Headed Steel Anchor under Combined Loading

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THE INCREASING USE of headed steel anchor studs under combined shear and tension loading has resulted in a need for more information on their behavior and strength. Some typical situations where this type of loading is encountered in design are shown schematically in Fig. 1. Anchor studs can provide an efficient method of joining steel and concrete members and can permit greater flexibility in the design of composite steel-concrete systems.

The existing criteria for designing headed steel anchor studs with partial embedment in concrete is based on limited test data and various models representing connector behavior. Several empirical relationships have been suggested in the literature.[1,2] However, a number of factors can affect the ultimate strength of a headed steel anchor stud. They include the embedment length, the development of full or partial concrete shear cones which depends on anchor spacing and boundary conditions, concrete shear strength, shear friction, and the attachment plate thickness.

Current design procedures assume that a full concrete shear cone at ultimate may develop depending on the embedment length of the anchors and the boundary conditions. A full shear cone is presently assumed to exist if adjacent anchor center lines are at least a distance of $2L_e + d_h$ from the center line of the anchor shear cone, or if no edge boundaries are closer to the cone than $L_e + (d_h/2)$, where L_e is the embedment length and d_h is the head diameter of the anchor.

The full concrete shear cone pull-out capacity $\bar{P}_{cu}$ is assumed to be controlled by the embedment length and the diagonal tension strength of the concrete.[1] The diagonal tension force is assumed to act perpendicular to the surface of the concrete cone.

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In the event that an anchor is located near a free edge, or if the spacing of anchors is less than $2L_e + d_h$, a reduction in capacity of the anchor is assumed. It has been suggested that this capacity is in proportion to the reduction of the surface area of the cone.[1]

When anchors are loaded in shear towards a free edge, their shear capacity may also be affected. A relationship for this condition was previously developed from tests on concrete inserts and was suggested for use with headed steel anchors.[1,2]

The purpose of this investigation was to develop interaction relationships and design criteria for headed steel anchor studs subjected to combined shear and tension loading. Anchors ¾-in. in diameter with full tensile embedment were tested under three different loading

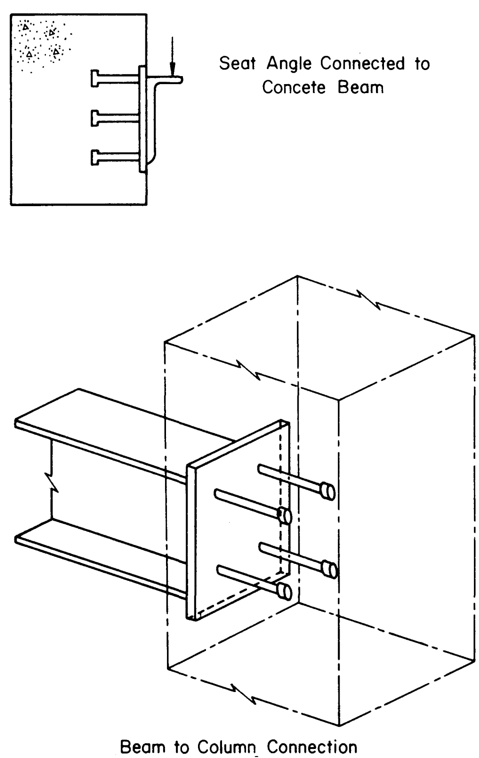
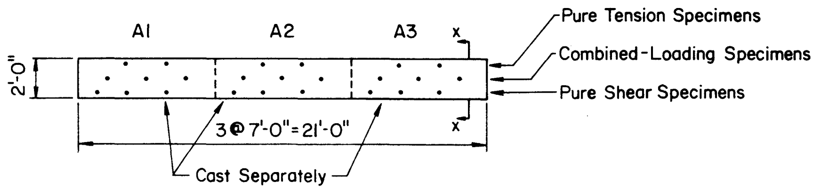
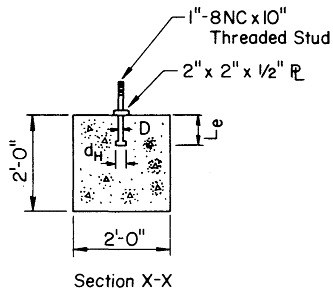


Fig. 1. Typical application of headed steel anchors.





SCHEDULE OF ANCHOR SIZES				
Number Tested	D (in.)	Le (in.)	dH (in.)	Shank Area (in.)
28	3/4	4	1 1/4	.442
23	3/4	7	1 1/4	.442
6	3/4	8	1 1/4	.442
3	7/8	8	1 3/8	.601

Fig. 2. Typical test beam and anchor arrangement.

conditions; 7/8-in. diameter anchors with full tensile embedment in normal weight concrete made up the remainder of the primary tests. In addition to these primary tests, 3/4-in. diameter anchors subjected to pure shear and pure tension near a free edge were also tested. The respective minimum embedment lengths for these two conditions were used and the tests were performed using normal weight concrete. Finally, 3/4-in. diameter anchors with partial embedment in normal weight concrete were tested in pure tension in order to examine the development of the full shear cone.

