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Brenda Wildrick

Stephen P. Pessiki

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ADVANCED TECHNOLOGY FOR
LARGE
STRUCTURAL SYSTEMS

Lehigh University

USE OF BRAIDING TECHNOLOGY TO IMPROVE ANCHORAGE SYSTEMS FOR NON-METALLIC CABLES

by

Brenda Wildrick
Research Assistant
Department of Civil and Environmental Engineering
Lehigh University

Stephen Pessiki
Assistant Professor
Department of Civil and Environmental Engineering
Lehigh University

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ATLSS Engineering Research Center
Lehigh University
117 ATLSS Dr., Imbt Laboratories
Bethlehem, PA 18015-4729
(610) 758-3525

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ABSTRACT

The high strength to weight ratio and corrosion resistant nature of many advanced composites make them useful materials in civil engineering applications. The use of composite cables in civil structures is presently an active area of research. Conventional anchorage methods can not be used with composite cables due to their unique properties. As a result, many studies have been performed to develop new anchorage systems with composite cables. However, work is still necessary to identify methods to improve the performance of the current anchorage systems and to identify more efficient anchorage concepts.

The present work is an effort to explore the potential use of braiding technology with composite materials in the development of reliable and practical anchors for non-metallic cables. This report contains the findings from a literature review of braiding technology and currently proposed anchorage systems. It is found from this research that braiding offers some opportunities to improve the efficiency and reliability of anchors for non-metallic cables. The concepts for two new anchorage systems with braided cables are developed. It is recommended to use experimental testing in conjunction with simple finite element models to study the behavior of the systems presented in this report for justification and further development of the concepts.

CHAPTER 1
INTRODUCTION

1.1 Background

1.1.1 Composite Materials

A composite material is generally defined as a combination of two or more materials which differ in form or composition on a macroscale. The components typically include reinforcing elements, such as fibers or particles, and a matrix binder material. A wide variety of available components and fabrication techniques generates a large range of properties which are attainable with composite materials. However, in general, composite materials exhibit high specific tensile strength (ratio of material strength to density) and non-metallic composite materials exhibit good resistance to corrosion.

The reinforcing elements are the primary providers of the strength and stiffness of a composite. One advantage of using fibers or particles imbedded in a matrix instead of a bulk material lies in the presence of manufacturing flaws. The potential size and number of flaws which are likely to occur in a plate of glass, for example, are much larger than those which might occur in a single drawn fiber of glass. Since the propagation of flaws is the cause of most failures of high-strength materials, the limited size and number of flaws makes fibers and particles inherently stronger than the bulk form of the same material. In addition, if failure of one fiber is to occur as a result of a manufacturing flaw, that failure will not propagate through the composite; the load is simply redistributed to the surrounding fibers. Another advantage with the use of fiber-reinforced composites is the ability to orient the fibers to attain desired strength and stiffness properties in various directions. Therefore, a material can be tailored with high strength in directions of high load without wasting the reinforcing material in directions of little or no load.

The matrix material binds the reinforcing elements together and protects them from the environment and handling. The matrix material is also used to ensure proper orientation of fibers and to more or less evenly distribute loads among the fibers. The matrix material is relatively weak and usually fails by microcracking and debonding from the fiber surfaces before the potential strength of the fibers can be utilized.

1.1.2 Applications of Composites

The aerospace community is highly concerned with material performance and has been the major proponent of the development of composite materials. Aluminum alloys are widely used in airplanes as structural materials, those designed for structural or load bearing applications, due to their relatively low weight and high strength. However, the cost of maintaining these materials is high due to corrosion and fatigue problems. Hence, the development and use of composite materials has been promoted because they generally possess the desired high strength and stiffness at low weight while providing good resistance to corrosion and crack formation. In addition, designs can take advantage of the anisotropy that is common with composite materials. An example of the successful application of composites in the aerospace industry is with the Voyager aircraft. In order to conserve fuel, weight was a critical factor in the design of the Voyager. Nearly 90% of this aircraft is made from graphite fibers. On the other hand, use of high-performance composites in commercial aircraft has been limited due to relatively high costs and lack of sufficient knowledge of their behavior. Currently, composite materials are used mostly for non-structural components of commercial aircraft and comprise less than 10% of the total weight (Broslus, 1991).

Composite materials have also been widely employed in recreational applications. These applications are highly specialized and have the necessary resources to conduct research and testing to develop and implement advanced composites. For example, many of today's recreational boats contain fiberglass composite hulls. The structure of K-2 TRC skis are made from braided graphite fibers. In addition, several tennis rackets, golf clubs, and bike frames are made from various composite materials.

The relatively high cost of materials, manufacturing, and testing has slowed the development and use of composites in the civil/ structural field. However, the cost of composite materials should reduce as they are produced and used more frequently and the knowledge-base of their behavior is enhanced. Composites are likely to become viable competitors of traditional structural materials, like concrete and steel. Many potential applications in civil engineering have been identified which take advantage of the unique properties offered by composite materials. Use of composites could significantly reduce the dead weight of a civil structure, which is typically a major portion of the load experienced by a structure. In addition, the corrosion resistant nature of composites is beneficial when the material is exposed to harsh environments, which is true of many civil structures.

1.1.3 Composites Used in Prestressed Concrete

Prestressed concrete is one area of civil engineering which would greatly benefit from the use of composite materials. A major concern with prestressed concrete is the loss of prestressing which results from a loss of section due to corrosion. Corrosion loss can be prevented by the use of fiber reinforced plastic (FRP) tendons, thus the long term performance of these structures can be improved. Considerable research has been conducted on the use of non-metallic tendons for prestressed concrete. One unresolved problem with the use of composite tendons in prestressed concrete is their lack of ductility. The ductility concern has been addressed by Burgoyne (1993) who suggests that FRP prestressing tendons should not be bonded to the concrete. Nanni (1994) has also addressed the ductility issue by proposing the use of a hybrid rod. A steel core would provide the desired ductility while a braided composite skin would protect the steel core from corrosion. The concept of a hybrid rod is discussed further in Chapter 4 of this report. Perhaps the most significant deterrent to the widespread use of composite tendons in prestressed concrete is the lack of reliable and efficient anchorage systems. The conventional hardware for anchoring tendons of steel is not acceptable with FRP tendons unless modifications are made in the design of the anchor. The developments which have been made in the search for a reliable anchorage system with non-metallic tendons are presented in Chapter 3 of this report.

1.2 Objectives

The principal focus of this research is to explore if and how braiding technology can be employed to improve the performance of anchorage systems with non-metallic composite cables. The following objectives are set to satisfy this research:

- To study the current technology of braiding with composite materials.
- To study previous research and developments in anchorage systems with non-metallic cables and identify noted problems with tested or employed systems.
- To evaluate how current anchors may be improved by employing braiding technology.
- To develop concepts for new anchorage systems which become possible with use of braiding technology.
- To identify methods to study the behavior of the new or improved anchorage systems proposed in this research.

1.3 Scope

The scope of this research involves the development of anchorages for non-metallic braided composite cables. Their are two aspects of this scope which require clarification: the use of non-metallic materials and the term "cable."

Composite materials can be composed with metallic and/ or non-metallic components (reinforcing elements and matrix materials). The anchorage of a cable with a metal matrix would most likely be different in design than that required for an entirely non-metallic composite cable. The scope of this research includes only the anchorage of non-metallic composite cables. This focus is in response to the need for materials in civil structures which are corrosion resistant. An additional application where non-metallic materials are necessary is with the use of magnetic fields, such as the concept of the magnetically levitated train. For example, non-metallic composite tendons used for prestressed concrete structures would not interfere with the magnetic fields necessary to support the levitated train.

The second aspect of the scope to be defined is the term "cable." Throughout this report, the term cable is used generically to represent any strong rope applied in a design to act in tension. The intent of this research is to develop anchorage systems for any application of a cable as defined here. Therefore, cables include, but are not restricted to, those used in prestressed concrete, ground anchors, guy wires, or cable-stayed bridges. Within this report, the term "tendon" is often used when referring specifically to the prestressing elements of prestressed concrete.

1.4 Approach

The approach to meet the objectives specified in Section 1.2 consisted of a review of current literature from pertinent research. A literature review was performed to study previous anchorage systems and identify problems or areas of improvement with these systems. A literature review was also performed to study the current technology with braiding with composite materials and to identify the opportunities for improvement of previous anchorage systems with use of braided shapes. Simple calculations, models, and finite element analyses were used to validate or reject the ideas.

1.5 Summary of Findings

The literature review revealed that there have been many developments in the search for reliable anchorage systems with non-metallic composite cables. Many anchorage systems have been proposed or implemented which are able to utilize the full tensile capacity of the cables. However, some unknowns about the performance and long-term behavior of these systems still exist.

Braiding technology offers some advantages for the anchorage of composite cables. First, computer-aided design and manufacturing of braided shapes facilitates the rapid production of cables and enables the use of intricate shapes at the ends of the cables for anchorage details. A significant benefit with the use of a braided shape as a cable instead of one with unidirectional fibers is the gain in through thickness strength. High shear and transverse tensile stresses often exist due to anchoring a cable. Given the ability to withstand high transverse tensile stresses, cables which are braided in the anchorage region should require anchors with smaller lengths and diameters than unidirectional cables. Another advantage with the use of braiding is the ability to vary the braid geometry through the length of the cable. The braiding angle can be high at the end of the cable, approximating an isotropic material to carry the transverse tensile stresses, and gradually change to become unidirectional fibers as the stresses become higher in the axial direction moving toward the loaded end of the cable. Two possible anchorage systems which employ braided cables are presented in Chapter 5 of this report.

Finally, the analysis and design process of braided shapes is very complex due to the interlacing of yarns and contribution of both the fibers and the matrix material. Therefore, it is very difficult to analyze or model new anchorage concepts which utilize braided shapes. It is recommended for continued research efforts to use experimental data to study the performance of braided cables and anchors.

1.6 Terminology

The following definitions are provided to clarify terminology which may not be readily understood throughout this report. The defined terms primarily consist of those associated with the field of composite materials. Several definitions have been adapted from a Glossary of Terms located in the Engineered Materials Handbook-- Composites produced by ASM International (Pebly 1987).

Aramid. A type of highly oriented organic material derived from polyamide (nylon) but incorporating aromatic ring structure. Used primarily as a high-strength high-modulus fiber. Kevlar and Nomex are trade name examples of aramids.

Carbon Fiber. Fiber produced by the pyrolysis of organic precursor fibers. Graphite is an ordered form of carbon. The basic differences between carbon and graphite fibers lie in the temperature at which the fibers are made and heat treated, and in the amount of elemental carbon produced.

Closed-cell Foam. Foamed or cellular material with cells that are not interconnected. Open cell refers to cells that are generally interconnected.

Composite Material. A combination of two or more materials (reinforcing elements, fillers and composite matrix binder), differing in form or composition on a macroscale. The constituents retain their identities; that is, they do not dissolve or merge completely into one another although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.

Delamination. Separation of the layers of material in a laminate, either local or covering a wide area. This phenomenon can occur during the curing cycle or in the subsequent life of the material and is one of the most common modes of failure of 2-D laminate composites.

Epoxy Plastic. A polymerizable thermoset polymer containing one or more epoxide groups and curable by reaction with amines, alcohols, phenols, carboxylic acids, acid anhydrides, and mercaptans. An important structural adhesive and matrix resin in composites.

Fiber. A general term used to refer to filamentary materials with a finite length that is at least 100 times its diameter, which is typically 0.1 to 0.13 mm (0.004 to 0.005 in). Fibers can be continuous or specific short lengths (discontinuous), normally no less than 3.2 mm (1/8 in).

Fiberglass. An individual filament made by drawing molten glass.

Filament. The smallest unit of a fibrous material. The basic units formed during drawing and spinning, which are gathered into strands of fiber for use in composites.

Filament Winding. A process for fabricating a composite structure in which continuous reinforcements (filament, wire, yarn, tape, or other) are placed over a rotating and removable form or mandrel in a prescribed way to meet certain stress conditions. Generally the shape is a surface of revolution.

Graphite Fiber. (see carbon fiber).

Interlaminar Shear. Shearing force tending to produce a relative displacement between two laminae in a laminate along the plane of their interface.

Lamina. A single ply or layer in a laminate made up of a series of layers (organic composite). A flat or curved surface containing unidirectional fibers or woven fibers embedded in a matrix (metal matrix composite). Plural form is laminae.

Laminate. (v.) To unite laminae with a bonding material, usually with pressure and heat. (n.) A product made by bonding laminae, usually with pressure and heat.

Mandrel. The core tool around which resin-impregnated paper, fabric, or fiber is wound to form pipes, tubes or structural shell shapes.

Matrix. The essentially homogeneous resin or polymer material in which the fiber system of a composite is imbedded. Both thermoplastic and thermoset resins may be used, as well as metals, ceramics and glasses.

PEEK. Abbreviation for polyether etherketone which is a linear aromatic crystalline thermoplastic. A composite with a PEEK matrix may have a continuous-use temperature as high as 250 °C (480 °F).

Preform. A preshaped fibrous reinforcement of mat or cloth formed to the desired shape on a mandrel or mock-up before being placed in a mold press.

Prepreg. Either ready-to-mold material in sheet form or ready-to-wind material in roving form, which may be cloth, mat, unidirectional fiber or paper impregnated with resin and stored for use. The resin is partially cured and supplied to the fabricator, who lays up the finished shape and completes the cure with heat and pressure.

Pultrusion. A continuous process for manufacturing composites that have a constant cross-sectional shape. The process consists of pulling a fiber-reinforced material through a resin impregnation bath and through a shaping die, where the resin is subsequently cured.

Resin. A solid or pseudosolid organic material usually of high molecular weight, that exhibits a tendency to flow when subjected to stress.

Roving. A number of yarns, strands, tows, or ends collected into a parallel bundle with little or no twist.

Take-up Speed. In reference to braiding machines, the predetermined rate at which a braid is delivered through a take-up roll. This rate can be varied to control the orientation of the braiding yarns and the diameter of the braided fabric.

Textile Fibers. Fibers or filaments that can be processed into yarn or made into a fabric by interlacing in a variety of methods, including weaving, knitting and braiding.

Thermoplastic. Capable of being repeatedly softened by an increase of temperature and hardened by a decrease of temperature. Applicable to those materials whose change upon heating is substantially physical rather than chemical and that in the softened stage can be shaped by flow into articles by molding or extrusion.

Thermoset. A plastic that, when cured by application of heat or chemical means, changes into a substantially infusible and insoluble material.

Tow. An untwisted bundle of continuous filaments. Commonly used in referring to man-made fibers, particularly carbon and graphite, but also glass and aramid.

Transversely Isotropic. Term describing a material exhibiting a special case of orthotropy in which properties are identical in both transverse directions but not in the longitudinal direction.

Unidirectional Laminate. A reinforced plastic laminate in which substantially all of the fibers are oriented in the same direction. Unidirectional is synonymous with uniaxial with regard to the primary direction of fibers in a composite.

Volume Fraction. Fraction of a constituent material based on its volume.

Wetting. The spreading, and sometimes absorption, of a fluid on or into a surface.

Yarn. An assemblage of twisted filaments, fibers, or strands, either natural or manufactured, to form a continuous length that is suitable for use in interweaving into textile materials.

CHAPTER 2
BRAIDING TECHNOLOGY

2.1 Introduction

The unique characteristics of composite structures are derived primarily from the reinforcing fibers. Placement of the fibers in a certain direction and form to attain specific properties for design functions can be achieved by an appropriate fabrication technique. The desire for low-cost approaches to fabrication has resulted in a wide variety of manufacturing processes for composite parts. Braiding is one manufacturing technique which has emerged for composite materials. Various other manufacturing processes include filament winding, weaving, pultrusion, and manual lay-up.

Cost of fabrication has been a major selling point for braided structures. For traditional textile materials, the braiding process has been a cost-effective alternative to other manufacturing techniques for applications such as axial load-bearing members and reinforcement for flexible pipes, cables, and hoses (Chou 1989). The interest in braiding with composite materials has developed in the past 20 years. In the late 1970's, researchers from McDonnell Douglas noted a reduction in the cost of producing structural shapes by using the braiding process for composite material preforms (Ko 1987). Subsequently, the use of braids as engineering materials has become the subject of much examination.

The intent of this chapter is to describe the braiding process, materials which are commonly used to produce composite braids and some of the unique characteristics which accompany braided shapes. There are countless applications which may exploit the properties of composite braided structures which go beyond the scope of this report. The present work is an effort to explore the potential use of the braiding process in the development of reliable and practical anchors for non-metallic cables. Therefore, properties which may be advantageous or deleterious to the function of braided cables and the anchorage systems will be discussed.

2.2 Braid Manufacturing

The braiding process is a simple, ancient technique of interlacing yarns to yield shapes of unusual strength and versatility. Braids are categorized as either two-dimensional or three-dimensional. The two types of braids have different properties and require different braiding machines to be produced. Two-dimensional and three-dimensional braids are discussed separately in the following sections. Braids are considered to be textile structures along with weaves and knits. For more information on weaving and knitting with composite materials, interested readers can refer to a book entitled Textile Structural Composites (Chou 1989).

2.2.1 Two-Dimensional Braiding

A two-dimensional braid is generally a continuous tubular fabric of interlaced yarns. The basic process of producing two-dimensional braids consists of two or more sets of yarn carriers moving in intersecting circular tracks to produce a series of crossovers. Currently, the largest available two-dimensional braiders have 144 carriers and a bed diameter of about 89 inches (Chou 1989). Figure 2.1 illustrates a typical 144 carrier horizontal braiding machine. The yarns which are shown in a radial pattern are attached to carriers which travel in circular paths. The yarns cross one another to form the braided fabric in the longitudinal direction. The speed of fabric formation can be adjusted to alter the braid geometry. The machine which is illustrated in Figure 2.1 has the capability of forming two braided structures at once, as shown by the two rings which support the yarn carriers. The machine is capable of biaxial and triaxial braiding. Biaxial braiding produces fabric with yarns running in two braiding directions. Triaxial braiding introduces longitudinal yarns between the braiding yarns for more axial reinforcement. Development of larger braiding machines with more carriers and an ability to yield larger shapes is presently being examined.

Typically, the braiding pattern is performed over a mandrel, or support structure, to mold the shape of the finished product. The thickness of these fabrics can be augmented by subsequent braiding passes over the existing shape. To improve resistance to delamination, these layers can be stitched together. An example of the use of the 144 carrier braiding machine for the formation of a fiberglass preform on a mandrel is shown in Figure 2.2. This machine has also been used to produce a preform for a racing car chassis.

Dimensions of two-dimensional braided structures can be altered by varying the selection of yarn bundle sizes. The orientation of the yarn, i.e. the braiding angle, Θ, with respect to the mandrel axis, can be controlled by the take-up speed and number of carriers.

If yarn is used in three directions and oriented at 60° from each other, the resulting structure has in-plane mechanical properties similar to isotropic material. If a very small braiding angle is used, the braid has properties similar to uniaxial tape. It is also possible to achieve specific properties in various regions through the length of the braid by altering the braid geometry. Axial yarns may be added or removed through the length of the braid to gain or reduce axial strength. Furthermore, axial yarns and braiders may be of different materials to acquire necessary strength in each load direction while maintaining an efficient design.

