Behaviour of grouted anchors

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Grouted anchors are often used to connect steel structures and microwave towers to concrete foundations. However, very little research has been done on the behaviour of such anchors and the codes of practices do not provide methods to check the adequacy of such connections. The paper presents a brief review on the topic with a discussion on suggested behaviour models. Also, the results of 229 tests conducted on both headed and un-headed anchors (installed using six cementitious and three polymer grouts) at the University of Florida are compared with those of the analytical models suggested in the literature and a suitable model is suggested for the use of designers. More tests are necessary to predict the shear and combined shear and tension behaviour of grouted anchors.

Fastening systems in the form of anchor bolts are usually used for connecting steel microwave towers or industrial steel structures to the concrete foundation through base plates, *Fig* 1. These fastening systems can be classified into cast-in-place systems and post-installed systems[1]. Cast-in-place systems are placed in the formwork before casting of the concrete, while post-installed systems are incorporated in hardened concrete. Advancements in drilling technology have resulted in reliable post-installed systems. Due to their ease in installation, post-installed anchors are used increasingly in new construction, as well as repair and retrofit projects.

The design methods of cast-in-place anchors and the recent developments in their design methods have been presented in earlier papers[2-3]. The methods of installation, behaviour and design of bonded anchors are also discussed elsewhere[4]. In this paper, the behaviour and design of grouted anchors, which are often encountered in India, are discussed.

Post-installed anchors

Advances in carbide-tipped bits and rotary hammer drills have made many new anchors practical because they can now be post-installed in hardened concrete. There are two types of post-installed anchors: mechanical and bonded.

Mechanical anchors

Post-installed mechanical anchors, which function on the principles of keying and friction, include undercut, heavy-duty sleeve, torque controlled expansion and deformation controlled expansion anchors. These anchors loaded in tension, apply reaction forces to the concrete at the expansion mechanism, usually near the end of the embedded part of the anchor. Failures typically occur when the anchor pulls out a cone of concrete, or slips out of the hole or simply breaks in response to the failure of the steel[1].
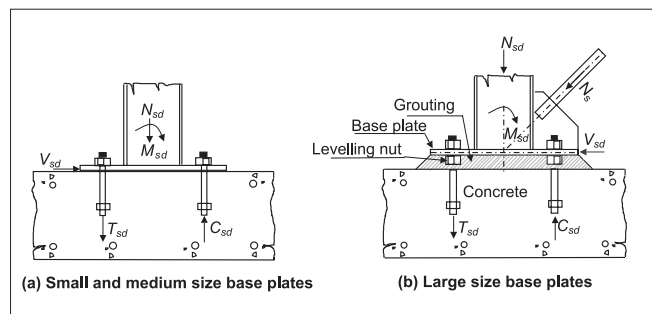

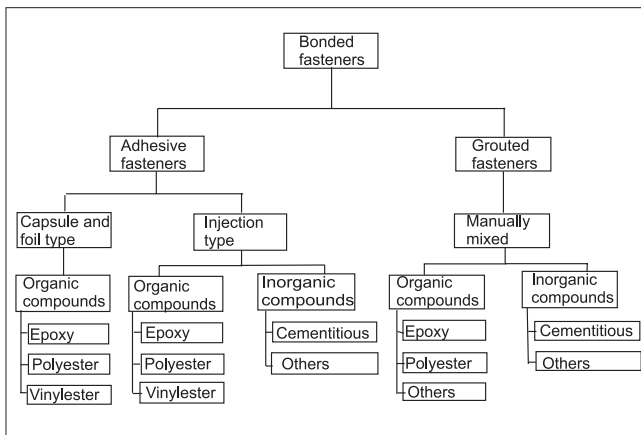**Fig 1 Typical connection between concrete foundation and steel columns**