TEST PROGRAM AND PROCEDURE

The variables considered were the type of concrete (normal or lightweight), connector length, angle of loading (for the combined shear and tension tests), and the free edge distance. The diameter of the anchors was held constant at 3/4-in. with the exception of three tests on 7/8-in. diameter anchor studs.

The anchors were embedded in twelve concrete blocks. Figure 2 shows a schematic of three typical test blocks and the anchor test schedule. The combined loading anchors were placed along the middle of the concrete block at 2-ft spacing. No anchor was closer than 12 in. to another. In order to facilitate handling and testing, blocks were cast in 7-ft long pieces. All concrete used was obtained from a commercial central mix plant. Table 1 summarizes the concrete properties.

Anchors 3/4-in. in diameter with both full (7-in.) and partial (4-in.) embedment lengths were tested under combined shear and tension loading. The 7-in. full embedment length was developed in earlier pure tension studies.[3] This length was shown to be adequate to develop the tensile anchor capacity in 3,000 psi normal weight concrete. Anchors with full embedment were tested in both normal weight and lightweight concrete while anchors with partial embedment were tested in normal weight concrete. Anchors with full and partial embedment were also tested at various free edge distances in normal weight concrete under pure tension loading. Anchors with adequate shear embedment were also loaded in pure shear with various free edge distances in normal weight concrete.

Six 3/4-in. anchors with an 8-in. embedment length were tested in lightweight concrete under both combined and pure tension loading. Finally, three 7/8-in. x 8 in. anchors were tested in normal weight concrete under both combined and pure tension loading. The head diameter of these anchors was 1 3/8 in. Three 3/4-in. x 4-in. anchors were also tested in normal weight concrete under pure tension.

Only loading angles of 30° and 60° were used for the combined loading conditions. The 30° and 60° angles were measured from the pure tension position (0°). Table 2 shows the type of loading, location, anchor size

Table 1. Average Concrete Strengths

Beams	28 Day Strengths		Testing Day Strength	Age
	Comp. (psi)	Tensile (psi)	Comp. (psi)	(days)
A	4500	359[c]	5270	87
B	4060	411	4900	85
C	4910[b]	497[b]	5180	68
D[a]	4660	467	5300	58

[a] D beam was lightweight concrete with average density of 121.6 pcf.
[b] Tested at 33 days.
[c] Result suspect due to non-uniform bearing along cylinder length during testing.

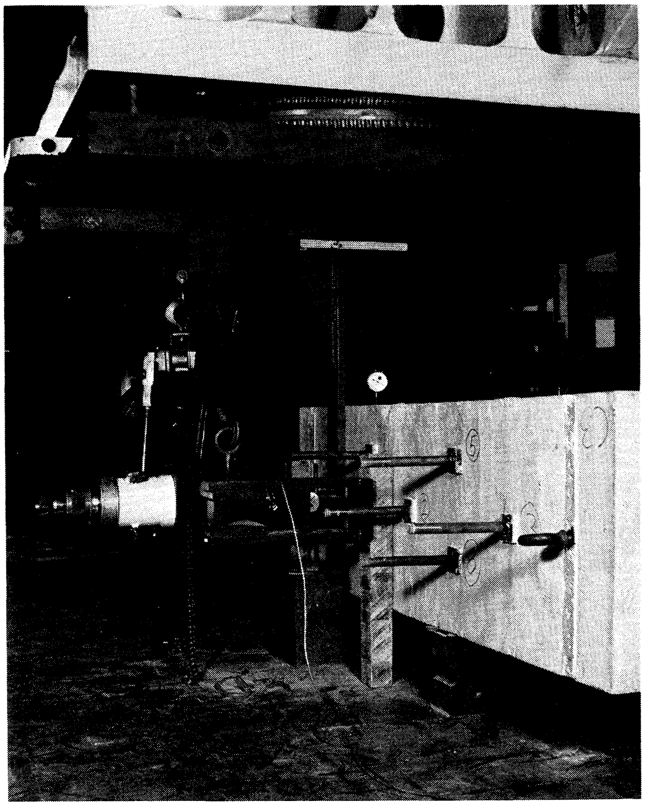


Fig. 3. *Apparatus for combined loading.*

and embedment size for all of the anchors tested, as well as the ultimate load attained and the mode of failure.

The shear load for both the pure shear and combined loading cases was applied by a 5,000 kip capacity Baldwin hydraulic testing machine through a loading rig designed specifically for the test program. The 200 kip load range was used during the conduct of the test. A hydraulic ram mounted on a jacking frame applied the tension load component. Figure 3 shows the loading apparatus.

For the combined shear and tension loading condition, both load indicating systems were connected to an X-Y recorder. This permitted the desired loading angle to be maintained throughout the test and eliminated the need for incremental loading. Deflections and loads were monitored and tabulated at intervals. The approximate time for a test was ten minutes.

Since the combined loading tests were of primary concern in the investigation, these tests were performed first on each beam. The anchors under pure tension near one free edge were tested next and the anchors under pure shear near the other free edge were tested last.

