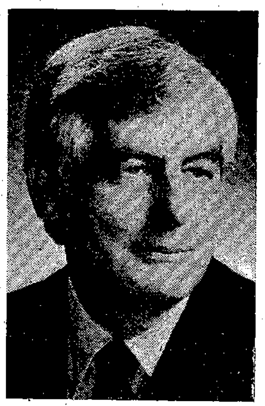
Bond characteristics of untensioned prestressing strand



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The use of untensioned, bonded prestressing strand for concrete reinforcing is quite common in the precast prestressed concrete industry.

This use includes such things as lifting handles, reinforcing for crack control and connection reinforcing between precast elements at their juncture. Regardless of the extent of the use of this method of reinforcing, an established, rational method of design is nonexistent.

Strand extending from the ends of precast prestressed I beams in highway bridges provided an economical solution to reinforcing for the resistance of volume change forces generated in these structures when made over supports.

This use provided justification for studies of fundamental behavior of the bonded untensioned strand.

Test Program

The nature of bond of untensioned prestressed strand in concrete differs from that of plain or deformed reinforcing bar as well as tensioned prestressed strand. There is a very limited amount of published research information regarding bonding of this type reinforcing.

In order to use and design untensioned strand as reinforcing, relationships defining the load transfer characteristics of the strand are necessary.

A program based upon pullout tests was designed to develop data relating the critical parameters for determining load transfer behavior of the untensioned strand.

The results of the test program are presented in the form of steel stress versus slip, and embedment length versus steel stress at general slip relationships which were considered to be the most meaningful parameters. The steel stress is based on the load at the free end of the strand and the deformation corresponds to free end slip.

For the second relationship, the point of general slip was obtained from the steel stress versus slip data. The condition of general slip is defined as the point where slip on the unloaded end of a strand is sufficient to produce a readable measurement.

Test parameters and specimens

Two basic shapes of specimens with three-strand configurations were tested. The points of application of the load and supports for each type of specimen are illustrated in Fig. 1.

First, straight configuration of specimens, as shown in Fig. 1(a), were used for straight unfrayed and frayed strands.

Second, unfrayed bent strands were tested with a specimen configuration as shown in Fig. 1(b). A listing of the specimens tested in this phase of the study is given in Table 1.

Five series of specimens were fabricated with a minimum of three identical units for each parameter variation. The duplication was to reduce the effect of scatter on the results. Three series were designed to study the embedment length versus bonded capacity of each of the strand configurations.

Specimens were tested with embedment lengths ranging from 5 to 45 in., 4 to 36 in., and 10 to 40 in. for straight unfrayed, straight frayed and bent unfrayed strand configurations, respectively.

For consideration of concrete strength and strand diameter, a straight unfrayed strand configuration with a constant 30-in. embedment length was used. For the concrete strength series, compression cylinder strengths ranged from 3750 to 6900 psi based on an

Synopsis

The bond behavior of untensioned prestressing strand was studied to evaluate load-deformation characteristics as well as load-embedment requirements.

The results of the study are applicable to bonded untensioned strand as reinforcing for concrete in particular for connection between precast elements.

Three strand configurations were studied, namely, straight, frayed and bent 90 deg over a reinforcing bar.

Relations were developed between loaded end slip and applied steel stress from test data for each configuration.

Design equations were developed which relate the embedment length necessary to insure against general slippage for a given steel stress.

Both working stress and ultimate strength equations, which account for a variation of pre-bond length for the bent strand configuration, are presented.

The influence of strand diameter, concrete strength, and containment reinforcing were also studied and found to be of little consequence.

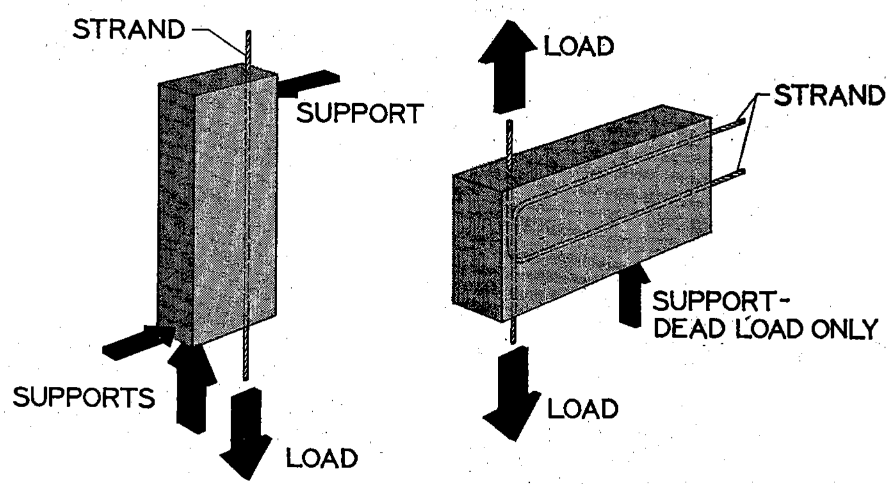


Fig. 1. Specimen configuration: (left) straight strand; (right) bent strand.

average of three test cylinders.

A complete list of concrete strengths for each specimen are given in Table 2. For the strand diameter series, ⅜, 7/16, ½, and 6/10 in. diameter strands were tested.

