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Prestressing with Carbon Composite Rods: A Numerical Method for Developing Reusable Prestressing Systems

by J. G. M. Kerstens, W. Bennenk, and J. W. Camp

The performance of a new type of conical connector for anchorage of carbon composite rods for prestressing concrete has been investigated. In addition to describing the behavior of composite rods under stress in concrete (bonded tendons), a numerical method is described for designing a new type of anchorage system.

Keywords: alternative prestressing rod materials; carbon composite prestressing rods; design method prestressing connectors; reusable prestressing connectors.

INTRODUCTION

Over the past ten years, various composite materials for prestressing concrete have appeared on the market as alternatives to steel, including glass, aramide, and carbon fibers. However, before such materials can be considered satisfactory, appropriate anchorage systems have to be developed for using them effectively.

A request was received from the Dutch concrete prefabrication industry for a simple method of anchoring the new fiber rods that would be both effective and reusable. A characteristic of prefabrication is mass production because speed and efficiency are important—the time between pouring the concrete and removing the formworks amounts to just a few hours. Therefore, this research project was targeted at non-permanent anchorage systems requiring that the prestressing be maintained only for a relatively short period so that the effects of long-term behavior could be excluded.

Carbon composite rods used at the Pieter van Musschenbroek Laboratory of Eindhoven University were normally prestressed with a conventional conical anchorage system that had been designed for use of the composite Arapree. Arapree is a carbon composite that fails at 60-65 percent of their tensile strength, which was unacceptable because the full strength of that composite could not be utilized.

Since the prototype of the new anchorage system was both labor-intensive and expensive, it was decided to develop a numerical method in order to get insight into the stresses distribution of conical anchorage systems. Analyzing the computed results would quickly and efficiently allow a new design of anchorage provided that a suitable finite element

method could be used. However, modeling the non-linear behavior of an anchorage system using a finite element method was considered to be too complex. For example: one modeling problem stems from the way that conical wedges act on the prestressing rod.

Therefore, a dedicated numerical method using the theory of elasticity has been developed, which allows more practicable modeling of the non-linear behavior.

RESEARCH SIGNIFICANCE

This paper offers a design method for reusable conical connectors that allow sensitive (carbon composite) rods to be prestressed. Further, with the aid of this method a new type of conical connector has been successfully developed enabling experimental research on the behavior of prestressed concrete with alternative rod materials.

STRESS DISTRIBUTION IN A CONICAL ANCHORAGE SYSTEM

Prestressing of steel rods can be achieved with an anchorage system that comprises steel conical wedges; the principle relies on pulling the conical wedges into a housing in axial direction (along the x-axis) so that they grip the prestressing rod and at the same time apply a tensile force to it. Further, the conical wedges exercise a clamping force on the rod in the radial direction (along the y-axis).

This compressive force will prevent the wedges from slipping during prestressing (see Fig. 1). The compressive force is often so large that a steel rod can become plastic at the point of contact.

In contrast to composite materials, steel can become plastic locally without failure.

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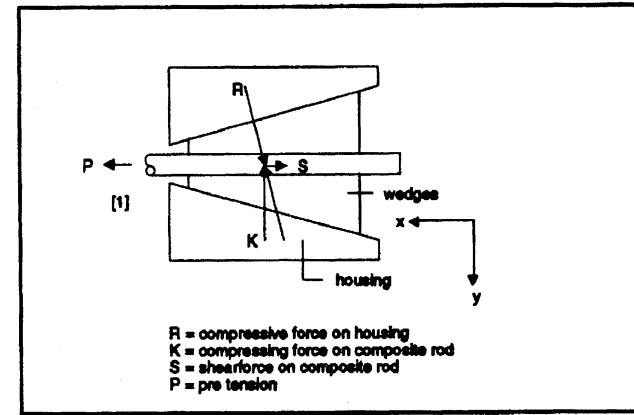


