Bond strength in concrete filled steel tubes

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Bond Strength in Concrete Filled Steel Tubes

Contrainte d'adhérence de tubes d'acier remplis de béton

Verbundfestigkeit in ausbetonierten Stahlrohren

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SUMMARY

Tests on several concrete filled steel tubes for establishing the strength of bond between the concrete core and the steel tube are reported. Several parameters were investigated including concrete compressive strength, length to diameter ratio for the interface, tube diameter to thickness ratio, etc. The tests show the importance of imperfections in the manufacture of the tubes, in contributing to the overall bond strength. A characteristic bond strength that may be used in design is recommended on the basis of these tests and this value has, in fact, been adopted by the joint ECCS — CEB — IABSE — FIP committee drafting the European code for composite construction.

RÉSUMÉ

L'article présente les essais effectués sur plusieurs tubes d'acier remplis de béton afin de déterminer l'adhérence ultime entre le noyau de béton et le tube d'acier. Plusieurs paramètres sont pris en compte, tels que la résistance du béton à la compression, le rapport longueur-diamètre, le rapport diamètre-épaisseur du tube, etc. Les essais montrent l'importance des imperfections lors de la fabrication des tubes sur l'adhérence ultime globale. Une valeur caractéristique de l'adhérence ultime a été proposée à la suite de ces essais et a été en fait reprise par le comité mixte CECM — CEB — AIPC — FIP, chargé de proposer une norme européenne pour les constructions mixtes.

ZUSAMMENFASSUNG

Es wird über Versuche an ausbetonierten Stahlrohren berichtet, welche im Hinblick auf den Einfluss der Verbundfestigkeit zwischen Betonkern und Stahlrohr durchgeführt wurden. Mehrere Parameter werden untersucht, so u.a. der Einfluss der Betondruckfestigkeit, das Verhältnis von Länge zu Durchvesser, das Verhältnis von Durchmesser zur Stärke der Rohrwandung, usw. Die Versuche zeigen den grossen Einfluss von Herstellungsungenauigkeiten auf die Verbundfestigkeit. Als Resultat dieser Versuche wurde ein Wert für die charakteristische Verbundfestigkeit vorgeschlagen, welcher in die Empfehlungen der gemischten Kommission EKS — CEB — IVBH — FIP für eine europäische Norm für Verbundbau Eingang gefunden hat.

1. INTRODUCTION

The analysis and design of composite columns has been the subject of many investigations in recent years(1-6).   Invariably, a complete continuity of strains between steel and concrete is assumed.   In other words, it is assumed that the bond between steel and concrete is not broken as the column is progressively loaded to failure.   A few studies(4,7) have indicated that provided the concrete and the steel areas at the column ends are loaded simultaneously, the actual bond strength has little or no significance in relation to the performance of composite columns.   However, in cases where longitudinal shearing stresses are likely to be predominant, for example in a column with a mid-height lateral load, it may be necessary to investigate the bond strength.   In the extreme case, with no axial thrust acting, the beam-column reduces to a composite beam in which case it would be imperative to use shear connectors.   It therefore becomes desirable to investigate the ultimate bond strength between steel and concrete in the absence of shear connectors as realised in composite columns.   With this objective in mind, the present series of push-out tests was undertaken.   Although the tests in this study were restricted to concrete filled steel tubes, the information obtained may also be applicable to encased columns where some hoop reinforcement is provided.   A number of parameters likely to influence the bond strength were identified and groups of tests were conducted varying one parameter at a time.

2. FACTORS INFLUENCING THE BOND STRENGTH

Some of the more important factors influencing the bond strength investigated in the present study are:

Surface roughness of steel
Length of steel tube-concrete core interface
Concrete strength and related factors.

A few exploratory tests were also carried out to measure the load slip relationship at different points down the depth of the concrete steel interface. Another group of tests was aimed at studying the distribution of hoop and longitudinal stresses down the depth of the steel shell.   The test results are discussed in relation to their parameters after a brief description of the experimental procedure.

3. TEST SPECIMENS

The bond strength was measured by means of pushout tests on circular seamless mild steel tubes filled with concrete.   The ends of the steel tubes were cut and machined to required length, ensuring that the two ends were parallel to each other and normal to the sides.   The inside of the tubes was wire brushed to remove any rust and loose scale present, and any deposits of grease and oil were cleaned away, except in the case of a few specimens mentioned later which had special surface treatment.   The internal diameter of each specimen was measured in two mutually perpendicular directions at the two ends and one-third length from either end.   Polystyrene plugs of 1.5 in (38 mm) thickness were fitted at the bottom of the specimens, removed later to allow for the travel of the concrete core, and the tubes were filled with concrete flush to the top.   The specimens were cured for four weeks, except for a few specimens which were tested at a shorter age.
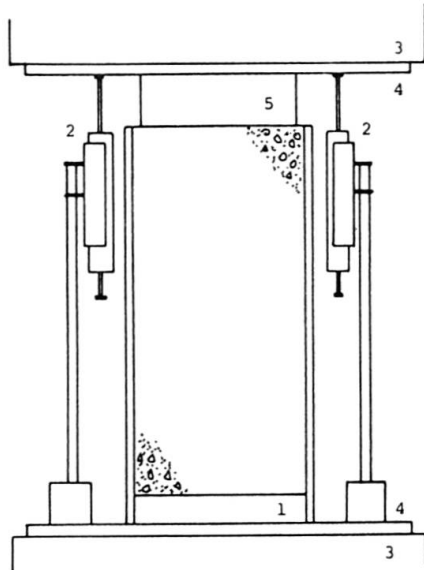
FIG. 1   Set-up for the test specimen
         (1-37mm air gap
          2-deflection transducer
          3-testing machine
          4-loading plates 400x400x18mm
          5-circular loading pad, diameter
             12mm smaller than inside
             diameter of the tube specimen)
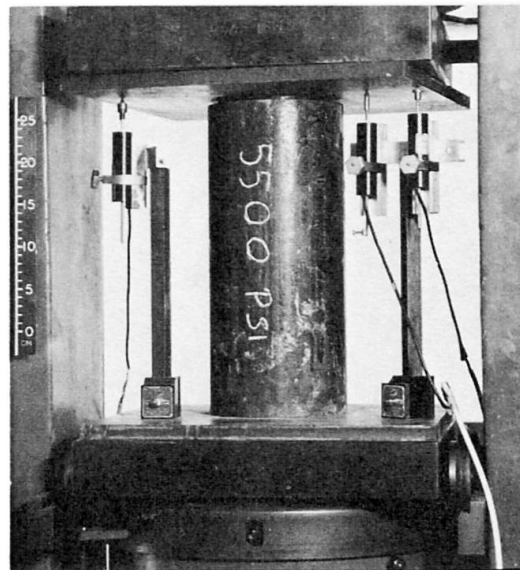
FIG. 2   Specimen under test