2.2.2 Three-Dimensional braiding

Where braiding yarns move between multiple layers, the system is considered to be a three-dimensional braid. Three-dimensional braiding is suitable when there is a need for multi-directionally reinforced composites and enhanced through-thickness properties. Due to the relatively poor through-thickness properties of conventional two-dimensional laminate composites, textile structures in three-dimensions have received considerable attention.

Braiding machines for three-dimensional braids vary in both the number of carriers and the arrangement of carriers on the braiding bed. The layout of carriers on three-dimensional braiders is commonly rectangular or circular, as shown in Figures 2.3 and 2.4. Each cell represents a yarn carrier which may be shifted from its original position to another position in an adjacent cell for each step in the process. With each shift of carriers, the yarns become interlaced. A series of shifts ultimately produces one cycle of the braid which may be repeated to generate the length of the fabric.

Contours which can be produced with conventional two-dimensional composite laminates are limited and with current hand lay-up methods it is difficult to consistently reproduce a given shape. In contrast, it is possible to braid virtually any shape with three-dimensional braiding techniques. This ability to reliably produce a wide variety of complex shapes lends to the popularity of the braiding system for composites applications. Some of the net shape structures produced by three-dimensional braiding at Drexel University are shown in Figure 2.5.

There are presently three methods of producing 3-D braided structures: two-step, four-step, and multilayer interlock braiding.

> The <u>two-step</u> braiding process consists of two distinct motions in the machine cycle and two principle sets of yarns, axials and braiders. The axials remain stationary in the fabric forming direction while the braiders move between the axials and interlace to form and stabilize the shape of the braid. The ratio of braiders to axials is always less than one for practical fabrics (Li 1988).
>
> The <u>four-step</u> braiding process may or may not employ axial yarns and has four distinct motions in the machine cycle. A multilayer structure results in which braiding yarns traverse internal layers to bind two exterior layers together. The process is relatively difficult to automate and consists of an additional step to push the yarn into a tight structure after each round of braiding (Mohamed 1990).
>
> <u>Multilayer interlock</u> braiding is a variation on two-step braiding with the addition of interlocking yarns between adjacent layers (Mohamed 1990).

A comparison of the two-step and four-step processes was performed and reported by Li (1988). It was shown that although both methods are capable of producing complex shapes, the fabric stability is better for the two-step process. In addition, the tensile strength and modulus in both the axial and through-thickness directions are higher for the two-step process. The multilayer interlock system provides even greater circumferential reinforcement than the two-step system and axial strength is gained by the addition of axial yarns.

While it relatively simple to automate the production of two-dimensional braids, it is a challenge to fully automate the process of forming three-dimensional shapes. Automation is hampered by the large number of carriers and the additional steps which are necessary to form three-dimensional braids. However, development of systems with complete automation is being pursued by various researchers. More information on the ability to control the manufacturing of braided shapes is provided in Section 4.2 of this report.

2.3 Braiding Materials

Braiding of composite parts can be achieved with either dry or prepreg tows. Fiberglass and aramid yarns can be braided as dry tows. Dry graphite is also braidable if covered by a protective coating which is removed after the braiding is complete (Sanders 1977). Twisted yarns should be used in the dry condition because their resistance to ravelling is higher than that of rovings. Dry tows may be impregnated with resin as they are braided or resin may be applied to the completed braided preform. Prepreg tows are impregnated with resin and partially cured prior to braiding. Epoxy-impregnated tows of glass, aramid, and graphite fibers are all commercially available. Reversal of a braid on a mandrel to yield multiple plies is more difficult with prepreg tows due to the stiffness imparted by the resin. However, fiber wetting is more uniform and the cost of applying the resin is lower when prepreg tows are used. Of the three composite fibers mentioned, fiberglass is the easiest to braid. In order to avoid fiber damage of graphite, lower tow tensions and larger carrier pulley radii must be used (Sanders 1977). Hence, it is more difficult to braid graphite fibers.

A mandrel, used as the support structure for the braid during formation, can be made of any suitable material. Metal may be used for the mandrel if it is desired or acceptable to leave the metal in place after completion of the braid. Otherwise, it is necessary to allow for removal of the mandrel after the braid is formed. Such a demand limits the shapes which are possible with use of a metal mandrel. Plaster or casting resin mandrels are commonly used for more complex braided shapes. With these materials, the mandrel can be later broken away or washed from the part. Other suitable mandrel materials include silicone rubber or a closed cell foam which is capable of thermal expansion and produces compaction of the composite during the thermal curing cycle (Chou 1989).

2.4 Properties of Braided Structures

It is the result of many desirable properties which is causing the growing interest in composite braided structures. Some properties include minimal delamination, abrasion resistance, high strength in all directions, and torsional stability.

Delamination, or the separating of layers, is the most common mode of failure in conventional two-dimensional laminate composites. Interlaminar shear and tension stresses due to impact, pressure, or other stresses cause parallel planes to separate. Three-dimensional braiding techniques provide structures which are integrated in all directions to resist delamination crack growth due to interlaminar shear and tension stresses. Resistance to delamination can also be enhanced for multiple layered two-dimensional braids by stitching between the braid layers.

The integrated nature of three-dimensional braided structures also yields improved through-thickness properties. With enhanced through-thickness strength, braided composite structures have better fatigue and impact resistance. Compared with conventional laminated constructions, 3-D braided shapes require higher impact energy to initiate and propagate damage. A significant advantage of 3-D braided composites is shown from a study by Ko et al. (1986) comparing the damage tolerance of braided and laminated carbon/PEEK composites. An order of magnitude lower damage area was attained with the braided composites as shown in Figure 2.6.

Poisson's ratio of braided composites is notably higher than other materials or fiber structures. Different braid patterns and fiber types for a graphite-epoxy composite demonstrated poisson's ratios ranging from 0.87 to 1.05 (Ko 1987). However, it was found at Drexel University that a reduction in the Poisson's ratio can be achieved with an associated loss in strength and modulus by the introduction of transverse yarns (Ko 1987).

An experiment was performed to determine some time-dependent mechanical properties of three-dimensional braided graphite/PEEK composites (Chu 1992). The composite braids were found to be viscoelastic materials by stress relaxation studies under constant strain. However, from 60 to 180 °C, the stress relaxation behavior was relatively temperature insensitive. Results also showed that the graphite/PEEK composite braids have lower damping factors relative to other types of fiber reinforced composites. The lower damping factor in three-dimensional composites implies that these materials may resist permanent change in use (Chu 1992).

Metal alloys are typically better able to absorb stress concentrations around holes and cutouts relative to composite materials. A study was performed to compare the reduction in tensile strength due to the presence of a drilled hole in a braided specimen and a laminate specimen (Chou 1989). It was shown that while there was a 50% reduction in strength for the laminate, 90% of the strength of the braid was retained. Furthermore, the braiding process enables the formation of an integrated hole in the final structure around which no fibers are cut or discontinuous. Table 2.1 presents the increase in tension failure loads for the integrally formed hole over the machined hole for braided cylinders. The failure loads for pin-loaded holes with braided and machined formation are provided in Table 2.2. It can be seen that an integrally braided hole carries almost twice the load of the machined hole for pin-loading. These results demonstrate the potential benefit of using the braiding process for composites with structural attachments.

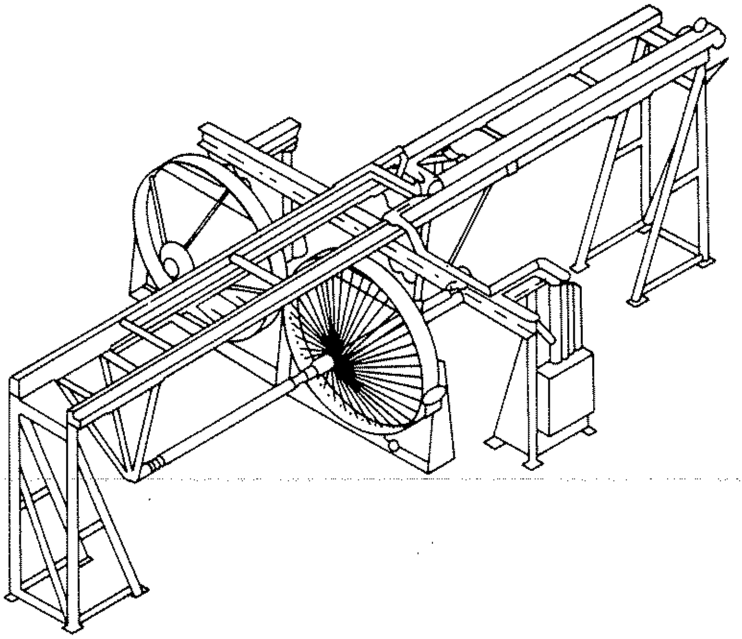


Figure 2.1: 144 carrier braiding machine (Ko 1987)

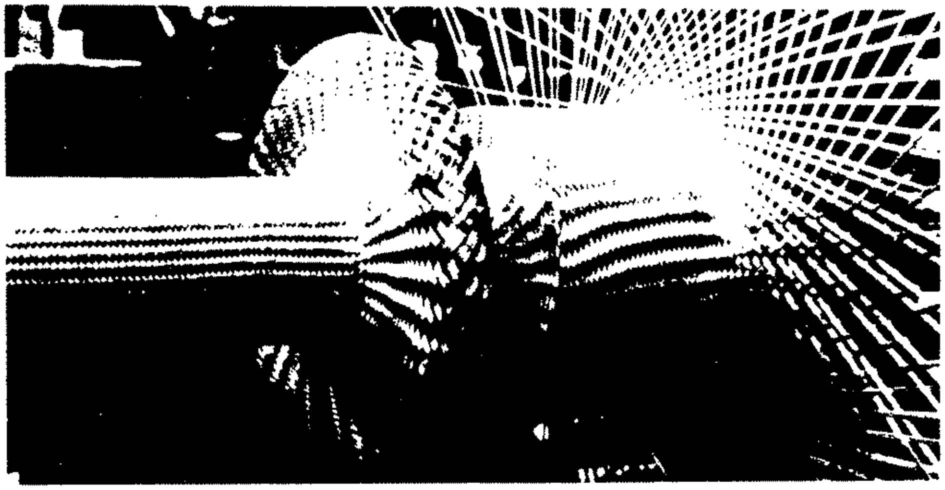


Figure 2.2: Fiberglass preform braided on 144 carrier machine (Ko 1987)

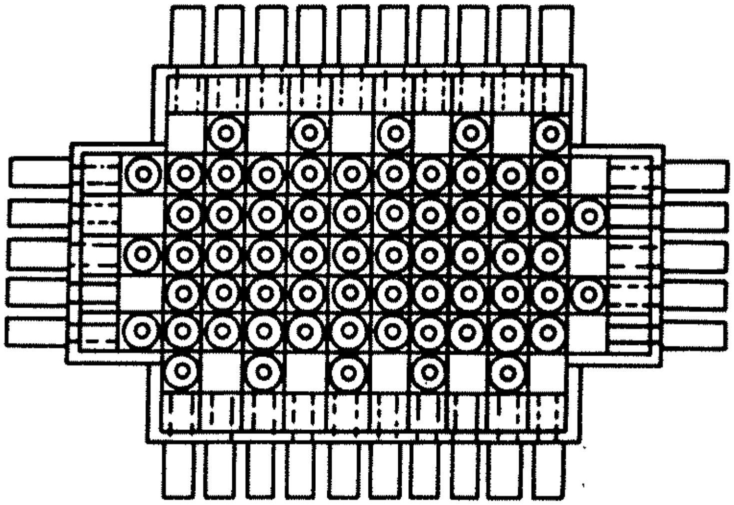


Figure 2.3: Rectangular three-dimensional braiding machine layout (Chou 1989)

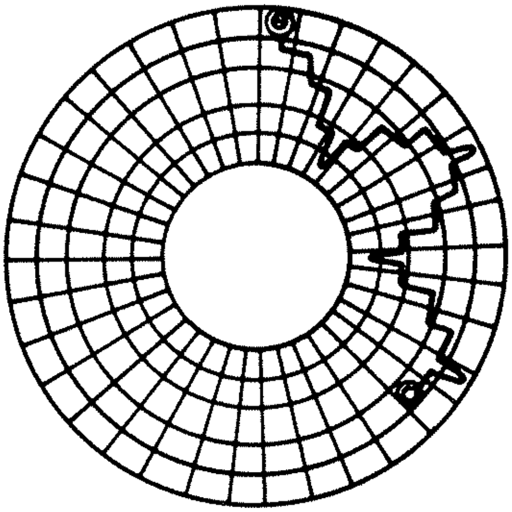


Figure 2.4: Circular three-dimensional braiding machine layout (Chou 1989)

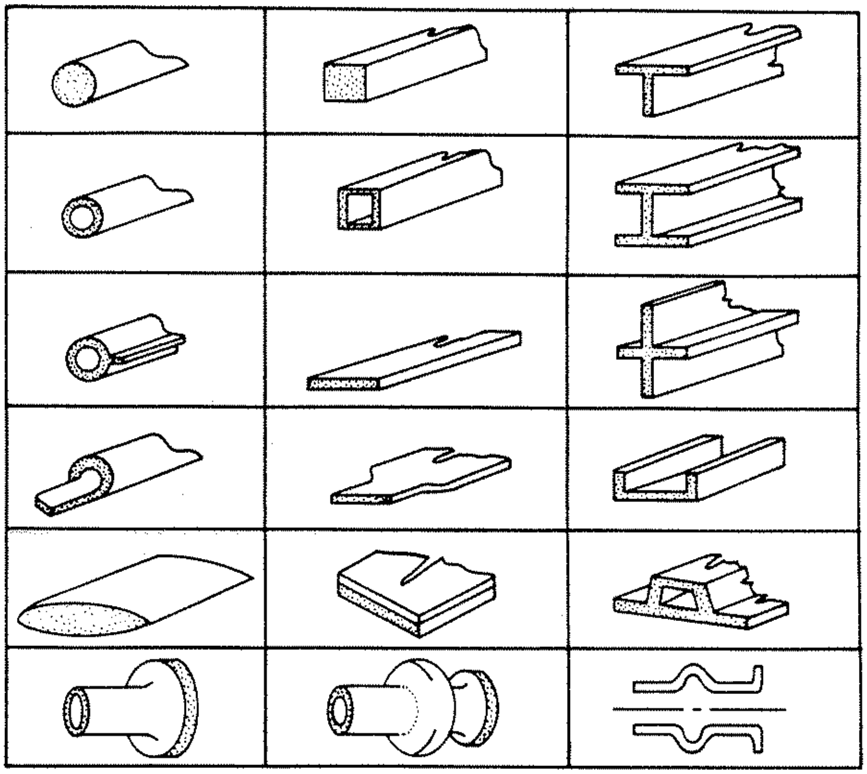


Figure 2.5: Net shape structures (Chou 1989)

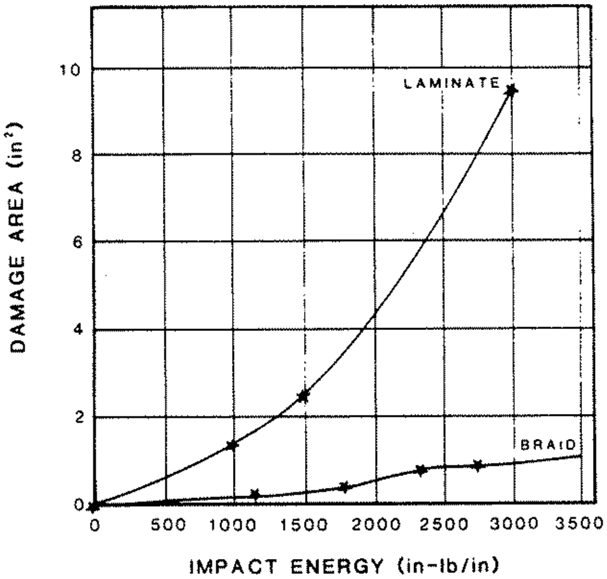


Figure 2.6: Impact Damage Area (Chou 1989)

Specimen No.	Braided Hole (lbs)	Machined Hole (lbs)
1	15,000	8,600
2	12,500	11,650
3	14,700	14,000
Average	14,067	11,417

Table 2.1: Tension failure loads of braided cylinders with open holes

Specimen No.	Braided Hole (lbs)	Machined Hole (lbs)
1	2,000	1,100
2	2,325	1,080
3	2,090	1,440
Average	2,140	1,210

Table 2.2: Failure loads of braided cylinders with pin-loaded holes

CHAPTER 3
REVIEW OF ANCHORAGE SYSTEMS WITH NON-METALLIC CABLES

3.1 Introduction

The attributes of non-metallic cables have been exploited by numerous research efforts in recent years. The most useful features include high strength and corrosion resistance. These features have led to a variety of proposed uses of FRP cables including permanent ground anchors (Mochida 1992) and cable-stayed bridges (Khalifa 1992). Many applications involve anchoring the cable while a tensile force is introduced. However, the unique properties of composite materials do not permit the use of conventional anchorage systems which have been developed for steel rods and cables. As a result, several anchors designed specifically for FRP cables have emerged from recent studies.

One area of particularly active research of reliable and practical anchorages for non-metallic tendons is in prestressed concrete applications. Several conferences and symposia have included sections focused on the use of composite tendons for prestressing. These gatherings include an international symposium in 1993 of the American Concrete Institute entitled *Fiber-Reinforced-Plastic Reinforcement for Concrete Structures* and an international conference held by the Canadian Society for Civil Engineering in 1992 on *Advanced Composite Materials in Bridges and Structures*. The American Society of Civil Engineers also sponsored a conference in 1991, *Advanced Composite Materials in Civil Engineering Structures*, which contained two sections on prestressed concrete with advanced composite tendons.

Numerous variations in anchor design have arisen from the many research programs undertaken in recent years. However, most of the proposed systems can be placed into any one of six generic categories as described by Holte (1993). The six categories include the split wedge anchor, the plug-in-cone anchor, the resin sleeve anchor, the resin potted anchor, the soft metal overlay anchor, and the swaged anchor. This chapter discusses the basic design concept for each anchor type.

3.2 Conditions For New Design Concepts

The first use of prestressed concrete utilizing high tendon stresses with steel was in Austria in 1921 with the fabrication of precast pretensioned roof panels. Post-tensioning with high strength steel was introduced in 1928 through the construction of several bridges on Germany's Autobahn. Since this time, anchors for steel tendons have been receiving extensive refinements. In addition, new methods for anchoring and jacking steel wires and strands have continued to surface. Non-metallic tendons, on the other hand, are relatively new to the field of prestressing and exhibit different properties and behavior than their steel counterparts. Hence, new anchorage concepts for non-metallic rods have evolved.

High shear stresses develop in the tendon end during the transfer of axial load to the anchor. The shear strength of steel is approximately one-third of its tensile strength; whereas, the shear strength of composite materials is typically only 5 to 10 percent of their tensile strength.