The loading setup and procedure achieved the desired combined tension and shear load condition for all load levels. It was possible to load the specimens so that the maximum deviation of the load vectors was within plus or minus two degrees. This permitted the loads at

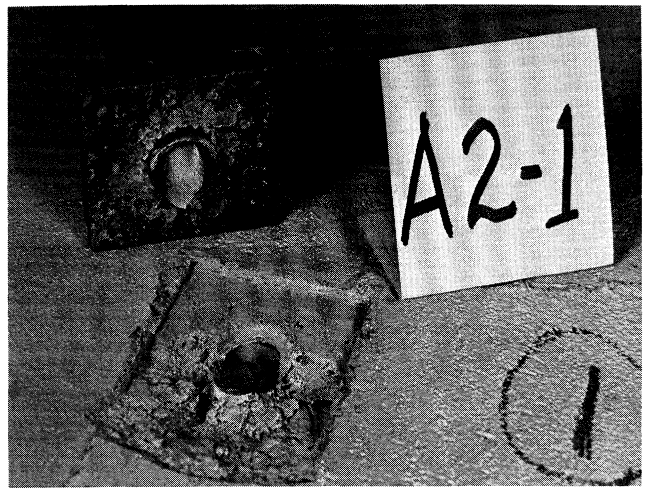


Fig. 4. *Specimen A2-1 after failure: ¾-in. x 7-in. anchor under combined loading (30°).*

ultimate to be determined with reasonable accuracy. In a number of instances, the failure mode under combined loading prevented additional tests from being performed on the test beam.

TEST RESULTS AND ANALYSIS

Anchors Subjected to Combined Loading—The primary objective was the investigation of stud anchors under combined shear and tension loading. Three categories were considered: (1) anchors with full embedment in normal weight concrete, (2) anchors with full embedment in lightweight concrete, and (3) anchors with partial embedment in normal weight concrete. The concrete compressive strengths were about 5,000 psi in this study. However, since the embedment lengths used were developed for much lower strength concretes,[3,4] the applicability of these test results to other

Fig. 5. *Specimen C1-3 showing shear cone: ¾-in. x 4-in. anchor under direct tension.*

Table 2. Test Results

Stud Number	Type of Loading	Location	Anchor Size & Embedment Length	Ultimate Load	[c]Mode of Failure
A1-1	Pure Tension.	℄	7″ x ¾	28.3	S
A1-2	"	"	"	28.5	S
A1-3	"	"	"	28.0	S
D3-1	"	"	"	28.7	S
A1-4	Pure Tension	2″ from edge	7″ x ¾″	19.5	C
A1-5	"	"	"	18.5	C
A2-4	Pure Tension	4″ from edge	7″ x ¾″	31.5	S
A2-5	"	"	"	29.3	S
B3-5	"	"	"	29.4	S
C2-4	"	"	"	29.4	C
A3-4	Pure Tension	6″ from edge	7″ x ¾″	29.3	S
A3-5	"	"	"	28.8	S
B3-4	"	"	"	31.5	S
C3-4	"	"	"	29.5	C
C3-5	"	"	"	27.3	S
A2-1	[a]Combined–30°	℄	7″ x ¾″	23.7–13.6[b]	S
A2-2	"	"	"	19.1–11.3	C
A2-3	"	"	"	23.6–13.75	S
D3-2	"	"	"	25.6–15.4	C
A3-1	Combined–60°	℄	7″ x ¾″	12.9–21.3	S
A3-2	"	"	"	11.7–21.2	S
A3-3	"	"	"	13.4–23.6	S
D3-3	"	"	"	10.8–19.4	S
B1-1	Pure Tension	℄	8″ x ⅞″	43.0	C
B1-2	Combined–30°	℄	8″ x ⅞″	33.0–19.5	S
B1-3	Combined–60°	℄	8″ x ⅞″	17.3–30.6	S
D1-1	Pure Tension	℄	8″ x ¾″	30.1	C
D1-2	"	"	"	31.5	C
D1-3	Combined–30°	℄	8″ x ¾″	21.6–12.4	S
D2-1	"	"	"	19.8–11.8	C
D2-2	Combined–60°	℄	8″ x ¾″	12.6–22.0	S
D2-3	"	"	"	13.3–23.6	C

concrete strengths below 5,000 psi is reasonable providing the embedment length is not less than that used here.

The test data are summarized in Table 2. The failure modes were basically of three types: failure of the stud anchor, severe concrete cracking, and concrete cone pull-out. Figures 4, 5, and 6 show examples of the different failure modes. The anchors exhibited very ductile behavior for both the full and partial embedment cases. Figures 4 and 6 show anchors exhibiting this ductile behavior.

All of the results obtained for the combined loading specimens indicate that the design formulas suggested in Refs. 1 and 2 provide a variable margin of safety.

Figures 7, 8, and 9 summarize the results of the combined loading tests plotted with tension as ordinate and shear as abscissa. Since the study did not include any anchors subjected to pure shear, test data for shear connectors reported in Ref. 5 were used for this condition. Since an embedment length of 3 in. (4 diameters) was used for these shear tests, the shear values shown are a conservative estimate for the longer embedment condition. It was shown in Ref. 5 that the difference in shear capacity was not great for longer embedment lengths. The concrete strengths in two studies were comparable.

