ϵ_o = uniaxial peak strain;
ϵ_{oct} = octahedral normal strain;
θ = Lode's angle;
ν = Poisson's ratio;
σ_1 = most principal compressive stress;
σ_o = uniaxial peak compressive strength;
σ_p = most principal compressive strength;
σ_s = stress in steel tube;
σ_{oct} = octahedral normal stress;
$\sigma_1, \sigma_2, \sigma_3$ = stresses in three principal directions;
τ_{oct} = octahedral shear stress; and
ψ = transformation factor.

EFFECT OF ABANDONED HOLES ON CAPACITY OF WEDGE BOLTS

By Edwin G. Burdette,[1] Subir Sen,[2] Members, ASCE
and Ergun Ismen[3]

ABSTRACT: Seventy, 5/8 in. diameter wedge anchors were tested in direct pull-out to determine the effect of various configurations of unused holes and different treatments of these holes on pull-out capacity. The test results indicated that for unused holes as close as approximately 2.0 bolt diameters, there was a measurable reduction in pull-out strength. When the holes were as far away as 3.0 bolt diameters, there was no reduction in capacity. When holes as close as 1.5 bolt diameters were filled with drypack mortar, the anchors behaved as if there were no additional holes present. Thus, no reduction in pull-out load, even for the extreme case of holes 1.5 bolt diameters away from an anchor, need be considered when the holes are filled with dry-pack mortar.

INTRODUCTION

A widely used method for anchoring structural attachments to concrete involves the use of a type of expansion anchor called a "wedge bolt" or "wedge anchor." The anchorage is accomplished by means of wedges at the end of the bolt; these wedges fit onto the bolt in such a way that the bolt can be driven into a hole essentially equal in diameter to the bolt itself, but when one tries to pull the bolt out of the concrete, the wedges engage the sides of the hole and resist motion. As further load is applied, the wedges further embed themselves in the concrete and anchorage to the concrete is accomplished.

Sometimes, in the process of drilling a hole to set a wedge bolt, interference is encountered which prevents completion of the hole, or setting of the bolt, or both. In some cases, a change in design or a failure to meet required tolerance necessitates the relocation of a hole. The location of the new hole is chosen to bypass whatever interfered with the original drilling or to satisfy tolerance requirements. Generally, a second try is successful; however, on occasion, a number of attempts may be necessary before the bolt is set.

Typically, in the process just described, the abandoned empty holes vary in depth between 3/4 in. (19 mm) and 2 in. (51 mm)—the clear cover distance. If, in such a case, the embedment depth of the bolt is as much as 5 in. (127

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tensile capacity of the anchor as the wedges are set well below the empty holes. If, however, the unused holes extend the full depth of the embedded wedge bolt, questions arise as to how far away from the bolt these holes must be in order not to reduce tensile capacity, and what treatment of these holes might be successfully used to mitigate any detrimental effects. It was the need to address these questions that led to the tests reported herein.

Extensive use is made of wedge bolts in the installation of pipe support systems, cable tray supports, and other systems in nuclear power plants. Because of the extensive use of these bolts and the fact that the problem addressed here is one that is often encountered, it is the opinion of the writers that structural engineers will find the results presented here to be timely and useful.

Objective of Tests.—The objectives of the tests were: (1) To determine the effect of holes drilled to full embedment depth, in the proximity of a wedge anchor, on the pull out capacity of that anchor; and (2) to determine whether or not the effect of extra holes could be mitigated by leaving cutoff bolts in the unused holes or by grouting the unused holes with dry-pack mortar.

Scope.—Seventy tests on 5/8 in. (16 mm) diam bolts were performed to accomplish the stated objectives. The location and number of the extra holes were varied, and the condition of the holes for a particular test was either empty, filled with cutoff bolts, or filled with dry-pack mortar.

DESCRIPTION OF TESTS

Testing Program.—This program was defined in terms of phases and series. The phase number was used to define bolt embedment depth and to specify the treatment, if any, of the unused holes. The series number defined the configuration of unused holes. The following series designations were used and are shown in Fig. 1.