The design strength of concrete for most specimens was 6000 lbf/in^2 (41 N/mm^2). For each batch of concrete mix used, three or more six inch cubes were also cast and cured in conditions similar to the related specimens. Some specimens were cast with concrete of different design strength and different degrees of compaction to study the influence of these factors. Three of the specimens were dry cured. The tops of the specimens were ground with carborundum stone before testing to give a level surface, flush with the steel rim.

As a rule, three specimens were tested for the study of a given parameter. The properties of the specimen in each group were made similar as far as possible, changing only the factor in question.

4.   TEST RIG AND INSTRUMENTATION

A 300 tonf capacity Amsler universal compression testing machine was used to test most specimens. A few of the larger specimens were too long for the 21 in (535 mm) clearance available in the machine and were tested in a 500 tonf capacity machine.

A 2 in (50 mm) thick steel loading pad with a diameter about 0.5 in (12 mm) smaller than the internal diameter of the steel tube being tested was placed at each end between the specimen and the loading surface of the testing machine. The movement of the concrete core with respect to the steel tube at the top end was measured by means of three 2 in (50 mm) travel electrical resistance gauge deflection transducers placed at equal spacing around the periphery of the steel tube. The deflection of the concrete core was then taken as the average of the three transducer values.

FIG. 3   Typical load-deflexion plot

The load on the tube was measured by means of a load cell which together with the three transducers was connected to a digital data logger. The load deflexion response was then available on paper-tape and printer in digital form. A fourth deflexion transducer and another load cell were connected to an x-y plotter to produce an instantly visual load-slip curve for each specimen. A schematic of the testing arrangement is given in Fig. 1. A typical specimen under test is shown in Fig. 2.

5.   TESTING PROCEDURE

The polystyrene plugs were removed before the test. A small V-notch was made at the bottom of the steel tube to release any pressure likely to build up in the trapped air, thereby altering the load deflexion response. An initial load of about 1 tonf was applied in most cases to eliminate any initial settlement effects due to irregularities on the concrete surface. The load was then released, and the zero readings were recorded. Load was increased at the rate of 1.5 tonf per minute in most cases. Initially, deflexions were recorded at every 0.5-0.6 tonf. However, once the specimen started to show a marked change in the slope of the load deflexion curve on the x-y plotter, the recordings were then taken after every 0.1 in (2 mm) movement of the concrete core. The loading was continued in most cases until the concrete core ran out of the available travel of 1.5 in (38 mm). The concrete cubes corresponding to each group were tested on the same date, and the loading rate of 1.5 tonf per minute was retained.

6.   TEST RESULTS

The load deflexion response of almost all specimens showed a uniform pattern. Initially, the stiffness offered by the bond is high. Later, a marked reduction in stiffness is observed with the load deflexion response becoming relatively flat. However, nearly all specimens except those with their inside surfaces machined smooth, showed some residual strength even when the concrete core ran out of travel. The load-deflexion plots for all specimens, arranged according to groups, are given in Reference (10).
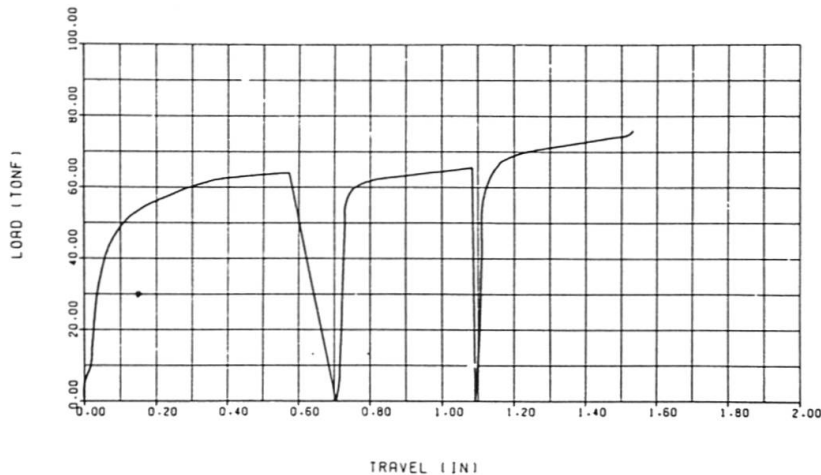
FIG. 4   Load-deflexion characteristic for tube MA1

7.   DEFINITION OF TEST BOND STRENGTH

The steadily non-linear nature of the load deflexion characteristics makes it difficult to adopt a single definition of bond strength.   A typical load deflexion plot is shown in Fig. 3.   The terminal point of the curve may correspond to either a sudden separation of the core from the steel shell or, as in a majority of tests, to the limit of the travel available to the concrete core.   Clearly, limiting travel as a criterion of ultimate bond strength cannot be considered satisfactory because specimens of different contact length would be at different level of bond strain for a particular value of limiting travel.

An important feature observed in the tests was the slope of the load deflexion response in the later stages of the tests.   The curves show remarkably parallel slopes, suggesting that the resistance offered in the later stages could be attributed entirely to friction.   To ascertain this, Tube MA1 was loaded first until it started to show the steady rate associated with friction.   At a load of 64 tonf the tube was unloaded.   No elastic or inelastic unloading was observed (Fig. 4).   In fact, the deflexions upon unloading were somewhat higher than at 64 tonf.   This can only be attributed to the pressure of load, albeit reducing, resulting in additional frictional movement.   Particularly noteworthy are the slopes of the two curves obtained upon reloading which are nearly the same, indicating that the frictional resistance remains unaffected by unloading.