Fig 2 Types of bonded fastener systems

Bonded adhesive anchors

Post-installed bonded anchors can be classified as adhesive or grouted depending on the bonding agent, anchor type, and hole dimensions, *Fig* 2. These types of anchors can be installed with or without a head at the embedded end. Adhesive anchors are installed using an unheaded threaded rod or a reinforcing bar inserted in a pre-drilled hole — that is 10-25 percent larger than the anchor diameter — using a polymer-based bonding agent including epoxies, polyesters, vinylesters, and hybrid systems. The installation methods, behaviour and design of bonded adhesive anchors are discussed elsewhere[4].
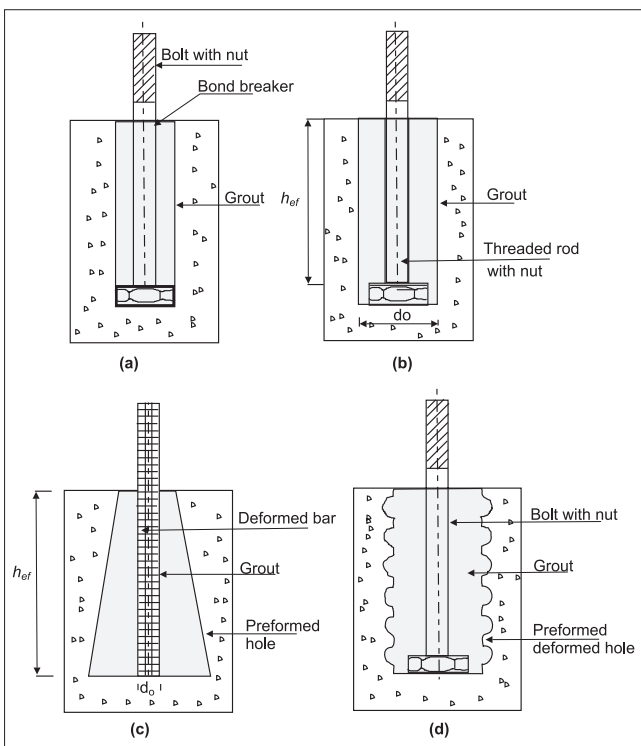

Fig 3 Types of grouted anchors

Bonded grouted anchors

Grouted anchors, *Fig* 3, may consist of headed bolts, threaded rods with nut and washer at the embedded end (block-end anchor) or deformed reinforcing bars with or without end anchorage. Commonly-used bolt diameters vary from 12-50 mm, although larger bolts are sometimes used. Grouted anchors are typically installed with a cementitious or polymer grout in a pre-drilled or pre-formed hole having a diameter range of 150-300 percent larger than the diameter of the fastener. Cementitious grouts are primarily composed of fine aggregates and portland cement. Polymer grouts are similar to adhesive anchors but with a fine aggregate component. Some proprietary grouts cater to controlled expansion and thus develop compression stress in the grout after setting. This may serve to increase the contribution of friction to the tension load-bearing resistance of the anchorage.

If an end anchorage is provided, the shank may be either bonded, *Fig* 3*(a)* or bonded, *Fig* 3*(b)*. De-bonded anchors prelude tension load transfer near the concrete surface. De-bonding is normally achieved by means of a thin sleeve, which prevents the resin from contacting the rod. Grouted anchors transfer tension loads to the base material by a combination of bond, friction and mechanical interlock. Belled or keyed holes, *Fig* 3*(c)* and 3*(d)* will increase the mechanical interlock while resisting tensile loads; however they can be produced only by placing block-outs in the concrete form work and as such cannot be considered as post-installed anchors[1].

The grouted anchors offer an advantage over cast-in-place anchors, since planning efforts and costs of special formwork are reduced.

As discussed above, grouted anchors can be distinguished from adhesive anchors by a larger hole-to-anchor diameter ratio that can accommodate a headed anchor, which ultimately affects the load transfer mechanism. Headed anchors transfer the load to the grout primarily by bearing on the anchor head. Unheaded anchors installed with threaded rod take advantage of mechanical interlock between the threads and the grout. In both cases, the load is transferred from the anchor to the grout and the grout then transfers the load to the concrete resulting in one of three potential failure modes, *Fig* 4.

Unheaded grouted anchors typically exhibit a failure mode similar to adhesive anchors; bond failure at the steel-grout
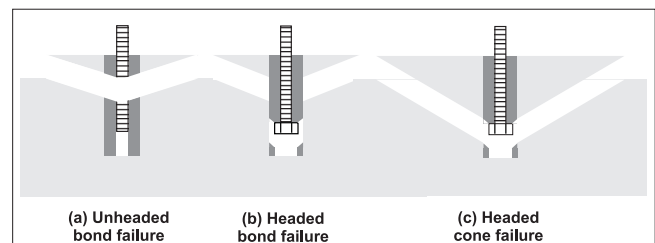

Fig 4 Potential failure modes for grouted anchors (excluding steel failure)

interface with a secondary, shallow concrete cone, *Fig 4(a)*. Headed anchors exhibit either bond at the grout-concrete interface or concrete breakout cone failure depending on the concrete strength, embedment depth, and grout-concrete bond strength, *Fig 4(b)* and (*c*).