Test procedure

Specimens were tested, as nearly as possible, in a stress field that would not distort the results. They were loaded in such a way as to minimize compression in the concrete surrounding the embedded strand.

The specimens used for the straight strand were in flexure; however, the support forces generating the bending couple were very small relative to the magnitude of the force applied to the strand. These specimens were similar to the type developed by Kemp *et al.*,[1] wherein the front face was not subjected to the concentrated compressive load.

The stress field of the bent specimen was considerably more complex since no forces were applied directly to the concrete. The load was applied to the strand which overlapped and caused the concrete between the two strands to be subjected to very high compressive stresses while that on the exterior was relatively unstressed.

The type of data required in the study and the configuration of the specimen in general dictated, the loading apparatus. The measured displacements were highly dependent upon the duration of the load.

As a result, a closed loop servo system was used which would maintain a constant load level over a period of time. Each load level was maintained until the monitored displacement was stabilized.

Stability of the displacement to equilibrium was an exponential function shown by limited time-dependent tests. The limiting stability criteria used for these tests was a slip rate of 1/10,000 in. per minute.

The free end slip was measured with a tripod of 1/10 in. travel direct current differential transformers (DCDT's) at the loaded end of the specimen. General slip, a readable value of slip which occurred at the unloaded end of the specimen, was measured by 1/10,000-in. dial gages.

Details of the supports and instrumentation arrangements are shown in Fig. 2. Specimens with straight and bent strand configurations during testing are shown in Figs. 3 and 4, respectively.

Test Results

The data obtained from these tests were processed in terms of both steel stress and bond stress. However, the results based on bond stress proved to be much less meaningful than those based on loaded end steel stress.

As a result, the information presented here is in the form of curves and equations relating displacement, embedment length, and steel stress only.

Bonding of untensioned strand

The helical texture of strand does not provide a positive means of mechanical interlocking since the strand tends to unscrew as it slips through the concrete. However, as a strand elongates,

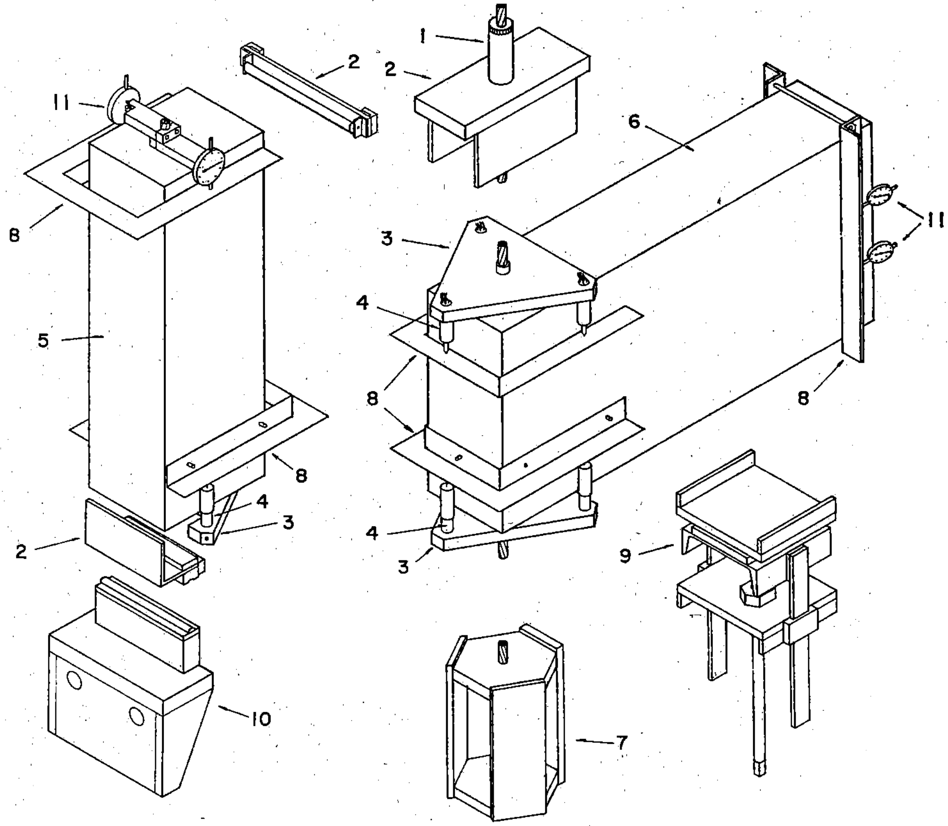
Table 1. Length, diameter, and number of specimens for various specimen types.

Specimen	Length, in.	Diameter, in.	No. of specimens
B*	40	1/2	3
B	30	1/2	3
B	20	1/2	3
B	10	1/2	4
B-NR	30	1/2	2
S	45	1/2	3
S	30	1/2	3
S	20	1/2	3
S	10	1/2	3
S	5	1/2	3
S-NR	30	1/2	2
F	36	1/2	3
F	24	1/2	3
F	16	1/2	3
F	8	1/2	3
F	4	1/2	3
F-NR	24	1/2	2
D	30	0.6	3
D	30	7/16	3
D	30	3/8	3
CC-1	30	1/2	3
CC-2	30	1/2	3
CC-3	30	1/2	3
CC-5	30	1/2	2
Total			69

*B - Bent, S - Straight, F - Frayed,
D - Strand Diameter Series.
CC - Concrete Strength Series.
NR - Non-reinforced.