1. Series A: No unused holes.
2. Series B: Two holes, 135° apart, 1.5 bolt diam away from the center of the bolt.
3. Series C: Four holes, 90° apart, 2.0 bolt diam away from the center of the bolt.
4. Series D: Four holes, 90° apart, 3.0 bolt diam away from the center of the bolt.
5. Series E: Eight holes, 45° apart, 3.0 bolt diam away from the center of the bolt.

The phase designations are as follows:

1. Phase I: 5/8 in. (16 mm) diam bolt with 3-1/2 in. (89 mm) embedment, unused holes left empty.
2. Phase II: 5/8 in. (16 mm) diam bolt with 5-1/2 in. (140 mm) embedment, unused holes left empty.
3. Phase III: 5/8 in. (16 mm) diam bolt with 3-1/2 in. (89 mm) embedment, cutoff bolts in unused holes.
4. Phase IV: 5/8 in. (16 mm) diam bolt with 5-1/2 in. (140 mm) embedment, cutoff bolts in unused holes.

5. Phase V: 5/8 in. (16 mm) diam bolt with 3-1/2 in. (89 mm) embedment, unused holes grouted.
6. Phase VI: 5/8 in. (16 mm) diam bolt with 5-1/2 in. (140 mm) embedment, unused holes grouted.

With a few exceptions noted in the presentation of the results, three tests were performed for each phase and series combination of interest. The combinations tested were as follows:

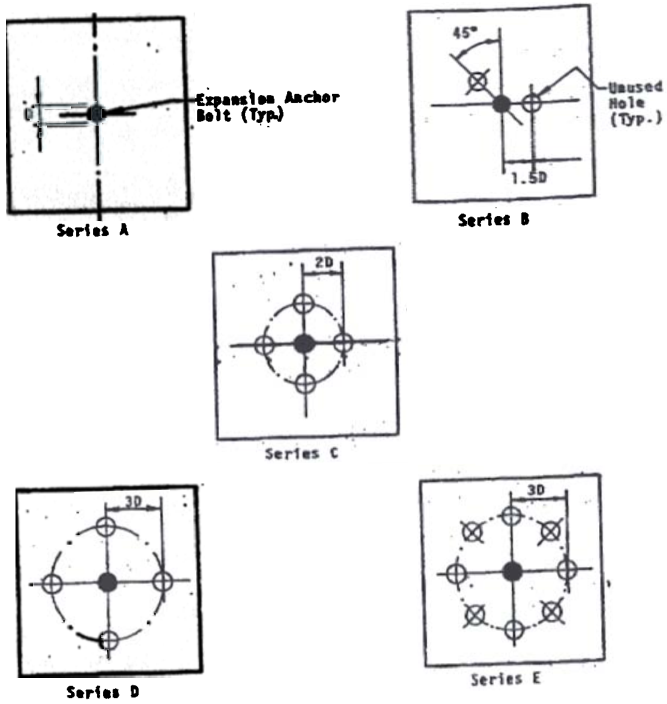


FIG. 1.—Configuration of Unused Holes in Different Series of Tests

1. Phase I, Series A, B, C, D, and E.
2. Phase II, Series A, B, C, D, and E.
3. Phase III, Series A, B, and C.
4. Phase IV, Series A, B, and C.
5. Phase V, Series B and C.
6. Phase VI, Series B and C.

Installation Procedure.—All holes were drilled with standard drill bits satisfying American National Standards Institute standards (1). Holes were drilled in a 1/2 in. (13 mm) thick sheet of plywood to make a template to use for drilling the holes for each of the test series. The bolts were installed according to the following procedure:

1. A hole was drilled to the required embedment depth and was cleaned thoroughly with a nylon brush and vacuum cleaner.
2. A wedge bolt was driven to the bottom of the hole.
3. Heavy washers were placed over the bolt and a nut turned down flush, utilizing an installation torque of 60 ft-lb (81 N·m).
4. The nut was then removed in preparation for the pull out test.

