinforcement is not proportional with the stirrup diameter. The improvement in bond strength efficiency for beams with

16 mm, 20 mm and 28 mm diameter main bars with 8 mm diameter stirrups are 22.00 %, 10.10 % and 3.85 % respectively, while that of 10 mm diameter stirrups are 23.1 %, 21.3 % and 21.8 % when compared to beams without transverse reinforcement. From the above data, it is obvious that the improvement is not proportional with the stirrup diameter.

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