Full Embedment, Normal Weight Concrete—Figure 7 summarizes the combined load test results for the anchor studs with full embedment in normal weight concrete. An elliptical interaction curve of the form

$$\left(\frac{P/A_s}{\bar{P}_u/A_s}\right)^{5/3} + \left(\frac{S/A_s}{\bar{S}_u/A_s}\right)^{5/3} = 1 \qquad (1)$$

was found to be the best fit to the test data, where

P = applied tension load
S = applied shear load
$\bar{P}_u$ = tensile capacity of the anchor $= \sigma_u A_s$
$\bar{S}_u$ = shear capacity of the anchor

Table 2. Test Results (cont'd)

Stud Number	Type of Loading	Location	Anchor Size & Embedment Length	Ultimate Load	[c]Model of Failure
C1-1	Pure Tension	℄	4″ x ¾″	18.5	C
C1-2	"	"	"	18.5	C
C1-3	"	"	"	17.3	C
B1-5	Pure Tension	2″ from edge	4″ x ¾″	11.0	C
A2-6	Pure Shear	2″ from edge	4″ x ¾″	4.35	C
A3-6	"	"	"	4.7	C
B1-7	"	"	"	2.9	C
C3-6	"	"	"	3.3	C
A1-7	Pure Shear	4″ from edge	4″ x ¾″	9.9	C
A1-8	"	"	"	10.2	C
A2-7	Pure Shear	6″ from edge	4″ x ¾″	20.0	C
A2-8	"	"	"	19.0	C
A3-7	Pure Shear	8″ from edge	4″ x ¾″	30.0	#
A3-8	"	"	"	32.0	#
B3-7	Pure Shear	10″ from edge	4″ x ¾″	28.6	C
B3-8	"	"	"	28.5	C
B2-1	Combined–30°	℄	4″ x ¾″	17.7–10.8	C
B2-2	"	"	"	17.6–10.8	C
B2-3	"	"	"	17.4–10.6	C
C2-1	"	"	"	13.8– 8.4	C
C2-2	"	"	"	15.5– 9.6	C
C2-3	"	"	"	16.4– 9.6	C
B3-1	Combined–60°	℄	4″ x ¾″	12.6–22.8	S
B3-2	"	"	"	10.4–18.4	C
B3-3	"	"	"	10.0–18.0	C
C3-1	"	"	"	12.6–22.2	S
C3-2	"	"	"	13.0–23.6	C
C3-3	"	"	"	12.0–21.2	S

[a] The angle is measured from the pure tension position being 0°.
[b] The first load is always the tension component.
[c] S Stud failure.
C Concrete failure.
Loading terminated before complete failure.

$$\bar{S}_u = 1.106\, A_s f_c'^{0.3} E_c^{0.44} \leq \bar{P}_u \quad \text{(Ref. 5)} \qquad (2)$$

where

A_s = area of the anchor
f_c' = 28 day compressive strength of concrete, ksi
E_c = concrete modulus of elasticity, ksi

The shear connectors reported in Ref. 5 and the anchors used in this study had directly comparable tensile strength ($\sigma_u \approx 64$ ksi) and exceeded the minimum tensile capacity required by the AWS specifications.[6] Since the compressive strength of the normal weight concrete was 5,000 psi, the shear capacity of the anchors was taken equal to their tensile capacity. The values of $\bar{P}_u/A_s$ and $\bar{S}_u/A_s$ were both taken as 64 ksi when plotted in Fig. 7.

For purposes of comparison, the test results obtained using ⅞-in. anchors with 8-in. embedment length are plotted in Fig. 7 as squares. The ⅞-in. anchors had greater tensile strength than the ¾-in. anchors. Under combined loading the increased tensile capacity was not a significant factor and only slight increases in the tensile and shear components were observed.

Full Embedment, Lightweight Concrete—Test results for anchors in lightweight concrete exhibited considerably more variability than those of anchors tested in normal weight concrete as illustrated in Fig. 8. Two anchor lengths were examined. However, it is apparent from the results that the concrete strength was high enough so that no appreciable difference could be attributed to the anchor length. It is probable that an increased length may be necessary for anchors embedded in lightweight concrete having lower compressive strength. The shear strength of the studs is also decreased when the connector is embedded in lightweight concrete.[5]

Equation (1) is compared with the test data for embedment in lightweight concrete in Fig. 8. The tensile capacity of the anchors was again taken as 64 ksi, since their full capacity was developed in direct tension. The

Fig. 6. Deformation of $\frac{3}{4}$-in. x 7-in. anchor under combined loading (30°).

shear capacity as determined from Eq. (2) was 50 ksi. It is apparent that Eq. (1) also provides a reasonable lower bound fit to the test data and accounts for the reduction observed for lightweight concrete.