In order to obtain a reliable estimate of the ultimate bond strength the frictional component would have to be ignored.   The ultimate bond strength would have to be defined on the basis of the load deflection response obtained in the earlier stages of the test, that is before the onset of the frictional movements.   This can be achieved in two possible ways.   First, as is common practice for materials with non-linear stress strain characteristics such as aluminium, a 0.2% offset stress could be adopted as the basis for defining the ultimate strength.   This approach requires an estimate of the initial modulus of elasticity from the load deflexion characteristics.   Slight errors would be inherent because in the early stages there occurs some initial settlement due to local crushing of concrete under the loading pad, making it difficult to calculate initial slope of the curve.

The second approach is more direct.   The ultimate bond strength could be defined on the basis of a critical bond strain.   This approach has the advantage that there exists no need to determine the initial slope of the load deflexion

TABLE 1. Results for Group MA

LABEL	DIAMETER	THICKNESS	LENGTH	CUBE STRENGTH	.0035 STRESS	OFFSET STRESS	AGE
	IN	IN	IN	LBF/SQ IN	LBF/SQ IN	LBF/SQ IN	DAYS
■ MA 1	6.086	.250	13.50	3720.0	312.70	375.00	7
■ MA 4	6.113	.250	13.50	5189.0	323.27	510.00	7
■ MA 5	6.089	.250	13.50	3723.0	324.81	376.00	7
■ MA 9	6.104	.250	13.50	4418.0	378.91	420.00	10
■ MA 2	6.114	.250	13.50	5189.0	301.22	420.00	14
■ MA 7	6.091	.250	13.50	5189.0	398.44	452.00	14
■ MA 8	6.089	.250	13.50	5189.0	340.83	465.00	14
■ MA10	6.104	.250	13.50	5400.0	398.95	530.00	21
MA 3	6.109	.250	13.50	5849.0	430.93	500.00	28
MA 6	6.086	.250	13.50	5849.0	387.73	430.00	28

characteristic. Further, the level of scatter in the results obtained by the
two methods would not be significantly different. The critical bond strain
could be related to the ultimate crushing strain of concrete. A commonly
accepted value for this is 0.0035. This value is recommended in some concrete
codes of practice[8]. A slightly higher value of 0.0040 may be more appropriate
if it is desired to allow for the initial settlements due to the local crushing
of concrete. The lower value would, on the other hand, be more conservative,
and it is this value that has been adopted in this paper.

8.   INFLUENCE OF AGE ON BOND STRENGTH (TEST GROUP MA)

Ten specimens belonging to this group were tested at different ages of concrete.
All specimens were cast on the same day from the same batch of concrete and were
compacted and cured in similar manner. The data and results for this group are
given in Table 1. It may be observed that on the basis of 0.0035 bond stress,
there occurs an increase in bond strength with age. The 0.2% offset stress
indicates a reduction in bond strength beyond the age of 21 days. If the results
for specimens CS15, CS17, and CS25 (Table 2), which had the same design data as
that of group MA, are also considered, a reduction in bond strength beyond the
age of 21 days is indicated on the basis of 0.0035 bond stress as well as on the
basis of 0.2% offset stress. This is further supported, to some extent, by the
results obtained for group SZ, which were all tested at the age of 47-48 days and
which showed noticeably lower values of bond strength.

TABLE 2. Results for Group CS

LABEL	DIAMETER	THICKNESS	LENGTH	CUBE STRENGTH	.0035 STRESS	OFFSET STRESS	AGE
	IN	IN	IN	LBF/SQ IN	LBF/SQ IN	LBF/SQ IN	DAYS
CS14	6.129	.250	13.50	3190.0	281.73	280.00	28
CS21	6.101	.250	13.50	3190.0	272.48	283.00	28
CS28	6.115	.250	13.50	3190.0	188.86	189.00	28
CS19	6.110	.250	13.50	3967.0	324.22	343.00	28
CS22	6.118	.250	13.50	3967.0	200.56	210.00	28
CS25	6.148	.250	13.50	3967.0	306.43	297.00	28
CS13	6.151	.250	13.50	4075.0	208.05	210.00	28
CS24	6.137	.250	13.50	4075.0	226.21	231.00	28
CS27	6.161	.250	13.50	4075.0	268.81	276.00	28
CS12	6.164	.250	13.50	4360.0	256.42	230.00	28
CS18	6.109	.250	13.50	4360.0	274.06	282.00	28
CS26	6.152	.250	13.50	4360.0	232.05	267.00	28
CS11	6.145	.250	13.50	5305.0	276.50	325.00	28
CS16	6.129	.250	13.50	5305.0	271.56	270.00	28
CS20	6.148	.250	13.50	5305.0	305.84	270.00	28
CS15	6.122	.250	13.50	6052.0	339.57	357.00	28
CS17	6.160	.250	13.50	6052.0	219.47	223.00	28
CS23	6.156	.250	13.50	6052.0	223.07	268.00	28

As indicated by the values given in Tables 1 and 2, there does not appear to be a great variation in the ultimate bond strength values obtained from the two approaches discussed earlier.   In the remainder of this paper, the term 'ultimate bond strength' would be used to mean the value associated with 0.0035 bond strain.

9.   INFLUENCE OF CONCRETE STRENGTH (TEST GROUP CS)

The ACI building code[9], as well as some other studies on bond between concrete and steel reinforcing bars, suggest that the bond strength varies with the square root of concrete strength.   This is based on the assumption that the bond strength is related to diagonal tension in reinforced concrete beams.   To investigate whether this kind of relationship existed in composite columns as well or not, three specimens each of six different design concrete strengths were tested in this group.   The design cube strengths ranged from 3500 lbf/in^2 (24 N/mm^2) to 6000 lbf/in^2 (41 N/mm^2).   The primary variables for these design strengths were the water/cement ratio, which was varied from 0.825 to 0.6, and the aggregate/cement ratio, which was varied from 7.5 to 5.5.   All specimens were wet cured in identical conditions.