Thus, for anchors grouted in place, four possible failure mechanisms can be considered[5]:

(i) tensile failure of the bolt

(ii) full depth concrete cone breakout

(iii) bond failure at the grout-concrete interface with a shallow concrete cone failure, and

(iv) bond failure at the steel-grout interface with a shallow concrete cone failure for unheaded grouted anchors.

It is to be emphasised that failure of the bolt needs to be the objective of the designer. However, practical limitations on the embedment depth may sometimes prevent full development of the bolt steel strength.

For polymer-grouted anchor bolts, the load capacity of the polymer grout is significantly affected by the hole size. The displacement of the bolt head within the polymer becomes more significant as the hole size is increased. Bond strengths of polymers used vary in the range 6.2-12.4 MPa[5,6,7]. Since these strengths are greater than the actual shear strength of concrete at the interface, interface shear failures are expected to occur primarily in concrete, unless good bond strength has not been achieved due to improper cleaning of concrete holes prior to grouting[5].

Behavioural models

The behaviour of grouted anchors was expected to be similar to either cast-in-place headed anchors or post-installed adhesive anchors depending on the anchor configuration (headed or unheaded) and material properties. The following presents a general discussion of suggested behavioural models.

Combined cone-bond stress model

Cones[7] and James *et al*[5] have suggested the following model for calculating the ultimate resistance of grouted anchors based on the mechanism shown in *Fig* 5.

$$N_u = f_t A_1 + u A_2 + f_g A_3 \qquad \ldots(1)$$

where,

A_1 = the horizontal projected area of the spall cone

A_2 = the area of the exposed vertical cylindrical surface of the grout

A_3 = the horizontal projected area of the grout annulus around the bolt head respectively

f_t = tensile strength of concrete

f_g = the tensile strength of the grout
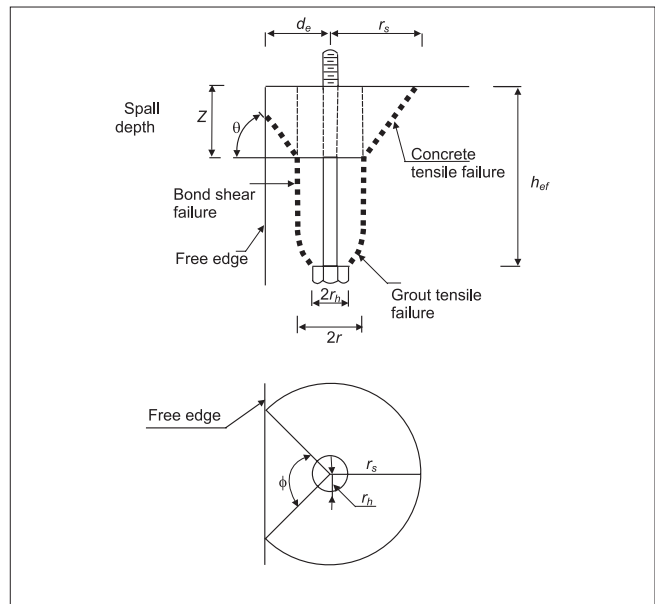
u = the shear strength of grout-concrete

Fig 5 Combination failure mechanism of grouted anchors

interface.

The effect of edge distance, d_e , may be incorporated into the calculation of A_1. Thus, the following formulae may be used.

When anchor is near a free edge:

$$A_1 = \pi (r_s^2 - r^2) - \phi/2 \left[r_s^2 + d_e \sqrt{(r_s^2 - d_e^2)} \right] \qquad \ldots(2)$$

when the anchor is not near the free edge:

$$A_1 = \pi(r_s^2 - r^2) \qquad \ldots(3)$$
$$A_2 = 2\pi r[h_{ef} - (r_s - r)\,tan\,\theta] \geq 0 \qquad \ldots(4)$$
$$A_3 = \pi(r^2 - r_h^2) \geq 0 \qquad \ldots(5)$$

where,

θ = the angle of the spall cone from the concrete surface (θ may be taken as 45°)

r_s = the radius of the spall cone at the surface

d_e = the distance from the anchor centre line to the free edge

h_{ef} = the embedment length

ϕ = $ar\,tan\,c/(\sqrt{(r_s^2 - d_e^2)}/d_e)$ = the angle in radians subtended in plan view by the intersection of the failure cone with the free edge

r_h = the radius of the anchor head or the anchor body in the case of headless anchors

r = the radius of the hole for grouted anchors.