Fig. 1—Principle of anchorage system

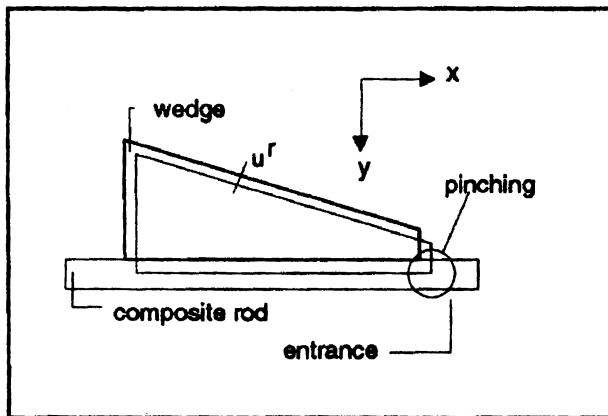


Fig. 2—Pinching by anchorage system

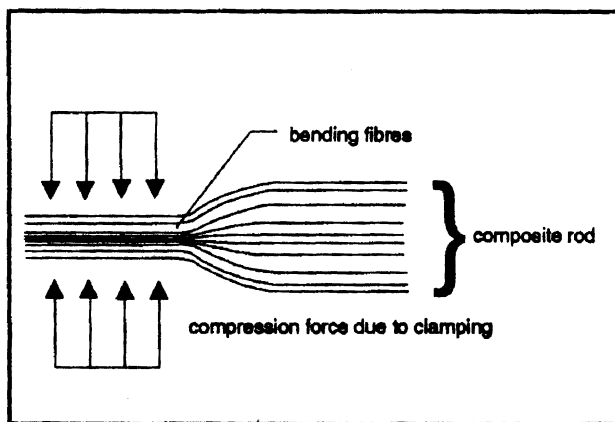


Fig. 3—Fibers in bending

CAUSES OF FAILURE

Carbon composites consist of uni-directional fibers in epoxy resin. Such composites are sensitive to compressive forces perpendicular to the direction of their fibers. The ratio of compressive force to tensile force is about 20:1. The prestressing rod is most affected by the compressive force at the smaller diameter of the conical wedges (entrance) which results in a pinching effect on the rod (see Fig. 2).

This results in the fibers being loaded in bending here due to compression. This compression can be so large that it will cause the fibers to fail as a result of the combined bending and axial action (see Fig. 3).

REDUCING COMPRESSIVE FORCES

As mentioned before, the principal cause of premature failure of carbon composite rods is the powerful compression on the rod as it enters the conical wedges. There the internal bending of the individual fibers occurs first.

Reducing that compressive force can be achieved by replacing the traditional steel conical wedges with conical wedges made of a material with a lower elasticity modulus. The reduced elasticity modulus will probably change the stress distribution on the composite rod where it is gripped.

The new wedges using nylon for their construction were designed and tested at Eindhoven University of Technology. The dimensions of the new anchorage system were larger than for conventional steel wedges in order to obtain sufficient grip on the rod to prevent it from slipping.

Due to the shape of the wedges, the compressive force will develop a peak at the entrance, which, as said before, is caused by the fact that the carbon composite rod is pinched at that place. However, introducing a slope difference between the wedges and the housing could reduce the peak compressive force at the entrance. Pulling the rod with the conical wedges in this configuration into the housing will reduce the compression at the entrance [see Fig. 4(a)] as the compression will start for a non-zero slope difference at the rear end of the conical wedges and not at the entrance.

Another method of reducing the compressive force could be by giving the conical wedges less local stiffness in order to reduce compression at the entrance [see Fig. 4(b)]. Unfortunately, the latter solution might have some disadvantages in practice as slipping might occur.

SIMULATION

In order to compute the stresses in a conical anchorage system, it was necessary to establish a simulation model. This was done by distributing the forces over a number of thin disk elements each having a finite thickness, dx (see Fig. 5). A disk is represented with a cross-section of the conical wedges with a thickness of dx that is modeled with a series of springs (see Fig. 6). The model comprises three springs, each having its own stiffness. The disks have the following components:

- steel housing
- nylon conical wedges
- carbon composite rod

The following assumptions have to be made in order to convert the springs diagram into a suitable model:

