Composite Circular Braid Mechanics

by

Robert Houston Hopper, Jr.

Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Engineering Mechanics

APPROVED:

J. Wallace Grant, Chairman

Odis H. Griffin, Jr.

Saad A. Ragab

Peter Popper

August 1991

Blacksburg, Virginia

c.2

LD
5655
V855
1991
H666
c.2

COMPOSITE CIRCULAR BRAID MECHANICS

by

Robert Houston Hopper, Jr.

(ABSTRACT)

Braided composites find many diverse applications in modern technology and tailoring the mechanical properties of these structures has become increasingly important. This thesis will examine one class of circular braids encompassing an elastic core. By hypothesizing four modes of operation and incorporating primary influences, the mechanical response of the composite is predicted based on its initial parameters and material properties. The ability to model the yarns that constitute the braid as nonlinear materials enables the simulated response to span finite deformations. A scheme for nondimensionalizing the model parameters and governing equations for each mode of operation is also proposed and implemented.

In an effort to validate the assumptions underlying the model's formulation, a series of experimental trials are documented that verify the fundamental braid mechanics. A wide variety of analytical cases are also introduced to investigate the influences of various model parameters. Possible extensions for the existing model are also noted.

ACKNOWLEDGEMENTS

The completion of this thesis would have been impossible without the assistance of several people to whom I am deeply indebted. Dr. Peter Popper at DuPont introduced me to textile technology and provided guidance in the early phases of this undertaking. It is my sincerest hope that this project will find utility and application in his future work. I would also like to thank my advisor, Dr. J. Wallace Grant, for his patience and guidance during revision. The aid and expertise of Bob Simonds during the experimental phase was also invaluable. In addition, I would like to thank Dr. and Mrs. Charles Nunnally who graciously allowed me to use their computing facilities. Without their assistance this portion of the project would never have been possible.

Finally, I would like to express the deepest gratitude to my parents who provided love and support while making the sacrifices that permitted me the opportunity to pursue my own dreams and goals. My achievements will always reflect their success.

TABLE OF CONTENTS

1.0 Composite Circular Braid Mechanics 1

1.1 Introduction 1

1.2 Problem Formulation 2

1.3 Literature Review 3

1.4 Overview 5

2.0 Model Formulation 6

2.1 Introduction 6

2.2 Dimensional Composite Parameters 13

2.3 Nondimensionalizing Parameters 15

2.4 Nondimensional Composite Parameters 16

2.5 Mode Transition Criteria 20

2.6 Modeling Overview 23

2.7 Mode One Equation Development 25

2.8 Mode Two Equation Development 27

2.9 Mode Three Equation Development 35

2.10 Mode Four Equation Development 37

2.11 Mode Summary 37

2.12 Output Parameters 38

2.13 Model Implementation 40

2.14 Program Features 40

3.0 Experimental Model Validation 45

3.1 Introduction 45

3.2 Core and Yarn Property Determination 48

3.3 Experimental Composite Testing 53

3.4 Theoretical and Experimental Comparison 57
3.5 Experimental Limitations 73

4.0 Nondimensional Parameter Influences on Composite Response 75
4.1 Introduction 75
4.2 Core Effects on Composite Response 75
4.3 Braid Angle Influences on Composite Response 82
4.4 Poisson Ratio Influences on Composite Response 99
4.5 Wall Thickness Ratio Influences on Composite Response 103
4.6 Core/Inner Braid Radius Ratio Influences on Composite Response 108
4.7 Yarn Aspect Ratio Influences on Composite Response 108
4.8 Yarn Packing Factor Influences on Composite Response 113
4.9 Core Packing Factor Influences on Composite Response 116
4.10 Cover Factor Influences on Composite Response 116
4.11 Modulus Ratio Influences on Composite Response 122

5.0 Summary and Conclusions 126
5.1 Introduction 126
5.2 Observations 127
5.3 Extensions and Recommendations 127
5.4 Conclusions 128