If the full tensile capacity of the tendon is to be utilized, high shear stresses near the anchor are more likely to result in failure of a composite cable. Therefore, tendon-anchorage systems must be modified to accommodate the relatively low shear strength of composite materials.

Steel tendon-anchorage systems commonly include wedges, buttonheads, sockets, or threaded ends. Although some of these design concepts may be useful, the current hardware is not acceptable for applications with non-metallic tendons. For example, high-carbon steel wires exhibit extreme hardness; hence, wedges have been a popular anchorage method. The wedges are typically provided with teeth which bite into the steel rod and deform its surface to provide a better grip. Composite materials, on the other hand, are susceptible to surface injury or notches. Progressive fracture due to the biting action of the teeth is a common mode of failure for this system as applied to FRP tendons (Holte 1993). However, without a serrated edge, friction between the rod and wedge alone maintains the grip during load transfer and slipping is likely to occur. For the wedge system to be successfully applied to non-metallic rods, alterations must be made to improve the grip in the tendon-anchorage zone without initiating premature failure.

3.3 Performance Requirements

The success of a new anchorage system is contingent upon its ability to satisfy certain performance requirements. These performance requirements involve reliability and economic issues. A set of objectives for anchor performance can be used as a guide for the development and evaluation of new anchorage systems with FRP tendons. These objectives include the following (Holte 1993, Rostasy 1993):

1. Develop the full tensile capacity of the prestressing tendon;
2. Allow correlation between prestressing force and tendon elongation;
3. Exhibit small and predictable losses at transfer of prestress;
4. Exhibit stable performance in service for its entire service life;
5. Assemble in the field in a relatively simple manner with minimum opportunity to compromise the integrity of the tendon; and,
6. Require that the stressing operation only have to be performed once.

3.4 Examples of Anchors for Non-Metallic Cables

In any new design venture, insight in to the design problem can be gained by reviewing the behavior and shortcomings of related, existing designs. To assist the development of ideas for this research, various anchors which have been proposed or employed for non-metallic tendons were studied. It was found that many different research efforts addressed similar anchor concepts. Six categories of anchors for non-metallic tendons which incorporate most of the presently suggested methods have been defined by Holte (1993). A brief description of each anchor type is provided in the following sections.

3.4.1 Split Wedge Anchor

Metal or plastic wedges surround the tendon inside a conical socket for the split wedge anchorage system, as shown in Figure 3.1. Teeth on the wedge surfaces may or may not be provided to grip the tendon.

Experimental work was performed by Holte (1993) on a variation of the split wedge anchor. The test anchor consisted of aluminum wedges with segmental varying tapers, as shown in Figure 3.2. The typical failure mode for the test specimens was pull out of the rod from the wedges. Various methods of improving the friction to prevent pull out were attempted, including bead blasting the contact surface and using epoxy with various sand mixtures coating the rod surface in the anchorage zone. A tensile stress of 224.6 ksi was achieved for a Kevlar 49 rod with an epoxy-sand layer; the rod had a rated tensile stress of 220 ksi. However, failure typically occurred within the anchorage region rather than in the free length of the rod.

A split wedge anchor was also tested for aramid fiber reinforced plastic (AFRP) rods (Kakihara 1991). The rods failed in the center of the specimens and 95% of the theoretical tensile strength of the rod was obtained. In order to improve the friction between the rod and wedges, surface roughness of the rods was achieved by winding aramid fibers around a straight fiber bundle.

3.4.2 Plug-in Cone Anchor

The plug-in cone anchor includes a fluted, solid cone which is driven into the center of a bundle of rods inside a conical anchor housing, as shown in Figure 3.3. The barrel and spike anchor is a similar arrangement developed for Parafil ropes comprised of parallel filaments of yarn within a thermoplastic sheath (Burgoyne 1992). A metal spike grips the fibers against an external conical barrel, as shown in Figure 3.4. Threads may be provided at the end of the barrel in prestressed concrete applications for pulling and locking to transmit the force in the rope to the concrete. The spike must be placed so that the fibers are spread properly and the gripping force is evenly distributed among the fibers. The length of the spike can be varied to achieve a transverse stress within the capacity of the fibers. The advantage of this system is that the fibers are individually anchored without the need for resin which may be subject to long-term degradation as noted in Section 3.5 of this report. A modified version of this anchor is suggested in Section 5.3 of this report.

3.4.3 Resin Sleeve Anchor

The basic design of the resin sleeve anchor, as shown in Figure 3.5, uses an epoxy resin to bond the tendon end inside a cylindrical metal sleeve. The outer surface of the sleeve may be threaded to provide a grip for applying the jacking force. This is a simple and widely accepted method of anchoring FRP tendons. Experimental tests of a resin sleeve anchor used by Tokyo Rope with carbon fiber composite cables showed that the full tensile capacity of the rods were able to be developed (Holte 1993). It has also been suggested to provide surface deformations to improve the bond between the cable end and the resin in the anchor (Kakihara 1991, Mochida 1992).

3.4.4 Resin Potted Anchor

The resin potted anchor employs an epoxy resin to bond the tendon inside a conical housing, as shown in Figure 3.6. This system combines features of the resin sleeve and split wedge anchors. A reduction in the peak shear stress at the front of the anchor results from the use of a parabolic taper in the anchor sleeve, as shown in Figure 3.7 (Holte et al. 1993). In addition, a significant reduction in the interlaminar shear stress at the tendon surface is achieved by prohibiting bond between the resin plug and the metal socket (Holte et al. 1993).

3.4.5 Soft Metal Overlay Anchor

A soft metal overlay anchor consists of a threaded metal sleeve which is permanently bonded to the tendon end, as shown in Figure 3.8, and gripped by conventional strand chucks. Tokyo Rope Manufacturing Company produces a metal overlay anchor by attaching steel tubes to the cable by means of a low melting brazing alloy (Zoch 1991). The steel tubes can then be clamped directly with wedges without damaging the carbon fiber composite cables. However, the strands, with diecast sleeves applied in the manufacturing shop, must be handled with care to avoid bond failure. After tensioning one strand with a similar anchorage arrangement for a prestressed concrete beam, bond failure occurred between the diecast sleeve and the tendon while attempting to remove the chuck used at the end of the jack for stressing (Naaman 1993).

3.4.6 Swaged Anchor

The basic concept of the swaged anchor is to increase the friction between the tendon and the surrounding material by applying transverse stress to a metal shell, as shown in Figure 3.9. Bolts or swaging may be used to induce the transverse stress. Figure 3.10 shows the arrangement of a clamping sleeve anchor for 8 single rods made from E-glass fibers (Sippel 1992). The rods are surrounded by mortar to transfer the bond stresses and provide a more uniform distribution of the transverse stresses. Tensile tests of these anchorage systems resulted in failure in the free length of the rods rather than in the anchorage for most of the specimens tested (Sippel 1992).

3.5 Concerns With Anchorage of Non-Metallic Cables

Several anchors for non-metallic tendons have been tested with varying degrees of success. An effective anchor should develop the ultimate tensile capacity of the anchored cable. An efficiency rating can be assigned to an anchor as the ratio of the tensile capacity of the rod to the strength developed by the anchor. Although efficiency ratings of 100 percent have been reported and some anchors have been successfully employed in construction, various design problems are associated with the overall performance of many currently proposed anchors.

Some concerns with the performance of anchorage systems with non-metallic composite cables include the following:

- poor through-thickness strength

- resin performance
- temperature effects
- cracking around tendon
- field flexibility

Each of these concerns are addressed in more detail in the following sections.

3.5.1 Poor Through-Thickness Strength

One concern with the anchorage of composite rods is poor through-thickness strength which is common with unidirectional composite cables. A unidirectional composite cable consists of fibers running primarily in the longitudinal direction bound together by a matrix material with relatively low strength. The poor through-thickness strength of these cables requires changes in the anchor designs.

In the anchorage region, high shear stresses develop at the surface of the cable. The state of stress on the cable surface is illustrated in Figure 3.11 for a unidirectional cable. Figure 3.12 demonstrates the Mohr's circle for the state of stress indicated in Figure 3.11. Shear is assumed to be positive in the counterclockwise direction on each face. By definition, the principal stresses act in directions normal to the faces which are rotated one-half of the angle θ which is shown in Figure 3.12. A schematic of the principal stresses is provided with the element rotated through an angle $\theta/2$. It can be seen from this element that the principal tensile stress is not aligned with the direction of fibers. The stress is taken primarily by the matrix material. The fibers are the main reinforcement of the composite and the matrix material is generally very weak. Therefore, a large principal tensile stress which does not act in the fiber direction might exceed the strength of the matrix material and tend to pull the composite material apart. This discussion demonstrates the weakness of unidirectional composite cables against stresses which act through the thickness of the cable.

The anchorage designs can be modified to overcome the poor through-thickness strength of the unidirectional cables. One solution is to orient fibers in the cable to the directions in which the large stresses act. Specific fiber orientation can be accomplished by use of braiding technology. The use of braided cables to overcome the problem of poor through-thickness strength is discussed in Chapter 4 of this report.

Another anchor modification to prevent failure of the composite cable is to increase the anchor length and diameter. The axial force in the cable is resisted by the shear forces which develop in the anchorage region. By increasing the surface area over which these shear forces are distributed, the shear stress on the cable surface is reduced. The effect of a reduction in shear stress on the Mohr's circle of Figure 3.12 is shown in Figure 3.13. A comparison of these two figures reveals a reduction in the angle of rotation to the direction of the principal stresses when the shear stress is smaller. An element showing the direction of principal stresses with respect to the fiber direction is also provided. The direction of the principal tensile stress is closer to the direction of fibers which is the strongest direction of the unidirectional cable. Therefore, an increase in the anchor length or diameter may alleviate the problem of the cable's poor through-thickness strength. However, an increase in the anchor size may cause other problems with the spacing or detailing surrounding the anchorage region.

All six anchor designs discussed in the previous sections produce a similar state of stress in a cable as shown in Figure 3.11; however, a transverse compressive force is added for the split wedge anchor, the swaged anchor, and the resin potted anchor if a bond release is provided between the resin and anchor sleeve. A transverse compressive force will also lower the angle of rotation to the direction of principal stresses, as shown in Figure 3.14. This feature is further discussed in an anchor modification presented in Section 5.2 of this report.

3.5.2 Resin Performance

Where resin is employed in the anchorage system, the type of resin to use is controversial. A low modulus resin should be used to limit the peak shear during transfer of axial load to the anchor. However, a high modulus resin is necessary to control creep movements (Dolan 1990). It was reported that the resistance to creep, fluids, and solvents is good for thermoset resins, including epoxy, polyester, and polyimide resins (Gosnell 1987). However, the long-term performance of resins in prestressing applications is unknown and recommended as an area of continued research. Deterioration of the resin is especially dangerous in anchors with unbonded post-tensioned construction due to complete reliance on the anchorage system to transfer tendon stress to the concrete. Potential problems associated with the use of resin in the anchor design include the following (Dolan 1990):

1. Creep of the resin may result in apparent relaxation due to tendon shortening;
2. Moisture sensitive resins may experience deterioration leading to loss of anchor capacity;
3. Bond failure may result from deterioration at the interface between the anchor resin and resin used in the composite rod;
4. Resin strength may deteriorate rapidly at elevated temperatures.

3.5.3 Temperature Effects

It is also necessary to consider the effects of temperature on the anchorage system. A temperature related problem was noted in an application of braided aramid FRP bars as prestressing rods anchored with steel sleeves and quartered wedges (Okamoto 1993). The tension force in the rods gradually decreased to between 85 and 94 percent of the original force. Subsequently, secondary tensioning was performed. The cause of the reduction in force is believed to be the different thermal expansion rates between the tendons and the steel reaction frames.

3.5.4 Cracking Around Tendon

Concrete cracking may be more likely to occur around a FRP tendon used for prestressing. This concern is outside the scope of this report, which pertains only to the improvement of the anchorage system. However, it is briefly mentioned here since the use of braided composite cables is more likely to result in this type of cracking. Poisson's ratio is higher for most FRP materials compared to steel. Furthermore, without the introduction of transverse yarns (as discussed in section 2.4), the poisson ratio of braided composites is exceedingly high. This feature leads to greater recovery of lateral contraction when loss of prestress occurs. One test exhibited concrete cracking around the tendon partially as a result of the high radial pressure due to recovery of tendon contraction (Nanni 1992).

3.5.5 Field Flexibility

Another concern with the proposed use of non-metallic prestressing tendons is the amount of flexibility in the field. Field modification is currently not possible with the soft metal overlay anchor used by Tokyo Rope. The metal sleeve for this anchor must be applied in the shop requiring that the length of the tendon is specified prior to installation. The use of resins in the anchor design may also limit field flexibility. Epoxy resin performance is highly dependent on the curing agent and curing conditions (May 1987). Hence, considerable experience is necessary to understand the particular handling characteristics of resins. Workers will need to be experienced in the application of resins if field assembled anchorages are desired.

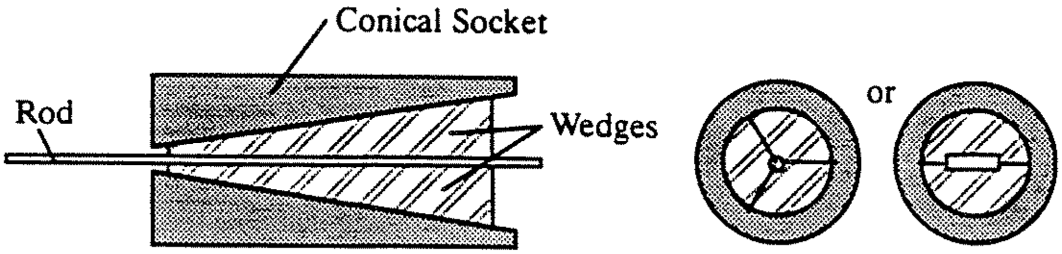


Figure 3.1: Split wedge anchor (Holte 1993)

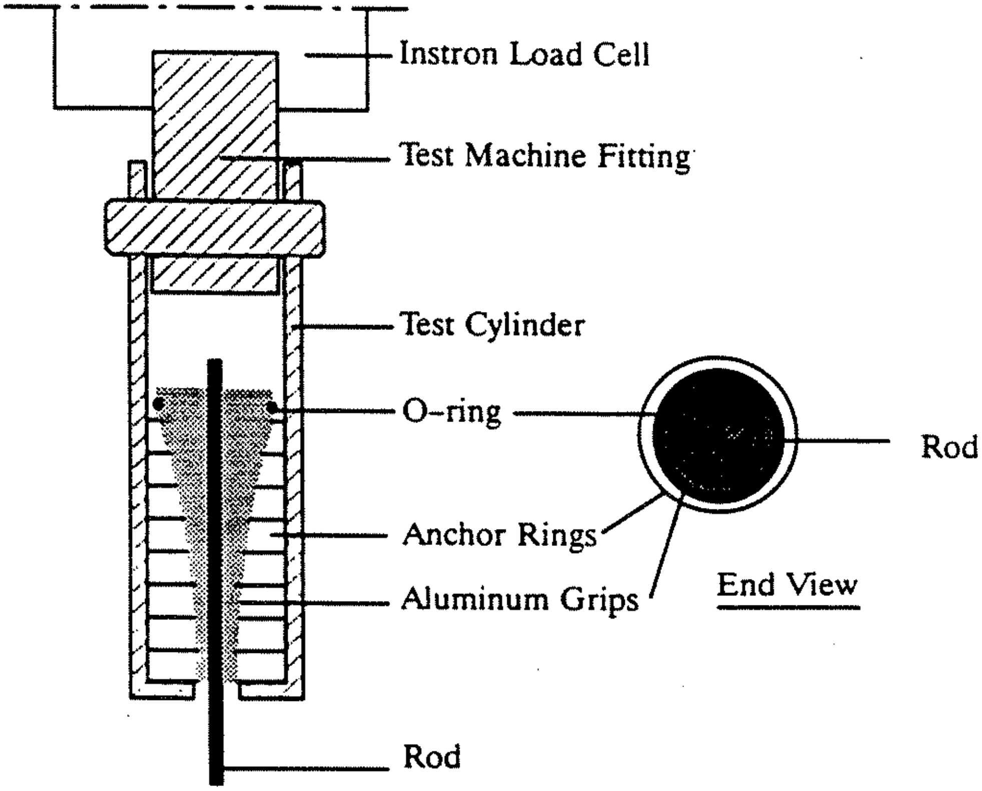


Figure 3.2: Split wedge test anchor with test cylinder (Holte 1993)

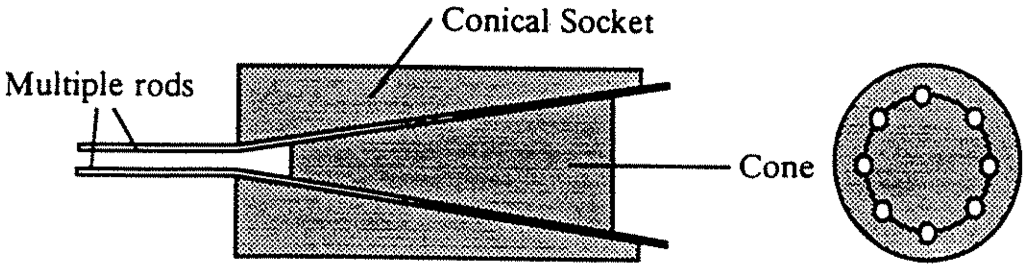


Figure 3.3: Plug-in cone anchor (Holte 1993)

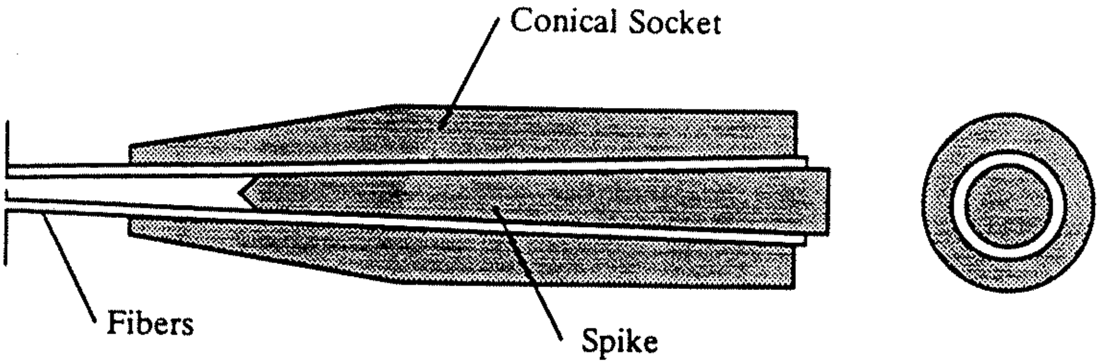


Figure 3.4: Parafil anchor (Holte 1993)

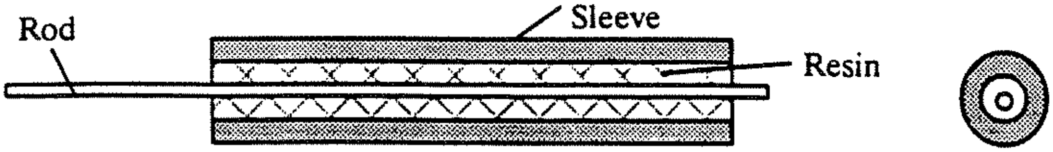


Figure 3.5: Resin sleeve anchor (Holte 1993)