The areas A_1 and A_2 depend on the depth of spall, Z. This has been derived by James *et al*[5] as

$$Z = 1/2(u/f_t - 1/\,tan\theta)\,d_h tan^2\theta \qquad \ldots(6)$$

The above equation shows that, for a fixed spall angle, θ, the spall depth is dependent only on the bond strength, the tensile strength of concrete and the hole diameter. With $\theta = 45°$ and using typical values of u/f_t, from 3-5, the predicted theoretical concrete spall depth should be between 1-1.5 times the diameter of drilled hole.

It has to be noted that the above equations are based on the simplifying assumptions that the stresses on conical area A_1 are pure tensile stresses at failure. The presence of significant shear stresses on this spall cone will increase the pull out resistance.

If the mechanism is assumed to be a simple one as shown in *Fig 5*, then the ultimate tensile capacity will be smallest of the following values.

$$P_{u1} = f_t A_1$$
$$P_{u2} = 0.87 F_{ut} A_s$$
$$P_{u3} = \pi D_h L_e \tau_{bu}$$

where,

F_{ut} = the ultimate tensile strength of the anchor bolt

A_s = the cross-sectional area of anchor

L_e = embedment length

D_h = diameter of grout hole and

τ_{bu} = ultimate bond stress at the interface between the grout and the surrounding concrete.

The quantities f_t and A_1 have already been defined. Tests have demonstrated that the bond between grout and concrete can be lost due to cracking.

Concrete capacity design method (CCD)

The CCD model evolved from a series of concrete cone models that were developed for fasteners that were observed to have full concrete cones at failure. These behavioural models assumed that the concrete failed in tension and that a full concrete cone formed from the embedded end of the anchor to the top of the concrete. There are several versions of the concrete cone model, but the CCD method is widely accepted. The CCD method evolved from the Kappa-method and predicts the ultimate load of an anchor loaded in tension or in shear[8]. This method was developed for cast-in-place headed anchors and post-installed mechanical anchors installed in uncracked concrete that developed a full concrete cone at failure. The CCD equation, used to predict the tensile capacity of a single anchor installed in uncracked concrete, is as follows[8]:

$$N_{cone} = k \sqrt{f_{ck}} \, h_{ef}^{1.5} \qquad (7)$$

where,

N_{cone} = mean tensile strength of concrete cone, N

f_{ck} = concrete compressive strength (200 mm side cubes), N/mm^2

h_{ef} = effective embedment length, mm

k = 15.5, for mean failure load of cast-in-place headed fasteners

Uniform bond stress model

The uniform bond stress model was developed to predict the failure loads of adhesive anchors in uncracked concrete by assuming a uniform bond stress throughout the embedment length of the anchor system[10,11,12]. This model assumes that the failure surface could occur either at the steel-adhesive or adhesive-concrete interface. As the hole-to-anchor diameter ratio for adhesive anchors is close to unity, the nominal anchor diameter can be used. Cook, *et al*[10,11,12] showed that for adhesive anchors the uniform bond stress is product dependent and its value, τ, must be determined experimentally. Grouted anchors can also develop failure surfaces at the steel-grout or grout-concrete interface but the hole-to-anchor diameter ratio is generally larger than 1.5. Therefore, the bond strength of each product should be evaluated at both potential failure surfaces. The uniform bond stress model equation is as follows:

$$N_{bond} = \tau \pi d h_{ef} \qquad ...(8)$$

$$N_{bond,\,do} = \tau_o \pi d_o h_{ef} \qquad ...(9)$$

where,

N_{bond} = mean tensile strength for a steel-grout failure, N

$N_{bond,do}$ = mean tensile strength for a grout-concrete failure, N

τ = uniform bond stress at the steel-grout interface, MPa

τ_0 = uniform bond stress at the grout-concrete interface, MPa

d = diameter of the anchor, mm

d_0 = diameter of the hole, mm

h_{ef} = effective embedment length, mm

Review of earlier experimental programme

To determine the strength and behavior of grouted anchors an extensive experimental programme with 229 tests on both headed and unheaded anchors installed using six cementitious and three polymer grouts was undertaken at the University of Florida, USA[11,13]. The investigation included parameters typically encountered during design and installation including binding agent (cementitious or polymer), anchor configuration (headed or unheaded), anchor and hole diameters, embedment depth, and concrete strength.