References 129
Bibliography 130
Appendix A 133
Appendix B 173
Vita 208

LIST OF ILLUSTRATIONS

Figure 1. Commercially Available Braid with 25 Picks per Inch 7

Figure 2. Typical Braid and Associated Parameters 11

Figure 3. Ideal Composite Cross-Section Illustrating Macro-Geometry 12

Figure 4. Fundamental Braid Unit Cell Micro-Geometry 14

Figure 5. Modes of Operation 21

Figure 6. Locked Braid 24

Figure 7. Helically Wound Yarn 30

Figure 8. Braided Dacron* Composites with Different Core Diameters 46

Figure 9. Actual Composite Cross-Section 47

Figure 10. Yarn Mounting Technique for Experimental Testing 49

Figure 11. Dacron* Fiber Properties 51

Figure 12. Experimental Verification - Braid Only 52

Figure 13. Experimental Verification and Failure Prediction - Braid Only 55

Figure 14. Theoretical Mode Transitions - Braid Only 56

Figure 15. Experimental Data 58

Figure 16. Experimental Verification - Specimen 4C 59

Figure 17. Experimental Verification and Failure Prediction - Specimen 4C 61

Figure 18. Theoretical Mode Transitions - Specimen 4C 62

Figure 19. Experimental Verification - Specimen 8A 63

Figure 20. Experimental Verification and Failure Prediction - Specimen 8A 65

Figure 21. Theoretical Mode Transitions - Specimen 8A 66

Figure 22. Experimental Verification - Specimen 12A 67

Figure 23. Experimental Verification and Failure Prediction - Specimen 12A 69

Figure 24. Theoretical Mode Transitions - Specimen 12A 70

Figure 25. Core Effects on Composite and Component Tension Variations 78

Figure 26. Core Effects on Composite and Component Toe-Region Tension Variations 79

Figure 27. Core Effects on Braid Angle and Locking Angle Variations 80

Figure 28. Core Effects on Inner Braid Radius Variations 81

Figure 29. Core Effects on Mode Transitions 83

Figure 30. Core Effects on Cover Factor Variations 84

Figure 31. Nondimensional Composite Tension Variations for Different Initial Braid Angles 85

Figure 32. Dimensional Composite Tension Variations for Different Initial Braid Angles 87

Figure 33. Nondimensional Composite Toe-Region Tension Variations for Different Initial Braid Angles 88

Figure 34. Dimensional Toe-Region Tension Variations for Different Initial Braid Angles 89

Figure 35. Radii Variations for 30 and 50 Degree Initial Braid Angles 90

Figure 36. Radii Variations for 50 and 70 Degree Initial Braid Angles 91

Figure 37. Braid Angle and Locking Angle Variations for 30 and 50 Degree Initial Braid Angles 92

Figure 38. Braid Angle and Locking Angle Variations for 50 and 70 Degree Initial Braid Angles 93

Figure 39. Mode Transitions for Different Initial Braid Angles 94

Figure 40. Cover Factor Variations for Different Initial Braid Angles 96

Figure 41. Radial Core Strain Variations for Different Initial Braid Angles 97

Figure 42. Yarn Strain Variations for Different Initial Braid Angles 98

Figure 43. Nondimensional Composite Tension Variations for Different Core Poisson Ratios 100

Figure 44. Nondimensional CompositeToe-Region Tension Variations for Different Core Poisson Ratios 101

Figure 45. Poisson Ratio Variations with Axial Strain for an Incompressible Cylinder 102

Figure 46. Mode Transitions for Different Core Poisson Ratios 104

Figure 47. Nondimensional Composite Tension Variations for Different Wall Thickness Ratios 105

Figure 48. Dimensional Composite Tension Variations for Different Wall Thickness Ratios 106

Figure 49. Mode Transitions for Different Wall Thickness Ratios 107

Figure 50. Nondimensional Composite Tension Variations for Different Core/Inner Braid Radius Ratios 109

Figure 51. Mode Transitions for Different Core/Inner Braid Radius Ratios 110

Figure 52. Nondimensional Composite Tension Variations for Different Yarn Aspect Ratios 111

Figure 53. Mode Transitions for Different Yarn Aspect Ratios 112

Figure 54. Nondimensional Composite Tension Variations for Different Yarn Packing Factors 114

Figure 55. Mode Transitions for Different Yarn Packing Factors 115

Figure 56. Nondimensional Composite Tension Variations for Different Core Packing Factors 117

Figure 57. Mode Transitions for Different Core Packing Factors 118

Figure 58. Nondimensional Composite Tension Variations for Different Initial Cover Factors 119

Figure 59. Dimensional Composite Tension Variations for Different Initial Cover Factors 120

Figure 60. Mode Transitions for Different Initial Cover Factors 121

Figure 61. Nondimensional Composite Tension Variations for Different Core/Yarn Modulus Ratios 123

Figure 62. Nondimensional Composite Toe-Region Tension Variations for Different Core/Yarn Modulus Ratios 124

Figure 63. Mode Transitions for Different Core/Yarn Modulus Ratios 125

LIST OF TABLES

Table 1. Nomenclature and Notational Conventions 8

Table 2. Mode Determination Criteria 22

Table 3. Dimensional Input Parameters 42

Table 4. Nondimensional Input Parameters 43

Table 5. Model Parameter Summary - Braid Only 54

Table 6. Model Parameter Summary - Specimen 4C 60

Table 7. Model Parameter Summary - Specimen 8A 64

Table 8. Model Parameter Summary - Specimen 12A 68

Table 9. Model Parameter Summary - Base Model 76

1.0 COMPOSITE CIRCULAR BRAID MECHANICS

1.1 Introduction

As composites become increasingly dominant in the world of materials, precisely engineering the properties of these structures becomes more essential. One class of textile structures that finds broad application is the circular braid. This thesis will focus on predicting the mechanical behavior of a composite consisting of a braid whose core is filled with an elastomer. Analysis and modeling efforts are predicated on the interactions and properties of the constituent materials. The composite characteristics are determined by considering the material properties of the constituent fibers, their initial geometric arrangement, and the interactions between the braid and core. Successful modeling will enable composite design to meet specific force/displacement requirements.