The actual cube strengths attained were close to the design cube strengths in many cases – 3190 lbf/in^2 for 3000 lbf/in^2, 3970 lbf/in^2 for 4000 lbf/in^2, 4075 lbf/in^2 for 4500 lbf/in^2, 4360 lbf/in^2 for 5000 lbf/in^2, 5305 lbf/in^2 for 5500 lbf/in^2, and 6052 lbf/in^2 for 6000 lbf/in^2.   The average values for the ultimate bond strength obtained corresponding to these cube strengths were 248 lbf/in^2 (coefficient of variation 20.7%), 277 lbf/in^2 (24.1%), 234 lbf/in^2 (13.3%), 254 lbf/in^2 (8.3%), 285 lbf/in^2 (6.5%), and 261 lbf/in^2 (26.2%), respectively, with an overall average of 260 lbf/in^2 and a coefficient of variation of 16.8%.   Clearly, the bond strength does not appear to be greatly influenced by the variation in the concrete cube strength.   This finding does not agree with earlier findings on the bond strength between concrete and reinforcing bars.   The explanation may lie in the basic difference in the nature of bond in the two cases.   In the case of reinforcing bars, a good keying action between steel and concrete makes a relationship between bond strength and cube strength more tangible.   In the case of filled tubes, higher strength concrete due to its naturally higher shrinkage will tend to diminish the keying action, thereby reducing the influence of concrete strength on bond strength.

10.   INFLUENCE OF CONCRETE STEEL INTERFACE LENGTH (TEST GROUP LN)

Three specimens each of five different lengths were tested to find the influence of contact length on bond strength.   The contact length was varied from 5.88 in (149 mm) to 17.625 in (445 mm) corresponding to length to diameter ratios of 1.0, 1.5, 2.0, 2.5, and 3.0.   The average values of the ultimate bond strength recorded (Table 3) for these values of length to diameter ratios were 305 lbf/in^2 (coefficient of variation 5.7%), 274 lbf/in^2 (11.8%), 325 lbf/in^2 (6.0%), 357 lbf/in^2 (3.7%), and 408 lbf/in^2 (3.2%), respectively, with an overall average of 331 lbf/in^2 (15.1%).   These values indicate that except for the shortest contact length, the bond strength appears to increase with the contact length.

If the results for specimens SZ50, SZ51, and SZ52, which had the same basic design data as that of Group LN and had a length to diameter ratio of 3.10, are also included, it would appear that the increase in bond strength with length is not of any significant order as the average bond strength for these specimens with a larger length was considerably less than the average bond strength for specimens with a length to diameter ratio of 3.0.

TABLE 3. Results for Group LN

LABEL	DIAMETER	THICKNESS	LENGTH	CUBE STRENGTH	.0035 STRESS	OFFSET STRESS	AGE
	IN	IN	IN	LBF/SQ IN	LBF/SQ IN	LBF/SQ IN	DAYS
LN41	5.918	.375	5.88	5848.0	285.14	340.00	28
LN42	5.889	.375	5.88	5848.0	318.01	335.00	28
LN43	5.876	.375	5.88	5848.0	311.39	350.00	28
LN29	5.846	.375	8.81	5848.0	236.99	283.00	28
LN30	5.853	.375	8.81	5848.0	291.22	322.00	28
LN31	5.862	.375	8.81	5848.0	294.63	306.00	28
LN32	5.850	.375	11.75	5848.0	304.52	302.00	28
LN33	5.895	.375	11.75	5848.0	327.19	327.00	28
LN34	5.941	.375	11.75	5848.0	343.55	361.00	28
LN35	5.867	.375	14.69	5848.0	356.56	430.00	28
LN36	5.932	.375	14.69	5848.0	370.86	450.00	28
LN37	5.926	.375	14.69	5848.0	344.38	392.00	28
LN38	5.872	.375	17.63	5848.0	421.25	444.00	28
LN39	5.889	.375	17.63	5848.0	408.31	395.00	28
LN40	5.897	.375	17.63	5848.0	395.33	373.00	28

TABLE 4. Results for Group SZ

LABEL	DIAMETER	THICKNESS	LENGTH	CUBE STRENGTH	.0035 STRESS	OFFSET STRESS	AGE
	IN	IN	IN	LBF/SQ IN	LBF/SQ IN	LBF/SQ IN	DAYS
SZ50	5.874	.381	18.25	6720.0	350.32	400.00	47
SZ51	5.908	.383	18.25	6720.0	259.55	325.00	47
SZ52	5.877	.379	18.25	6720.0	344.57	360.00	47
SZ53	6.157	.257	18.25	6720.0	159.21	190.00	47
SZ54	6.153	.258	18.25	6720.0	187.84	210.00	47
SZ55	6.173	.261	18.25	6720.0	146.83	175.00	47
SZ56	6.256	.226	18.25	6720.0	213.10	285.00	47
SZ57	6.214	.224	18.25	6720.0	181.08	295.00	47
SZ58	6.251	.221	18.25	6720.0	209.72	290.00	47
SZ59	8.149	.256	18.25	6720.0	275.63	300.00	47
SZ60	8.176	.261	18.25	6720.0	281.99	300.00	47
SZ61	8.135	.268	18.25	6720.0	255.53	275.00	47
SZ62	9.117	.289	18.25	6720.0	90.87	100.00	47
SZ63	9.105	.289	18.25	6720.0	75.39	75.00	47
SZ64	9.132	.283	18.25	6720.0	84.17	100.00	47
SZ65	12.040	.376	18.25	6720.0	291.78	320.00	47
SZ66	12.022	.377	18.25	6720.0	288.73	425.00	47
SZ67	12.047	.375	18.25	6720.0	290.41	350.00	47

The average value of the ultimate bond strength obtained from the 18 specimens including specimens SZ50, SZ51, and SZ52, is 334 lbf/in^2 with a coefficient of variation of 15.1%. The scatter of the average values of the bond strength for different values of length to diameter ratios, with respect to the overall average for the 18 specimens is not very much larger than the scatter within the individual sub-groups. It may, therefore, be concluded that the contact length of the concrete and steel interface does not have any appreciable influence on the bond strength.