Test results for unheaded anchors

As hypothesised, the observed failure mode for unheaded anchors was a bond failure located at the steel-grout interface with a secondary shallow cone. From all the test series

Table 1: Steel-grout bond stress and coefficient of variation for unheaded anchors

Product	CA	CB	CC	CD	CE	CF	PA	PB	PC
Average bond stress, MPa	20.5	21.8	7.3	21.1	21.6	15.9	17.8	19.4	17.8
Coefficient of variation	0.11	0.18	0.22	0.08	0.09	0.20	0.06	0.09	0.13

Note: Products starting with the letter 'C' are cementitious grouts and with the letter 'P' are polymer grouts

evaluated in this test programme, only one test series (four anchors) exhibited a failure mode at a location other than at the steel-grout-interface. This series was installed with product CE and produced a failure mode at the grout-concrete interface. Two other test series were performed using the same product, but they developed a steel-grout failure mode. The only difference between these tests series was the dimensions of the anchor system. Therefore, transition from one failure mode to another can be explained by observing that the anchors in the test series exhibiting bond failure at the grout-concrete interface were installed using large diameter anchors. This allowed the anchor system to develop the ultimate bond strength of the grout-concrete interface before it could develop a steel-grout failure mode.

Product variability and anchor strength

Table 1 provides a summary of the steel-grout bond stress, τ, and coefficient of variation for the products tested with un-headed anchors. For the entire unheaded data set, the mean bond stress was 18.4 MPa with a coefficient of variation of 0.27. As shown in *Table* 1, the variation between all products is greater than that within any individual product. This indicates that the unheaded bond strength is product dependent. (It is of interest to note that Lang[14] reported an ultimate bond strength of 8MPa for a concrete with f_{ck} = 20 MPa for capsule type anchors utilising polyester resin with a quartz sand filler. For high strength concrete the bond strength was found to be 12 MPa or more).

Behavioural model comparison

The observed failure loads for all data sets as a function of bonded area are illustrated in *Fig 6(a)*. Failure loads shown in *Fig* 6(a) were normalised to the mean steel-concrete bond stress, τ, of 18.4 MPa by multiplying actual failure loads by the factor $18.4/\tau_{product}$. The solid line shown in this figure represents the mean value for the uniform bond stress model based on the bonded area and τ = 18.4 MPa. *Fig* 6(a) shows a linear relationship, indicating that the uniform bond stress model is appropriate for unheaded grouted anchors. Also shown in *Fig 6(a)* is a 5 percent fractile boundary based on a coefficient of variation of 0.20 and a large database. *Fig 6(a)* indicates that out of the 121 anchors tested, only 2 anchors (1.6 percent) fall below this 5 percent fractile boundary line.

Test results for headed grouted anchors

For headed grouted anchors, two failure modes are possible. For low bond strength grouts, bond failure at the grout-concrete interface may occur. This failure mode can best be

represented by a uniform bond stress model calculated using the grout-concrete bond strength of the product, τ_o, applied to the bonded area at the grout-concrete interface. This is given by:

$$N_{bond,\ do} = \tau_o \pi d_o h_e \qquad ...(10)$$

For higher bond strength grouts, a full concrete breakout failure occurs and the mean concrete breakout strength developed by Fuchs *et al*[8] is appropriate. This is given by[9]:

$$N_{cone} = 15.5 \sqrt{f_{ck}} h_{ef}^{1.5} \qquad ...(11)$$

The predicted mean strength of a headed grouted anchor is determined by the lower value of equation (10) and equation (11).