In a braided structure, the yarns are incorporated in a self-supporting interconnected network.[1] Each yarn results from the consolidation of many fibers. In typical structures the individual yarns run in interlacing helices. The mechanical response of a braid depends upon its initial parameters and the properties of its constituent materials. If the braided network incorporates spaces, the yarns will freely extend under the action of an axial force until they impinge upon each other. Once the yarns contact each other, the braid is said to be locked or jammed and any additional axial extension must be accompanied by yarn deformation. As a consequence of this phenomenon, the braid's mechanical response is characterized by free extension until locking at which point the the stress-strain response becomes a function of the yarn properties and helix angle. To avoid this abrupt transition, elastic materials may be inserted in the hollow core of the braid. The resulting composite structure exhibits a synergistic mechanical response that cannot be regarded as the mere superposition of its constituents' independent behavior.

In effect, the mechanical response of the composite may be characterized by four distinct modes of operation that are determined by the relationship between the core and

yarns and the geometric configuration of the braid. If the braid has not locked and the inner wall of the braid is not touching the outer wall of the core, the yarns will pivot freely under the action of an axial displacement and only the elastic response of the core resists deformation. This condition defines mode one operation. Once the diameter of the braid contracts enough to contact the core, any additional braid contraction must be accommodated by radially compressing the core. Under these conditions, a fiber strain must develop to generate an external pressure that compresses the core. While the braid is in contact with the core but not yet locked, the composite is in mode two operation. As the axial extension continues, the yarns ultimately come in contact with each other, causing the braid to lock on itself while it remains in contact with the core. At this point the braided yarns begin to support their own compressive load and any additional axial extension must be accompanied by significant fiber strain. This condition defines mode three operation. Ultimately, the Poisson contraction of the core results in its withdrawal from the inner braid wall and both constituents behave independently. When the braid is locked but not in contact with the core, the composite is in mode four operation. Thus while the composite response in both the first and fourth mode may be regarded as a simple superposition of constituent responses, the response in the second and third modes is a unique synergism that demands a more sophisticated model to predict the mechanical properties.

1.2 Problem Formulation

In the modeling procedure only primary influences will be considered. Friction between both the yarns themselves and with the core will be neglected. The individual yarns that constitute the braid are modeled as helices wound around a uniform cylinder. Any bending resulting from the interlaced geometry of the yarn themselves is neglected in the formulation but crimp within the individual fibers that constitute the yarns may be accommodated by modeling the yarn nonlinearly. Each yarn is also assumed to be in a state of uniaxial tension with a constant cross-sectional area that does not vary with strain.

The core is regarded as a linearly elastic, isotropic, cylindrical structure and is characterized by an elastic modulus and Poisson's ratio. Unlike the yarns, the core is treated as a three-dimensional axisymmetric structure that shows distinct cross-sectional variations with strain. Experimental verification will determine the validity of these assumptions.

Successful modeling will enable rope-like composite structures to be tailored to meet specific force-displacement requirements. These composites could find diverse applications for recreational, industrial, and medical uses. In the recreational arena, ropes for climbing and mooring lines for boats could be designed to minimize jerk without compromising ultimate strength or permitting excessive elongation. Applied to automobile seat belts, these composites could replace existing woven belts. More efficient energy dissipation and a smooth transition from low to high modulus would reduce the severity of injuries sustained during impact resulting from seat belt restraints. The gross mechanical response of the composite also emulates soft tissue properties and could find application as a prosthetic ligament or other connective tissue.

1.3 Literature Review

While braided ropes have been in use for hundreds of years, it was during the last century that much of the automated machinery used in mass production was pioneered.[2] The advent of computers later revolutionized control but did little to change the existing machinery. Since that time however, the braid has found broader applications beyond its traditional uses. Today braided structures find applications in prosthetic technology and as high-performance composites. New computer controlled automated braiders fabricate complex three-dimensional parts including turbine blades, heat resistant tiles on the space shuttle, and large rocket nozzles among other shapes.[3] In the field of medical technology, Gore* has developed a synthetic braided ligament suitable for replacing the anterior cruciate ligament in the knee.