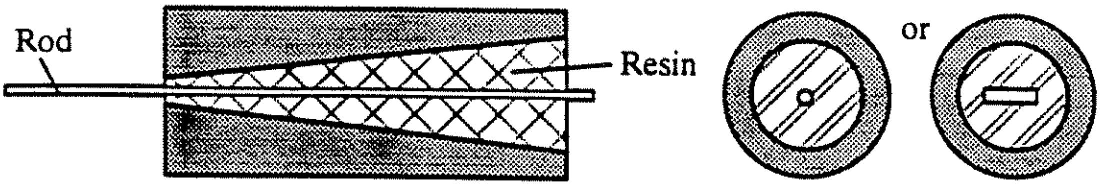


Figure 3.6: Resin potted anchor (Holte 1993)

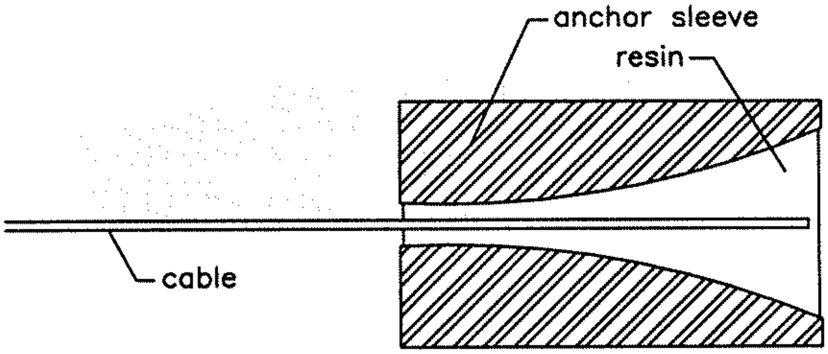


Figure 3.7: Parabolic taper in anchor sleeve for reduction in peak shear stress

Figure 3.8: Soft metal overlay anchor (Holte 1993)

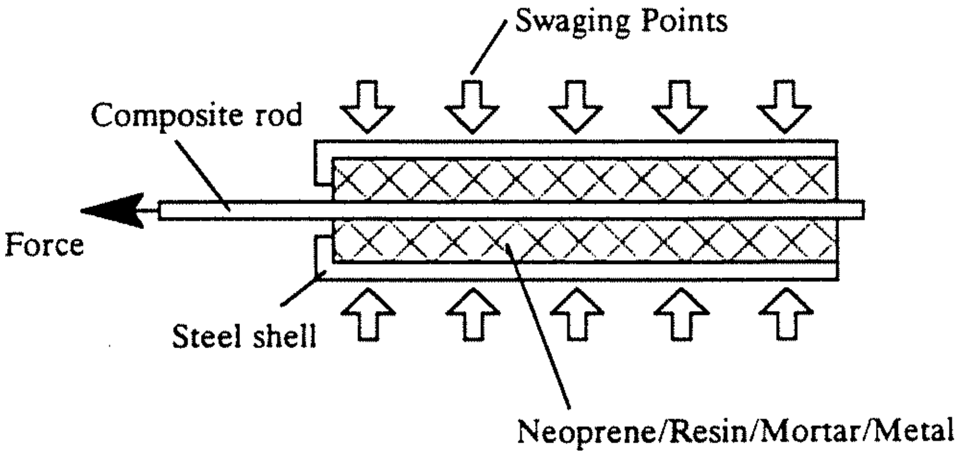


Figure 3.9: Swaged anchor (Holte 1993)

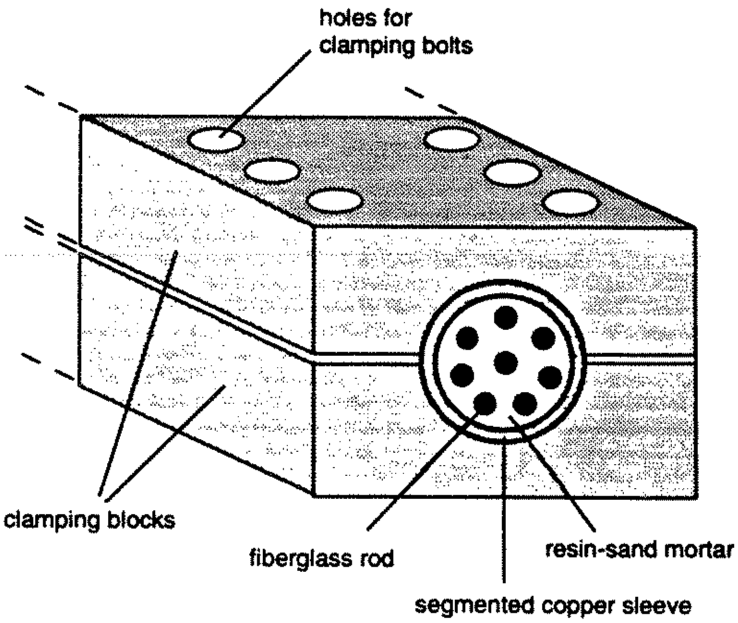


Figure 3.10: Clamping sleeve anchor (Sippel 1992)

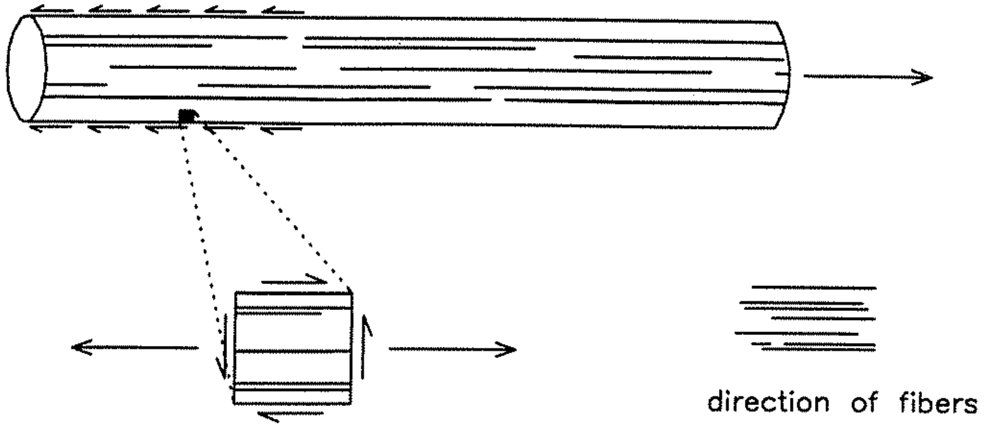


Figure 3.11: State of stress in unidirectional cable in anchorage region

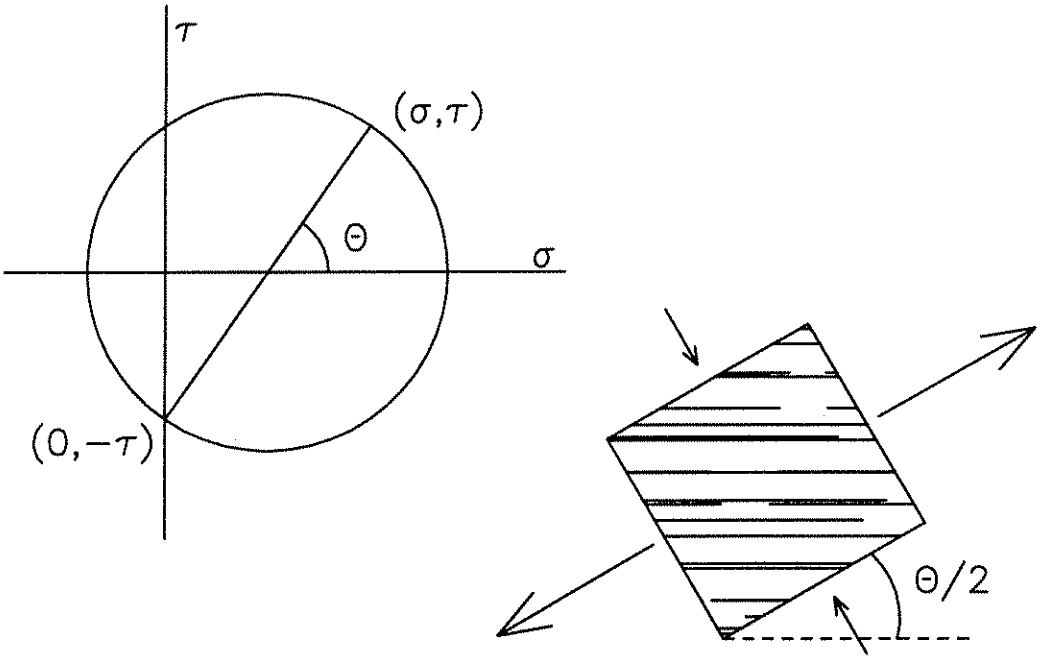


Figure 3.12: Mohr's circle and direction of principal stress

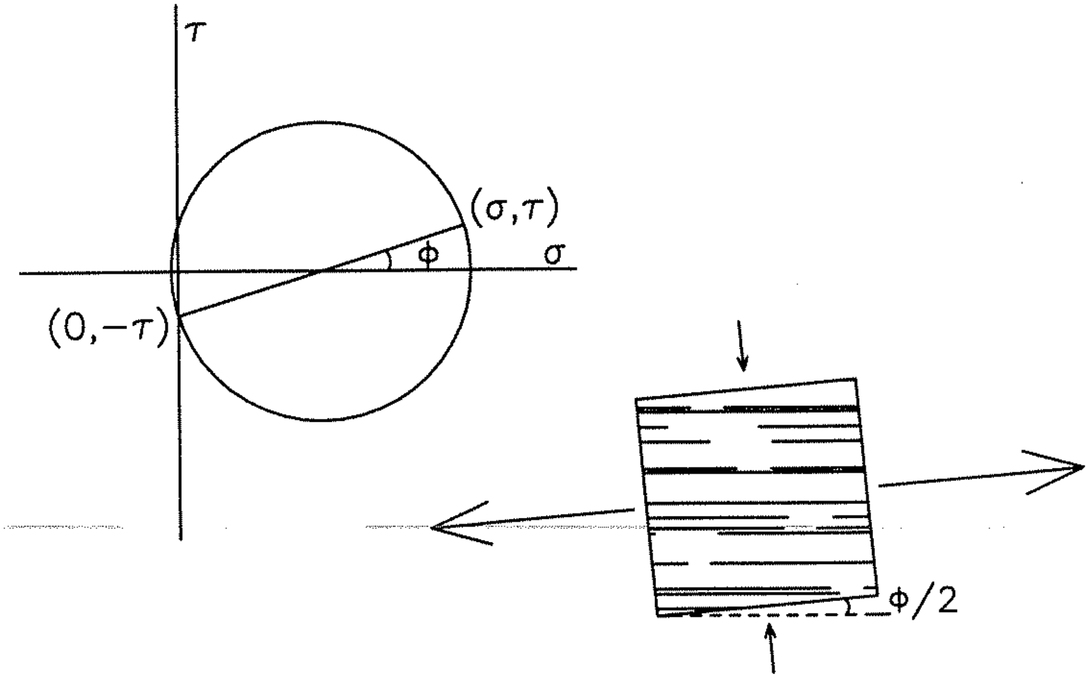


Figure 3.13: Mohr's circle and direction of principal stresses with reduction in shear stress

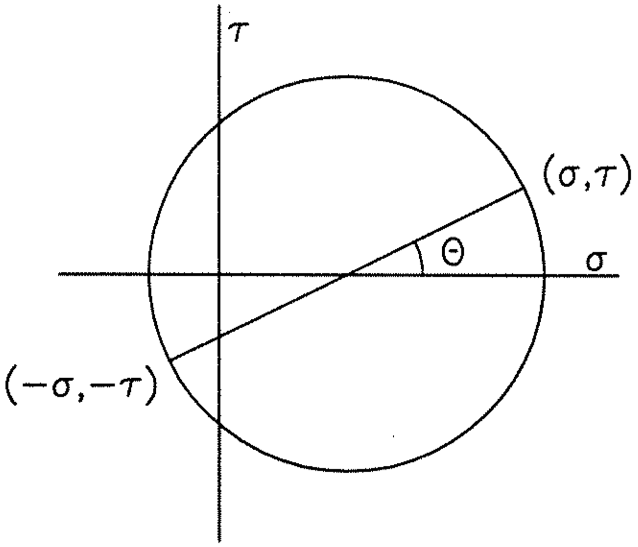


Figure 3.14: Mohr's circle with transverse compressive stress

CHAPTER 4
OPPORTUNITIES WITH BRAIDING IN ANCHOR DESIGNS

4.1 Introduction

The development of anchorage systems with braided composite cables is important whether or not it is determined that the use of braids can improve the performance of the anchorages. The use of braids may be beneficial elsewhere in the design. For example, future research may prove that braided composite cables perform better at harp points or as draped tendons than unidirectional composite cables. Therefore, an efficient and reliable anchorage system would be necessary for the braided cables. However, braiding technology with composite materials does offer many opportunities which may improve the performance of anchorages with non-metallic cables or overcome some of the problems associated with these anchors, as presented in Section 3.5 of this report. Furthermore, braiding technology provides the opportunity to develop new, all non-metallic anchors.

The intent of this chapter is to explore some of the opportunities which arise when considering braiding technology in the design of anchors for non-metallic cables. The attributes of the braiding process discussed in this chapter include the following:

- Controlled manufacturing
- Enhanced mechanical properties
- Ability to vary cross-section shape and properties
- Hybrid rod

Chapter 5 expands on some of the concepts presented in this chapter and provides details of possible anchorage designs which utilize braiding technology.

4.2 Controlled Manufacturing

Cost and productivity are important issues in cable production, especially in prestressing applications where hundreds of tendons may be needed for one job. The reliability of producing complex shapes, such as those used in anchor designs, is also a significant concern. Cost, productivity and reliability should be considered when selecting a manufacturing process for composite materials.

One feature of the braiding process which makes it more attractive than other manufacturing techniques is the extent of control. Low cost and high productivity result from the use of computer aided design and manufacturing (CAD/CAM) for braided composites.

A CAD/CAM system, the braiding control system (BCS), has been developed and implemented with a 144 carrier braiding machine at Drexel University (Pastore 1988). The BCS is designed so that it may be applied to any braiding machine. A software package for braided composite analysis, which was also developed at Drexel, assists the design of the braid in terms of the fiber orientation and fiber volume fraction. The necessary rotational and traverse velocities to produce the structural geometry of the fabric are then determined by the BCS. Finally, the necessary machine control parameters are communicated to the braiding machine by the BCS and the fabric is formed.

As described above, the BCS completely automates the design and manufacturing process. The automation of producing braided shapes results in low labor intensity, cost savings and reliable and consistent reproduction of a given shape. Therefore, an opportunity with the use of the braiding process is the benefit of controlled manufacturing from implementing CAD/CAM.

4.3 Mechanical Properties

Many of the mechanical properties of braids are particularly advantageous for composite cables and their anchors. The opportunities to improve the anchor designs by using braiding technology are discussed with respect to the following mechanical properties:

- Through-thickness strength
- Surface roughness
- Damage tolerance
- Poisson's ratio
- Modulus of Elasticity

4.3.1. Through-Thickness Strength

As discussed in Section 3.5 of this report, poor through-thickness strength is a common problem in the design of anchors for unidirectional composite cables. A cable encounters high shear and transverse tensile stresses in the anchorage region. These stresses require strength through the thickness of the cable. However, composite cables are typically reinforced with fibers only in the axial direction. These cables are transversely isotropic with little strength in the through-thickness direction. The anchor length must be relatively large to distribute the stresses to avoid failure of the unidirectionally reinforced cables.

A high level of through-thickness reinforcement can be achieved by employing three-dimensional braiding. Braiding yarns traverse all directions of the fabric when three-dimensional techniques are used. The fabric is fully integrated and high strength is available in all directions. Therefore, the required length of the anchor to ensure acceptable stresses in a 3-D braided cable should be less than the length required for a comparable unidirectionally reinforced cable.

There is an additional benefit of having fibers interlaced through the cross-section. Aside from the barrel and spike anchor for Parafil ropes introduced in Section 3.4.2, the anchorage systems discussed in Section 3.4 of this report develop compression in the outer layers of the cables. The ramification of this for unidirectional cables is that the inner fibers are not necessarily fully anchored. Differential strains through the cross-section may be significant if the diameter or thickness of the cable is too high. With the use of a braided cable, the fibers are interlaced and may better distribute the strains through the cross-section. The permissible diameter or thickness of the cable may be larger and the cable would be able to carry a larger force. With larger forces per cable, fewer cables would be necessary to develop the design prestressing force.

Resistance to fatigue is also dependent on a material's through-thickness strength. By utilizing three-dimensional braiding which generates relatively high through-thickness strength, the ability to withstand fatigue failure may be improved. The opportunity to improve fatigue resistance is beneficial in applications where the cable might undergo stress cycles, such as suspension or cable-stayed bridges.

4.3.2 Surface Roughness

Research has been conducted to show the value of adding surface deformations at the rod end to improve the bond and friction between the rod and the anchor (Kakihara 1991). Tapes of woven aramid fiber bundles encased in an epoxy resin have been used by Enka in Holland (Dolan 1990). The weave provides a roughened surface and improves the bond between the tendon and the concrete in pretensioning applications.

Braided fabrics also have a roughened surface due to the interlacing of yarns. This surface roughness can improve the bond between the cable end and the anchor. Because the surface is roughened as a result of the fabric structure, there is no need for an additional fabrication step to provide the surface deformations. This shows the advantage of the braiding process over other manufacturing techniques where bonded anchors are to be employed.

4.3.3 Damage Tolerance

As discussed in Section 2.4 of this report, the impact resistance of braided shapes is very good. Cables used in civil structures do not typically encounter impact stresses. However, damage could be incurred during transporting and handling of the cables. Although no tests were found to compare the damage tolerance of braided cables with unidirectional cables, tests have shown that braided composites require higher levels of energy to initiate and propagate damage than laminated composites (Ko 1987).

4.3.4 Poisson's Ratio

Poisson's ratio for composite braids is unusually high, typically near 0.6. As discussed in Section 2.4 of this report, Poisson's ratio can be reduced by using additional transverse yarns in the fabric. However, this unique property may present an opportunity in the design of anchors for non-metallic cables.

The high poisson's ratio of a braided cable suggests that the cable will contract considerably in the transverse direction while it is being stretched axially. Any loss of prestress will result in recovery of the lateral contraction. As the cable expands laterally within the anchor, the resulting transverse stress will improve the friction forces between the cable and the anchor. The higher friction forces are better able to resist slip in the anchor.

4.3.5 Modulus of Elasticity

Braided composites generally have lower elastic moduli than steel. This property provides the potential to reduce the effect that concrete creep has on the amount of prestress over time. Figure 4.1 shows relative stress-strain diagrams for steel and a braided composite. A change in strain, $\Delta\epsilon$, is shown to represent the shortening of the concrete due to creep. It is evident from this figure that the steel experiences a greater loss of prestress due to creep than the braided composite.