Reference 1 suggested a combined tension and shear relationship for the following ultimate strength design condition:

$$\left(\frac{P}{P_u}\right)^2 + \left(\frac{S}{S_u}\right)^2 \leq 1 \tag{3}$$

where

$$P_u = \phi\sigma_u A_s = 0.9\sigma_u A_s$$
$$S_u = 0.75\sigma_u A_s$$

Equation 3 is plotted in Figs. 7 and 8. It is readily apparent that Eq. (3) does not provide a uniform margin of safety for all conditions of combined tension and shear and does not reflect the reduction for lightweight concrete.

A better design relationship can be obtained from Eq. (1) by applying an appropriate reduction factor ϕ. A uniform ϕ factor of 0.9 for ultimate strength design results in

$$P_u = 0.9\sigma_u A_s = 54A_s \tag{4a}$$

$$S_u = 0.9 \times 1.106 A_s f_c'^{0.3} E_c^{0.44} \leq 54A_s \tag{4b}$$

when Eqs. (4a) and (4b) are substituted into Eq. (1), the following design equation is obtained:

$$\left(\frac{P}{P_u}\right)^{5/3} + \left(\frac{S}{S_u}\right) \leq 1 \tag{5}$$

Equation 5 is also plotted in Figs. 7 and 8 and provides a good estimate of the ultimate strength under all conditions of combined loading for both normal weight and lightweight concrete.

SYMBOL	BEAM	STUD SIZE D x Le	fc (psi)	CONCRETE TYPE
▲	A	3/4" x 7"	5270	Normal
■	B	7/8" x 8"	4900	"
X	Ref. 5	3/4" x 3"	5080	"

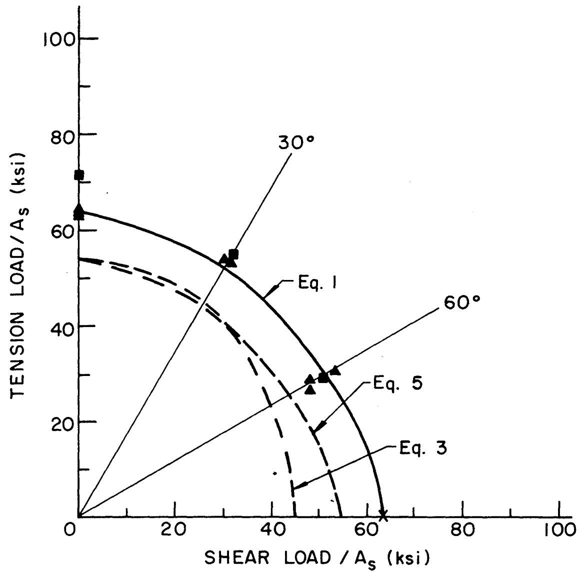


Fig. 7. Strength of anchors in normal weight concrete—full embedment.

SYMBOL	BEAM	STUD SIZE D x Le	fc (psi)	CONCRETE TYPE
△	D	3/4" x 7"	5300	Light-Weight
□	D	3/4" x 8"	5300	"
Ɪ	Ref. 5	3/4" x 3"	4300	"

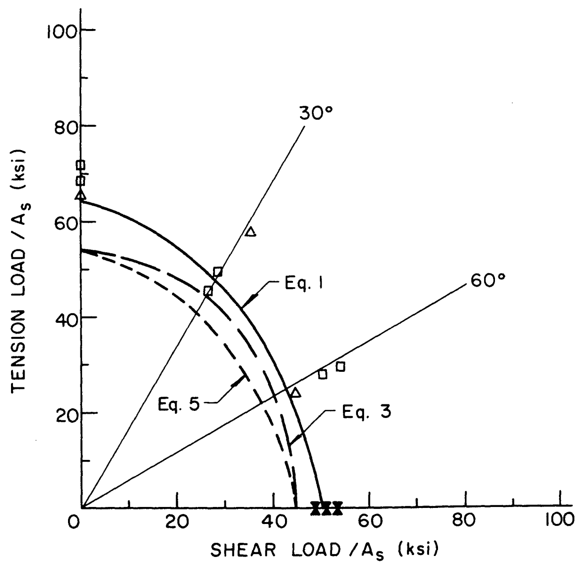


Fig. 8. Strength of anchors in lightweight concrete—full embedment.

SYMBOL	BEAM	STUD SIZE D x Le	fc (psi)	CONCRETE TYPE
■	B	3/4" x 4"	4900	Normal
●	C	3/4" x 4"	5180	"
X	Ref. 5	3/4" x 3"	5080	"

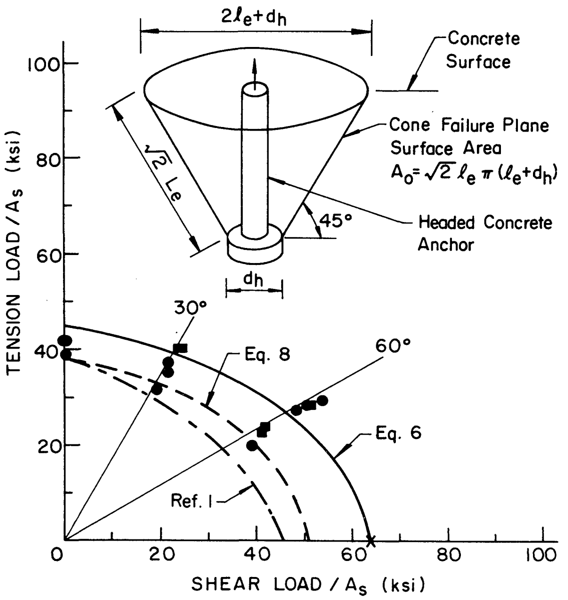


Fig. 9. Strength of anchors in normal weight concrete—partial embedment.