The cutoff bolts were installed after an anchor bolt was in place by driving a bolt into the hole to a depth approx 1 in. (25 mm) from the bottom of the hole. The bolt was then burned off flush with the concrete and driven to the bottom of the hole.

The grouting procedure was consistent with the procedure described for dry-pack mortar in Ref. 2. The order of installation for the tests with grouted holes was as follows:

1. All the holes for a particular test were drilled.
2. The anchor was installed and torqued.
3. The unused holes were grouted with dry-pack mortar having a cylinder strength of approximately 3,100 psi (21.4 MPa) at the time of testing.

This method of installation was considered to be more severe than if the holes were grouted prior to the torquing of the bolts.

Test Apparatus.—The test apparatus is shown in Figs. 2 and 3. Key elements include a center hole hydraulic cylinder, a 1-1/4 in. (32 mm) thick plate on which the cylinder rests, three pipe column supports, a 1 in. (25 mm) diam ASTM A325 bolt gaged and calibrated to measure tensile load, and a dial gage to measure pullout deflection. Leveling screws in the support plate were utilized at each of the three supporting columns to assure that the plate was level, and, in turn, that the wedge bolt was pulled straight out of the concrete. A hand pump was used to activate the hydraulic cylinder.

Test Procedure.—The first step in the testing procedure was to locate the test apparatus in proper position on the top of the concrete block. Special care was taken to locate the support columns outside the area on the block face formed by a 45° cone originating at the wedges on the anchor bolt.

Load was applied to the bolt through the activation of the center hole ram by the hand pump. The first increment of load was taken as that required to produce a pull out deflection ("slip") of 0.10 in. (2.5 mm). Further load was applied, with measurements of load and deflection taken at slip increments of 0.10 in. (2.5 mm). The load was increased incrementally until, at some value of slip, the applied load did not increase. The test was continued until measured load decreased in order to assure that the peak pull out load had been identified. In some of the tests, the slip required to obtain peak load exceeded the travel of the dial gage; in these cases, the dial was reset and the test continued. Finally, the maximum measured load and the mode of failure were recorded on the data sheet.

Concrete.—The concrete used in the tests was a flyash mix utilizing limestone coarse aggregate with a Moh's Hardness of 4. The strengths of the concrete in the test blocks are listed with the test results. A typical test block was a 27 in. (686 mm) cube. All blocks were of this size except for two which were 34 in. (864 mm) cubes.

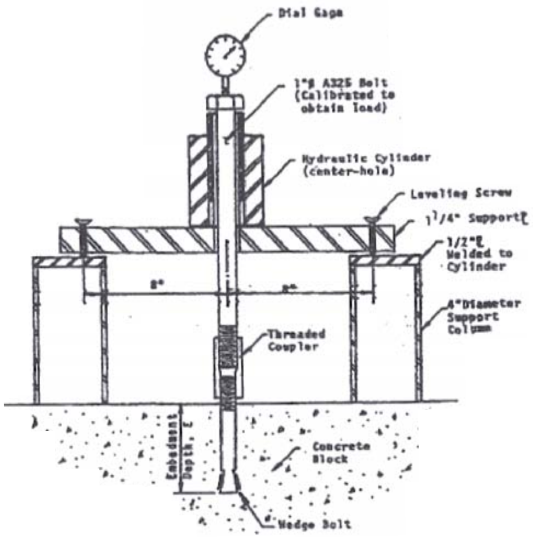


FIG. 2.—Cross-Section through Test Apparatus

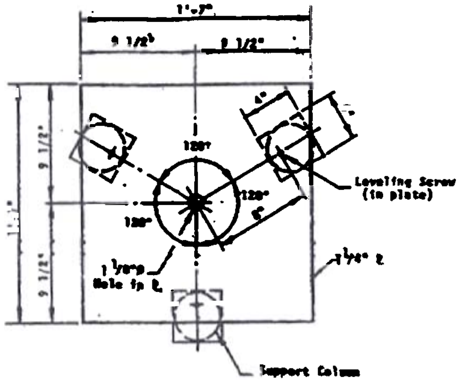


FIG. 3.—Plan of Support Plate

TEST RESULTS

The pull out loads obtained in all the tests are listed in Tables 1 and 2. A summary of the test results in terms of averages for a set of tests of a particular phase-series combination is given in Fig. 4. For each phase of tests, the percentage decrease in pull out load is given, based on Series A as a standard.