4.4 Variety of Shapes and Properties

Another opportunity with the use of braiding technology in the development of anchors for non-metallic tendons is the ability to produce a wide variety of braided shapes and properties. Many advantages of the flexibility of the braiding process are described in this section.

The manufacturing of braids enables a variation of the properties in both the longitudinal and transverse directions through the length of the braid. Near the anchorage, where transverse tensile and shear stresses are high, more transverse yarns and a large braiding angle can be used. Throughout the length of the cable, away from the anchorage, a smaller braiding angle can be used to approximate a unidirectionally reinforced cable and provide more strength in the axial direction. In addition, longitudinal yarns can be added to enhance the axial strength. Figure 4.2 demonstrates how the geometry of the braid can be altered through the length of the cable to achieve the necessary properties in each region.

Another useful property of the braiding process is the ability to form integrally braided holes around which no fibers are cut or discontinuous. Specimens with these holes have higher strength than holes which are machine cut, as shown in Section 2.4 of this report. Holes formed in the cable during manufacturing may be useful in the anchor design. In addition, machined holes in braided parts do not cause as much damage or loss of strength as compared with machined holes in conventional two-dimensional laminate structures, which was also discussed in Section 2.4 of this report. The transfer of load within the anchorage can be accomplished by passing bolts through the cable for a more even distribution of transverse stress to improve friction. This could be a simple and effective method of anchoring the cable and is pursued further in Section 5.2 of this report.

The ability to vary the cross-sectional dimensions of the braided cable is also an opportunity with the use of braiding technology. This ability can be used to integrate the fixed end anchor with a cable during its manufacturing. The use of buttonheads in steel tendons for prestressing achieves the same goal. A possible shape to be used at the fixed end of the cable is shown in Figure 4.3. The advantages include less work in field assembly of the anchors and an entirely corrosion resistant fixed end anchor.

The ability to produce complex shapes utilizing the braiding process can be an opportunity to improve the anchor designs for non-metallic cables. Braiding can be used to create shapes for the anchorage hardware in addition to the cable. Use of a corrosion resistant material for the anchor and the cable would eliminate the need to provide corrosion protection for prestressing materials, as required by the American Concrete Institute. Section 18.19.4 of the Building

Code Requirements for Reinforced Concrete (ACI 318-89) states, "anchorages, couplers, and fittings shall be permanently protected against corrosion." Similarly, corrosion protection should be provided for any application of a cable and anchor to ensure utility and safety of a structure throughout its design life.

4.5 Hybrid Rod

Another opportunity with the use of braiding for composite materials which is currently being explored is the concept of a hybrid rod (Nanni 1994). A hybrid rod is composed of a steel core and a braided covering, as shown in Figure 4.4. The braided covering protects the steel core from corrosion and provides additional strength. A composite covering over a steel core can be manufactured easily with use of the braiding process. As mentioned in Section 2.2, braiding can be performed over a mandrel which is the support structure to mold the shape of the braid. Hence, a steel rod can be used as the mandrel and the braided composite part can be formed over the mandrel to generate the hybrid rod. One issue which is still a concern with the use of FRP reinforcement for concrete structures is their lack of ductility. Steel provides the ductility and the composite covering provides the corrosion protection with use of a hybrid rod. Therefore, the introduction of FRP for concrete reinforcement is made gradually while the ductility concerns are studied and overcome (Nanni 1994).

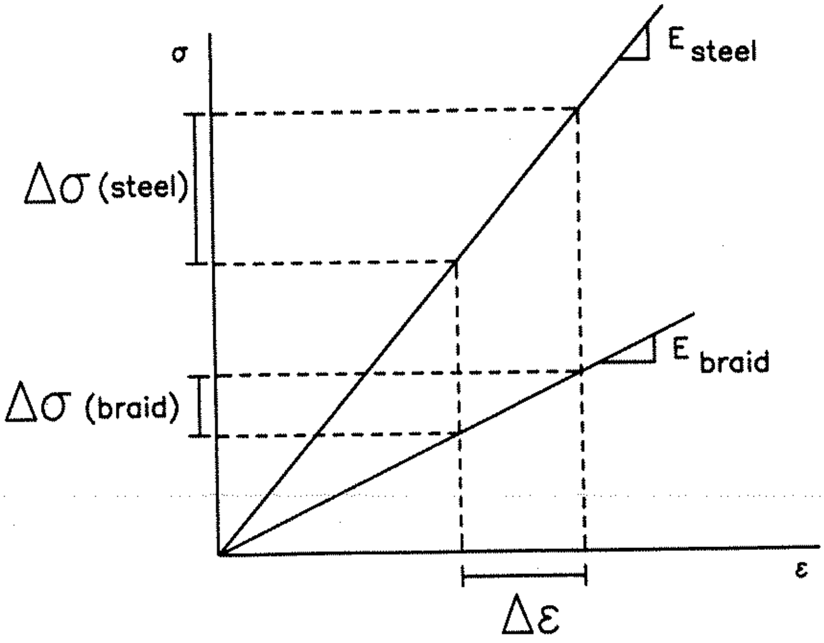


Figure 4.1: Effect of creep on prestress with steel and braided tendons

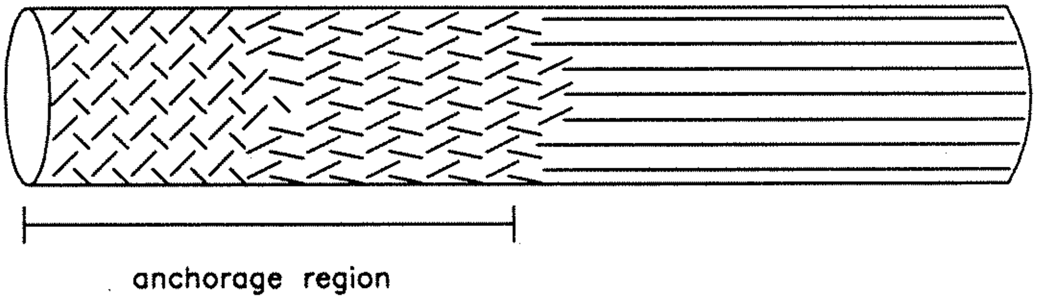


Figure 4.2: Variation of braid geometry along length of cable

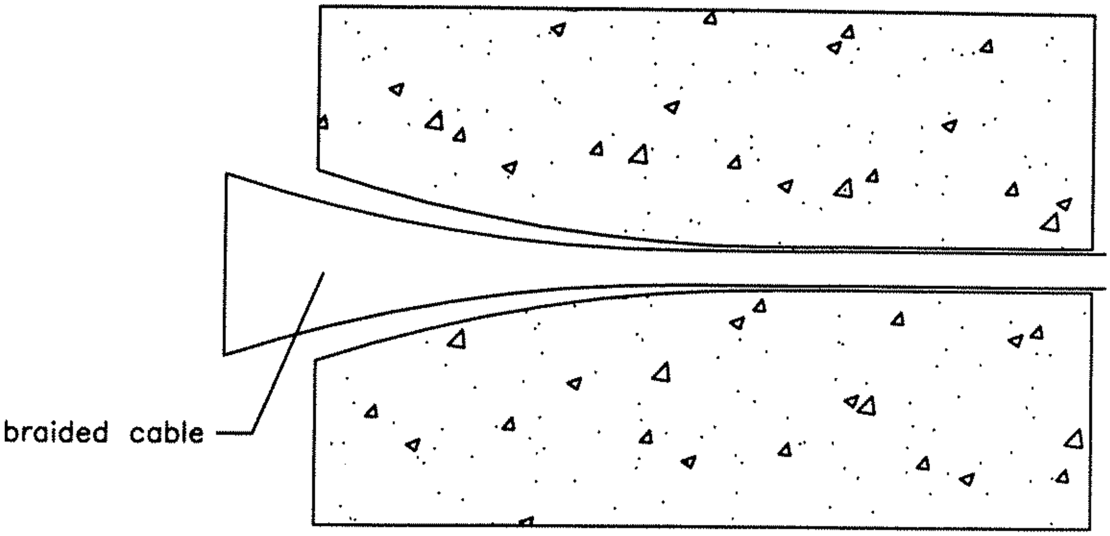


Figure 4.3: Potted fixed end anchor for braided cable

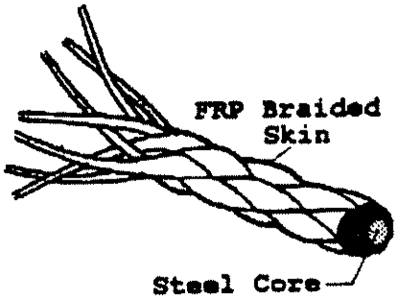


Figure 4.4: Diagram of a hybrid rod (Nanni 1994)

CHAPTER 5
NEW ANCHORAGE SYSTEMS WITH BRAIDING TECHNOLOGY

5.1 Introduction

The features and properties attainable with use of the braiding process provide many opportunities to improve the performance of anchorages with non-metallic cables, as presented in Chapter 4 of this report. These opportunities have been examined to develop new concepts for anchor designs. The intent of this chapter is to discuss new anchorage systems and the features of the braiding process which enable the development of these concepts. The ideas suggested in this chapter have originated from a review of currently tested or installed anchors, which are discussed in Chapter 3 of this report. The behavior and problems associated with these anchors have been examined to identify methods in which braiding can improve or overcome the problems. Further research and experimental testing is necessary to justify and enhance the concepts presented in this chapter.

Two anchorage systems with braided cables are presented in the following sections, including:

- Swaged anchor with braided tape cable
- Plug-in cone anchor with braided tube cable

For each concept, a discussion is provided on the design objectives and how the braiding process is valuable to achieve the objectives. Possible methods of stressing the cables are provided. The potential advantages and disadvantages of each anchor design are suggested. The outstanding issues to be studied and the possible variations of each anchorage system are also discussed.

5.2 Swaged Anchor With Braided Tape Cable

5.2.1 Design Objectives

The development of this anchorage system originated from the concept of the swaged anchor introduced in Section 3.4.6. The design objective of the swaged anchor with a braided tape cable is to increase the friction (surface shear stress) between the cable and the anchor hardware by applying a uniform transverse stress by clamping the system with the use of bolts, as shown in Figure 5.1. The applied transverse stress can be varied along the length of the anchor to control the load transfer. A low modulus material, such as neoprene or resin, can be used between the cable and anchor plates to transfer the load from the cable to the anchor plates. The purpose of the low modulus material is to limit the peak shear which results at the entrance of the cable to the anchor. This is further discussed in Section 5.2.2. Also, as axial stress is applied in the cable, it will contract in the transverse direction due to Poisson's effect. Loss of bolt prestress will result from this contraction. Use of a low modulus material in the system reduces the amount of bolt prestress loss because recovery of the contraction is partially taken by this material.

The first consideration to achieve the design objective of this system is the shape of the cable end which will produce the greatest benefits for the anchorage performance. In the swaged anchor, friction (surface shear stress) acts to transfer force from the cable to the surrounding material. It is desirable to increase the active frictional surface area to volume ratio of the cable within the anchorage region since this leads to a lower average surface shear stress on the cable for a given cable force. With use of a cylindrical shape for the cable end, the surface area to volume ratio is minimized. This ratio can be increased by use of a flat end of the cable in the anchorage region, as shown in Figure 5.1. A second benefit with the use of a flat-ended cable is the relative simplicity of the anchor hardware design compared to the hardware necessary with use of a cylindrical shape. With a rectangular shape for the cable end, the anchor hardware can be plates which fit on the top and bottom of the cable. The shape does not have to include a specific radial groove in which the cable can be compressed.

The second consideration in achieving the design objective for this anchorage system is how to distribute the transverse stress. The transverse stress is used to increase the friction forces between the cable end and the surrounding material. The increased friction forces are necessary to resist the axial tension in the cable. Where a transverse stress is not applied, the friction forces are not increased. At any given cross-section in the anchorage region, it is desirable to apply a uniform transverse stress. Figure 5.2 (a) shows how the transverse stress might be provided with bolts through the hardware which do not pass through the cable itself. A possible distribution of the transverse stress on the cable surface is shown for this anchorage design. The transverse stress distribution is non-uniform because of flexibility in the plates. It can be seen that this stress distribution would provide greater friction forces acting at the sides of the cable as compared to the center. Two possible methods of providing a more uniform distribution of stress are shown conceptually in Figures 5.2 (b) and (c). The use of thicker (stiffer) plates for the anchor hardware is demonstrated in Figure 5.2 (b) and it is shown that this design would produce a more uniform stress distribution. However, the size of the anchor hardware, both the plates and the necessary bolt size, should be small to avoid problems with spacing in the anchorage region and to reduce the material costs for the design. Figure 5.2 (c) depicts how the transverse stress can be more uniformly distributed by using additional bolts through the cable. With this anchor design, the hardware does not have to be as large in order to achieve the uniform stress distribution.

If bolts are to be used through the cable for the anchorage design, it is necessary to ensure that a significant reduction in strength does not occur by providing the holes in the cable through which the bolts would pass. For metallic materials, tension connections are commonly made by using bolts through the material; high stress concentrations result near the cutouts, but holes can generally be used if they are not too large. The use of holes in laminate or unidirectional composites seriously compromises the strength of the material. Machined holes in the composite cut the fibers which provide the reinforcement for the material. If the fibers are cut so that they do not have a sufficient bonded length within the matrix, they are no longer useful in providing strength for the composite. Also, the process of cutting holes damages the surface of composites and may lead to delamination of the material if a conventional laminate composite is used.

The use of a braided tape for the cable end in the proposed anchorage system can overcome the concerns noted above with the presence of holes through the cable. It is possible to integrally braid the holes during the fabrication of the cable. As discussed in Section 2.4, no fibers are cut or discontinuous around holes formed in this manner. However, with preformed holes it would be difficult to align holes in the braided cable with holes in the anchor blocks. This anchorage concept would be most practical if holes are drilled through the entire assemblage for the placement of bolts. As described in Section 2.4, machined holes in braided shapes do not significantly reduce the strength of the shape or damage the surrounding material. Therefore, it would be acceptable to drill through the entire assemblage of anchor plates, filler material, and cable. This feature of the braiding process enables the concept of providing a more uniform distribution of transverse stress with the swaged anchor by using bolts through the cable end.

5.2.2 Finite Element Analysis

The finite element method was used to gain a better understanding of the mechanical behavior of the swaged anchor. Finite element analyses were performed using the NISA II Finite Element Program by the Engineering Mechanics Research Corporation (EMRC 1993). Pre- and post-processing was executed in the DISPLAY III - Geometry Modeling System (1993). The models were comprised of plane strain, quadratic, isoparametric elements and assumed linear elastic response.

Due to the complicated nature of modeling braided shapes, as discussed in Chapter 6 of this report, assumptions are made about the cable properties. The properties of a braid can be very similar to isotropic if a braid angle of 60° is used. Therefore, it is assumed for this analysis that the properties of the cable are isotropic. A modulus of elasticity of 15,000 ksi and a Poisson's ratio of 0.6 is used. Due to the approximation of the material properties, the models developed for this research are used only to obtain information about the relative behavior of the anchors due to variations in some parameters.

5.2.2.1 Finite Element Models

Symmetry of the anchor is used in developing the finite element models. The first geometric model of the anchor, including the cable and anchor plates with no filler material, is shown in Figure 5.3. The boundary conditions of the model represent restrictions on the degrees of freedom at various nodes. There would be no vertical deflection at the center of the cable, due to symmetry. Therefore, these nodes are restricted from moving in the vertical direction, while they are free to move in the horizontal, or axial, direction. Restraints are also imposed along the right side of the anchor plates, representing the location where the plates bear against the structure. At these nodes, motion is restricted in the horizontal direction while free in the vertical direction. It is assumed that the transverse force due to the bolts is sufficient to develop the necessary friction between the cable and the plates to resist slip. The anchor is assumed to be 13 inches long based on initial hand calculations. The cable is assumed to be 0.25 inches thick and the plates are 5 inches thick. A stress of 125 ksi is uniformly distributed over the nodes at the free end of the cable, with each node taking the stress from its tributary area. Forces of 40 kips are applied to represent the clamping application of bolt prestress. The assumption of 40 kips is based on use of A325 3/4 inch diameter bolts with a maximum allowable force of 39 kips.

The second finite element model is shown in Figure 5.4. This model includes a layer of filler material between the cable and anchor plate. Analyses were made with different filler layer thicknesses to determine its effect on the behavior of the anchor. The filler material is assumed to be a resin or neoprene with a modulus of elasticity of 500 ksi. The other dimensions, boundary conditions, and loading used in the model are similar to that used for the first model described above.

5.2.2.2 Finite Element Results

A critical stress in the anchor performance is the shear which results along the surface between the cable and the anchor plates. A plot of the shear stress along the cable for each model is shown in Figure 5.5. The peak shear stress determined for the model with no filler material is relatively high due to the assumption of no relative slip between the cable and the anchor plates. Some reduction in the peak shear stress can be achieved by more gradually transferring the axial stress of the cable to the anchor plates and allowing some relative slip of the cable where it first enters the anchorage region. The transfer of axial stress in the cable to the anchor plates can be moderated along the length of the anchorage by varying the amount of transverse bolt force.

The use of a filler material between the cable and anchor plates can also be used to reduce the amount of peak shear stress which results at the front of the anchorage. It can be seen from Figure 5.5 that use of a layer of low modulus material produces a significant reduction of shear stress in the cable. Figure 5.6 shows a plot which compares the results for the shear stress along the cable for the model with a 0.25 inch thick filler layer when the filler material has a modulus of 500 ksi and 100 ksi. It can be seen that the peak shear stress may also be reduced by use of a filler material with a lower modulus of elasticity.

Plots of the deflection of the cable within the anchorage region are shown in Figure 5.7. The cable does not elongate within the anchorage region for the system with no filler material due to the initial assumption that no relative slip occurs between the cable and the surrounding material. Use of the filler material allows for the deflection of the cable within the anchorage region. With the use of a 0.25 inch thick filler layer, positive deflection of the cable occurs within the front half of the anchorage. As thicker layers of filler material are used, the transverse compression simulating the bolt stresses causes more negative deflection in the filler layer and cable near the tail end.

The use of a lower modulus filler material causes an increase in the deflection of the cable in the anchorage region. This is shown in Figure 5.8 which shows the results for the deflection of the cable for the model with a 0.25 inch thick layer of filler material with a modulus of 500 ksi and 100 ksi.

5.2.3 Stressing Operations

A practical and safe method of stressing and locking off the force in the cable is difficult to determine with the concept of the swaged anchor as described above. One possible operation to apply stress in the cable is shown schematically in Figure 5.9. The anchor pieces are fitted to the end of the cable prior to installation. A possible mechanism for gripping the anchor plates and attaching a jack is shown in Figure 5.9 (b). The prestress is applied and the cable is elongated. Shim plates are installed to transfer the force in the cable to the structure.