Table 2. 28-day cylinder strength (psi) of concrete used in pullout specimens.

Specimens	S-45-1	S-45-2 S-10	S-30	S-20 S-5	F-36	F-24	F-16 F-8	F-4 B-10-2
Cyl. 1	4790	6370	5940	6930	5460	4490	5760	5760
Cyl. 2	3620	6280	5660	6010	6080	5160	5710	6080
Cyl. 3	3980	6300	5380	6900	5850	4740	5960	6000
Avg. f'_c	4130	6310	5660	6610	5800	4800	5810	5950
Specimens	**B-40-1**	**B-40-2**	**B-30-1**	**B-30-2**	**B-20**	**B-10-1**	**D-6/10**	**D-7/16**
Cyl. 1	6000	7500	6790	7960	6540	6720	5840	5010
Cyl. 2	6000	7270	6790	6490	6220	6540	5570	5820
Cyl. 3		6490	7180	7000	6240	6970	6650	5730
Avg. f'_c	6000	7080	6920	7150	6340	6740	6020	5520
Specimens	**D-3/8**	**CC-1**	**CC-2**	**CC-3**	**CC-5**	**S-30-NR**	**B-30-NR**	**F-24-NR**
Cyl. 1	4930	4990	6880	5940	3640	8520	7340	8240
Cyl. 2	4810	5680	6930	6000	3770	8420	7480	7360
Cyl. 3	5040	5570	6900	6460	3840	8490	7040	8030
Avg. f'_c	4930	5410	6900	6130	3750	8480	7290	7880



1 Strand Vice	5 Straight Specimen	9 Leveling Device
2 Support	6 Bent Specimen	10 Corbel
3 Equilateral Triangle	7 Clevis	11 Displacement Dial
4 Differential Transformer	8 Bracket	

Fig. 2. Details of equipment attached to bent and straight specimens.

the pitch of the strand changes with respect to the surrounding impression in the concrete.

This effect causes increased normal and frictional forces which more than compensates for the effect of radian contraction associated with the strand at elongation.

Untensioned strand subjected to a slowly applied load produces a non-linear load slip curve by means of elastic straining and frictional sliding. As the strand is unloaded the frictional forces reverse themselves and create some permanent deformation. In addition, the untensioned strand under load exhibits a tendency to creep.

The creep is caused by high, normal and shearing stresses in the concrete surrounding the strand. Local crushing occurs at the strand-concrete interface at the loaded end as slip progresses.

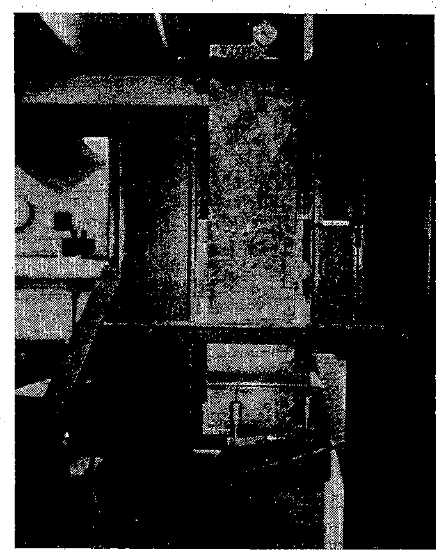


Fig. 3. Straight strand specimen during testing.

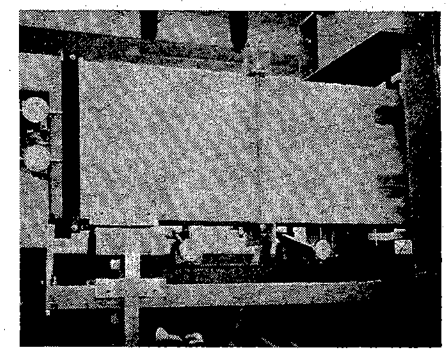


Fig. 4. Bent strand specimen during testing.

Under cyclic loading, local crushing of the matrix in the loaded end region has already occurred and no appreciable creep occurs until the load approaches that of previous cycles. A typical steel stress versus slip curve for a bent strand specimen under a single cycle of loading is shown in Fig. 5.

The curves shown in this figure were obtained from instantaneous slip and slip at equilibrium at each load level. It should be noted that upon reloading, the creep is greatly reduced at lower stress levels.