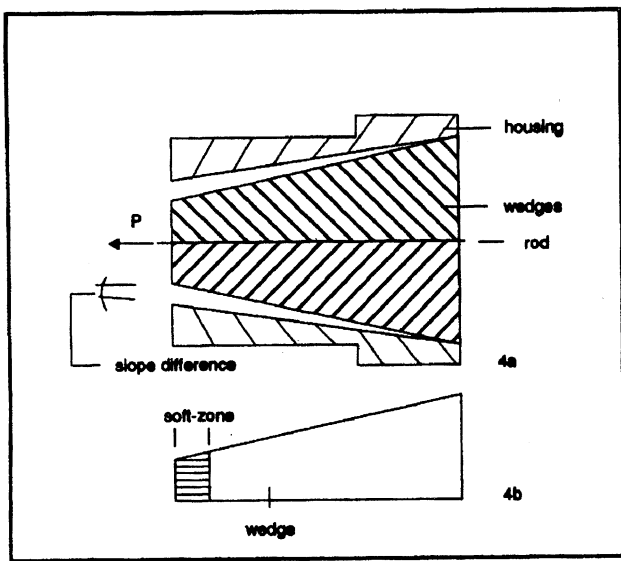


Fig. 4—Possible special measure to reduce pinching effect

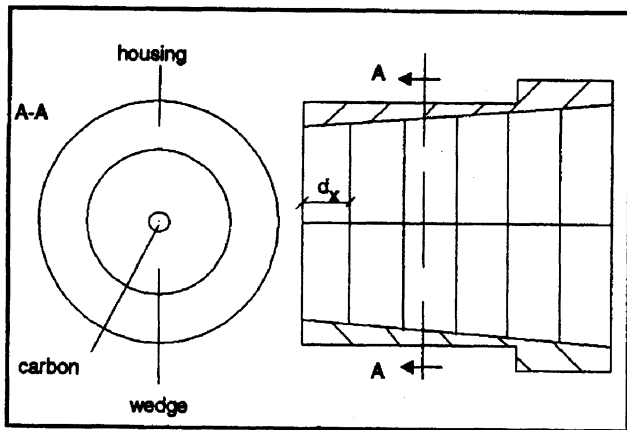


Fig. 5—Disk elements

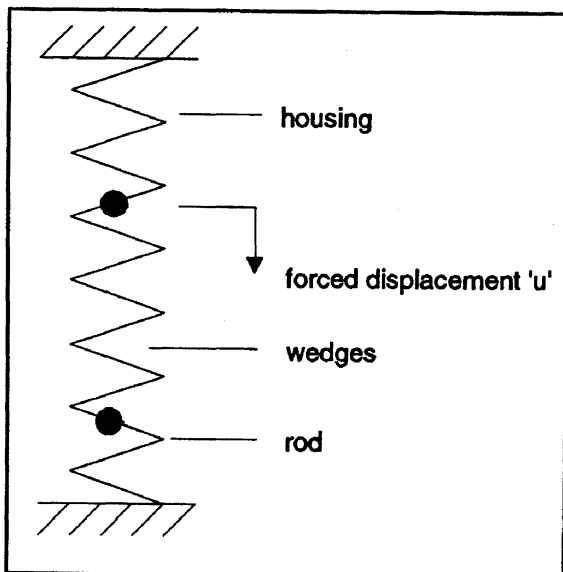


Fig. 6—Spring model of anchorage system

- A plane stress condition will exist in the disk elements; in actual fact there will be no such condition as compression will generate a force perpendicular to the element due to lateral contraction. The material will try to retain its original volume and due to the perpendicular force it will deform in the axial direction and by consequence generate axial tension if it cannot entirely deform freely.

However, the perpendicular deformation will be small and will therefore have no significant effect on the stresses of the rod. Any friction between the disk elements can be neglected. In fact, any relative radial movements are inconsequential. Eventually, a conservative model can be produced which means that the computed stresses will be somewhat greater than the actual stresses:

- The two wedges of the conus can be schematized as into a single conus. The effect on a carbon composite rod by the contact surfaces of the two wedges will not affect the stress in the composite material because each half has an equal axial displacement and will cause the rod to be compressed radially. Consequently, the internal radial and tangential forces are always compressive and therefore contact surfaces will press against each other at all times. Therefore, it cannot disturb the stress situation inside the material of the conus.

The model is built up by two springs assuming that the steel housing is infinitely stiff. The steel housing has an elasticity modulus of at least 200,000 N/mm² and the conical wedges made of Nylon 6 having a modulus of 2200 N/mm², which is a factor of 80. This allows the disk to be modeled by only two springs (see Fig 7).

From the results of a sensitivity analysis, it appeared that the effect of lateral contraction of the carbon composite rod during prestressing has a negligible compressive effect within the composite material and hence could be omitted.

In order to determine spring stiffnesses, the theory for thin disk elements in a plane stress condition was used based on the theory of elasticity (see Ref. 1). In Fig. 8, the stress situation is shown for a thin element dx for a plane stress condition.

For σ_r and σ_t , the following equations apply:

$$\sigma_r = \frac{a^2 b^2 (P_o - P_i)}{b^2 - a^2} \frac{1}{r^2} + \frac{P_i a^2 - P_o b^2}{b^2 - a^2}$$

$$\sigma_t = \frac{-a^2 b^2 (P_o - P_i)}{b^2 - a^2} \frac{1}{r^2} + \frac{P_i a^2 - P_o b^2}{b^2 - a^2}$$

Where P_o and P_i are respectively the outside and inside pressures.

The relation between the assumed deformation due to pulling the conical wedges into the housing and the resulting pressures can be expressed as follows:

$$u^r = (\sigma_t - \nu \sigma_r) r \frac{1}{E}$$

Where:

NUMERICAL ANALYSIS OF STRESS DISTRIBUTION

As mentioned before, the conical anchorage system will be divided over the length of the horizontal axis into a number of disk elements with a thickness dx . Stress in the carbon composite rod in each element has been computed for each incremental axial displacement of the wedges with the aid of the relationships presented earlier. Totaling the elemental stresses has been done with a computer program written in TURBO-PASCAL language. The change in stress in the composite rod is computed for each disk (see Fig. 5) by incrementing the axial displacement. The input parameters for the geometry as well as the material properties of both the conus and the compressed rod could be varied.

From the investigation of the material properties of the Nylon 6 conical wedges, it appeared that the stress-strain relationship behaved in a non-linear manner which meant that the elasticity modulus will decrease with each stress increment. Since the computer program presented the incremental axial displacements in steps, it allowed the elasticity modulus to be calculated as a function of the stress in the material of the conical wedges for each step.