A total of nine different products were tested which consisted of six cementitious grouts and three polymer grouts. Test results showed that out of the 108 tests included in the headed grouted anchor test programme, 61 (56 percent)
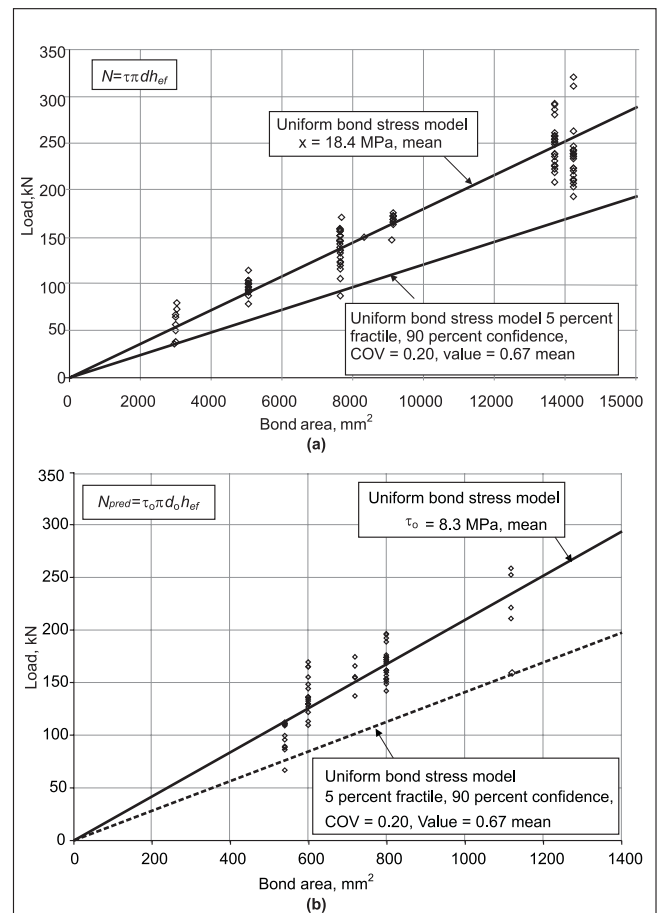

Fig 6 *(a)* **Unheaded grouted anchor test results compared to the uniform bond stress model for adhesive anchors** *(b)* **Headed grouted anchor tests exhibiting grout/concrete bond failure compared to the uniform bond stress model for grout/concrete bond failure**

Table 2: Grout-concrete bond stress and coefficient of variation for headed anchors

Product	CA	CB	CC	CD	CF	PA	PB	PC
Average bond stress, MPa	10.2	7.8	4.8	9.1	8.4	7.9	7.7	11.1
Coefficient of variation	0.12	0.15	0.12	0.21	0.24	0.10	0.06	0.07

anchors developed a bond failure at the grout-concrete interface and 47 (44 percent) anchors developed a concrete tensile failure that resulted in a full concrete cone. This confirms the assumption that headed grouted anchors can develop either a concrete cone failure mode or a bond failure at the grout-concrete interface depending on the properties of the grout and the dimensions of the anchor system.

Product variability and anchor strength

The strength of a headed grouted anchor system is dependent on the grout-concrete bond strength and the concrete cone breakout capacity of the concrete. Therefore, headed anchors that produced a bond failure were analysed separately from those that developed a concrete cone. *Table* 2 illustrates the average bond strength and corresponding coefficient of variation calculated for the different products that exhibited bond failure at the grout-concrete interface. For all eight products tested with headed anchors and exhibiting grout-concrete bond failure, the mean grout-concrete bond stress was 8.1 MPa with a coefficient of variation of 0.30. This indicates that the variation between all products is greater than that within any individual product. Therefore, there is enough evidence to indicate that the unheaded bond strength is product dependent.

The other failure mode observed in headed grouted anchors was a full concrete cone failure. As indicated by equation (7), the capacity of this failure mechanism depends on the strength of the concrete and embedment length of the anchor. The compressive strength of the concrete for the headed anchor tests ranged from 27.4 MPa to 63.7 MPa and the embedment length ranged from 102 mm to 178 mm.
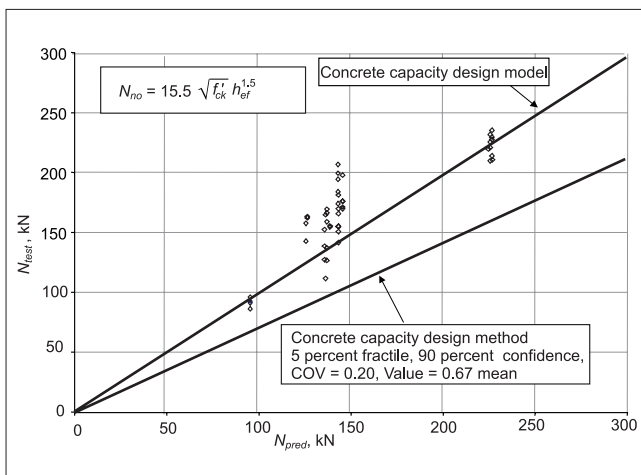