Analysis of data

Displacement readings were taken at both the loaded end and the free end of the specimens. Load increments

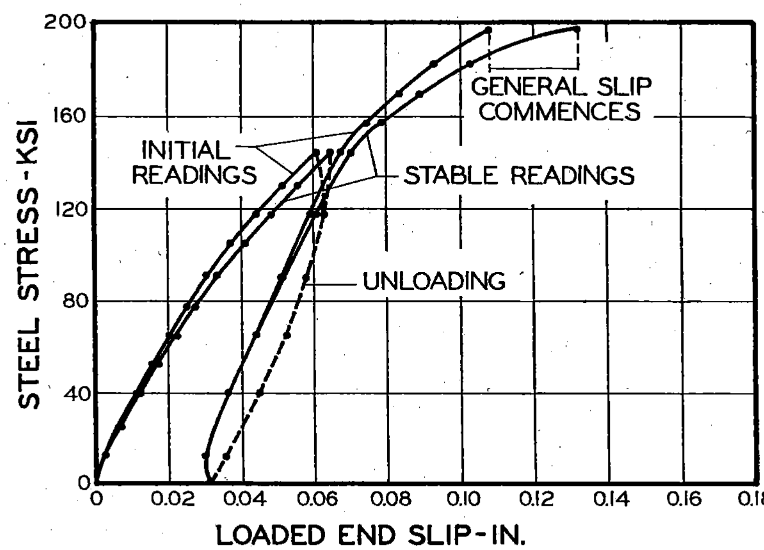


Fig. 5. Loaded end steel stress versus slip. Initial and stable slip readings.

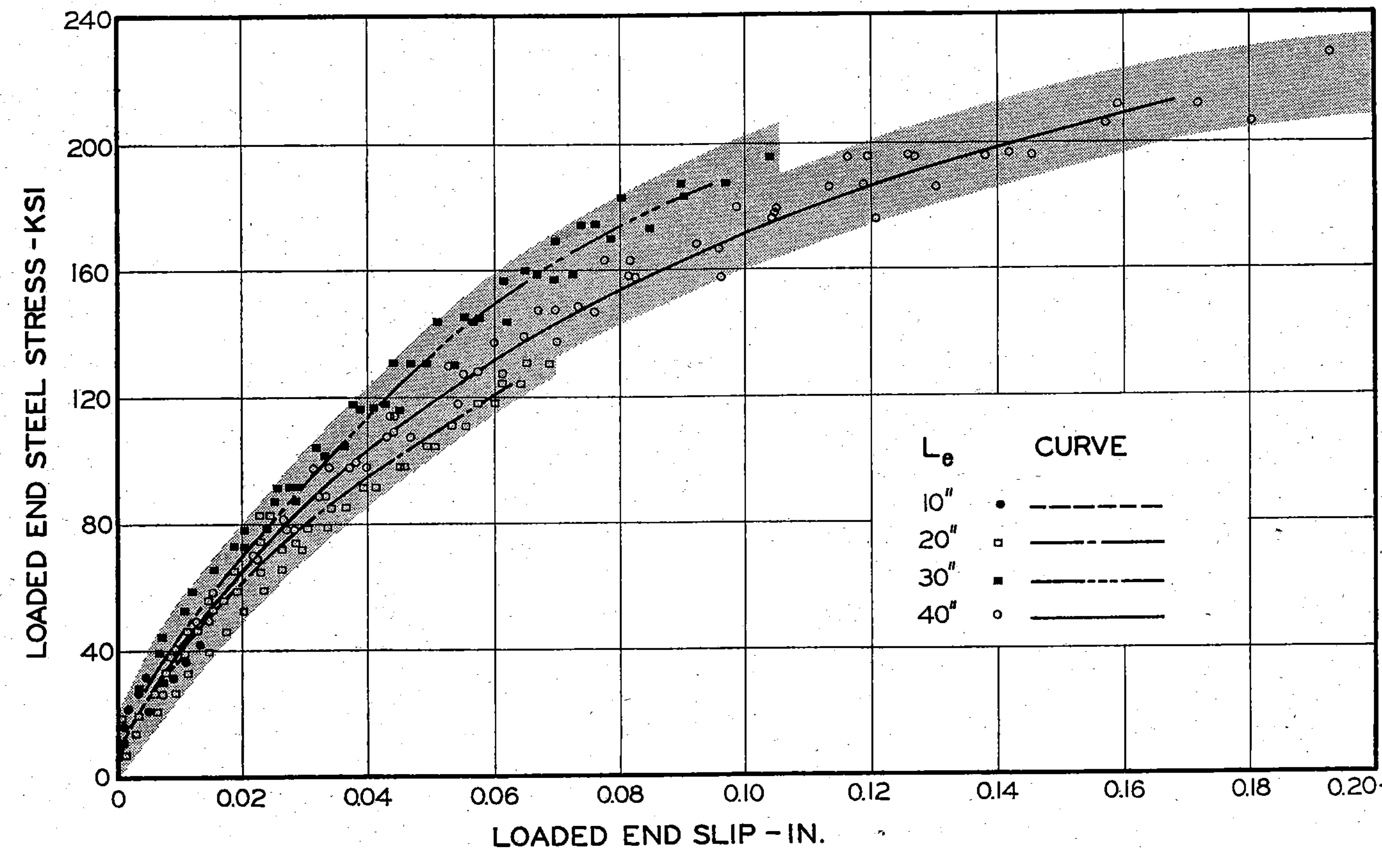


Fig. 6. Slip as a function of loaded end steel stress for the four embedment lengths of the bent series.