By inserting different slopes of the conical wedges and the housing, geometrical non-linear behavior has to be modeled. Thus, the final computer program should incorporate both geometrical and physical non-linear effects. In Fig. 9, the contact area between the wedges and the housing can be seen in steps—the length gripped or firm contact area increased with each incremental axial displacement. As can be seen here, the pinching will not start at the entrance, but at rear. It should be realized that the most ideal pressure distribution would be one that is uniformly distributed over the length of the rod.

Figures 10(a), 10(b), 11(a), 11(b), 12(a), and 12(b) show the displacement characteristics and the stress distribution along the rod. The total compressive forces on the composite rod are presented in Fig. 10(a) for an incremental axial displacement of the conical wedges into the housing. Here, the nylon material is assumed to have a constant elasticity modulus. The slope difference between the conical wedges and the housing is equivalent to zero.

The pressure distribution over the length of the rod is shown in Fig. 10(b). Both figures show that the compressive force on the carbon composite rod increases linearly with each incremental displacement of the conus and that large compressive stress at the entrance of the wedges will be generated as the rod becomes pinched there.

In Fig. 11(a), the ratio of compressive force to conus displacement is shown for a slope difference between the conus and the housing. Due to geometrical non-linearities the compressive force increase is non-linear over Section I, but it changes to linear over Section II. This can be explained as follows: in Section I, the conus is displaced into the housing with increasing the contact area (see Fig. 9). Since the stiffness of the stressed disk elements is related to the distance of the conus is displaced into the housing, the force increase is non-linear.

In Section II, all the disk elements have become in firm contact with the housing surface. The incremental displacements

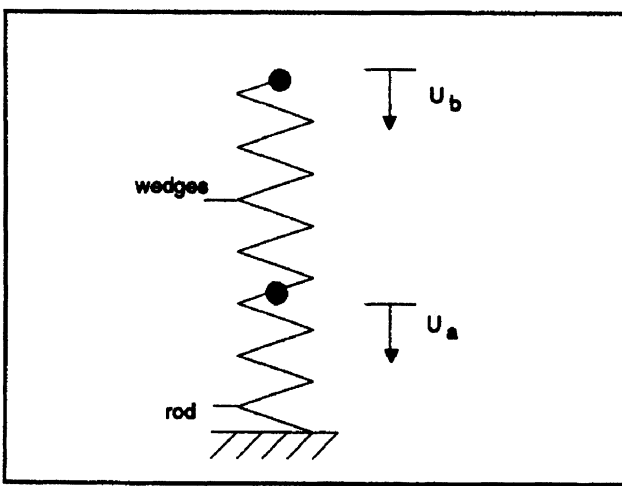


Fig. 7—Spring model for infinitive stiff housing

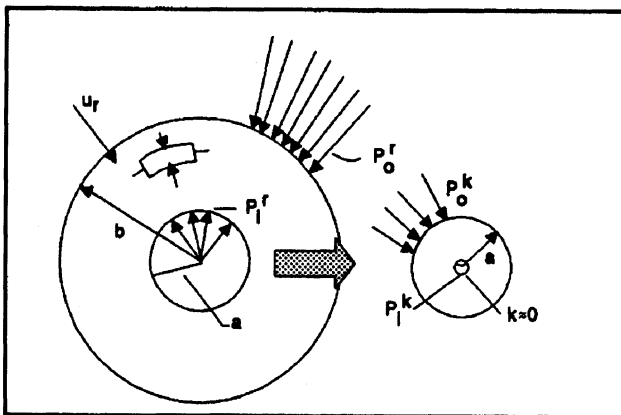


Fig. 8—Stresses in cross section anchorage system

u^r = the stress relationship

σ_t = the tangential stress

σ_r = the radial stress

ν = Poisson's Ratio

r = the radius of the rod

E = the Elasticity Modulus

The following functions can be derived:

$$u_a^r = f^r(P_o^r, P_i^r, a^r)$$

$$u_b^r = g^r(P_o^r, P_i^r, b^r)$$

$$u_k^k = f^k(P_o^k, P_i^k, k^k)$$

$$u_a^k = g^k(P_o^k, P_i^k, a^k)$$

The pressure situation in the model can be computed using the following constraints:

$$P_i^r = P_o^k$$

$$u_a^r = u_a^k$$

From these constraints it can be shown that:

$$\begin{bmatrix} u_a^r \\ -u_b^r \end{bmatrix} = \frac{1}{E_n(b^2 - a^2)}$$

$$\begin{bmatrix} \frac{E_n(1-\nu)(b^2 - a^2)}{E_k} + [a^2(1-\nu) + b^2(1+\nu)] & -2ab \\ -2ab & a^2(1-\nu) + b^2(1-\nu) \end{bmatrix}$$

ment of the conus over this sector means all disks are activated. In other words the slope difference has disappeared, so that the stress increase becomes linear again. In Fig. 11(b) the stress over the length of the conus has been given to show that compression increases gradually after the entrance point.