Partial Embedment, Normal Weight Concrete—Figure 9 summarizes the test results for anchors with partial embedment length (4 in.) in normal weight concrete.

An elliptical interaction curve of the form:

$$\left(\frac{P}{\bar{P}_{cu}}\right)^{5/3} + \left(\frac{S}{\bar{S}_u}\right)^{5/3} = 1 \qquad (6)$$

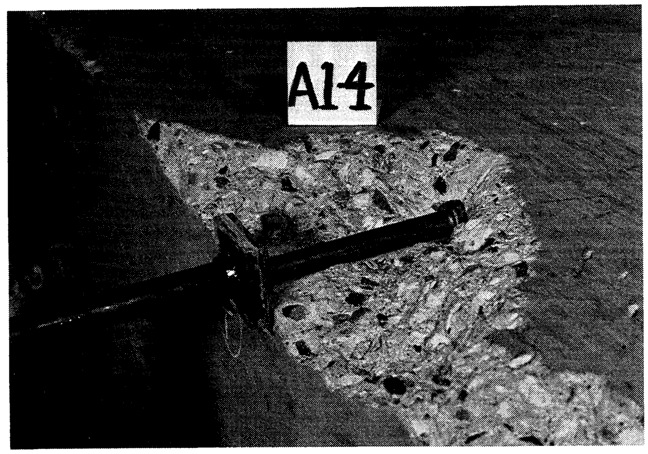


Fig. 11. Failure done of $\frac{3}{4}$-in. x 7-in. anchor in direct tension located 2 in. from boundary.

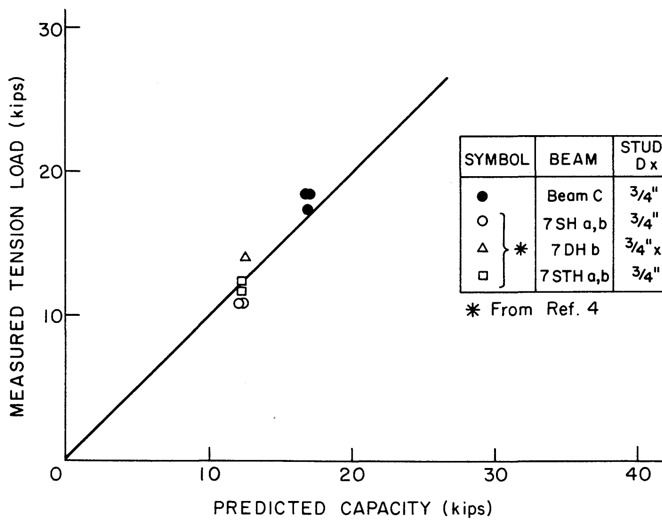
was found to best fit the test data where P and S are the applied load in kips and where

$$\bar{P}_{cu} = 4\sqrt{f_c'}A_c \quad \text{(Refs. 1 and 2)}$$
$$= 0.56C(L_e + d_h)L_e\sqrt{f_c'} \leq \sigma_u A_s$$

where

L_e = embedment length
d_h = head diameter
C = 0.75 for "all lightweight concrete"
= 0.85 for sanded lightweight concrete
= 1.0 for normal weight concrete

The full shear cone tensile strength $\bar{P}_{cu}$ was taken from the relationships suggested in Refs. 1, 2, and 7 for the anchor capacity with partial embedment, providing a full shear cone develops. The shear capacity $\bar{S}_u$ is defined by Eq. (2).



SYMBOL	BEAM	STUD SIZE D x Le	fc (psi)	CONCRETE TYPE
●	Beam C	3/4" x 4"	5180	Normal
○ ✱	7 SH a,b	3/4" x 4"	3000	"
△ ✱	7 DH b	3/4" x 3 13/16"	3000	"
□ ✱	7 STH a,b	3/4" x 4"	3000	"

✱ From Ref. 4

Fig. 10. Comparison of measured and predicted strength for partial embedment.