Mode of Failure.—The most commonly occurring mode of failure of the wedge bolts was slip failure, noted by the letter "s" in the tabulation of test results. Bolts with this mode of failure simply slipped out of the hole in the concrete with no visible damage done to the concrete outside the hole. Approximately 70% of the 5/8 in. (16 mm) diam bolts failed by slip.

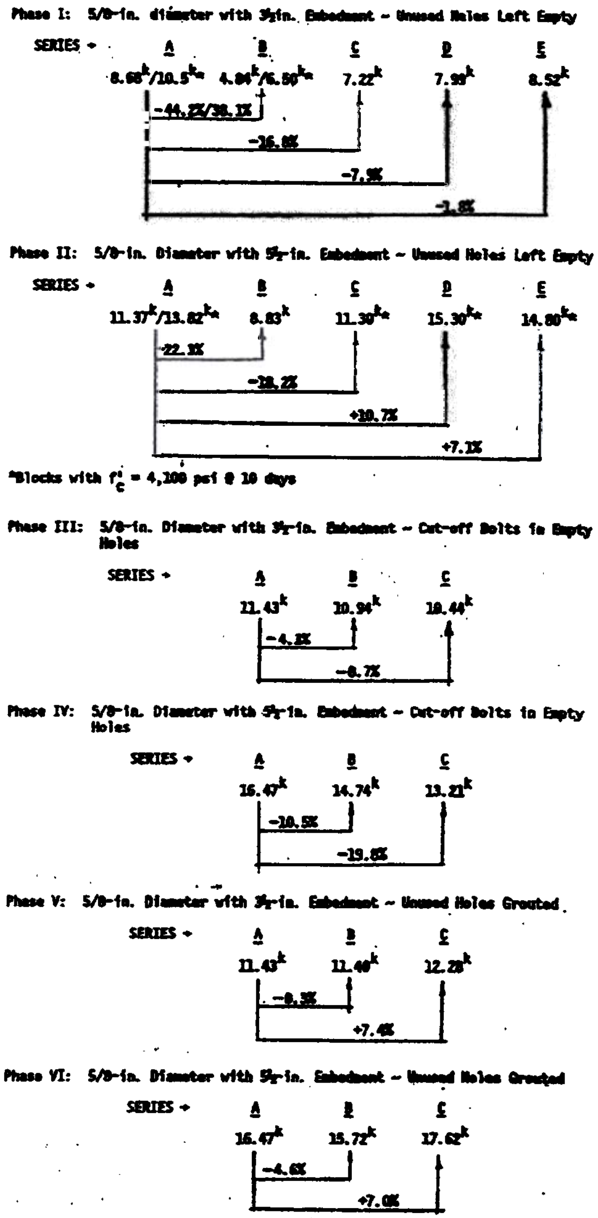
A second mode of failure, denoted in the tabulation of results by "cs," was a combination of concrete cracking and anchor bolt slip. A total of 20 of the 70 bolts failed in this mode, most of these failures occurring in the first group of tests (March–April 1980) in which concrete blocks with compressive strengths of approx 4,000 psi (27.6 MPa) were used. In the later group of tests (May–June), concrete blocks with compressive strengths between 4,900 and 5,500 psi (33 and 37 MPa) were used, and the proportion of cs failures was lower. In a cs failure a definite crack (or cracks) appeared in the concrete block. The crack originated at the bolt and propagated to a free edge. In some tests, the crack appeared just before peak load was reached, i.e., the crack would appear, but another one or two increments of load would be required to reach maximum pull out capacity. In other tests, the crack would not appear until after the peak load had been passed and the load-slip curve was on the "down" side. In neither case did the formation of the crack result in an abrupt change in the behavior of the test anchor.