Figure 12(a) is a diagram to show the ratio of compressive force to the conus displacement; the input parameters are similar to those in Fig. 11(a) and 11(b); however, the elasticity modulus of the conus made of Nylon 6 depends upon the initial stress (non-linear). The point where change in curvature begins is shown in Fig. 12(a). After that point, when the conus is in complete contact with the surface of the housing, compression continues to increase but less visibly. That is because the elasticity modulus is increasing with each stress (displacement) increment. In Fig. 12(b), the stress distribution over the length of the conus can be seen; the compression of the carbon composite rod has favorably been reduced to a more uniform stress distribution due to the non-linear nature of the conus material.

FRICTION COEFFICIENT

As already discussed, the dedicated computer program was able to determine the compressive force exerted on the composite rod for a given incremental displacement of the conus. This force will prevent the rod from slipping between the conical wedges. In order to determine the necessary force on the rod for a particular stress level, it was important to know the friction coefficient between the surfaces of the rod and conical wedges. However, establishing the friction coefficient was not an easy task. Some idea of the friction coefficient between Nylon 6 and the carbon composite could be obtained by extrapolating existing test results. It was estimated from laboratory tests that the friction coefficient has a maximum value of 0.4.

DESIGN OF A NEW CONICAL ANCHORAGE SYSTEM

In order to develop an improved conical anchorage system, firstly, the compressive force leading to fracture of the rod needs to be determined. Thereafter, a number of carbon composite rods have been pre-stressed to their breaking points using the conventional anchorage systems. Having all this information, the actual displacement of the conus in the housing has been measured.

With the aid of the computer program the stress distribution over the length of the rod has been calculated using the aforementioned obtained input parameters. It was found that for a conventional anchorage system the carbon composite rod in all cases failed at the entrance of the conus. The corresponding compression at the entrance was 80 N/mm^2 for a nominal wedge conus displacement of about 10 mm. The maximum compression permitted on the carbon composite was 60 N/mm^2 [see Figs. 13(a) and 13(b)].

Designing an improved system, an initial prestressing level of 90 percent of the tensile strength of the carbon composite has been targeted which represents a compressive force of 41.4 kN for a 5.2 mm diameter rod. The total compressive force on the carbon composite rod amounts to 100 kN with a

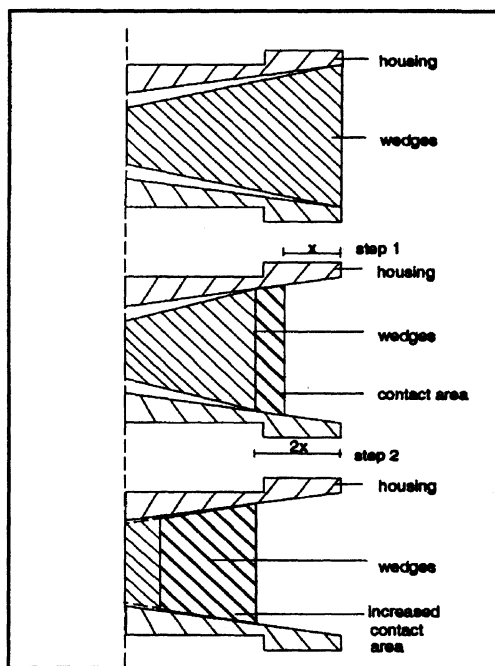


Fig. 9(a)—Displacement of cones in axial direction

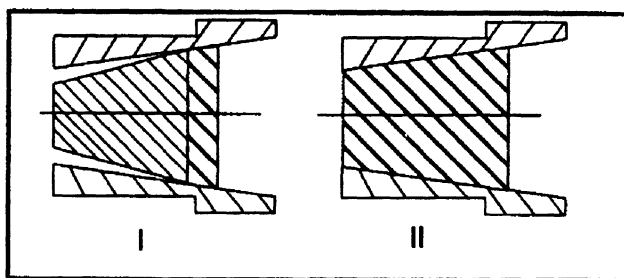


Fig. 9(b)—Definition of Section I and Section II

friction coefficient of 0.4 when using a conus made of Nylon 6.

The computer program was able to produce results for a wide range of conical anchorage systems by changing the input parameters such as: the length of the conus, the slope of the conus, and the difference between the slopes of conus and housing. Hence, it was possible to arrive at an optimal design for conical anchorage systems [see Figures 14(a) and 14(b)].

The specifications for an optimal design are:

- conus length = 160 mm
- housing length = 185 mm
- slope of conus = 3.32 deg
- slope of housing = 3.52 deg
- material for the conus = Nylon 6 (polyamide 6)
- material for the housing = Model construction steel (42 CrMo 4)
- stopper (see Figure) = adjustment variable over 25 mm
- diameter of carbon composite rod = 5.36 mm

The required prestressing level for gripping the rod could be attained by initially pulling the conical wedges about 9 mm into the housing using a screw jack [see Figures 15(a)