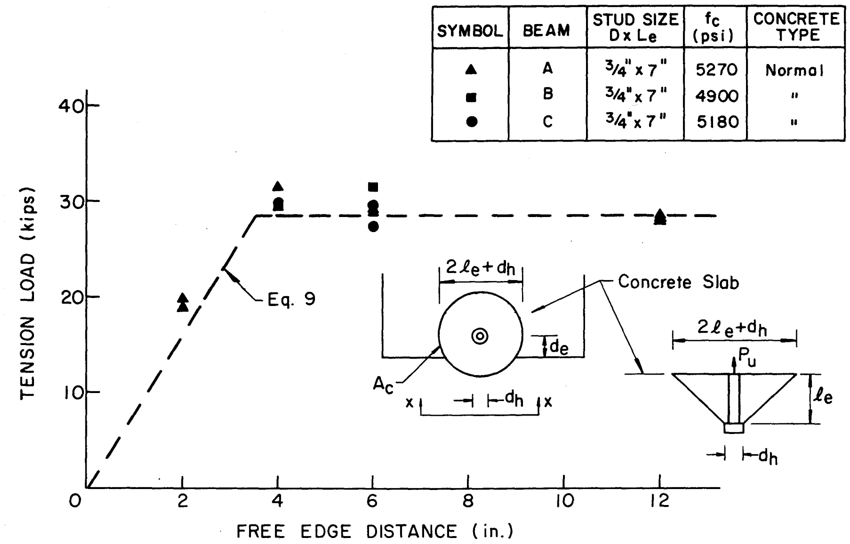


Fig. 12. Strength in tension of connectors located near a free boundary—full embedment.

Equation 6 is plotted in Fig. 9 and is in reasonable agreement with the test data. It is again apparent that Eq. (2) provides a better estimate of the shear capacity than the value suggested in Ref. 1.

An ultimate strength design equation can be obtained from Eq. (6) by applying an appropriate reduction factor ϕ. A uniform ϕ factor of 0.85 results in the following equations:

$$P_{cu} = 0.475C(L_e + d_h)L_e\sqrt{f_c'} \leq 0.85\sigma_u A_s \quad (7a)$$

$$S_u = 0.94A_s f_c'^{0.3}E_c^{0.44} \leq 0.85\sigma_u A_s \quad (7b)$$

When Eqs. (7a) and (7b) are substituted into Eq. (6), the following design equation is obtained:

$$\left(\frac{P}{P_{cu}}\right)^{5/3} + \left(\frac{S}{S_u}\right)^{5/3} \leq 1 \quad (8)$$

Equation 8 is also plotted in Fig. 9 and provides a reasonable design relationship.

Comparison of Predicted- and Measured Anchor Capacity in Tension—To permit the development of full shear cones, ¾-in. x 4-in. anchors embedded in normal weight concrete were tested in pure tension. The results are summarized in Fig. 10. The predicted anchor capacity is compared with the test results. Also plotted are the results of tests on concrete anchors reported in Ref. 4. The predicted load was determined from Eq. (7a).

It is apparent from the results summarized in Figs. 9 and 10 that Eq. (7a) provides a reasonable estimate of the anchor capacity for a full shear cone and partial embedment. This is true for direct tension or for a combined shear and tension condition.

Anchors Subjected to Tension Loading at a Free Edge—The investigation of anchors with full embedment in normal weight concrete and loaded in tension a various free edge distances was one of the secondary objectives of this program. The test results are summarized in Table 2. A typical failure mode is shown in Fig. 11.

The test data are plotted in Fig. 12 as a function of the free edge distance. It is apparent that an edge distance of four or more inches is needed to develop the full capacity of the ¾-in. x 7-in. anchors. References 1 and 2 suggest that for the depth of embedment and concrete strength of the tests summarized in Fig. 12, the partial shear cone provided by an edge distance of only one inch should develop the anchor capacity. It is ap-

Fig. 13. Failure of ¾-in. x 4-in. anchor in shear located 2 in. from boundary.

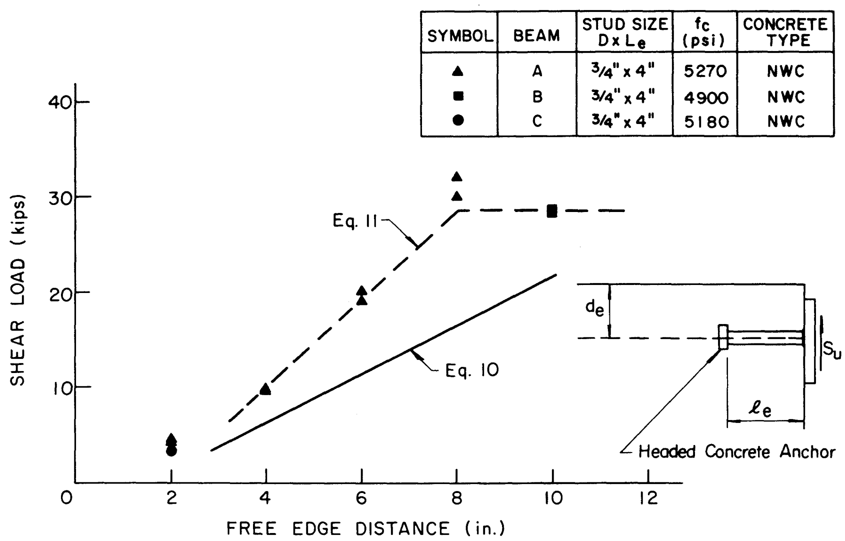


Fig. 14. Strength in shear toward a free boundary.

parent from the test results that this is not true. Only about 60 percent of the anchor capacity was developed at an edge distance of 2 in. The model suggested in Refs. 1 and 2 overestimated the anchor capacity.