11. INFLUENCE OF TUBE SIZE ON BOND STRENGTH (TEST GROUP SZ)

Eighteen specimens were tested to investigate the influence of the size of the tube measured in terms of internal diameter to tube thickness ratio. All specimens were cast from the same batch of concrete, were cured in similar conditions, and were tested within two days at the age of 47-48 days. The specimens had diameter to thickness ratios of 17.7 (3 specimens), 26.5 (3), 31.2 (3), 34.3 (3), 34.5 (3), and 34.0 (3). The average values of the ultimate

TABLE 5. Results for Group CC

LABEL	DIAMETER	THICKNESS	LENGTH	CUBE STRENGTH	.0035 STRESS	OFFSET STRESS	AGE
	IN	IN	IN	LBF/SQ IN	LBF/SQ IN	LBF/SQ IN	DAYS
CC70	5.896	.383	13.50	4457.0	381.74	450.00	28
CC71	5.860	.391	13.50	4457.0	370.53	420.00	28
CC72	5.862	.389	13.50	4457.0	359.86	410.00	28
CC73	5.882	.385	13.50	5405.0	293.40	365.00	28
CC74	5.860	.382	13.50	5405.0	306.57	335.00	28
CC75	5.900	.382	13.50	5405.0	310.82	345.00	28
CC76	5.917	.386	13.50	5133.0	308.29	420.00	28
CC77	5.862	.386	13.50	5133.0	329.86	415.00	28
CC78	5.878	.384	13.50	5133.0	310.07	360.00	28
CC79	5.917	.381	13.50	5133.0	267.95	305.00	28
CC80	5.911	.381	13.50	5133.0	320.88	380.00	28
CC81	5.892	.378	13.50	5133.0	216.71	245.00	28
CC82	5.858	.381	13.50	5133.0	260.84	280.00	28
CC83	5.842	.382	13.50	5133.0	223.58	260.00	28
CC84	5.858	.382	13.50	5133.0	217.58	235.00	28
CC85	5.864	.382	13.50	5133.0	168.50	180.00	28
CC86	5.903	.381	13.50	5133.0	213.83	240.00	28
CC87	5.885	.397	13.50	5133.0	241.16	265.00	28

bond strength for these values were 318 lbf/in^2 (coefficient of variation 16.0%), 166 lbf/in^2 (12.8%), 201 lbf/in^2 (8.7%), 271 lbf/in^2 (5.1%), 83 lbf/in (9.3%), and 290 lbf/in^2 (0.5%), respectively, with an overall average of 222 lbf/in^2 and a coefficient of variation of 38.7 (Table 4). These values have two significant features. First, the overall average for this particular group is much smaller than the overall average values recorded for other groups. The other feature is the greater amount of scatter in the results. Both these factors may be related to the same cause, namely, the age at the time of testing. As pointed out earlier, specimens of this group were tested at the age of 47-48 days, not by design it may be added, and this may have caused larger shrinkage than at the age of 28 days resulting in a generally lower effectiveness of the bond. The important conclusions emerging from the results of this group, therefore, are that the size of the tube in relation to the tube diameter does not have any influence on the ultimate bond strength, and that the bond strength at an age greater than 28 days may be somewhat lower than that obtained at an age of 28 days.

12. INFLUENCE OF COMPACTION OF CONCRETE ON THE BOND STRENGTH (TEST GROUP CC)

Specimens of this group were tested for different conditions likely to arise in the manufacture of concrete. Three specimens were tested for each of the following conditions:

Specimens 70-72 - Aggregate/cement ratio 5.0, dry cured, well compacted with poker vibrator

73-75 - Aggregate/cement ratio 5.0, wet cured, well compacted with poker vibrator

76-78 - Aggregate/cement ratio 5.5, wet cured, well compacted with poker vibrator

79-81 - Aggregate/cement ratio 5.5, wet cured, lightly compacted with poker vibrator

82-84 - Aggregate/cement ratio 5.5, wet cured, well compacted by hand (3 layers with 40 strokes each)

85-87 - Aggregate/cement ratio 5.5, wet cured, lightly compacted by hand (3 layers with 20 strokes each).

Comparing results (Table 5) for dry curing against wet curing, it is found that the former gave rise to a higher value of ultimate bond strength of 371 lbf/in^2 than in the case of wet curing for which the ultimate bond strength realised was
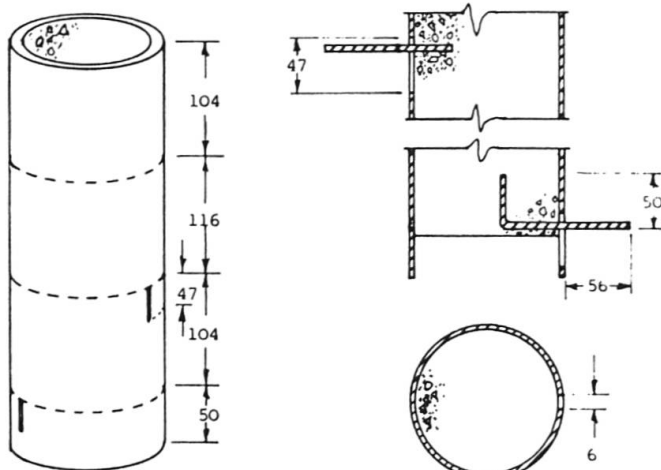
FIG. 5   Arrangement of projecting bars
         to record the slip of the concrete
         core at two-thirds height, one-
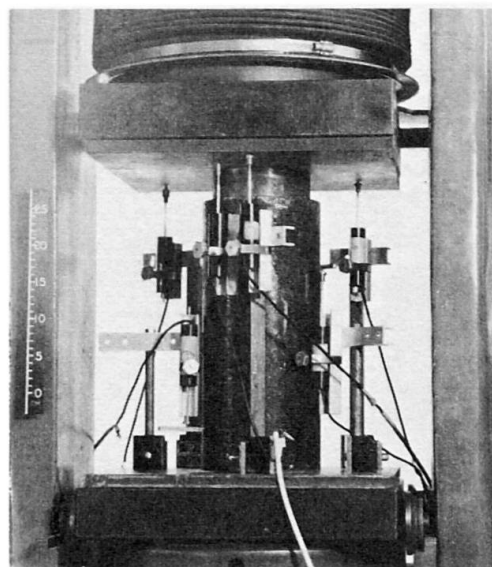   third height and the bottom of
         the core