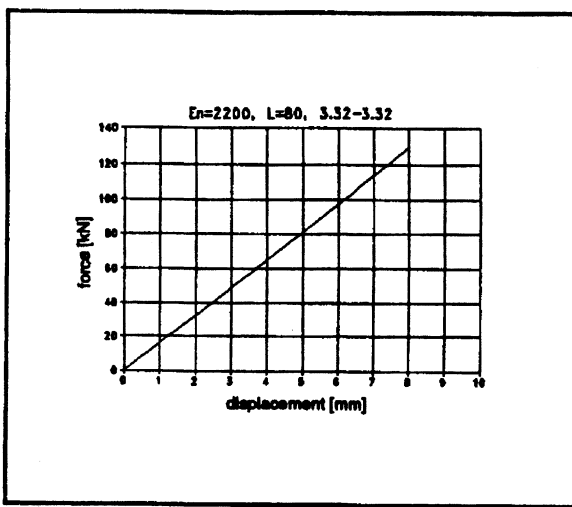


Fig. 10(a)—Force displacement for $E_n = \text{constant}$ and zero slope difference

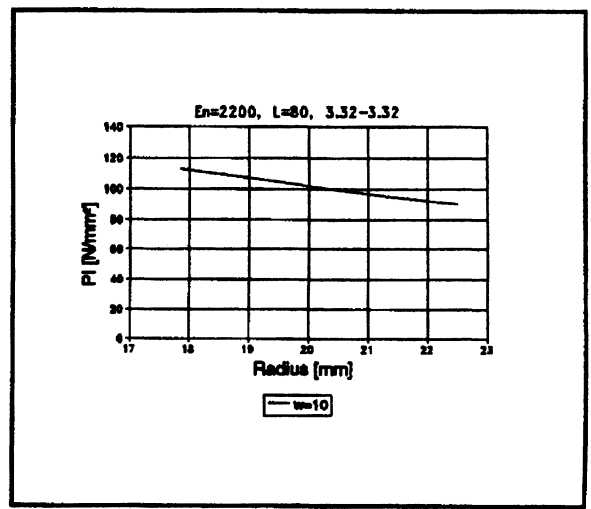


Fig. 10(b)—Stress displacement for $E_n = \text{constant}$ and zero slope difference

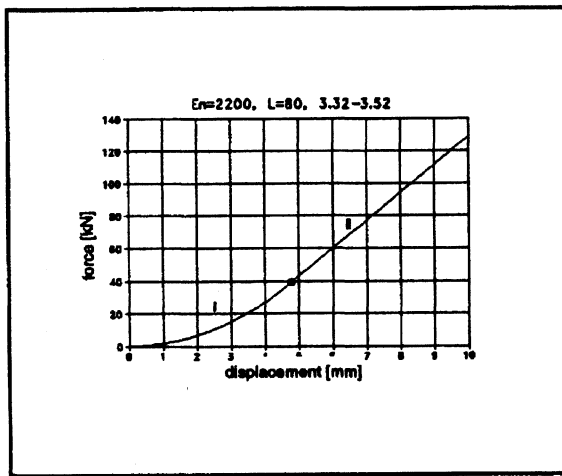


Fig. 11(a)—Force displacement for $E_n = \text{constant}$ and non-zero slope difference

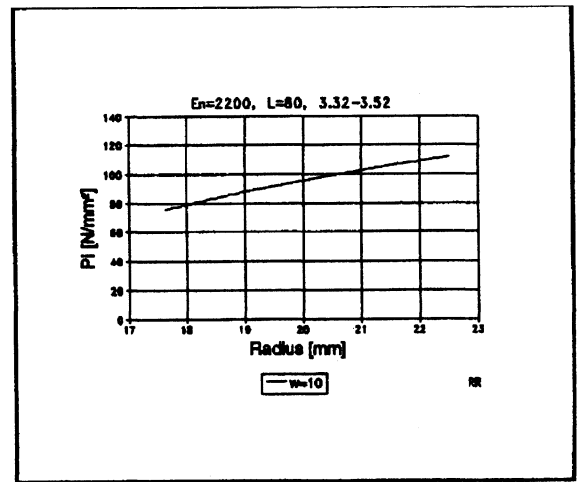


Fig. 11(b)—Stress displacement for $E_n = \text{constant}$ and non-zero slope difference

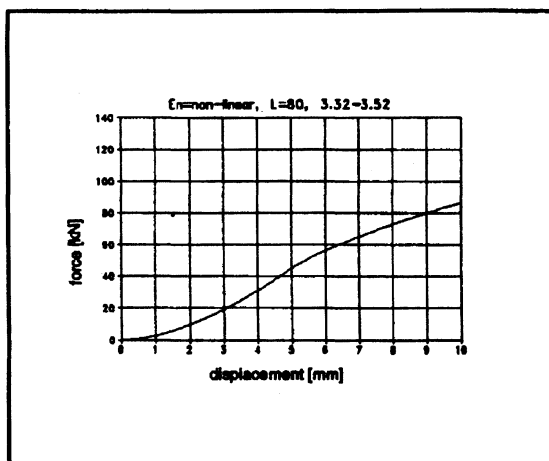


Fig. 12(a)—Force displacement relation for non-linear E_n and non-zero slope difference