Fig 7 Headed grouted anchor tests exhibiting concrete cone failure compared to the CCD method

Comparison of behavioural models

The presence of two failure mechanisms in headed grouted anchor systems requires the use of two different behavioural models to predict behavior. For grouted anchors that exhibited a concrete cone breakout, the failure loads were compared to the CCD method, equation (7). Anchors that exhibited a grout-concrete bond failure were compared to the uniform bond stress model for failure at the grout-concrete interface, equation (9). The results of these comparisons are presented in *Figs* 6(b) and 7.

Fig 6(b) shows a graph of the tensile failure load versus bonded area for all headed anchors that developed a bond failure at the grout-concrete interface. In *Fig* 6(b), actual failure loads were normalised to $\tau_0 = 8.3$ MPa, which is the mean value for τ_0 for all tests that exhibited grout-concrete bond failure. *Fig* 6(b) shows a linear relationship, indicating that the uniform bond stress model for failure at the grout-concrete interface, equation (9) is appropriate for headed grouted anchors that exhibit grout-concrete bond failure. Also shown in *Fig* 6(b) is a 5 percent fractile boundary based on a coefficient of variation of 0.20 and a large database. *Fig* 6(b) shows that out of the 59 anchors that exhibited the grout-concrete failure mode, only 2 anchors (3.3 percent) fall below this 5 percent fractile boundary.

Fig 7 shows a comparison of the headed grouted anchor tests that were observed to develop a full concrete cone breakout failure to the CCD method, equation (7), as represented by the solid line in *Fig* 7. As shown by *Fig* 7, the test data typically fall above the solid line indicating a conservative model. It is believed that the conservative results indicate that the threaded rod used in the majority of the headed anchor tests may have contributed to the increased capacity due to a combination of thread-grout interlock and bearing at the head of the anchor. A dashed line representing the 5 percent fractile associated with the CCD method is also shown in *Fig* 7.

Recomended design model

Equations (8) to (11) provide predictions for the mean strength of grouted fasteners. For design purposes, these strengths must be reduced. For load and resistance factor design, the determination of design strength from behavioral models which represent mean strengths is typically based on establishing a nominal strength (some lower bound fractile of the mean strength) and then applying a capacity reduction factor, ϕ, to limit the probability of failure.

In current US and European design standards, the nominal strength is commonly taken as the lower 5 percent fractile of the test data. The 5 percent fractile represents the value where it would be expected that 95 percent of the tests performed would exceed the specified nominal strength. The determination of the 5 percent fractile depends on the number of tests available and the scatter of the test results. The scatter of the test results is typically expressed as the coefficient of variation (V) which is defined as the standard deviation of

the test results divided by the mean. This leads to the following for nominal bond strengths:

$$\tau' = \tau(1 - \alpha V) \qquad \qquad ...(12)$$

$$\tau'_0 = \tau_0(1 - \alpha V) \qquad \qquad ...(13)$$

The selection of the α factor depends on the number of tests available.

The selection of an appropriate capacity reduction factor (φ) for bond can be based on detailed studies of probability of failure and/or on what φ factors are used for similar failure modes in existing building codes. Bond failure can be compared to shear-friction since it involves slip along an interface. In ACI 318, the φ factor for shear-friction and shear is 0.85. A capacity reduction factor. φ , for bond of 0.85 is recommended for designs controlled by bond failure.

Various behavioral models for both edge effects and group effects for grouted fasteners are being studied in both the US and Europe.

Factors influencing the strength of bonded anchors

The evaluation of both the mean bond stress (τ and τ_o) and design bond stress τ' and τ'_0) must be based on product approval tests that include the effects of installation and in-service conditions. As noted by Cook *et al*[14] there are significant differences between adhesive products. Basic tests for mean bond stress in clean, dry holes at room temperature indicate that the mean bond stress can range from 2 MPa to 20 MPa for adhesives and 7 MPa to 21 MPa for grouts. The coefficient of variation for these tests can vary between 0.05 and 0.25. In many cases, products that exhibit high bond stress in clean, dry holes at room temperature are inadequate under typical installation and in-service conditions such as damp holes and elevated temperatures. It is mandatory that designers require product testing for expected in-service and installation conditions prior to the final design.