As braids find broader applications, modeling efforts are underway to better characterize their mechanical behavior. But while much of the modeling focuses on three-dimensional braids embedded in a rigid matrix, little attention has been devoted to the traditional circular braid. The previous work most relevant to this undertaking was initiated by Canadian researchers attempting to model a composite prosthesis for quasi-cylindrical ligaments. Since the structure of a ligament consists of muco-polysaccharides, elastin, and collagen fibers, it must be considered as a composite. Its mechanical behavior and particularly its force-deformation curve, reflect a nonlinearity analogous to strain stiffening. Initially the modulus appears relatively low but as the strain increases, the stiffness of the ligament dramatically increases.

To emulate the soft tissue properties of the natural ligament, the Canadian prosthesis incorporated a strong yet flexible fiber coiled helically around a soft elastic core. This composite structure afforded large elastic deformations while preserving a high rupture strength. To derive an analytical relationship between tensile force and elongation, they assumed the core to be under uniform radial compression, neglected end effects and friction, characterized the core material as nonlinear while the yarn fibers were treated as linearly elastic materials, and regarded the fiber helix angle as constant. These assumptions effectively limited the application of the resulting model to small deformations.[4]

In the context of this thesis, the Canadian work essentially attempts to model small deformations in mode two where the yarns are in contact with the core but not yet jammed on themselves. In the model presented here, friction and end effects are neglected and the core is also assumed to be subject to a uniform radial compression. The most significant assumption relaxed is the small deformation restriction. In order to permit large deformations on the order of 50 to 100 percent and even to failure, the helix or braid angle is allowed to change with axial deformation and yarn strain. The yarn fibers are also modeled as nonlinear materials in order to accommodate both elastic and plastic behavior in

addition to crimp. The core however, because of its three-dimensional state of stress and comparatively low modulus is regarded as linearly elastic. The extension of linearly elastic behavior to finite deformations must be verified experimentally.

While the theoretical and experimental results from the Canadian model agree fairly well for deformations smaller than ten percent, the model proved deficient for larger strains.[5] Relaxing the assumptions associated with small deformations will result in a model that can predict composite mechanical response for finite deformations of the constituent materials.

1.4 Overview

Chapter 2 introduces the model formulation and develops the governing equations for each mode from both dimensional and nondimensional perspectives. It also details the simulation program that implements the model. Chapter 3 details the attempts to experimentally verify the model and also documents experimental limitations. Chapter 4 investigates the influence of the nondimensional parameters that characterize the composite in an attempt to better understand, further explore, and comprehensively validate the model. Chapter 5 summarizes the work and briefly addresses extensions for future work.

2.0 MODEL FORMULATION

2.1 Introduction

The response of the composite is uniquely determined by both its constituent materials and their initial geometric arrangement. The braid may be completely described by several parameters including the number of yarns incorporated in the structure, the individual yarn dimensions, the braid diameter, and the braid density. While the number of yarns is governed by the number of carriers on the machine used to fabricate the braid, the braid density may be widely varied. Within the textile industry, braid density is quantified by the number of picks per inch (ppi). Two yarns overlapping within the braid constitute a pick and the picks per inch is defined as the number of times that the yarns cross along a one inch segment that is parallel to the axis of the braid. Figure 1 illustrates a commercially available braid with 25 picks per inch. Coupled with the initial braid diameter and the number of yarns incorporated in the braid, the braid density quantified by the number of picks per inch may be used to calculate a braid angle that describes the helical configuration of the yarns. Since the number of picks per inch may be experimentally determined more accurately than the braid angle, this parameter is used to describe the initial condition of the braid using dimensional parameters. In subsequent calculations throughout this thesis however, the nondimensional braid angle is utilized.

The nomenclature used to characterize the composite is described in Table 1 and several quantities describing the macro-geometry of the composite are illustrated in Figures 2 and 3. Figure 2 depicts a typical braid and its associated parameters. Figure 3 illustrates an ideal model of a braid cross-section and its associated dimensions. Since the braid consists of two intertwined yarn layers, the mean braid radius is given by the distance from the geometric center-line of the braid to the inner wall plus a single yarn thickness. In reality, each yarn consists of many fibers and exhibits an elliptical cross-section. For the purposes of modeling however, the elliptical cross-section is approximated by a rectangle.