FIG. 6   Specimen in which slip
         distribution was measured,
         shown under test

304 lbf/in^2. This is contrary to expectation in that the specimens with dry
curing were likely to have greater amount of shrinkage and hence a lower bond
strength. The only explanation may lie in the general variability in the value
of ultimate bond strength from specimen to specimen.

Results more consistent with expectations were obtained for varying degrees of
compaction. Specimens compacted by mechanical vibration (CC76-CC81) developed
higher bond strength than those compacted by hand (CC82-CC87). Again, specimens
with greater compaction by vibration as well as hand strokes (CC76-CC78 and
CC82-CC84) developed higher bond strength than those that were lightly compacted
(CC79-CC81 and CC85-CC87). These and earlier results show that perhaps the most
significant factor influencing the ultimate bond strength might be compaction
and the consequent better keying of concrete between surface irregularities in
the steel.

13. DISTRIBUTION OF SLIP DOWN THE DEPTH (TEST GROUP RD)

In this group three specimens were tested to observe the variation of load slip
characteristic at different points along the length of the concrete and steel
interface. Additional instrumentation for this purpose consisted of slits in
the sides of the tube through which were inserted 4.25 in (106 mm) long bars
embedding them 2 in (50 mm) in the concrete core at the time of casting. The
length of the slits was 1.875 in (47 mm), just enough to allow a travel of
about 1.5 in (38 mm) to the projecting steel bars. The lowest bar was bent at
90° to provide better anchorage. The projecting bars were located so as to
measure the movement of the concrete core at points 1/3, 2/3 and full depth
from the top (Figs. 5 and 6). The movements at the ends of the bars were
measured by means of additional deflexion transducers. The load slip curves
recorded are shown in Fig. 7. In the early stages a gradual reduction in the
slip is noted from top to bottom, indicating a steady rate of strain in the
concrete steel interface. However, at high loads, the movements at all levels
is nearly the same, indicating the movement of the concrete core as a whole.
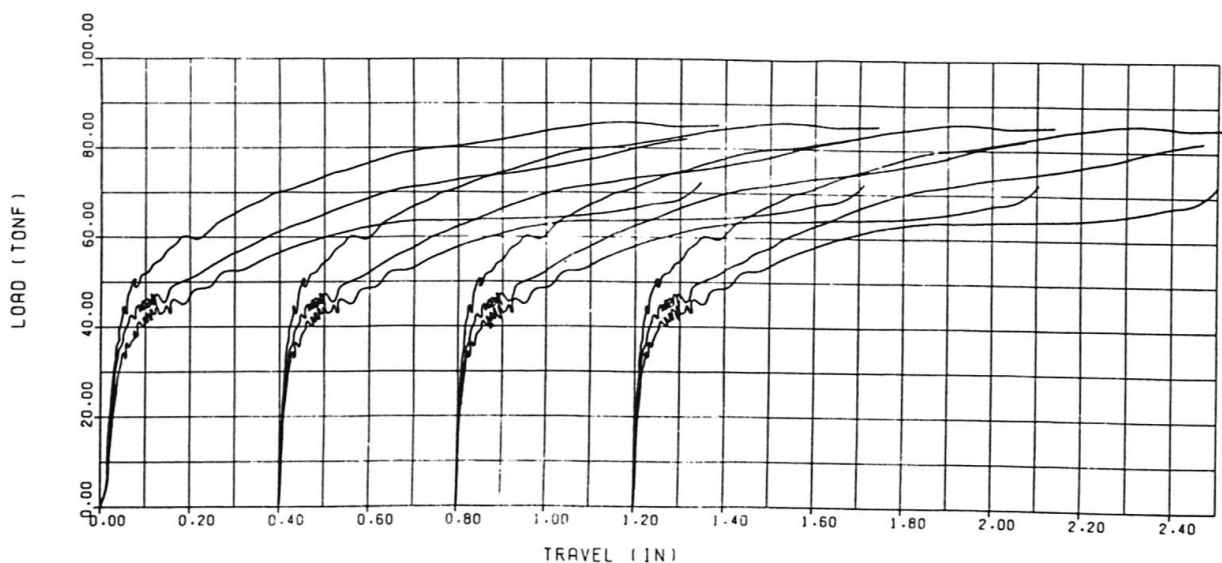
FIG. 7 Load-deflexion plots for Group RD (from left to right) at the top,
        two-third height, one-third height, and the bottom of the concrete core

The somewhat wavy nature of the load deflexion characteristics recorded for
this group may have been due to the fact that the tube had several openings,
causing some interlocking and subsequent release of small aggregate in these
slits.   The nature of the load slip characteristics lends weight to the earlier
proposition that the movement in the later stages of the tests is principally
related to friction between the steel shell and the concrete core.

The average value of 0.0035 bond strain corresponding to the top of the concrete
core is 320 lbf/in^2 (Table 6).