The following provides examples of the factors influencing bond strength that need to be considered for product approval tests of grouted fastener products[12,15]:

- concrete mix (equal concrete strength does not ensure equal results)
- temperature effects
- damp hole
- improperly cleaned hole
- curing time
- freeze-thaw effects
- installation direction (vertical down, horizontal, overhead)
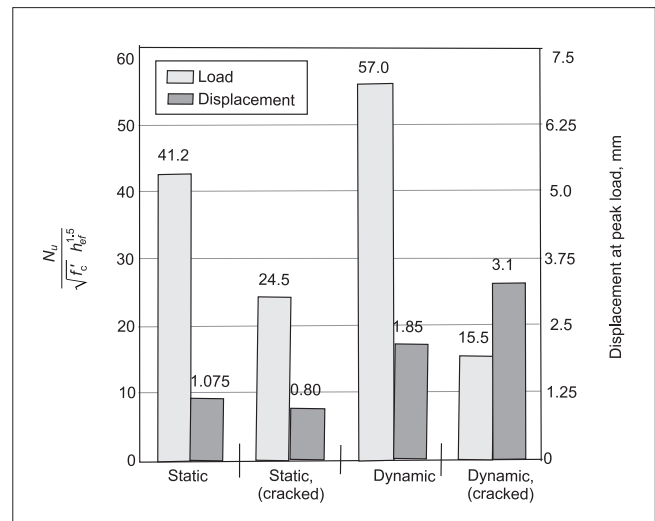- creep (normal and elevated temperatures)

Fig 8 Effect of cracking and dynamic loading on maximum load and displacements at maximum load of grouted anchors[16]

- mix proportioning (primarily manually-mixed products)
- fire resistance
- wet (submerged) hole
- maximum torque
- repeated load
- seismic load
- environmental effects (chemicals)
- cracked concrete (static cracks and moving cracks)
- other possible factors:
  - age of concrete
  - presence of oil (compressed air cleanout of holes)
  - hole size
  - hole drilling
  - UV radiation.

As can be observed from the above list, a product approval standard for bonded fasteners must be quite comprehensive to ensure reliable performance of products.

Dynamic behaviour

Rodriguez *at al* studied the dynamic behaviour of tensile grouted anchors in concrete[16]. The effect of cracking and dynamic loading on maximum load and displacements is shown in *Fig* 8. They found that during crack opening, the crack propagated along the interface between the grout and surrounding concrete in most of the tests. As a result, the friction between the grout and concrete reduced considerably resulting in the pull out of the grout plug. Due to this effect, the average maximum capacity under static loading in cracked concrete decreased by 40 percent compared with the

test in uncracked concrete. Due to the reduced dynamic friction coefficient between the grout and the concrete, the capacity still reduced under dynamic loading. The grout plugs were observed to be pulled out of the cored holes, with little or even no damage to the surrounding concrete. Further study is needed to see if behaviour would be improved in rough, drilled holes instead of smooth cored holes.

Conclusions

The behaviour of grouted anchors is dependent on the product and whether or not the anchor is unheaded or headed.

For most engineered grout products, the behaviour of unheaded grouted anchors can be predicted by the uniform bond stress model recommended for adhesive anchors, equation (8). This model is based on a product's bond strength, τ, at the steel-concrete interface. For products with a low grout-concrete bond stress, τ_0, bond failure may occur at the grout-concrete interface, equation (9). In general, product approval tests need to be developed to establish both the grout product's steel-grout bond strength, τ, and grout-concrete bond strength, τ_0. The controlling embedment strength can then be determined as the smaller of the strength controlled by steel-grout bond failure, equation (8) and grout-concrete bond failure, equation (9).

For headed grouted anchors, bond failure at the steel-grout interface is precluded by the presence of the anchor head. For headed grouted anchors, embedment failure can occur by bond failure at the grout-concrete interface, equation (9) or more likely by a full concrete cone breakout failure as occurs with cast-in-place headed anchors, equation (7). For headed grouted anchors, the controlling embedment strength should be determined as the smaller of that determined by grout-concrete bond strength, equation (9), or concrete cone breakout strength, equation (7).

Due to dynamic loading, the friction between the grout and the concrete is reduced considerably and results in pullout of the grout plug. Hence if the anchor will experience dynamic loading, it is preferable to reduce the static pull-out strength by 40 percent.

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