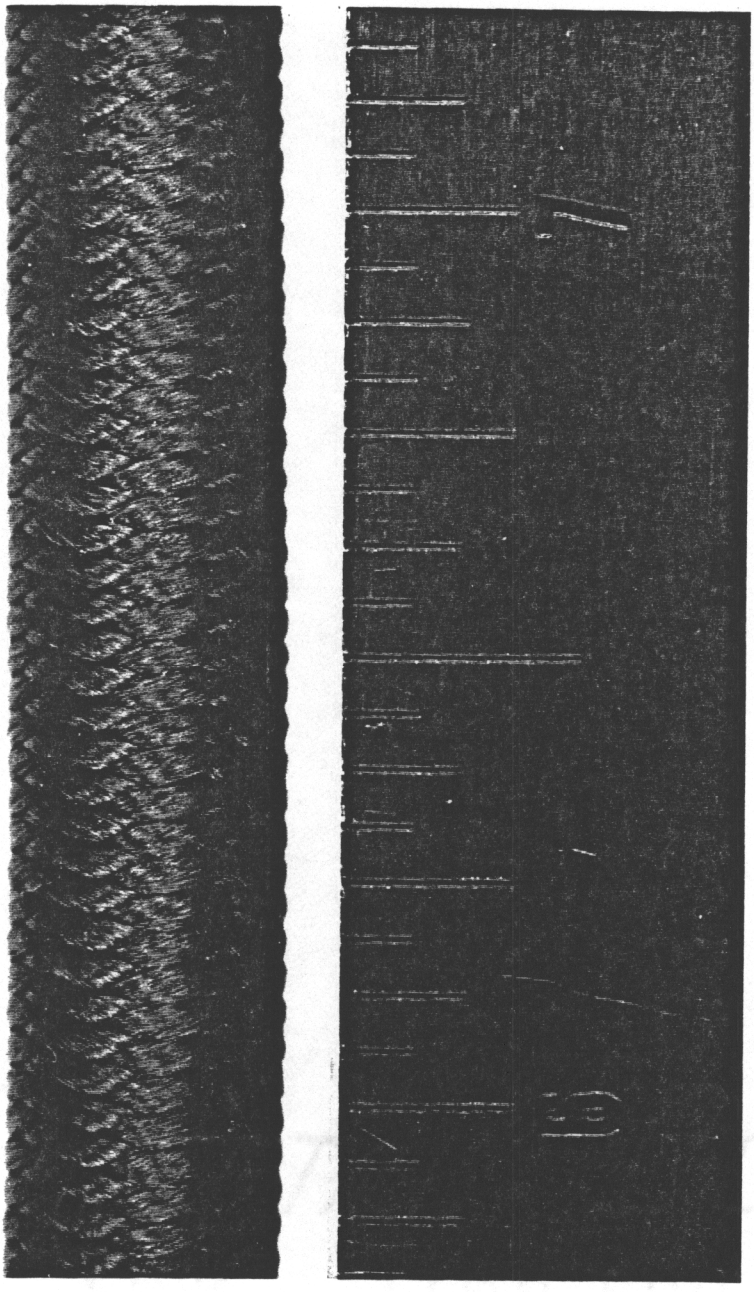


Figure 1. Commercially Available Braid with 25 Picks per Inch

Table 1. Nomenclature and Notational Conventions

Nomenclature

Quantity	Definition
A	area over which the normal component of the yarn tension acts
A_b	braid surface area at the mean braid radius
A_c	....core cross-sectional area
A_p	projected yarn surface area
A_y	yarn cross-sectional area
C	mean braid circumference
CF	braid cover factor, defined by the ratio of the projected yarn surface area to the braid surface area
CIBR	core/inner braid radius ratio
CPF	core packing factor
D_{bo}	outer braid diameter
Disp	composite displacement
E_c	core modulus
E_y	yarn fiber modulus
K	yarn curvature
L	leg length of the fundamental braid unit cell
L_{comp}	total composite length
N	normal or radial component of the yarn tension
N_c	number of yarns in the braid, determined by the number of carriers on the machine used to fabricate the braid
P	pressure generated by the braid tension acting over the surface of the core
ppi	dimensional braid density quantified by the number of picks per inch
r(t)	vector equation describing the helically wound braid yarns

Table 1. Nomenclature and Notational Conventions

(Continued)

Quantity	Definition
r_c	core radius
r_b	mean braid radius
r_{bi}	inner braid radius
r_{bo}	outer braid radius
RMOD	core/yarn modulus ratio
T_b	axial braid tension
T_c	axial core tension
T_{comp}	axial composite tension
T_y	yarn tension
u_θ	tangential core displacement
u_r	radial core displacement
V_y	yarn volume fraction, defined as the ratio of the yarn volume to the braid volume
WTR	wall thickness ratio, defined as twice the yarn thickness divided by the mean braid radius
X	transverse dimension of the fundamental braid unit cell
Y	axial dimension of the fundamental braid unit cell
YAR	yarn aspect ratio, defined as the ratio of the yarn thickness to the yarn width
YPF	yarn packing factor, defined as the ratio of the fiber volume to the total yarn volume
y_t	yarn thickness, measured radially along the braid axis
YVF	cross-sectional composite yarn fraction, defined by the ratio of the total yarn cross-sectional area divided by the area enclosed by the mean braid radius

Table 1. Nomenclature and Notational Conventions

(Continued)