TABLE 6. Results for Group RD

LABEL	DIAMETER	THICKNESS	LENGTH	CUBE STRENGTH	.0035 STRESS	OFFSET STRESS	AGE
	IN	IN	IN	LBF/SQ IN	LBF/SQ IN	LBF/SQ IN	DAYS
■ RD91	6.121	.267	13.50	6713.0	285.57	415.00	28
■ RD92	6.082	.285	13.50	6713.0	312.77	350.00	28
■ RD93	6.097	.274	13.50	6713.0	362.19	319.00	28

TABLE 7. Results for Groups ST, PH and CS

| LABEL	DIAMETER	THICKNESS	LENGTH	CUBE STRENGTH	.0035 STRESS	OFFSET STRESS	AGE
	IN	IN	IN	LBF/SQ IN	LBF/SQ IN	LBF/SQ IN	DAYS
■ ST44	6.198	.283	13.50	6713.0	60.63	44.00	28
■ ST45	6.170	.283	13.50	6713.0	45.12	46.00	28
■ ST46	6.178	.283	13.50	6713.0	38.51	55.00	28
■ PH47	6.110	.260	13.50	6713.0	109.23	185.00	28
■ PH48	6.119	.270	13.50	6713.0	163.93	220.00	28
■ PH49	6.116	.270	13.50	6713.0	104.24	120.00	28
CS15	6.122	.250	13.50	6052.0	339.57	357.00	28
CS17	6.160	.250	13.50	6052.0	219.47	223.00	28
CS23	6.156	.250	13.50	6052.0	223.07	268.00	28
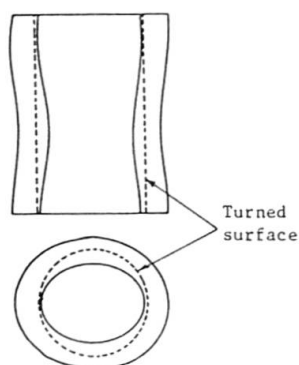
FIG. 8   Surface irregularities
         in the tube showing
         deviation from the
         true cylindrical
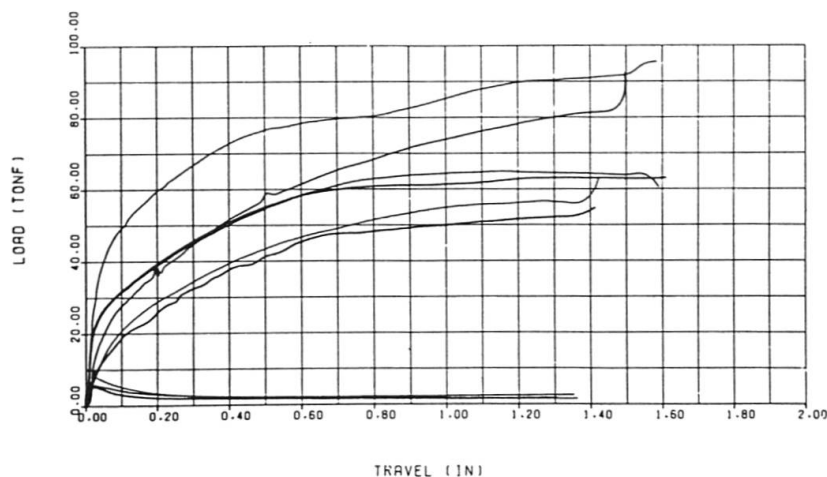   surface

FIG. 9   Load-deflexion plots for Groups ST
         (machined) and PH (lubricated) and
         specimens 15, 17 and 23 of Group CS
         (normal).

14.   STEEL SURFACE TREATMENT (TEST GROUPS ST AND PH)

To study the effect of the steel surface conditions, two types of steel
surfaces were prepared. Three specimens of Group ST had their inside surfaces
machine turned to. a smooth finish. An attempt was made to obtain a good
cylindrical surface from top to bottom. In this way it was hoped to avoid,
or at least minimise, the mechanical keying of the concrete core in the surface
irregularities shown to an exaggerated scale in Fig. 8. Another group of
three specimens (Group PH) had their surfaces treated with a lubricant (Phebcur)
in five coats. The surface roughness was otherwise the same as in the 'normal'
specimens. For the sake of comparison, results for tubes CS15, CS17, and
CS23 (Table 2) may also be considered, as these tubes had the same basic design
data as Group PH, but were cast in the normal way without any surface treatment.

The load deflexion response of specimens belonging to Groups PH and ST together
with that of specimens CS15, CS17 and CS23 is shown in Fig. 9. The response of
Group PH is very similar to that of all the other groups described earlier, in
that it is characterised by a distinct segment related to frictional movement.
The response, however, shows a near absence of the initially stiff region. The
ultimate strength obtained for this group is 125 lbf/in^2 (Table 7), which is
less than the corresponding value of 261 lbf/in^2 for the three specimens from
Group CS included here. The lower value of this stress associated with 0.0035
strain in the case of Group PH is directly due to the absence of the initially
stiff region in the response.

The load deflexion response of Group ST, on the other hand, shows remarkable
features. Only in the case of these specimens a sudden movement of the concrete
core, together with a sharp reduction in the load, was recorded. The core
continued to slip within the steel tube with a much faster rate than that
observed for normal specimens. This leads to the conclusion that in the absence
of the keying action, the resistance to movement is greatly reduced. The
0.0035 stress obtained is 49 lbf/in^2. It is worth noting that these specimens
show a distinct, although small, region of initial stiffness. This clearly
points to the relationship between the initial stiffness of the bond
characteristics and the surface roughness.

15. DISCUSSION OF TEST RESULTS

Results obtained from a large number of tests carried out indicate that the bond strength is not affected to any measurable extent by factors such as the contact length, tube size, tube thickness, and concrete strength. There is sufficient evidence to indicate that the most important factor is the mechanical keying of the concrete core with the irregularities in the steel tube. This mechanical keying could however, arise due to two different types of irregularities. The first type occurs due to the roughness of the steel surface. Before the concrete core as a whole can begin to move, it is this interlocking that has to be broken first. For this reason, this type of interlocking may be thought to contribute mainly to the ultimate bond strength. The rupture of this primary interlocking may then be related to the local crushing of concrete near the interface. This lends substance to the adoption of 0.0035 strain as the critical value for the definition of ultimate bond strength.