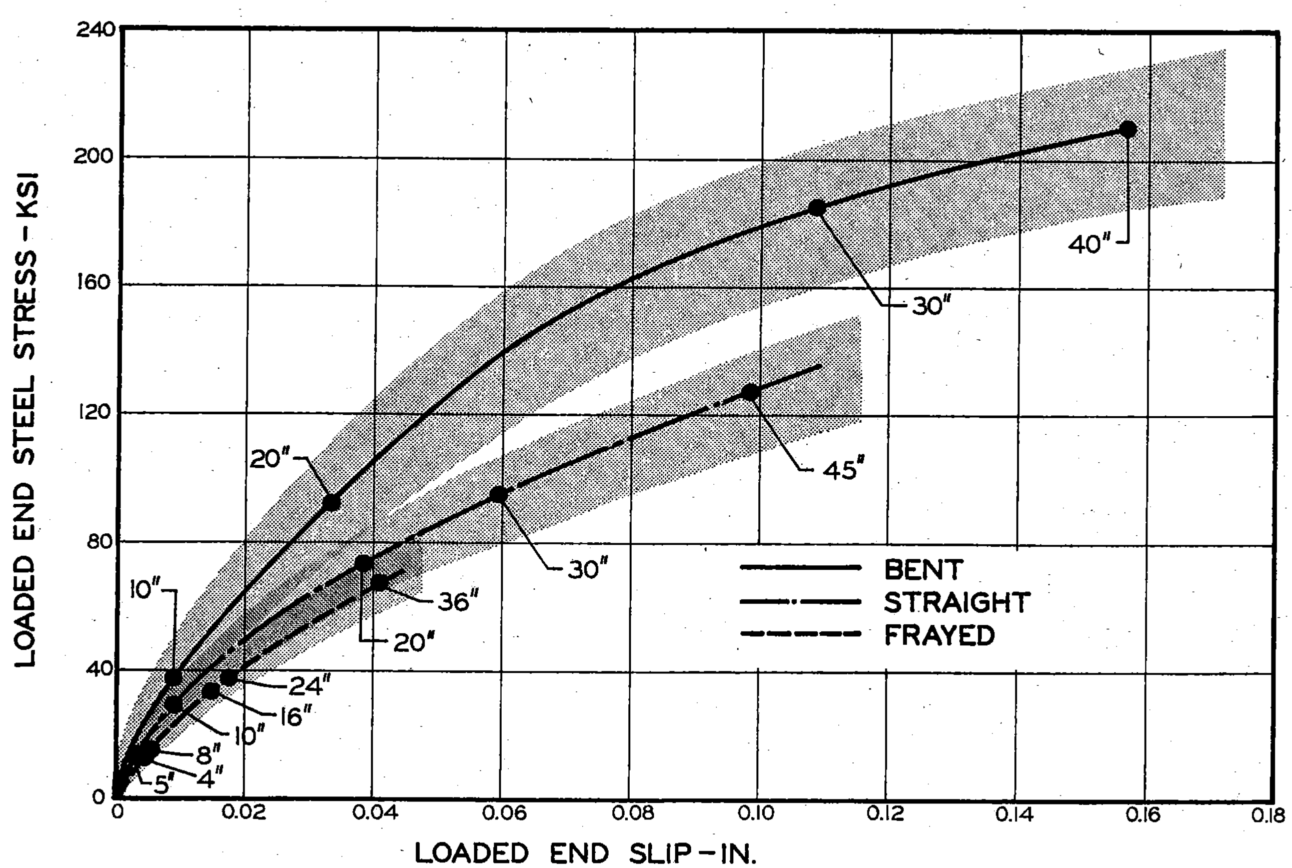


Fig. 7. Steel stress versus loaded end slip for the three strand configurations.

were established for each specimen in sufficient number to establish the load-displacement curves. The parameter used to express displacement was loaded end slip through all the data analyses.

The number of pieces of data generated from this series of tests was very large. As a result, the information presented will be based on condensations of this data and no attempt will be made to represent each individual data point.

A typical distribution of the data is shown in Fig. 6. In the remainder of the tests the distribution of data will be represented simply by a band similar to that shown in Fig. 6.

Steel stress versus loaded end slip

The relationship between loaded end steel stress and slip appears to be independent of the embedment length being considered. The data and curves shown in Fig. 6 verify this within the limits of the normal scatter for tests of this type. In addition to displaying data points, curves are shown on this figure which are least square fits to the data for a particular embedment length.

As can be seen from these curves, there is no rational pattern to the small deviation between the curves. As a result, the entire set of data taken for all tests in the series was combined for a single polynomial fit.

The generated steel stress slip functions for the entire test series are illustrated in Fig. 7. As can be seen from these curves, polynomial fits represent very well the data band.

The order of each of the polynomial functions for the three strand configurations was chosen so that the function would adequately follow the data and be within the sensitivity of the slip readings (0.0001 in.). The points indicated at 4, 5, 8, 10, 16, 20 in., etc. denote the point at which general slip commences for the various embedment lengths.

Within the range of values used in the test program, the parameters of strand diameter and concrete strength proved to have a negligible effect when steel stress and slip were considered as the prime parameters. The results of these test series showed that there was no consistent pattern when comparing strength of concrete or strand diameter to the steel stress versus loaded end slip or general slip relationships.

In addition to consideration of the parameters designed as part of the test program, confinement reinforcing was also examined. It was initially believed that cracking of the specimens during testing was highly probable. As a result, confinement reinforcing was designed and used in the majority of the tests.

Since cracking of the specimens did not occur, an additional series with no confinement reinforcing showed a negligible effect on the load transfer characteristics of the untensioned strand.