Quantity	Definition
y_w	yarn width, measured along the yarn surface at the mean braid radius normal to the yarn axis
ε_θ	tangential core strain
ε_r	radial core strain
ε_y	yarn strain
ε_{ycorr}	nonlinear correction factor used to accommodate nonlinear yarn models
ε_z	axial core and composite strain
ρ	yarn fiber volume density
ρ_L	linear yarn density
θ	braid or helix angle, measured relative to the braid axis
σ_θ	tangential core stress
σ_r	radial core stress
σ_y	yarn stress
σ_z	axial core stress
ν	core Poisson's ratio, defined as the negative ratio of the radial core strain to the axial core strain

Notational Conventions

The subscript "0" denotes the initial value of a parameter

A bar over a parameter designates a nondimensional quantity

A bold variable name represents a vector quantity

An asterisk (*) denotes a trademark

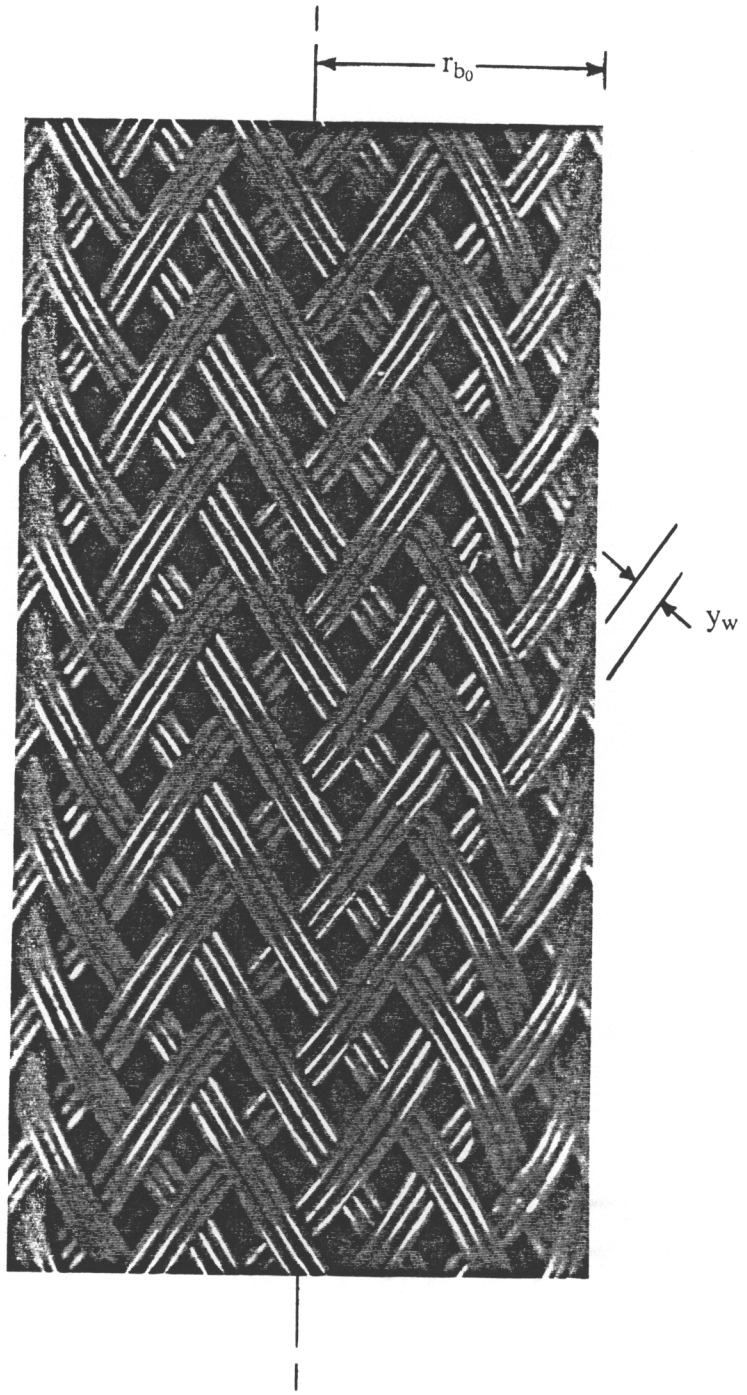


Figure 2. Typical Braid and Associated Parameters

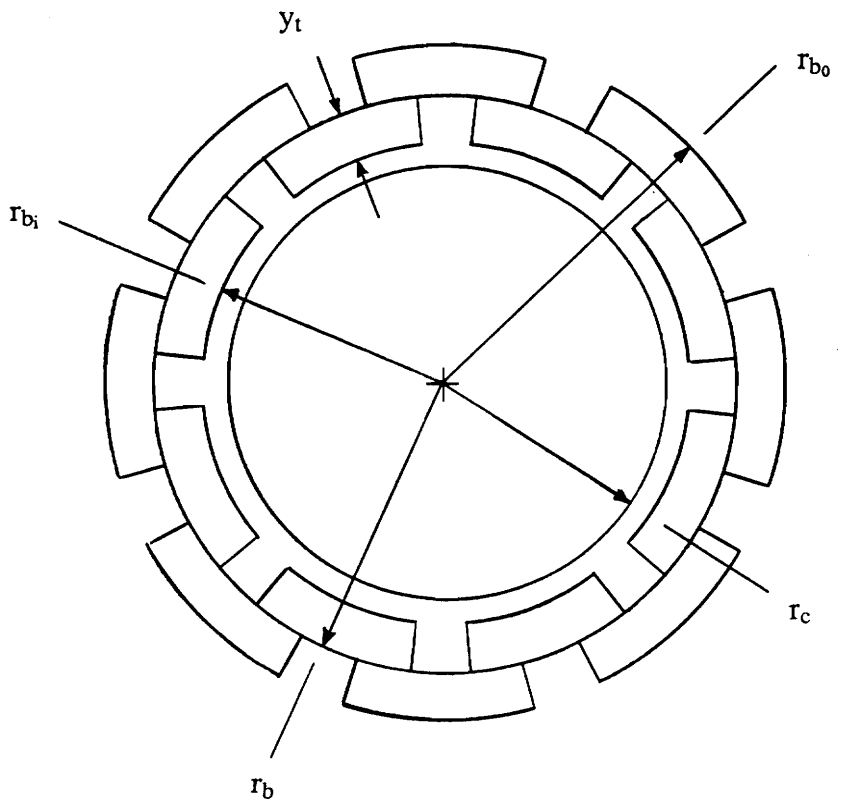


Figure 3. Ideal Composite Cross-Section Illustrating Macro-Geometry

The cross-sectional dimensions are quantified by the ratio of the yarn thickness divided by the yarn width, defined to be the yarn aspect ratio. Theoretically, the determination of this quantity would be quite complex since the aspect ratio depends on the individual fiber surface finish, the fiber material, and the yarn consolidation technique. Experimentally however, the yarn aspect ratio at the braid locking point may be found by stretching the braid to its locking point and fixing it rigidly by covering it with epoxy or a comparable adhesive. Subsequently, cross-sections may be cut and the yarn dimensions determined by direct measurement.

The fundamental braid unit cell is a parallelogram forming a diamond with four equal sides resulting from four overlapping yarns. The parameters that describe the micro-geometry of the braid unit are depicted in Figure 4. The helix or braid angle is measured relative to the braid axis and is a quantitative measure of braid density. The mechanical behavior of the braid is determined by these geometric parameters coupled with the material properties of the yarns.

2.2 Dimensional Composite Parameters

The dimensional quantities that describe the composite may be grouped into two categories, those characterizing the braid and those characterizing the core. The quantities that describe the initial condition of the braid are the yarn density, linear yarn density, yarn aspect ratio, yarn packing factor, number of yarns in the braid, initial braid density, and outer braid diameter. Since the yarns are assumed to be in a state of uniaxial tension showing no cross-sectional variation with strain, the material properties may be characterized completely by an elastic modulus if the behavior is assumed to be linear, or by a table of stress-strain properties if the yarns are regarded as nonlinear materials. The core can be completely described by four independent parameters if it is assumed to be linearly elastic. Its geometric configuration is characterized by its initial diameter and packing factor. If it is assumed to be homogeneous and isotropic, its material properties