The second type of bond resistance occurs due to the manufacturing tolerances associated with the internal diameter of the tube. This type of interlocking, shown in Fig. 8, contributes in essence to the frictional resistance associated with the later, flat portion of the load deflexion response. The remarkably parallel nature of the load deflexion characteristics in this region obtained for different specimens cut from the same manufacturer's length tends to support this relationship. For want of better terms, the first type of keying action will be referred to as microlocking, and the second type as macrolocking.

The results of Group ST, with the inside surface machined to a near smooth cylindrical surface, show a total absence of macrolocking and a much reduced microlocking consistent with the diminished surface roughness. Results for Group PH, on the other hand, show only a small amount of microlocking with a normal level of locking, evidenced by the near absence of the initially stiff region of the load deflexion characteristics but developing normal resistance to large movements associated with friction. Further, results for Group CC show that by better compaction both microlocking and macrolocking can be improved, resulting in higher values of ultimate bond strength.

Viewed in the light of microlocking and macrolocking, the variation in the load deflexion characteristics between various groups can be adequately explained. It also lends support to the conclusions drawn earlier that the bond resistance is not related to factors such as tube diameter, tube thickness, concrete steel contact length and concrete strength.

It has been pointed out that the specimens cast under identical conditions showed considerable scatter in the results. This may be due to a variation in the surface roughness affecting microlocking to varying degrees in specimens which were otherwise identical. As is well known there can be a large variation in the value of crushing strain of concrete between different specimens cast from the same mix, and consequently one may expect a similar variation in the ultimate bond strength calculated on the basis of a fixed value of crushing strain.

The general scatter in the ultimate bond strength obtained for the bulk of the normal specimens may be attributed to the usual variability in the properties of concrete. The results obtained may, therefore, be subjected to the same type of statistical analysis as recommended for obtaining the characteristic strength of concrete. In CP110(8) and in the CEB-FIP Recommendations(10), the characteristic strength is defined as:

$$f_k = f_m - 1.64 \ S$$

where f_m is the mean strength obtained from tests, and S is the standard deviation of all test results. Applying this criterion to the present test results except those marked with an asterisk (*) which are excluded on

the ground that they were not 'normal' specimens, f_m is found to be 281.6 lbf/in^2 and S to be 77.9 lbf/in^2, resulting in a characteristic bond strength of 154 lbf/in^2 (1 N/mm^2). In view of the large sample involved, this value may be recommended as a sound value for use in design.

16. CONCLUSION

The test results have shown that the resistance to push out loads in filled tubes derives primarily from the interlocking of concrete in two types of imperfections in steel.   The first relates to the surface roughness of steel and the second to variation in the shape of the cross section, away from the ideal cylindrical surface.   The interlocking of concrete in the surface roughness of steel, that is microlocking, contributes to the useful component of the ultimate bond strength related to the initially stiff region of the load deflexion characteristics obtained from the tests.   This bond is broken when the concrete interface attains a local strain of 0.0035 associated with the compressive crushing of concrete.   This component of bond resistance is distinguished from the resistance obtained due to the interlocking of the concrete in the undulating surface of steel due to manufacturing tolerances. This latter type of interlocking, termed macrolocking, is related to the later stages of the load deflexion characteristics associated with the primarily frictional movement.   The remarkably parallel nature of the characteristics in this region tends to confirm this relationship.   This was further supported by tests on Group ST which had smooth and cylindrical inner surface and showed a total absence of macrolocking.   It was found that by better compaction both microlocking and macrolocking could be enhanced resulting in higher values of ultimate bond strength.   Results from a sufficiently large sample of tests suggest that the ultimate bond strength is not influenced to any appreciable degree by factors such as the length of concrete and steel interface, the diameter of the tube, the thickness of the tube, or the concrete strength. A characteristic ultimate bond strength was obtained by applying statistical corrections to the mean test value obtained from all normal specimens.   Thus a value of 150 - 160 lbf/in^2 (Approx. 1 N/mm^2) may be recommended for use in design.   It may be added that this value, although obtained from tests on filled tubes, may also be used for other types of composite construction where some hoop reinforcement is provided, for example in concrete encased steel stanchions.

17. REFERENCES

1.   BONDALE, D.S., Column theory with special reference to composite columns. *Consulting Engineer (London)*, 1966, Vol. 30, July, August and September.

2.   BASU, A.K. and HILL, W.F., A more exact computation of failure loads of composite columns. *Proceedings, Institution of Civil Engineers*, 1968, Vol. 40, May.

3.   BASU, A.K. and SOMMERVILLE, W., Derivation of formulae for the design of rectangular composite columns. *Proceedings, Institution of Civil Engineers*, 1969, Supplementary Volume, Paper 7206S.

4.   FURLONG, R.W., Strength of steel encased concrete beam-columns. *Journal of the Structural Division*, Proc. ASCE, 1967, Vol. 93, No. ST10, October.

5.   VIRDI, K.S., and DOWLING, P.J., A unified design method for composite columns. *Publications*, IABSE, 1976, Vol. 36 - II.

6. _____, Composite steel - concrete construction, *Journal of the Structural Division,* Proc. ASCE, 1974, Vol. 100, No. ST5, May. (Contains bibliography upto 1973).

7. VIRDI, K.S., and DOWLING, P.J., The ultimate strength of composite columns in biaxial bending. *Proceedings, Institution of Civil Engineers,* 1973, Vol. 55, March.

8. BRITISH STANDARDS INSTITUTION, The structural use of Concrete, *Code of practice,* CP110-1972.

9. AMERICAN CONCRETE INSTITUTE, Building Code requirements for reinforced concrete, *ACI Standard 318-71,* 1971.

10. VIRDI, K.S., and DOWLING, P.J., Bond strength in concrete filled circular steel tubes. *CESLIC Report CC11,* Department of Civil Engineering, Imperial College, London, 1975, December.

CONVERSION FACTORS: Imperial to SI units

$$1 \text{ lbf} = 4.448 \text{ N}$$
$$1 \text{ lbf/in}^2 = 0.006895 \text{ N/mm}^2$$
$$1 \text{ in} = 25.4 \text{ mm}$$