It was concluded from the evaluation of the test data in terms of steel stress versus loaded end slip that the parameters of embedment length, concrete strength, and strand diameter did not appreciably affect the basic relationship. On the other hand, this was not the case when a nominal bond stress was used as the load parameter.

General slip versus embedment length

Since it was not within the scope of the study to develop complete time-dependent load relationships, the condition of general slip was used to terminate the elastic portion of the load displacement relationships. The load-slip relationships generated up to the point of general slip were based on stable equilibrium and can be considered valid for design.

A set of curves of embedment length versus steel stress at general slip is shown in Fig. 8. Included on this figure are equations for steel stress and embedment length based on a least square fit of the data.

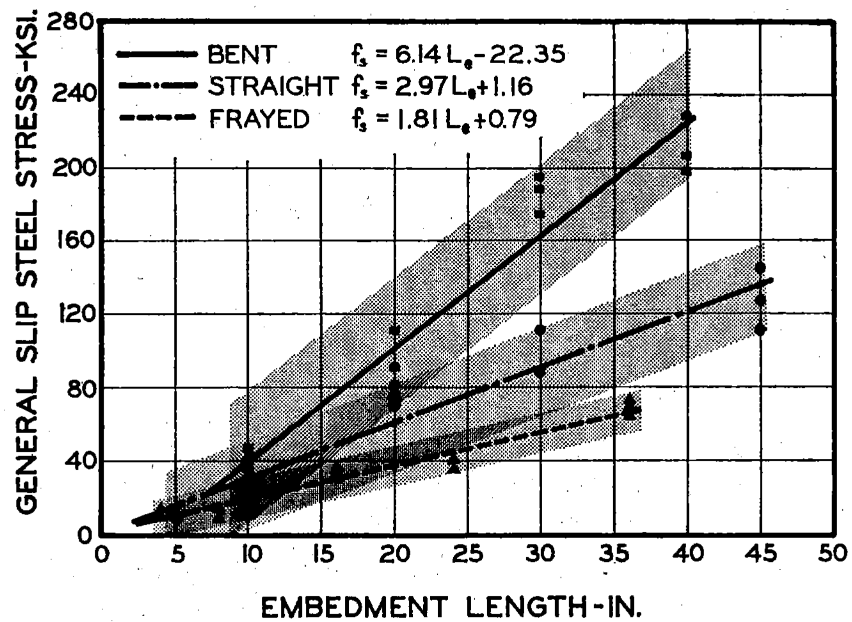


Fig. 8. General slip steel stress as a function of embedment length for the three strand configurations.

The curves generated from the data presented in Fig. 8 appear to be quite consistent. If the curves for straight and frayed strand were extended, they would pass through or very near zero.

On the other hand, if the pre-bend length is considered for the bent specimens, the curve for the bent series intersects that of the straight series at approximately the pre-bend length (6 in.).

Even though the equations shown in Fig. 8 are those which best fit the data, for the purposes of design a lower bound on the scatter is recommended for prevention of general slip.

Ultimate capacity

The scope of this study was not sufficient to determine an accurate value for the ultimate capacity of untensioned strand under sustained loads.

It is believed that the ultimate capacity is in excess of the general slip value; however, sufficient tests were not made to determine the exact increase that could be expected. On the other hand, some short duration ultimate capacities were determined.

Approximately one-half of the specimens in this study were loaded to failure. The method of evaluating this load was to increase the magnitude of the load at a uniform rate until the strand pulled free, broke or the load reached 90 percent of the specified strand ultimate.

No attempt was made to determine when or if the load level was reached at which progressive displacement would lead to failure.

It should be pointed out that at each load increment, the load was maintained for a given period of time (approximately 10 minutes). As a result, this could not be considered as a dynamic loading.

In addition, it may be of interest to

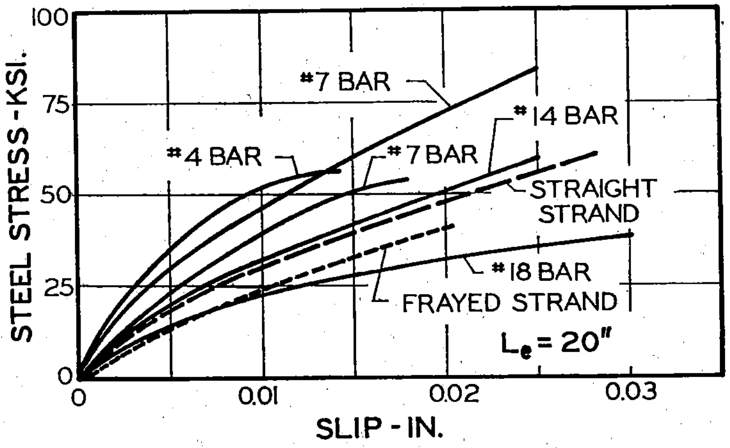


Fig. 9. Comparison of straight strand and deformed reinforcing steel.

note that a displacement in the neighborhood of 1 to 2 in. was achieved prior to or at the failure under this short duration loading.

The short duration ultimate loads for the specimens tested are presented in Table 3.

Strand versus deformed reinforcing

Although much research has been done on the bonding behavior of deformed reinforcing bars, there is a limited number of reports which address themselves to steel stress and loaded end slip, the method of evaluation of results in this study.