The method of stressing outlined above is likely to be impractical due to the space utilized by the entire system. The amount of elongation in a braided composite cable for a typical stress is high due to a relatively low modulus of elasticity. For example, assume the stress in a braided cable used as a prestressing tendon is 150 ksi and the modulus of elasticity of the cable is 15,000 ksi. If the initial length of the cable is 60 feet, the amount of elongation is 7.2 inches. This elongation, in addition to the length of the anchor, requires a relatively large space. The anchorage could be placed within a recess in the structure, however, access to install the shim plates would be limited.

A second possible method of applying stress in the cable is to use two sets of anchors, which is shown schematically in Figure 5.10. The first anchor is temporarily arranged at the end of the cable and provides a grip for the jack to apply the stress and elongate the cable. The permanent anchor is arranged on the cable at the location at which it ultimately bears against the structure. The jack is then removed and the temporary anchor is disassembled. The plates and bolts used for the temporary anchor may be re-used. Less space is occupied by the anchorage system with this method of stressing. However, it would most likely be difficult and dangerous to manually drill and apply bolts to the cable while it is in its stressed state. This approach would clearly require further study.

5.2.4 Potential Advantages and Disadvantages

One advantage with the use of composite materials is that they are relatively light weight. Handling composites during fabrication and construction is much easier due to their light weight. Therefore, use of composites provides the opportunity to use single large cables rather than many smaller cables for prestressing applications. It would be necessary to increase the anchor length in order to develop the friction forces to resist a larger cable force. As discussed above, efficiency is gained in developing the friction forces and evenly distributing them over the cable surface with use of the swaged anchor with a braided tape cable. This system provides the potential of using only one cable rather than a set of cables to generate a desired force.

Another advantage is acquired with the use of a flat cable at hold-down points for harped tendons or as draped tendons in prestressed concrete applications. The transverse stresses which are developed in harped or draped tendons are better distributed over the cross section for a flat cable than with a cylindrical cable.

As discussed in Section 3.4 of this report, the use of resins in the anchor design is still questionable due to the lack of knowledge of their long-term behavior. It has been shown that it may be necessary to use a low modulus material, such as a resin, to control the peak shear stress in the cable. However, with the design of the swaged anchor, the transfer of stress is achieved as a result of the applied transverse clamping stress. Since it is not necessary to develop a bond between the cable and the filler material, the material selection is not limited to resins or other adhesive materials. Various materials, such as neoprene, can be investigated and it may be determined that they are more reliable or that their long-term behavior is better understood.

The stressing operations required with the use of the swaged anchor with a braided tape cable may render a disadvantage for this anchor design. As discussed in Section 5.2.3, additional space is utilized by the anchorage system due to the stretch of the cable if the anchor is pre-assembled and then pulled. However, if two sets of anchors are used, the problem arises of drilling and setting the permanent anchor while the cable is in its stressed condition.

Another disadvantage with this anchorage design arises if the cable encounters an increase in axial stress during its use. The axial stress in the cable may rise, such as with prestressing tendons as more load is applied to the beam. If this occurs, the cable will contract in the transverse direction due to the poisson effect. The contraction will be most significant where the cable first enters the anchor and the axial stress is still high. The potential impact this contraction has on the anchor is a loss of prestress in the bolts. The low modulus filler material can be used in the system to reduce the amount of bolt prestress loss. It should also be noted that if a stressing operation similar to option 1 discussed in the previous section is used, the contraction due to poisson's effect must be taken into account in the initial determination of required bolt force.

The need for many components of the anchor (i.e. plates, bolts, and possibly filler material) is another disadvantage with this system. If the anchor is assembled in the fabrication shop prior to installation of the cable, this concern is not as significant. However, assembly of such an anchorage system in situ may be time consuming, complicated, and may result in improper installation.

5.3 Plug-in Cone Anchor With Braided Tube Cable

5.3.1 Design Objectives

The concept of the plug-in cone anchor was introduced in Section 3.4.2 of this report. A "barrel and spike" termination, which is based on the plug-in cone anchor concept, has been used for tests and applications of Parafil ropes, which are ropes made from parallel filaments of yarn within a thermoplastic sheath (Burgoyne 1992). A similar anchor design could be effectively employed with a braided tube at the end of the cable, as shown in Figure 5.11. The cone is used to compress the braid within the housing and allow the friction to develop the tensile strength of the cable. The braid may be impregnated with a resin or covered within a thermoplastic sheath to protect the fibers from surface damage due to the anchorage hardware. If unidirectional fibers are used, there is an opportunity for the fibers to bunch in one area or for the spike to be misplaced so as not to be centrally located within the fiber bundle. With use of a braid, the cable is guaranteed to be uniform over the cross-section and the cone can be easily placed in the center of the tube.

5.3.2 Stressing Operations

In order to apply the prestress in the cable, it is necessary to modify the anchor housing at the jacking end, as shown in Figure 5.12. An internal and external thread could be provided at the end of the housing to facilitate the jacking and locking process. The basic steps in this stressing procedure are shown in Figure 5.13. First, the cable is installed within the duct of the structure or anchoring block. A pull-rod, which is connected to the internal threads of the anchor housing, is passed through the center hole of a hydraulic jack. The jack is used to apply the prestressing force and elongate the cable. A lock nut is then threaded on the external threads of the anchor housing to transfer the stress to the anchorage block or structure.

5.3.3 Potential Advantages and Disadvantages

There are many advantages and disadvantages with the concept of the plug-in cone anchor with a braided tube cable. The main advantage is there is no use of resin in the anchorage system. As discussed in Section 3.5 of this report, the long-term behavior of resins is unknown and resins are a potential weak link in many anchor designs currently proposed for non-metallic cables.

A second advantage with this anchorage concept is the amount of flexibility offered in the field. The anchorage assembly can be put together either in the shop or in the field. Therefore, the exact length of the cable does not necessarily have to be specified prior to installation. The placement of the cone is simplified by the use of a braided tube which keeps all the fibers in place. In other words, there is no need to individually separate the fibers to ensure proper placement of the cone within the center of the fibers and obtain even distribution of the fibers over the cross section. The installment of the anchorage hardware is relatively quick and simple and there is no need to wait for resin to set before the stressing operation can begin.

The design relies on the development of friction to resist the force in the cable. More force can be resisted by increasing the length of contact between the cone and cable within the housing. However, the length of the anchorage system is limited by the available space near the anchorage region. Therefore, for applications with large cable forces, it may be necessary to use several cables to achieve the desired force. A disadvantage of this anchorage system is that the stressing operation outlined in the previous section can not be easily modified to accommodate stressing several cables at once. A commonly used method to stress several cables at one time is to use two sets of anchors: a temporary set is pushed by a jack while a permanent set is used for final transfer of the force to the structure, as shown in Figure 5.14. However, because the cone is placed on the inside of the fibers for the plug-in cone anchor, access to the cone for final setting within the housing of the permanent anchor would be limited with the use of two anchorage sets as described above.

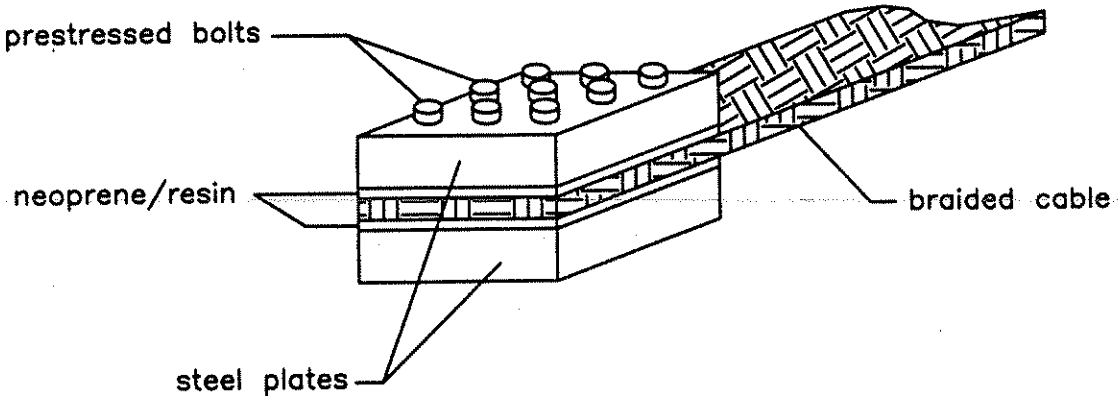


Figure 5.1: Swaged anchor with braided tape cable

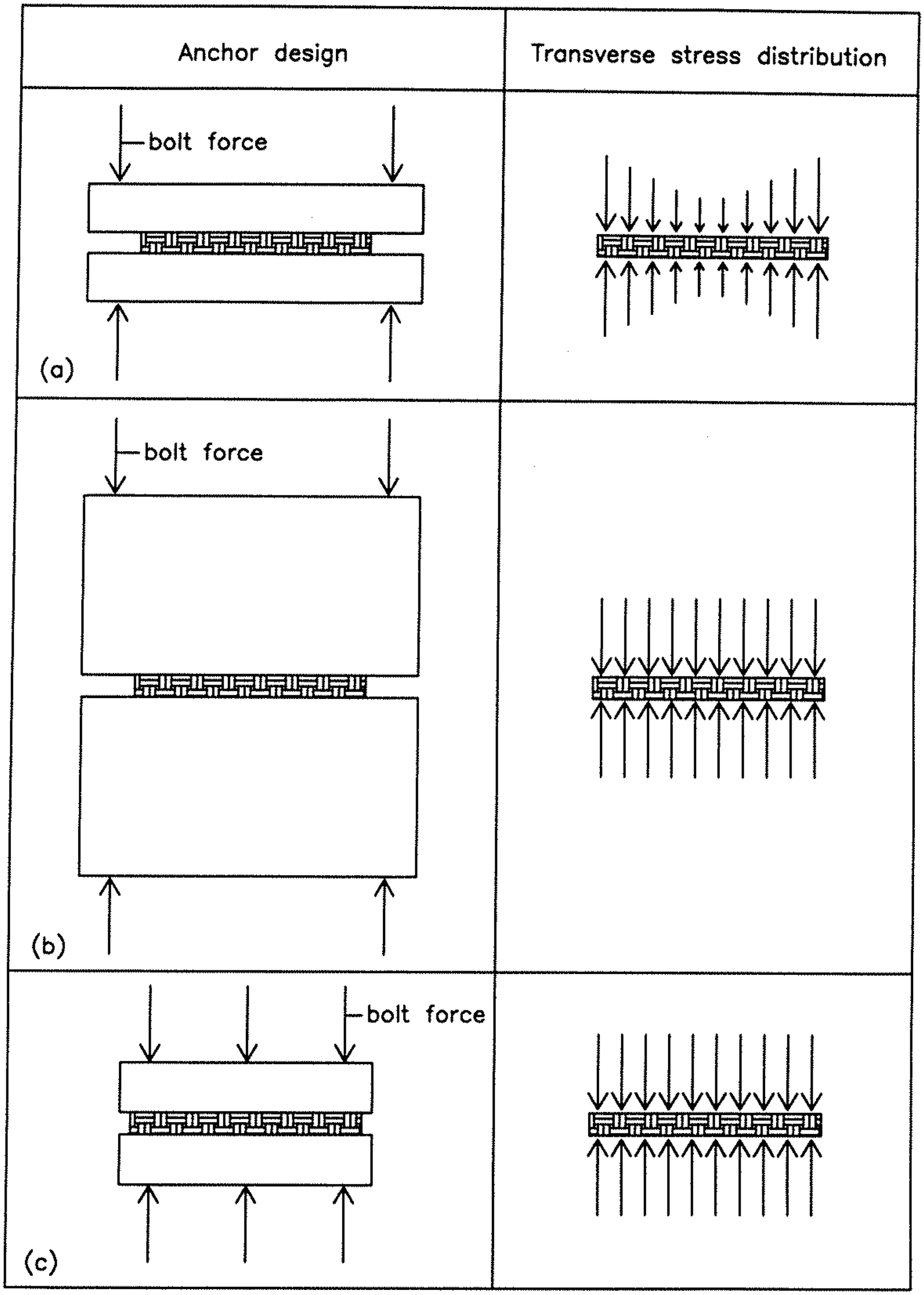


Figure 5.2: Effect of bolt location and block size on transverse stress distribution

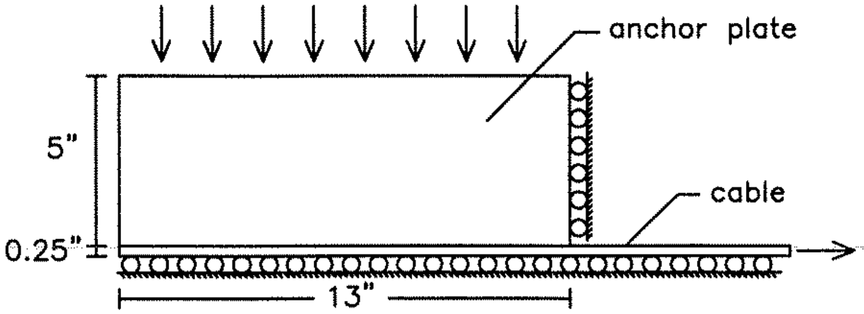


Figure 5.3: Finite element model for swaged anchor

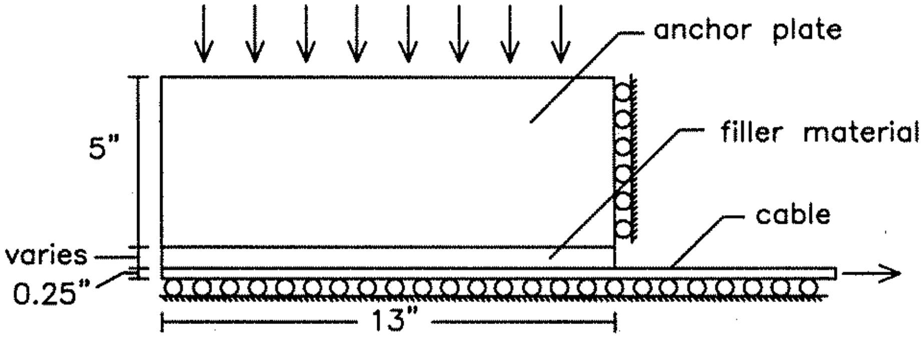


Figure 5.4: Finite element model for swaged anchor with layer of filler material

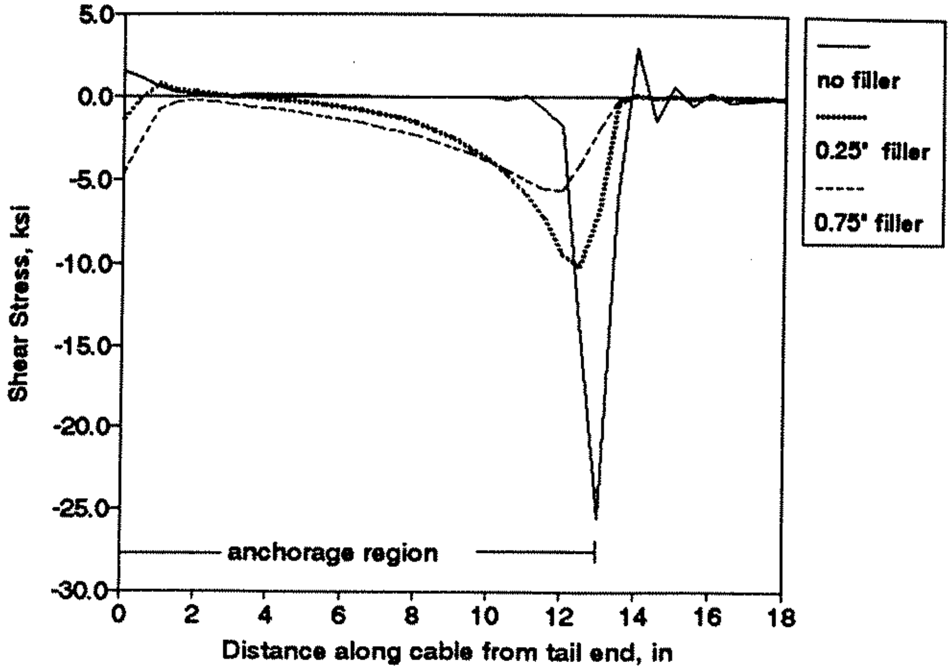


Figure 5.5: Shear stress along cable for anchor with (1) no filler material, (2) filler thickness of 0.25" and (3) filler thickness of 0.75"

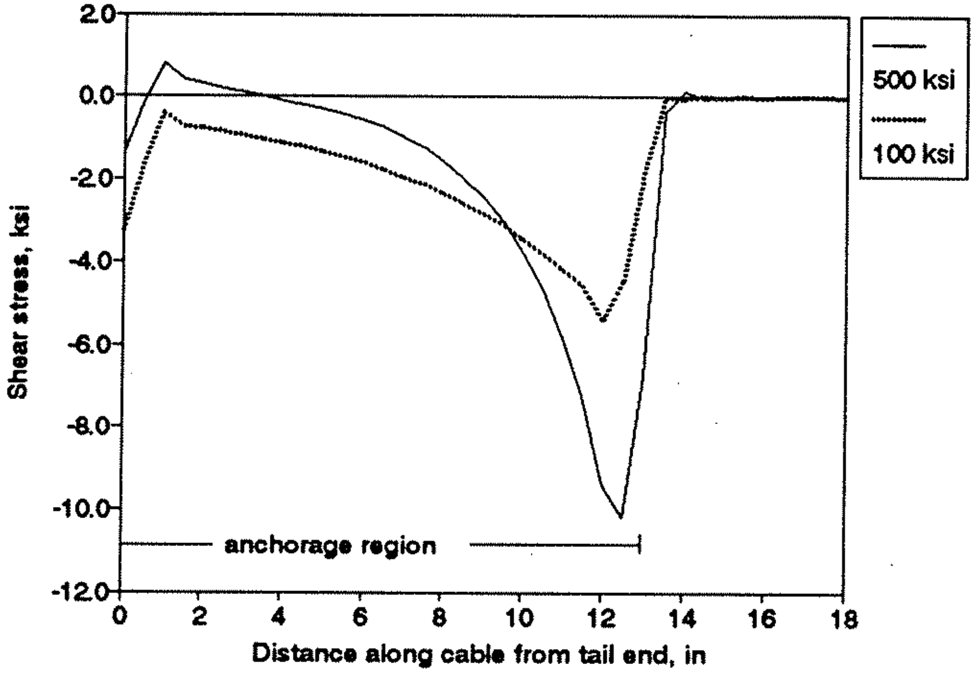


Figure 5.6: Shear stress along cable for anchor with filler modulus of elasticity of (1) 500 ksi and (2) 100 ksi