TABLE 1.—Results of Tests on 5/8 in. Diameter Wedge Anchors Performed March/April, 1980

Test number (1)	Series A (2)	A* (3)	B (4)	B* (5)	C (6)	D (7)	E (8)
(*a*) Phase I: 5/8 in. diam with 3-1/2 in. embedment-unused holes left empty							
	8.03 cs	11.04 cs	7.04 s	5.30 cs	7.36 s	7.40 s	8.77 s
2	8.88 cs	10.28 cs	3.36 s	8.88 cs	7.36 cs	8.01 cs	8.01 s
3	9.14 s	10.18 cs	4.11 s	3.79 cs	6.93 cs	8.55 s	8.77 cs
4	—	—	—	8.01 s	—	—	—
Average	8.68	10.50	4.84	6.50	7.22	7.99	8.52
(*b*) Phase II: 5/8 in. diam with 5-1/2 in. embedment-unused holes left empty							
	10.39 s	15.16 cs	8.01 s	—	9.53 s	11.69 s	15.16 s
2	12.13 s	12.67 s	9.64 s	—	11.69 s	15.16 s	15.05 s
3	11.58 s	13.64 s	10.32* s	—	12.67 s	19.05 s	14.18 s
Average	11.37	13.82	8.83	—	11.30	15.30	14.80

Note: Ultimate Tensile Load in kips; s = slip failure; cs = concrete crack plus slip. Concrete blocks with f'_c = 3,800 psi except where * appears; then f'_c = 4,100 psi at 10 days. 1 kip = 4.445 kN.

It is important to note that failure in the cs mode did not result in reduced pull out loads as compared to tests with s failures. This statement is based on the results listed in Tables 1 and 2 and is true for cases with one crack propagating to one free edge, or two cracks propagating to the two free edges at a corner; it is true also whether the cracks formed before or after peak load was reached. The minimum edge distances used in the tests were 1.5 times the embedment depth of the bolt. The results of the pull out tests indicate



NOTE: To convert kips to kN multiply by 4.445.

FIG. 4.—Summary of Test Results in Terms of Averages

that this criterion, which is somewhat overly conservative for many practical situations, was adequate to assure meaningful, repeatable test results.

A third mode of failure, which occurred in these tests only once, is a concrete "cone" failure. This type failure occurs when the force developed at the head of an embedded bolt—in these tests, the wedges of a wedge bolt—is large enough to produce diagonal tension failure of the concrete. It is called a "cone" failure because the failure surface resembles a cone with its apex at the head of the embedded bolt. This type failure occurred in Test 3 of Phase V, Series C, with a 5/8 in. (16 mm) diam bolt with a 3-1/2 in. (89 mm) embedment. The failure surface was actually a partial cone, extending primarily to one side of the bolt. At the bottom of the hole, this surface was oriented at approx 45° from the horizontal. As the failure surface approached the face of the block, the orientation with the horizontal became somewhat flatter with an "average" angle of inclination on the order of 30°. It should be noted that of the three tests in Phase V, Series C, two failed in slip and one with a cone failure. The pull out load for the one with the cone failure was within 1% of the average pull out load for the other two.