Two reports dealing with this concept are by Ferguson *et al.*,[2] and Hriba *et al.*[3]

Ferguson's report dealt with straight embedment lengths of #7, #14, and #18S bars which were enclosed in a #6 or #7 wire spiral and had yield strengths greater than 100 ksi. Jacking forces were applied concentrically to the front face of the specimen and slip measurement was continued after general slip commenced.

The report by Hribar dealt with #4, #7, and #11 bars with a yield point of 57 ksi. Embedment lengths consisted of straight, 90-deg bent and 180-deg bent bars. The bars were embedded in a large unreinforced block of concrete and were unbonded to a sufficient depth to reduce the effects of the jacking force to a nominal level.

There was no means of detecting general slip in these tests. Granting these differences between the three test procedures, comparisons are presented in Fig. 9 for straight bars and in Fig. 10 for 90 deg bent bars.

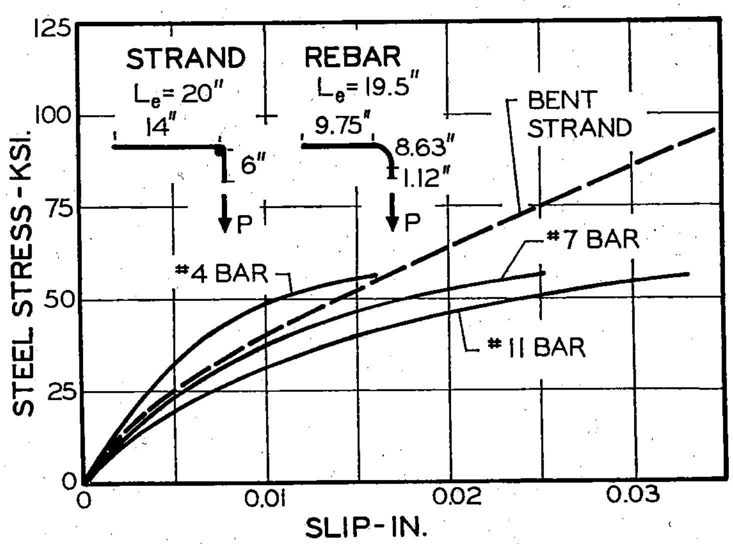


Fig. 10. Comparison of 90-day bent strand and deformed reinforcing steel.

Table 3. Ultimate strength—short duration loading—versus general slip.

IDENTIFICATION (see footnote)*	f'_c (psi)	GENERAL SLIP f_s (ksi)	ULTIMATE f_s (ksi)	OVERLOAD** FACTOR	FAILURE MODE
B-40-2	7090	228	250	-	90%
B-30-2	7150	188	250	-	90%
B-30-NR-B	7280	180	216	1.20	Specimen Split
B-20-C	6340	111	228	2.05	Strand Broke in Spec.
B-10-C	5950	35	137	3.92	Pull-out
S-45-2	6320	146	262	-	90%
S-30-C	5660	111	262	-	90%
S-30-NR-A	8480	68	248	-	90%
S-30-NR-B	"	78	248	-	Strand Broke in Vice
S-20-C	6610	71	235	3.31	Pull-out
S-5-C	6610	9	59	6.55	Pull-out
F-36-C	5810	65	183	2.82	Pull-out
F-24-A	4800	39	104	2.67	Pull-out
F-24-B	"	36	124	3.44	Pull-out
F-24-NR-A	7870	86	150	1.74	Pull-out
F-24-NR-B	"	85	163	1.92	Pull-out
F-8-A	5820	13	65	4.23	Pull-out
F-8-B	"	14	52	3.71	Pull-out
F-8-C	"	11	65	5.90	Pull-out
F-4-C	5950	10	42	4.20	Pull-out
D-.6-B	6010	111	198	1.78	Pull-out
D-7/16-B	5520	88	272	-	Strand Broke in Vice
D-7/16-C	"	78	248	-	Strand Broke in Vice
D-3/8-B	4930	96	188	-	Strand Broke in Vice
CC-1-A	5410	75	245	3.27	Pull-out
CC-1-B	"	79	217	2.75	Pull-out
CC-1-C	"	98	235	2.40	Pull-out
CC-2-A	6900	85	261	-	Strand Broke in Vice
CC-2-C	"	85	261	-	90%
CC-3-B	6130	117	268	-	Strand Broke in Vice
CC-5-A	3750	100	216	2.16	Pull-out
CC-5-B		115	216	1.88	Pull-out

* B = Bent Series; L_e = 40, 30, 20, 10; Dia. = .5
S = Straight Series; L_e = 45, 30, 20, 10, 5; Dia. = .5
F = Frayed Series; L_e = 36, 24, 16, 8, 4; Dia. = .5
D = Diameter Series; L_e = 30; Dia. = .6, .5, 7/16, 3/8
CC = Concrete Strength; L_e = 30; Batch No. = 1, 2, 3, 4, 5
NR = Not Reinforced with spiral
A, B, C = Designates testing order

**The ultimate load factor was computed only for specimens which failed from some internal mechanism. That is, pullout, specimen splitting or strand fracture within the specimen. Those for which strand broke in the strand vice or which achieved 90% of the strand ultimate were not considered a bond failure.