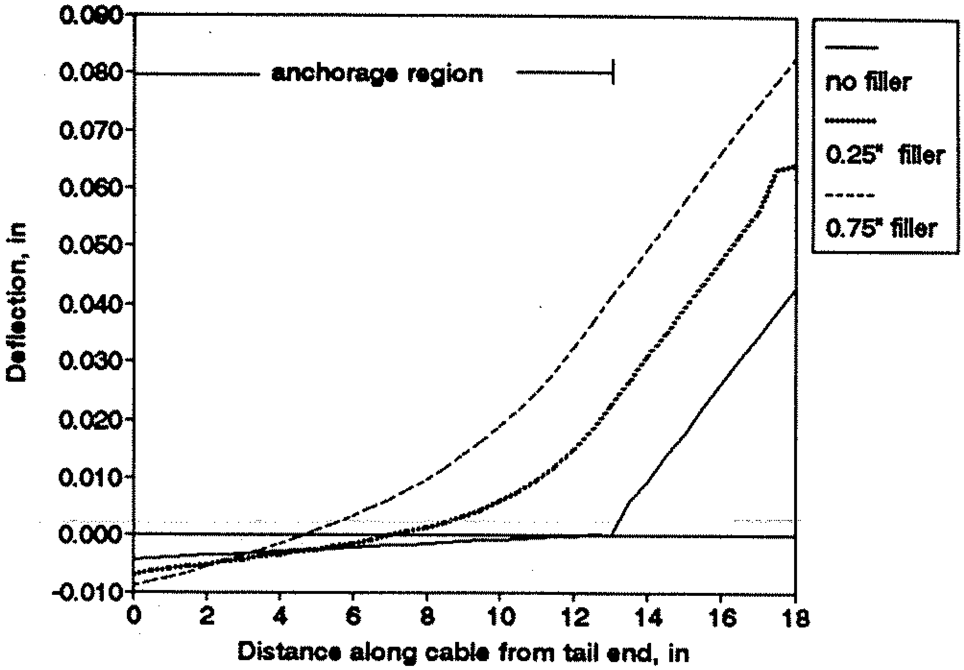


Figure 5.7: Deflection along cable for anchor with (1) no filler material, (2) filler thickness of 0.25" and (3) filler thickness of 0.75"

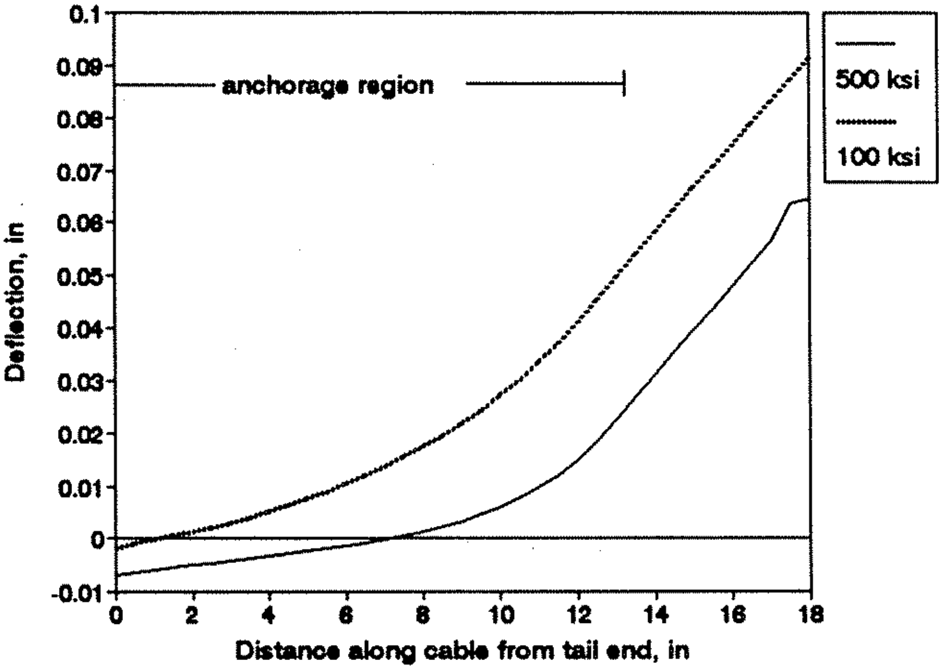
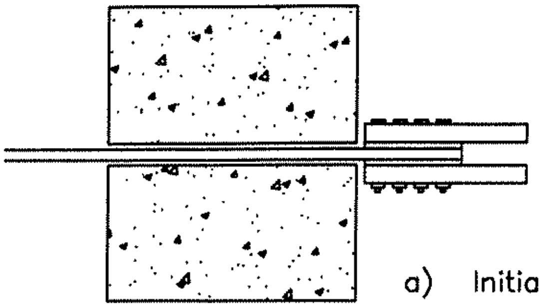
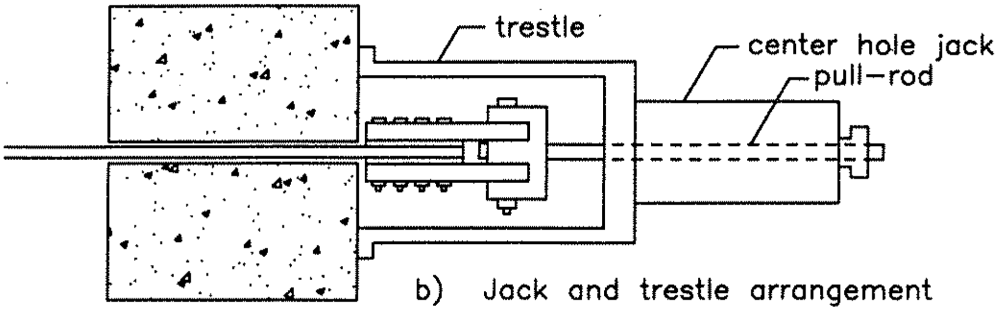


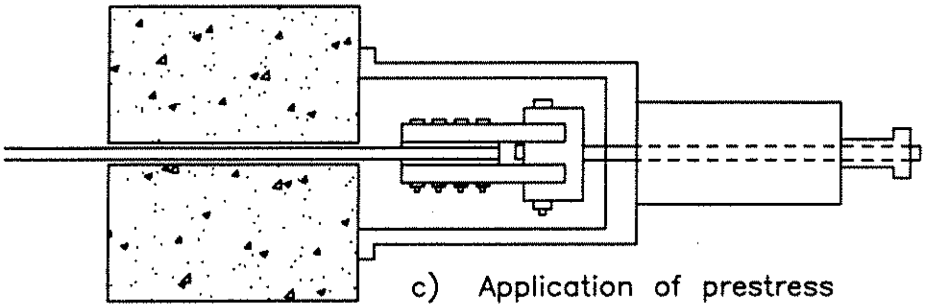
Figure 5.8: Deflection along cable for anchor with filler modulus of elasticity of (1) 500 ksi and (2) 100 ksi



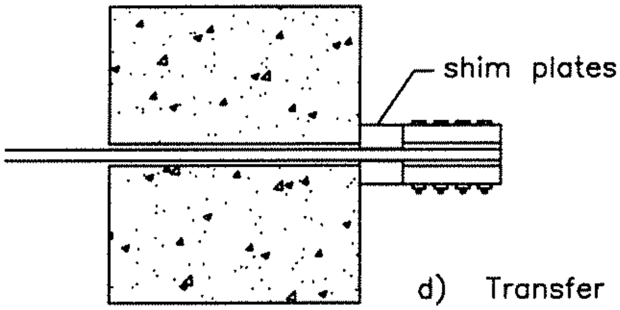
a) Initial tendon placement



b) Jack and trestle arrangement

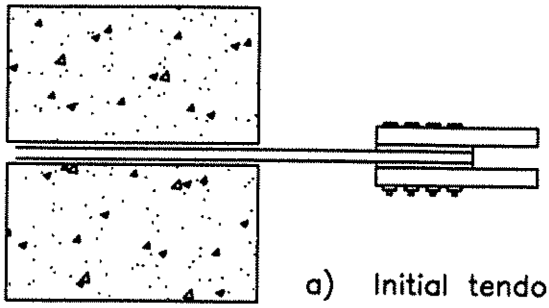


c) Application of prestress

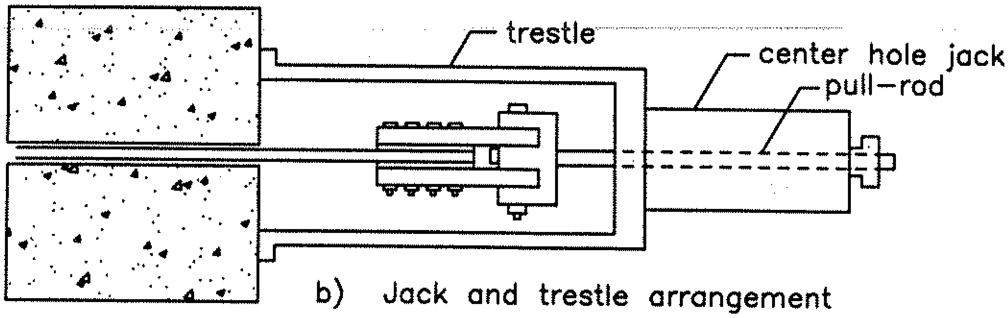


d) Transfer of prestress to structure

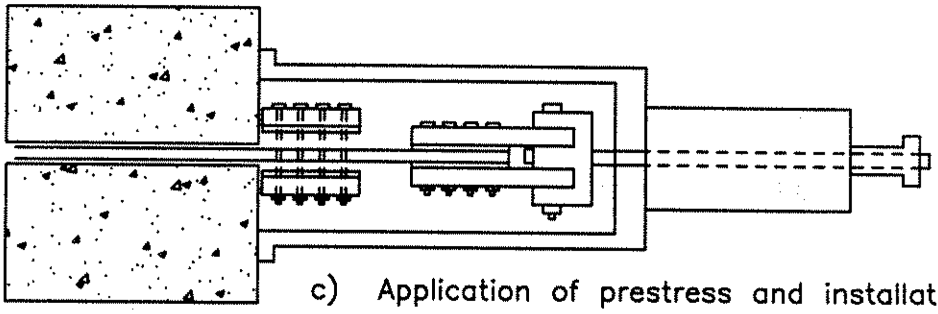
Figure 5.9: Prestressing procedure for swaged anchor (option 1)



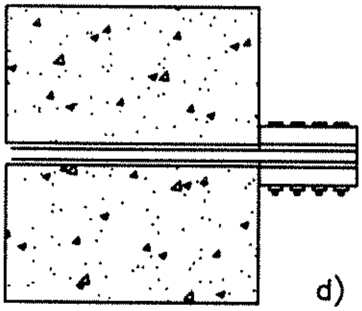
a) Initial tendon placement



b) Jack and trestle arrangement



c) Application of prestress and installation of permanent anchor



d) Transfer of prestress to structure

Figure 5.10: Prestressing procedure for swaged anchor (option 2)

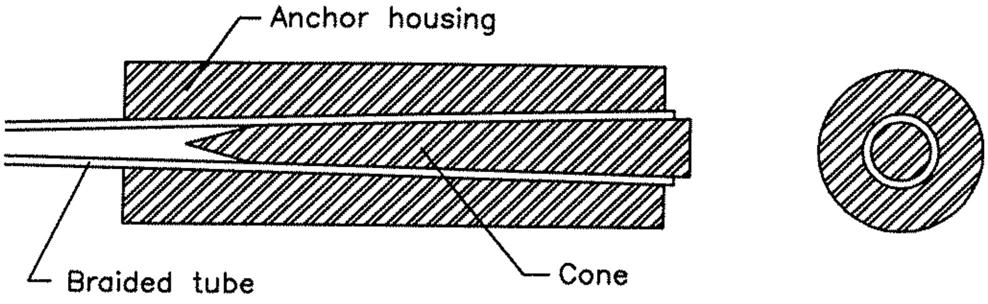


Figure 5.11: Plug-in cone anchor with braided tube cable

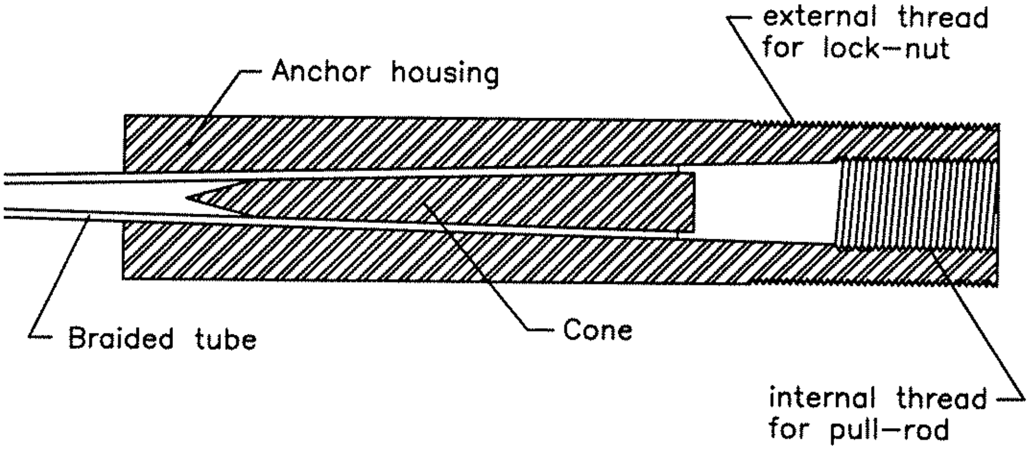
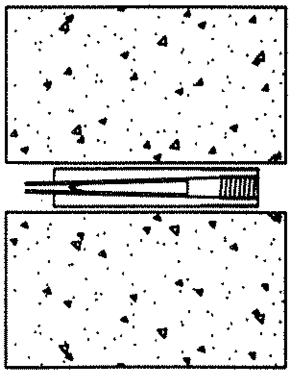
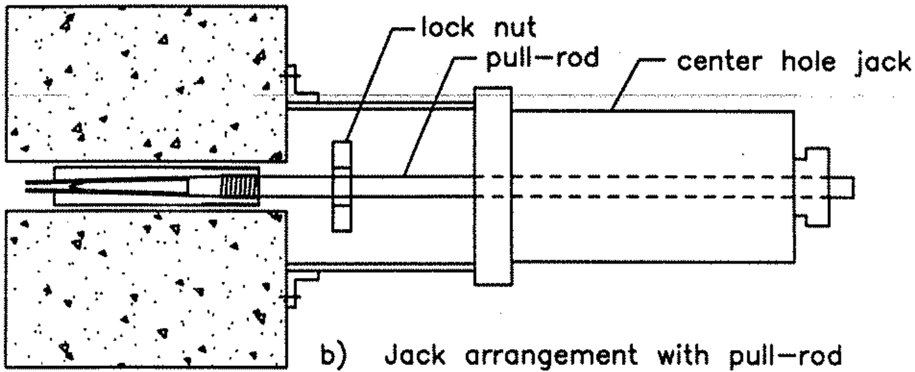


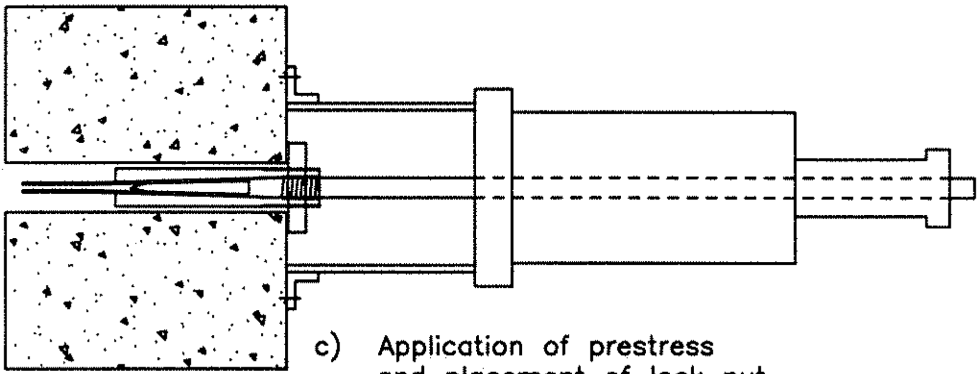
Figure 5.12: Plug-in cone anchor modified for stressing operation



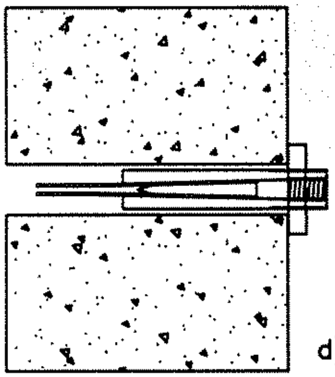
a) Initial tendon placement



b) Jack arrangement with pull–rod connected to anchor housing



c) Application of prestress and placement of lock nut



d) Transfer of prestress to structure

Figure 5.13: Prestressing procedure for plug-in cone anchor

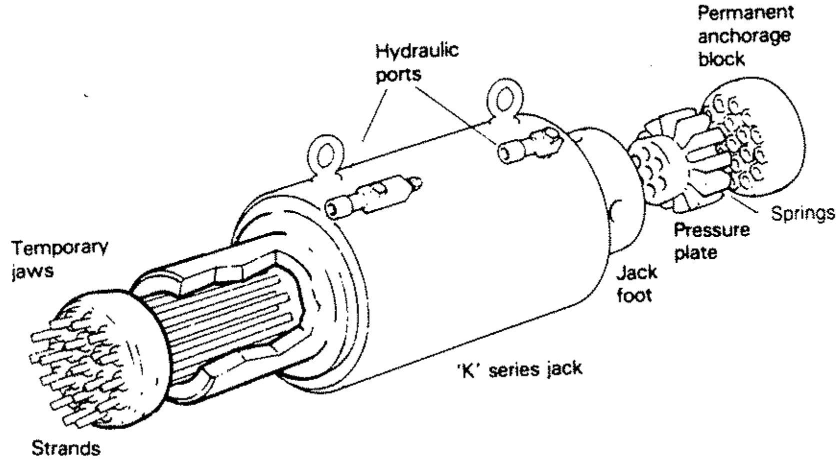


Figure 5.14: Typical installation of wedge anchors for steel tendons with temporary and permanent anchor sets (Post-Tensioning Institute 1985)

CHAPTER 6
MODELING APPROACHES FOR ANALYSIS OF BRAIDED STRUCTURES

6.1 Introduction

Engineering design and analysis of braided composite structures is extraordinarily complex. The intricate microstructure of the interlacing yarns in addition to the fiber properties, matrix properties and the fiber-matrix interface must be considered. Traditional finite elements may be used to analyze a braided structure, however, the number of elements required to adequately model the various material properties and orientation of those properties at each element location makes this approach impractical.

Many methods of simplifying the analysis and design processes of textile composites have been introduced. Some of the analytical methods are used to determine average elastic constants of the textile fabric. These methods include the Stiffness Averaging Method (Kregers 1978), a modified classical laminate theory (Ishikawa 1982) and the Fabric Geometry Model (Whyte 1986). Other analytical approaches involve finite element methods, such as the use of Macro Finite Elements (Whitcomb 1994). Computer-aided geometric modelling (CAGM) can also be used to characterize the fiber architecture of three-dimensional braids. CAGM in conjunction with finite element procedures has been used to predict the mechanical behavior of three-dimensional braided composites (Lei 1992).