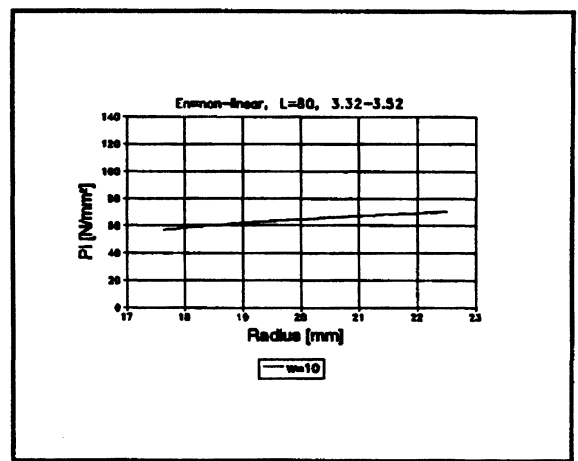


Fig. 12(b)—Stress displacement relation for non-linear E_n and non-zero slope difference

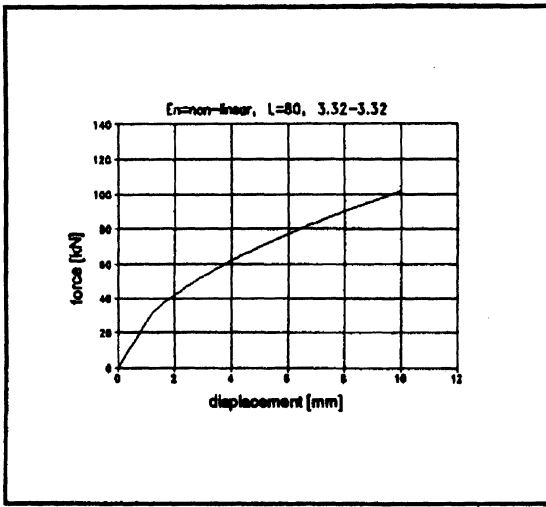


Fig. 13(a)—Force displacement for existing anchorage system

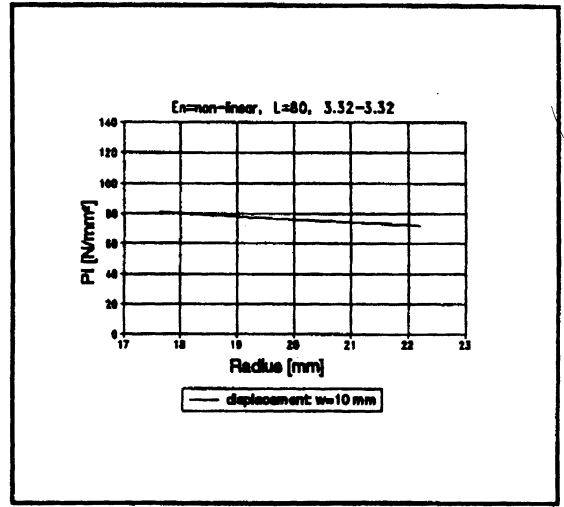


Fig. 13(b)—Stress distribution for existing anchorage system

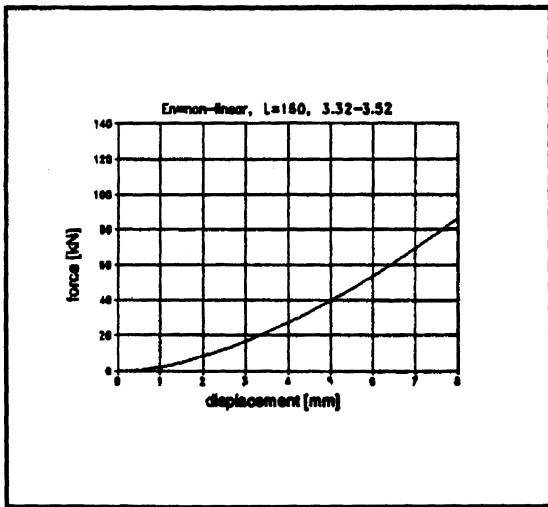


Fig. 14(a)—Force displacement for new design

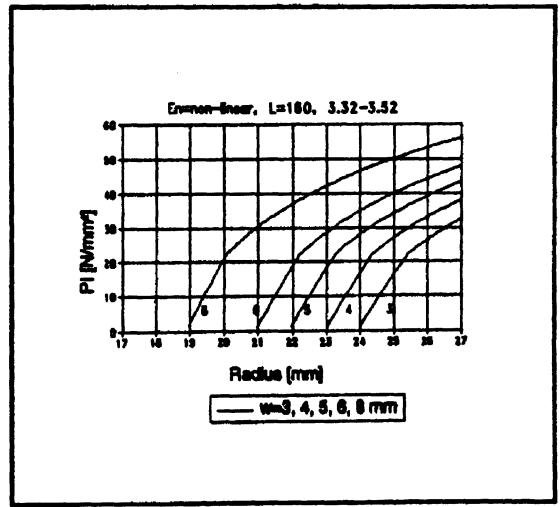


Fig. 14(b)—Stress distribution for new design

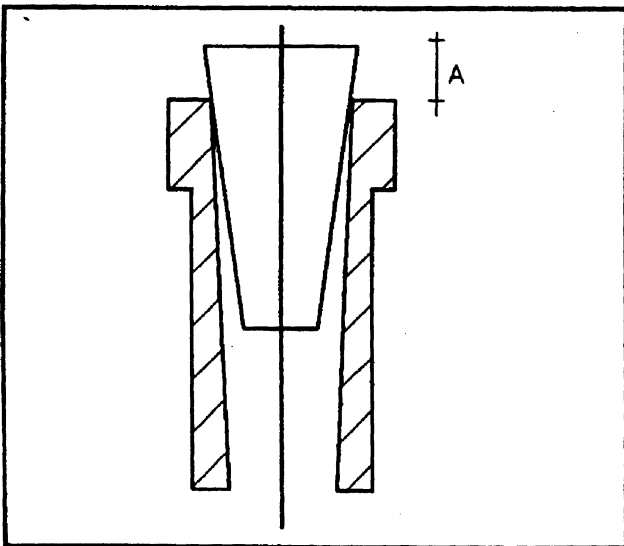


Fig. 15(a)—Position of wedges after pressing by hand

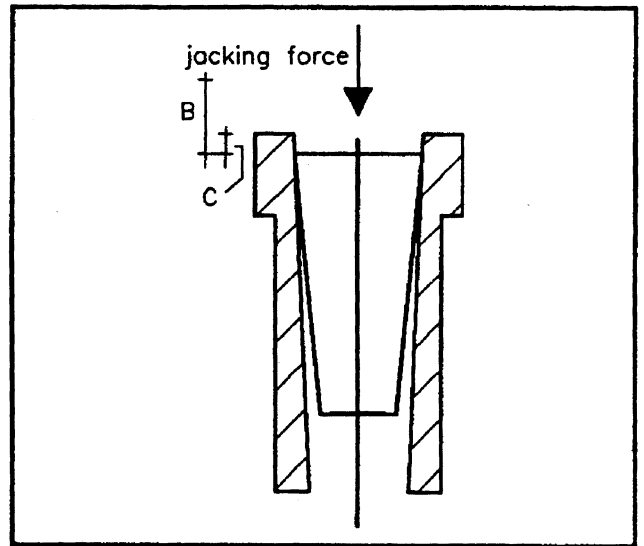


Fig. 15(b)—Position of wedges after pressing by jack

and 15(b)]. This will prevent the friction between the wedges and the housing from being too small for the wedge to grip the rod sufficiently.

TEST RESULTS

The prototype of the improved conical anchorage system was tested in the laboratory where ten tests have been carried out. Those tests differed in so much as the carbon composite rod was pretreated in some cases in order to increase the friction coefficient for the surfaces of the conical wedges and the rods. For example, the surface of the rods were provided with a layer of aluminium oxide resembling sandpaper.

Experimentally, it could be established that the redesigned anchorage system could reach a prestress level of 90 percent of the breaking strength of carbon fiber rods (90 percent = 40 kN = 4 tons). The displacement of the conus, measured from the end of the steel housing, lay between 3 mm and 5 mm instead of the 9 mm which has previously been calculated. This difference could be explained by the fact that the friction coefficient was greater than the value assumed in the calculations..

Subsequently, sandpapering the rods could have played a part as it might have reduced their diameter slightly which in turn has an influence on the stress pattern.