TABLE 2.—Results of Tests on 5/8 in. Diameter Wedge Anchors Performed May/June, 1980

Test number (1)	Series A (2)	 B (3)	 C (4)
(*a*) Phase III: 5/8 in. diam with 3-1/2 in. embedment—cutoff bolts in unused holes			
1	10.13 s	12.03 s	9.39 cs
2	12.43 s	9.71 s	11.92 s
3	11.72 s	11.08 cs	10.02 cs
Average	11.43	10.94	10.44
(*b*) Phase IV: 5/8 in. diam with 5-1/2 in. embedment—cutoff bolts in unused holes			
1	15.94 s	16.93 s	15.09 s
2	17.43 cs	14.78 s	13.09 s
3	16.04 s	12.52 s	11.46 s
Average	16.47	14.74	13.21
(*c*) Phase V: 5/8 in. diameter with 3-1/2 in. embedment—unused holes grouted			
1		11.08 cs	13.19 s
2		11.19 cs	11.50 s
3		11.93 cs	12.14 c
Average		11.40	12.28
(*d*) Phase VI: 5/8 in. diameter with 5-1/2 in. embedment—unused holes grouted			
1		17.94 s	18.47 s
2		15.83 s	17.29 s
3		13.40 s	17.10 s
Average		15.72	17.62

Note: Ultimate Tensile Load in kips; s = slip failure; cs = concrete crack plus slip; and c = concrete cone failure; concrete blocks with f'_c between 4,900 and 5,500 psi. 1 kip = 4.445 kN.

Effect of Extra Holes Left Empty.—The summary of test results in Fig. 4 for Phases I and II indicates, with reasonable clarity, the effect of empty holes in the vicinity of an anchor bolt. These holes, it should be recalled, were drilled to the same depth as the hole for the anchor bolt itself.

The results of the Series B tests (two holes spaced 1.5 diam from the test bolt) clearly indicate a sharp reduction in tensile load capacity. The percentage reduction varied with embedment depth, with the percentage reduction being less for the more deeply embedded bolts. The percentage reduction varied between approx 20 and 45%.

As the distance between the empty holes and the test bolt was increased to 2.0 bolt diam in the Series C tests, the percentage reduction was reduced significantly. However, as the percentages in Fig. 4 indicate, there was still a definite reduction in pull out load due to the presence of these holes. As the distance between the holes and the test bolt was increased to 3.0 bolt diam in Series D and E, any difference between the loads obtained for Series A (no holes) and Series D and E appeared to lie within normal scatter of the test data. In no case was the average of the Series D and E results lower than the Series A values by more than 8%, and the average was, in some cases, higher. The averages of all the test loads for Series A and for Series D and E were within 1% of each other.

Effect of Extra Holes with Cutoff Bolts.—Series B and C tests with cutoff bolts in the empty holes were performed. The results were inconclusive: for the B-Series tests with shallow embedment (Phase III), the reduction in tensile load was almost eliminated; and for the B-Series tests with deep embedment (Phase IV), the reduction was only 10.5%. However, the results for the C-Series tests for both Phases III and IV were less encouraging; the C-Series results for the Phase IV tests actually indicated a slightly worse case with the cutoff bolts present in the holes than without the bolts (Phase II).

Any beneficial effect of cutoff bolts in the extra holes would be expected to derive from the stiffening effect of the bolts as the concrete resists the lateral pressure generated by the actions of the wedges of the test bolt. If the cutoff bolts completely filled the holes, one would expect this beneficial effect to be significant. If the bolts almost fill the holes but leave some space, or spaces, in the vicinity of the wedges, then the beneficial effect would be expected to be reduced sharply. The test results indicate that the magnitude of the reduction in pullout capacity due to the presence of extra holes is somewhat less when cutoff bolts are present; the variability of the results makes it difficult to assign a definite percentage to this lesser reduction.

Effect of Extra Holes Filled with Grout.—Series B and C tests with the extra holes filled with dry-pack mortar were performed. The cylinder strengths of the mortar, as noted earlier, was approx 3,100 psi (21.4 MPa) at the time the tests were performed—six days after the mortar was placed. Thus, the grout was far short of reaching its maximum compressive strength or its maximum modulus of elasticity. The results of the two series of tests with grouted holes were consistent and, in the opinion of these writers, conclusive. Any detrimental effect of the extra holes on pullout capacity of an anchor was eliminated by grouting the holes.