A task in this research effort is to review modeling approaches which may be used to effectively analyze braided composite anchorage components. The purpose of an analytical approach in this research is to assist refinements in the anchorage design prior to experimental testing. The models should be relatively simple yet able to adequately predict the mechanical behavior of the anchorages. Two approaches appear to be viable methods for such modeling: The Fabric Geometry Model, which was developed at Drexel University, and the use of Macro Finite Elements which were introduced by researchers at Texas A&M. Each of these approaches will be discussed briefly in this chapter.

6.2 Fabric Geometry Model

The Fabric Geometry Model (FGM) was developed at Drexel University to obtain approximate elastic constants for analysis and design of braided composite fabrics. The FGM is based on a modified laminate theory and requires knowledge of the fiber properties, matrix properties and the fiber architecture.

A unit cell is used to describe the fiber structure for the braided fabric, as shown in Figure 6.1. A general braided fabric consists of three yarn components: the triaxial system (0°) shown as the striped yarns, and the two bias systems ($+\theta$, $-\theta$) shown as the shaded yarns. A fractional volume for each system of yarns in the unit cell is determined based on yarn size, ends per inch and stitch type.

A stiffness matrix for each system of yarns is obtained by transforming a stiffness matrix for a comparable unidirectional composite material through the following equation:

$$[C_i] = [T_{\Sigma,i}][C][T_{\Sigma,i}]^{-1} \qquad \text{(Equation 6.1)}$$

where $[C_i]$ is the stiffness matrix of the ith system of yarns
$[C]$ is the stiffness matrix of a unidirectional composite
$[T_{\varepsilon,i}]$ is a transformation matrix based on various sines and cosines of the orientation angle of the ith system of yarns

The total stiffness matrix for the braided structure can be obtained by the summation of each $[C_i]$ multiplied by the fractional volume of the ith system of yarns. Details of these equations can be found in (Chou 1989). The resulting stiffness matrix is strain dependent due to the potentially nonlinear behavior of the matrix material and the distortion of the fabric geometry (Pastore 1988).

A failure point for each system of yarns is calculated by using the maximum strain energy criterion (Pastore 1988). When a system of yarns is determined to fail, its contribution to the stiffness matrix is removed. Failure of the braid is indicated by failure of the last system of yarns.

6.3 Macro Finite Elements

The development and use of macro finite elements are being studied at Texas A&M University (Whitcomb 1992 and 1994). The concept of macro elements was formulated to model heterogeneous materials, particularly the complex microstructure of textile composite fabrics. The main advantage of this modeling approach for the analysis of braided structures is that the microstructure of a braid is accounted for within a practical number of elements.

Fewer elements are necessary to model a composite braid with the use of macro finite elements than when traditional finite elements are employed. A traditional element must be defined for each boundary of a type or orientation of the material properties. However, a macro element contains subelements for the changes of material properties within the element. A macro element is identical to a traditional element when it has only one subelement. An example of a macro element is provided in Figure 6.2. The large numbers (1-4) represent the macro element node numbers and the circled numbers label each of the subelements. Subelements 2, 5 and 9 might represent the direction of one braiding yarn while the other subelements are used to describe the path of other braiding yarns.

The material properties vary smoothly within each subelement and interpolation functions are used to map these properties onto a new co-ordinate system to facilitate the integrations in determining the stiffness matrix. A similar process is performed for traditional finite elements in which an element in the x-y system is mapped into the ξ-η system. An additional step is necessary with macro elements to map into an r-s system. The whole process is shown in Figure 6.3 (a), (b) and (c). Details of this mapping can be reviewed in papers on macro finite elements (Whitcomb 1992 and 1994).

In an actual model, a pattern would be chosen because it is repeated in the braided structure. If traditional elements had been used to model the same pattern of that shown in Figure 6.2, ten elements (like the ten subelements) may have been necessary to obtain the same description provided in the one macro element. When this pattern is repeated over the structure being modeled, the reduction in the number of elements required becomes substantial. Fewer elements require less computer time and space when the program is executed.

Local stress distributions near the material interfaces, or subelement boundaries, are not accurately determined due to a violation of equilibrium at those interfaces from the approximations which are used. It is recommended to use traditional finite elements if a local analysis is desired (Whitcomb 1994). However, initial tests have shown that macro elements perform very well for a global analysis. A comparison has been made of traditional and macro elements to predict the deformed shape of a single plain weave mat (Whitcomb 1992). 120 traditional elements and 4 macro elements produced virtually identical deformed shapes. The reduction in elements from use of macro elements can be used to expedite the global analysis process.

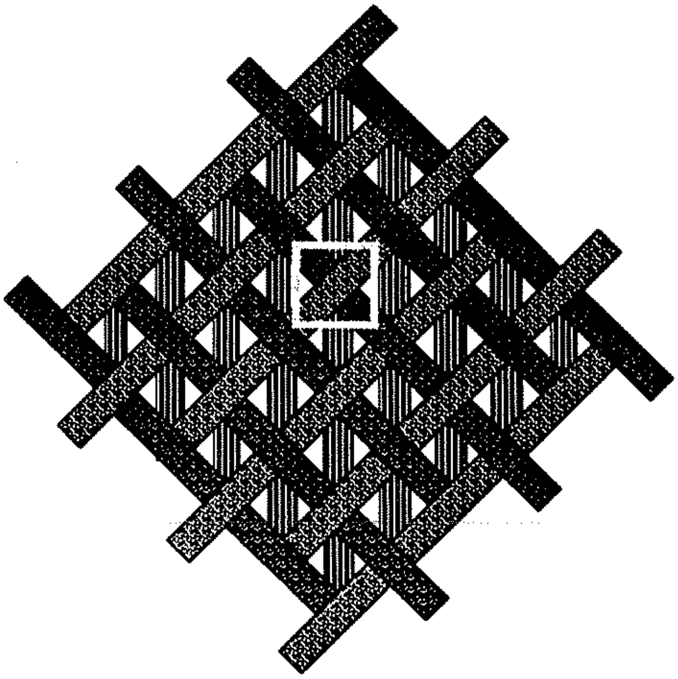


Figure 6.1: Unit cell of a braided fabric (Pastore 1988)

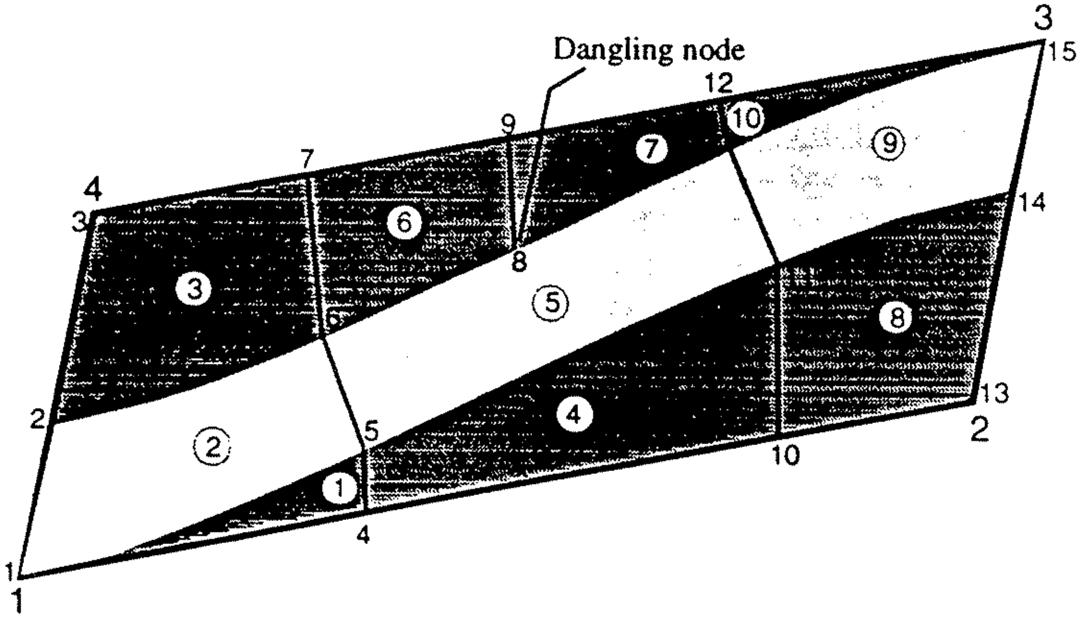


Figure 6.2: Macro element with 10 subelements (Whitcomb 1994)

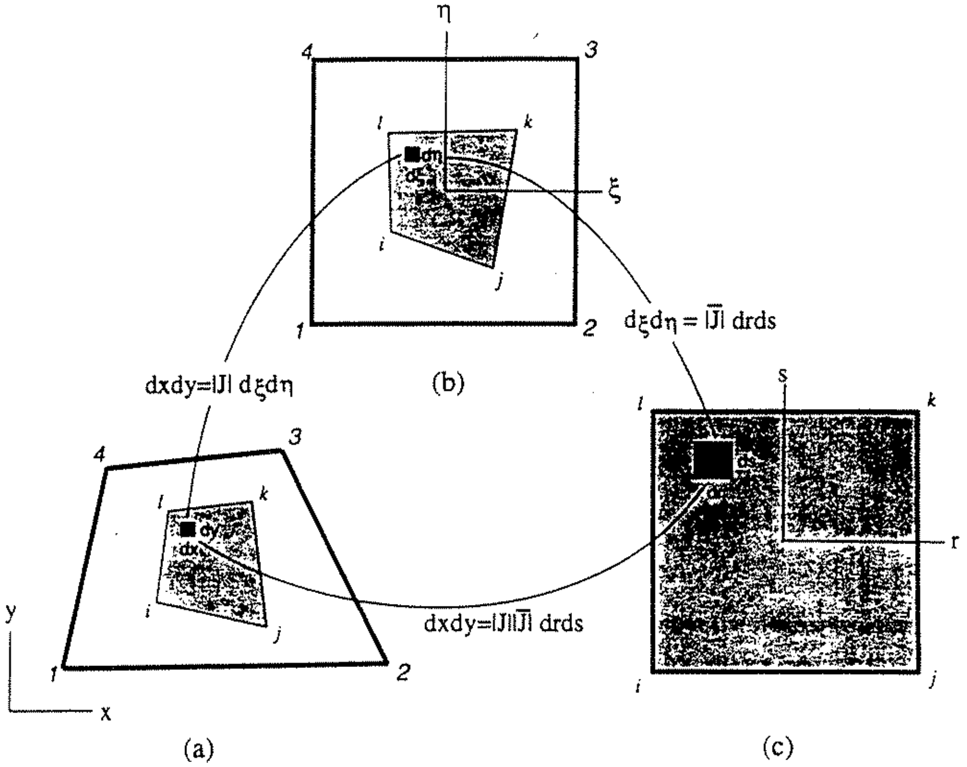


Figure 6.3: Mapping between three co-ordinate systems (Whitcomb 1993)

CHAPTER 7
SUMMARY OF FINDINGS

7.1 Summary

Due to the unique properties of composite materials, anchors for non-metallic composite cables must be modified from conventional steel anchor designs. Consequently, the anchorage of composite cables has been the subject of many research efforts. Variations on six anchorage concepts comprise the presently suggested methods of anchoring non-metallic composite cables. The six anchorage concepts include the split wedge, plug-in cone, resin sleeve, resin potted, soft metal overlay, and swaged anchors. Each of these concepts is briefly discussed in Section 3.4 of this report. Although many of these anchors have exhibited good performance in tests and some have been successfully employed in actual structures, further investigation is needed to uncover more efficient and reliable methods of anchoring composite cables. It is found from this research that braiding technology with composite materials offers some opportunities to improve the efficiency and performance of anchors for non-metallic cables.

7.1.1 Opportunities with Braiding

Most of the opportunities gained by use of braiding pertain to the inherent properties or features of the braiding process. Low cost and high productivity of manufacturing braided shapes result from the use of computer aided design and manufacturing. Therefore, braiding cables may be more efficient than if other manufacturing techniques are used for their production. In addition, braided cables have more through-thickness strength than unidirectional cables. This property is useful in the anchorage region where high shear and transverse tensile stresses are present. Surface roughness is also provided on braided cables as a result of the interlacing of yarns. Deforming a cable's surface is one method of improving its bond characteristics. This feature is useful where a strong bond with the cable is required, such as where resins are used in the anchor design or with pretensioned prestressed concrete. The damage tolerance of braided shapes is another useful property in civil engineering applications. Damage could be incurred during transporting and handling of the cable or due to vandalism or accidental impact while the cable is in use.

The current methods of anchoring unidirectional cables can be used for braided cables. Experimental tests may show that the anchor performance is improved by exploiting the properties offered by the braiding process mentioned above. However, given equivalent fibers, matrix and fiber volume fraction, a braided cable would not possess as much axial strength as a unidirectional cable since not all fibers are placed in the axial direction. This is a disadvantage with the use of braided cables which may overshadow the benefits mentioned above. In any case, the nature of the braiding process allows for a change in the braid geometry through the length of the braid. Therefore, the braid angle can be high in the anchorage region where high through thickness strength is needed, and the angle can be lowered gradually or transferred to unidirectional fibers as more axial strength is necessary away from the anchor.

Details of two possible methods for anchoring braided cables are presented in this report. They include the swaged anchor with a braided tape cable and the plug-in cone anchor with a braided tube cable.

7.1.2 Swaged Anchor with Braided Tape Cable

The swaged anchor introduces the concept of ensuring uniform distribution of transverse stress to improve the friction between the cable and anchor components by using bolts through the cable itself. The use of a braided shape provides the ability to drill holes through the cable without causing significant damage. The flat rectangular shape offers a better surface area to volume ratio than a circular cross-section. With circular shapes, the amount of force which can be developed in one cable is limited due to the anchor requirements. Friction forces are developed in the outer region of the cable to resist the cable force. But if the cable diameter is too large and the cable force is too high, the inner fibers of the cable would not be sufficiently anchored. With the swaged anchor concept, the width of the cable can be increased to obtain a larger force. It is only necessary to use larger anchor plates and more bolts to develop the necessary resisting friction forces. This advantage enables the use of fewer cables to develop a specified force. And because composite materials are generally much lighter than steel, the weight of a single large cable is not as significant when considering transportation and handling concerns. The flat shape of the cable is also able to better distribute the transverse stresses which result at harp points or where draped tendons are used.

7.1.3 Plug-in Cone Anchor with Braided Tube Cable

The second anchor concept presented in this report is the plug-in cone with a braided tube cable. With this anchor, a cone is used to compress the braided tube within an anchor housing and use the developed friction to resist the force in the cable. Because the structure of the braid maintains the fibers in a tubular shape, placement of the cone in the center of the braided tube is guaranteed. The main advantage with this anchorage system is there is no use of resin.

For verification and further development of the ideas presented in this report, experimental tests are necessary. Numerical modeling of the anchor designs would enable refinements prior to experimental testing. However, the analytical tools for engineering design and analysis of braided composite structures are limited. Therefore, it is recommended to continue simple parametric studies with the necessary assumptions and perform experimental tests to improve the anchor designs.

CHAPTER 8
SUGGESTIONS FOR FURTHER DEVELOPMENT

8.1 Introduction

Braiding technology with composite materials offers many advantages for applications in civil engineering. In order to fully exploit these advantages, continued research in the use of braided composite shapes is necessary. This chapter suggests some of the areas of further development of the concepts presented in this report as well as the more general future opportunities with use of braided composites in civil engineering.

8.2 Use of Braiding in Anchorage Systems

8.2.1 Variations on Swaged Anchor with Braided Tape Cable

Many variations may be considered for further development of the swaged anchor with a braided tape cable. The results of a finite element study of the behavior of the anchor are presented in Section 5.2.2 of this report. These results show that a reduction in the peak shear stress on the cable at the front end of the anchorage region can be achieved by use of a thicker layer of filler material or a filler material with a lower modulus of elasticity. However, either of these alterations result in a larger deflection of the cable within the anchorage region. One method to overcome these problems is to use a large thickness of filler material at the front of the anchor to reduce the peak shear stress, then gradually lower the thickness toward the tail end of the anchor. A second method is to vary the modulus of elasticity of the filler material from the front to the tail end of the anchor. A very low modulus material can be used at the front of the anchor while a higher modulus is used deeper within the anchorage region. In addition, the effect of varying the transverse clamping stress along the length of the anchorage should be studied.

8.2.2 Experimental Testing

Experimental testing is an important step in the development of anchorage systems with braided composite cables. Tests are required to compare the performance of anchorage systems with braided versus unidirectional composite cables. Tests are also necessary to determine the adequacy of the swaged anchor and the plug-in cone anchor concepts presented in this report. Long term tests should be performed to determine the fatigue, creep, and relaxation behavior of the braided cables and the anchorage system. Tests to evaluate the effects of extreme temperature and different coefficients of thermal expansion are also needed. Finally, the reaction of the composite cables and materials used in the anchor designs to various environmental factors should be studied.

8.2.3 Material Properties

Lack of ductility is a problem which is common with many of today's high strength materials. The ability to provide warning of impending failure is an important feature of materials used in civil engineering applications. Although the modulus of elasticity of composite materials is typically lower than that of steel, the ultimate strain at failure is much lower. Sufficient warning may not be provided before failure of a composite component occurs. The ductility issue should be studied further to overcome the concern of catastrophic failure.

A property of composite braids which also needs to be further reviewed for particular applications is the relatively low modulus of elasticity. This property may be useful in some applications and detrimental in others. For example, the low modulus of elasticity may help control the amount of loss of prestress due to creep in prestressed concrete. However, a low modulus may be a concern with excessive elongation during stressing operations.

8.3 Potential Applications in Civil Engineering

The relatively high cost of composites compared with conventional structural materials is one issue which is slowing their widespread use in civil engineering applications. The increased cost must be weighed against the advantages which are gained with use of composites. For example, there is no need for corrosion protection with composites while this is an additional cost which must be considered with steel members. However, methods of reducing the material costs should be recognized in order to make composites more attractive alternative materials. Braiding technology with composite materials is more cost effective than other manufacturing techniques for composite shapes due to automation and computer aided design and manufacturing.

The particular application studied in this research is the use of braided composite cables. Their high strength and corrosion resistant nature may be useful for such structures as prestressed concrete, cable stayed bridges, suspension bridges, guy wires, or mooring cables for deep sea structures. Further investigation may reveal other applications where composite cables may be useful.

The properties offered by braiding with composite materials may be particularly useful for many applications in civil engineering. For example, a significant advantage with braiding technology is the opportunity to improve the performance of connections. High through-thickness stresses are frequently developed in the connection region. Therefore, the high through-thickness strength of braided shapes may be useful. In addition, connections which require holes for fasteners are a problem with laminate composites because drilled holes tend to cause delamination of the material. With braided shapes, it is possible to provide integrally braided holes which are much stronger in pin loading than holes which are drilled in laminate composites. Hence, standard connections which rely on bolts through holes in the members can be used for braided composites.

The interest in composite materials in civil engineering applications is expanding mostly because of their corrosion resistant nature, high strength and light weight. However, relatively little is known about the behavior and long term performance of composites in civil structures as compared with conventional structural materials. Further research is necessary to enhance the knowledge base of the behavior of composites before they can be safely employed in widespread use in civil engineering.

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