Initial pressing of the wedges into the housing already will exercise some force on the rod when part of the conus still protruded from the housing. The conus displacement was no more than 8 mm [distance B in Fig. 15(b)]. Therefore, it was assumed that the distance calculated did correspond with practice. However, it should be realized that there shall be a certain spread in the measured displacement.

CONCLUSIONS AND RECOMMENDATIONS

From the test results for the redesigned conical anchorage system, it can be concluded that a carbon composite rod can attain 90 percent of the breaking strength of carbon fiber rods (90 percent prestressing level) without breaking. The new computer program seemed to be particularly valuable to design efficiently conical anchorage systems. It can predict the stress distribution over the length of conus made of various materials with different geometries (diameter, slopes, etc.).

Additional research will be necessary in order to further improve the conical anchorage system; for instance, by improving the way that composite rods are gripped in practice, and by developing a method which allows the conical wedges to be released automatically. Also attention should be given to the wear resistance of the wedges at the point of failure. Applying surfaces with aluminium oxide could help to reduce wear.

NOTATION

For Fig. 15(a) and 15(b), the following legends apply:

A = the distance that a wedge protrudes beyond the rear of the housing after initially pulling in the conical wedges manually.

B = the full protrusion of a wedge after pulling the wedge jaws into the housing with a screw jack.

C = the length of a wedge into the housing as measured from the rear of the anchorage.

Note: the illustrations only give rough approximations; for instance, the computed length of the conus that compresses the rod does not agree with practice exactly.

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