A better estimate of anchor capacity is provided by

$$P_{cu}' = \frac{2d_e}{9D} P_{cu} \leq 0.85\sigma_u A_s \tag{9}$$

where

P_{cu} is defined by Eq. (7a)
d_e = distance from the center of the anchor to the free edge, in.
D = stud diameter, in.

In many cases encountered in design, anchor center-to-center spacings or edge boundary conditions will seldom permit development of the full capacity of the stud. A similar condition may occur when a cluster of anchors are spaced less than the embedment length of the anchors. The possibility of failing an entire truncated pyramid of concrete rather than individual shear cones must be considered. This may result in a lower capacity than estimated from individual anchors. The resistance of the truncated pyramid of concrete can be estimated from the ACI Code provisions.

Anchors Subjected to Shear Loading at a Free Edge—The other secondary objective of this program was the investigation of anchors with adequate shear embedment in normal weight concrete and loaded in shear at various free edge distances. The test results are summarized in Table 2. A typical failure mode is illustrated in Fig. 13. The results are plotted in Fig. 14 as a function of the edge distance. The edge distance was measured from the center line of the anchor to the edge of the beam.

References 1, 2 and 8 have suggested that the design capacity of anchors subjected to shear loading near a free edge is given by

$$S_{cu} = \phi(2.5d_e - 3.5) \tag{10}$$

where

d_e = edge distance in the direction of load, in.
S_{cu} = ultimate shear capacity, kips

Equation 10 is compared with the test data in Fig. 14. The test results indicate that Eq. (10) is conservative for the high concrete strengths used in the investigation. It was also noted in Ref. 1 that Eq. (10) provided a conservative estimate.

A better estimate of the anchor capacity under this type of loading is given by

$$S_u' = S_u\left(\frac{d_e - 1}{8D}\right) \leq 0.85 T_u A_s \tag{11}$$

where

S_u is given by Eq. (7b)
d_e = distance from the center of the anchor to the free edge, in.
D = stud diameter, in.

The results indicate that an edge distance of about 8 in. is required to develop the capacity of the ¾-in. anchor stud.

SUMMARY AND CONCLUSIONS

The findings of this program provide an indication of the behavior and strength of headed concrete anchor studs under a variety of loading conditions. The results provide reasonable estimates of the capacity of headed concrete anchor studs in tension, shear, and combined tension and shear.

The results of the tests on anchors with full embedment in normal weight concrete loaded in combined shear and tension show that the design interaction curve given by Eq. (5) provides a reasonable estimate of anchor capacity. The results of the tests on the anchors with full tensile embedment in lightweight concrete loaded in combined shear and tension were also described by Eq. (5).

The anchor studs with partial embedment in normal weight concrete tested under combined shear and tension yielded results that were reasonably described by the interaction curve given by Eq. (8). The margin of safety for pure tension and the 30° loading cases was not quite as great as the 60° and pure shear conditions. The interaction relationship differed from the full embedment case only in the tension resistance. A tensile shear cone was used to describe the tension component.

About 4 in. of edge distance was required to develop the capacity of anchors with 7-in. embedment lengths loaded in pure tension in normal weight concrete. The truncated shear cone[1,2] overestimated the capacity of anchors closer to a free edge. Equation (9) was observed to provide a more reasonable estimate of the reduced anchor capacity when anchors are located near a free edge.

The results of tests on anchors with adequate shear embedment ($4d$) in normal weight concrete loaded in pure shear at a free edge, indicate that Eq. (11) provides a more reasonable estimate of the anchor capacity under this type of loading.

The test results of anchors with partial embedment and full shear cones in normal weight concrete loaded in pure tension indicate that the capacity predicted by Eq. (7a) was reasonable.

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REFERENCES

1. *Prestressed Concrete Institute* PCI Design Handbook *Chicago, Illinois, 1971.*
2. *PCI Committee on Connection Details* Summary of Basic Information on Precast Concrete Connections *PCI Journal, December 1969, Vol. 14, No. 6.*
3. *Shoup, T. E. and Singleton, R. C.* Headed Concrete Anchors *ACI Journal, September 1963.*
4. *Nelson Stud Welding Company* Report No. 1966-5, Concrete Anchor Tests No. 7, *Nelson Stud Project No. 802, 1966.*
5. *Ollgaard, J. G., R. G. Slutter, and J. W. Fisher* Shear Strength of Stud Connectors in Lightweight and Normal Weight Concrete *AISC Engineering Journal, Vol. 8, No. 2, April 1971, pp. 55–64.*
6. *American Welding Society* Supplement to AWS D1.0-66 Code for Welding in Building Construction and AWS D2.0-66 Specifications for Welded Highway and Railway Bridges on Requirements for Stud Welding *September 1968.*
7. *Courtois, P.* Industrial Research on Connections for Precast and In-Situ Concrete *paper Sp22-10, Mechanical Fasteners for Concrete, ACI Publication No. SP-22, 1969.*
8. *Superior Concrete Accessories, Inc.* Handbook of Superior Products for Precast Concrete *Booklet Pr-3, 1968.*