Comments.—It is unreasonable to expect that results of pullout tests on wedge bolts will not exhibit significant scatter. The wedging device bearing against the sides of a hole in nonhomogeneous concrete could not be expected to lead to perfectly consistent results. Examining the data from this viewpoint, one finds the results of the pull out tests on 5/8 in. (16 mm) diam bolts to be remarkably consistent. The B-Series tests with empty holes were, not surprisingly, exceptions; apparently, the relatively thin walls of concrete between the hole for the test anchor and the empty holes led to inconsistencies in the magnitude of load that the wedges were able to develop.

CONCLUSIONS

From the test results presented and analyzed earlier, the following conclusions may be drawn.

1. Empty holes as close as 1.5 bolt diam from a wedge bolt cause a significant reduction in strength. The percentage reduction is difficult to predict; it varied between approx 20 and 45%.
2. The presence of cutoff bolts in the unused holes helped significantly for the 5/8 in. (16 mm) diam bolts with shallow embedments, resulting in a load reduction between 4 and 9% compared to 17 and 45% obtained with empty holes. A particularly dramatic change in load reduction occurred in the B-Series tests as the load reduction changed from approx 45–4%. Unfortunately, no such claim can be made for the 5/8 in. (16 mm) bolts with deep embedments; the results seem to indicate a slight enhancement of capacity due to the cutoff bolts, but further testing would be required before definite conclusions could be drawn.
3. Empty holes as close as 2.0 bolt diam cause a reduction in pullout load between 15 and 20%.
4. When the empty holes are spaced as far away from the anchor as 3.0 bolt diam, the pullout loads were essentially the same as for the case with no extra holes. There was no reduction in capacity for this case.
5. When the holes were filled with dry-pack mortar, the anchors behaved as if there were no additional holes present. Thus, the situation with empty holes as close as 1.5 diam from an anchor can be fixed by placing dry-pack mortar in the empty holes. Then, no reduction in pullout load capacity need be considered.

ACKNOWLEDGMENT

The work reported herein was sponsored by the Bechtel Power Corporation, and the facilities of the Department of Civil Engineering at The University of Tennessee, Knoxville, were used to perform the tests. A number of graduate and undergraduate students in Civil Engineering participated in the performance of the tests, with special commendation due to Steven Stethen and Bobby Page.

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BAYESIAN APPROACH TO PROTOTYPE TESTING

By Peter Hauge Madsen[1] and Niels C. Lind[2]

ABSTRACT: The strength of series-produced structures is uncertain because of modeling error and material parameter uncertainty. By testing of prototypes, information on both uncertainties is obtained. Because of strength correlation in a series, sampling is considered non-random. The Bayesian Method is used to consider the problem of relating prior knowledge and test data to a prescribed characteristic value of the load carrying capacity, i.e., a prescribed fractile of the strength distribution, or a target value of a reliability index. Examples show application to prototype testing structural assemblies or parts. It is concluded that even a slight correlation may have a significant influence on the estimated strength.

INTRODUCTION

Many new structural design codes explicitly refer to limit states, with safety factors derived from probability-based rationales. Increasingly, the rationales are explained to the professional forum in code commentaries. For example, the National Building Code of Canada has had a limit states design option since 1975, and the goal is for all structural standards incident on the code to have a common probabilistic rationale. For the foreseeable future, this rationale is of the "level 2" reliability index type. Design by testing is an available alternative in many of the technologies of structural production, and it is part of the goal that a common rationale be developed to select procedures and safety factors.

Testing is always an important link in the justification of a structure. Usually, the testing is performed on material samples and yields indices of material strength, durability, etc. on the particle level. These indices are then compared with nominal values used in the design calculations. Occasionally, it is expedient to test parts (e.g. bolts or connections), members, or subassemblies; sometimes entire structures are tested. There is, therefore, a continuous spectrum of testing and calculation on various levels of substructure. As a consequence, the common rationale for testing cannot be developed in isolation; it must be logically reconcilable with that for conventional calculations of structural strength.

There is a great variety of load testing situations, differing in destructivity, objective, realism of test loads, number of tests and fraction of population

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