It can be seen that the steel stress versus slip characteristics of straight strand are somewhat inferior to #4 and #7 bars but are comparable to #14 and superior to #18S bars. The 90 deg bent strand is only inferior to #4 bars but is superior to #7 and #11 bars.

When the added advantage of being able to achieve much higher stresses is combined with this information, strand appears to be desirable for some uses as untensioned reinforcing.

Conclusions

The following are the conclusions considered to be of most significance with respect to the embedded strand behavior:

1. Lower bound relationships between embedment length and steel stress at general slip are as follows:

   a. Strand bent 90 deg over reinforcing bar (6-in. pre-bend length)

   $$L_e = 0.163f_s + 8.25 \text{ in.}$$

   b. Straight strand

   $$L_e = 0.337f_s + 8.00 \text{ in.}$$

   c. Frayed strand without bends

   $$L_e = 0.552f_s + 5.50 \text{ in.}$$

2. The strength and stiffness with respect to embedded strand configurations in descending order were: (a) strand bent 90 deg over reinforcing bar, (b) straight strand, and (c) frayed unbent strand.

3. The general slip conditions provide the conservative lower bound estimate for the ultimate capacity of embedded untensioned strand.

4. Concrete strengths from 3750 to 6900 psi had no apparent effect on the bonding characteristics of embedded strand prior to general slip.

5. Strand diameters (3/8, 7/16, 1/2, 0.6 in.) considered in the study have no apparent effect on behavior when considered in terms of relationships between slip and steel stress.

Recommended Design Equations

The relationships presented for evaluating strand forces are in the form of equations relating embedment length to stress in the embedded strand.

Even though in all pullout tests the pre-bend length was limited to a fixed value, the consistency of the results indicates that an extension of the equations to account for variable prebends would be justified. As a result, both working stress and ultimate equations have been extended to cover the case where the pre-bend length has an increased value.

The general slip point is a conservative estimate for ultimate strand force under sustained load. The relationships used for working stress were derived from modifying the steel stresses at general slip by a factor of 0.71 (1/1.4).

Working Stress

The following equations can be used for evaluating the embedment length of straight and bent strand, respectively, based on working stress considerations:

Straight strand

$$L_e = 0.472f_s + 8.00 \text{ in.}$$

Bent strand

$$L_e = 0.228f_s + 8.25 \text{ in.}$$

where $L_{pb} \leq 8.25$ in., and

$$L_e = 0.228\left[f_s - \left(\frac{L_{pb} - 8.25}{0.472}\right)\right] + L_{pb} \text{ in.}$$

where $L_{pb} > 8.25$ in.

Ultimate Capacity

The following equations can be used for evaluating the embedment length of straight and bent strand, respectively, based on ultimate capacity considerations:

Straight strand

$$L_e = 0.337f_s + 8.00 \text{ in.}$$

Bent strand

$$L_e = 0.163f_s + 8.25 \text{ in.}$$

where $L_{pb} \leq 8.25$ in., and

$$L_e = 0.163\left[f_s - \left(\frac{L_{pb} - 8.25}{0.337}\right)\right] + L_{pb} \text{ in.}$$

where $L_{pb} > 8.25$ in.

The equations can be used directly to evaluate the required embedment for a strand loaded with a particular force or the maximum design force for a strand with a particular embedment length. With a defined relationship between the stress and embedment length any solution which satisfies the equations will be satisfactory and can be arrived at through an iteration process.

Notation

L_e = embedment length of strand, in.

L_{pb} = pre-bend length of embedded strand, in.

f_s = maximum stress in the strand, ksi

Acknowledgment

This study was conducted in the Civil Engineering Laboratories of the University of Missouri-Columbia, Columbia, Missouri. This work[4,5] represents a portion of the study, Missouri Cooperative Research Study Number 72-2, "End Connections For Continuous Pretensioned Bridge Beams" sponsored by the Missouri State Highway Commission in cooperation with the Federal Highway Administration of the U.S. Department of Transportation.

References

1. Kemp, E. L., Brezny, F. S., and Uterspan, J. A., "Effect of Rust and Scale on the Bond Characteristics of Deformed Reinforcing Bars," *ACI Journal*, Proceedings V. 65, No. 54, Sept. 1968, pp. 743-756.
2. Ferguson, Phil M., Breen, John E., and Thompson, Neils J., "Pull-Out Tests on High Strength Reinforcing Bars," *ACI Journal*, Proceedings V. 62, No. 55, Aug. 1965, pp. 933-950.
3. Hribar, John A., and Vasko, Raymond C., "End Anchorage of High Strength Steel Reinforcing Bars," *ACI Journal*, Proceedings V. 66, No. 74, Nov. 1969, pp. 875-883.
4. Salmons, J. R., and McCrate, Timothy E., "Bond of Untensioned Prestress Strand," Missouri Cooperative Highway Report 73-5A, University of Missouri-Columbia, Department of Civil Engineering, April 1973.
5. Salmons, J. R., "End Connections of Pretensioned I-Beam Bridges," Missouri Cooperative Highway Report 73-5C, University of Missouri-Columbia, Department of Civil Engineering, March 1975.

Discussion of this paper is invited. Please forward your comments to PCI Headquarters by July 1, 1977.