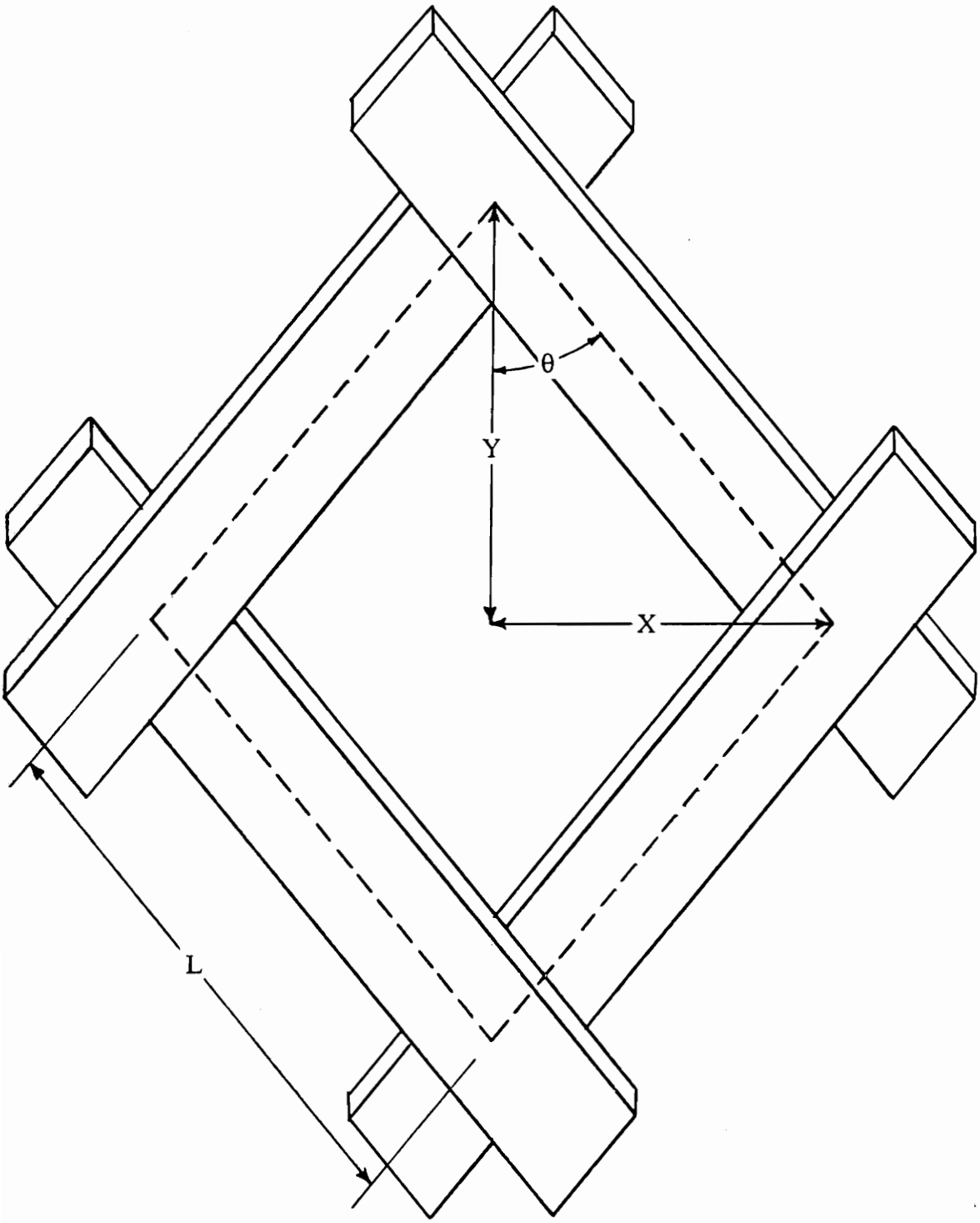


Figure 4. Fundamental Braid Unit Cell Micro-Geometry

may be described by an elastic modulus and Poisson's ratio. Collectively, these twelve parameters completely describe the initial condition of the composite and allow the prediction of its gross mechanical response.

2.3 Nondimensionalizing Parameters

In order to isolate primary variable groups and their influence, the dimensional quantities that describe the composite are nondimensionalized by a characteristic length and force. The characteristic length applied to the micro-geometry of the fundamental braid unit is the initial transverse dimension, X_0. For the macro-geometry that describes the composite, the nondimensionalizing length is the initial mean braid radius. Since the circumference of the braid may be expressed in terms of either the mean braid radius or the transverse dimension of the fundamental braid unit, a relationship between r_b and X may be found. The circumference of the braid in terms of the radius is given by

$$C = 2\pi r_b \tag{2.3 - 1}$$

Since the number of braid units spanning the circumference is equal to half the number of yarns and the width of each braid unit is 2X,

$$C = N_c X \tag{2.3 - 2}$$

Equating these expressions,

$$N_c X = 2\pi r_b \tag{2.3 - 3}$$

Since the number of yarns in the braid, N_c, is a constant, the ratio between X and r_b is also a constant given by

$$\frac{X}{r_b} = \frac{2\pi}{N_c} \tag{2.3 - 4}$$

Nondimensionally, the transverse dimension of the fundamental braid unit cell is given by

$$\overline{X} = \frac{X}{X_0} \tag{2.3 - 5}$$

while the nondimensional mean braid radius is defined as

$$\overline{r_b} = \frac{r_b}{r_{b_0}} \tag{2.3 - 6}$$

Substituting the nondimensional quantities into equation (2.3 - 4), it follows that

$$\overline{r_b} = \overline{X} \qquad (2.3 - 7)$$

Hence the nondimensional braid radius and nondimensional transverse dimension of the braid unit cell are identical. Equation (2.3 - 4) also reflects that the nondimensionalizing parameters applied to the micro and macro-geometry of the composite differ only by a constant scaling factor.

In a similar fashion, the nondimensionalizing force for a single yarn is the equivalent tension in a single yarn at 100 percent axial strain. Applied to the braid, core, and composite, the nondimensionalizing force is equivalent to the tension in the same number of yarns that constitute the braid at an axial strain of 100 percent. These quantities enable the nondimensional yarn tension to be expressed solely by the product of the yarn strain and the yarn packing factor while the nondimensional braid tension is represented by the product of the yarn tension and the cosine of the helix angle. Like the geometric parameters, these nondimensionalizing force parameters differ only by a constant equal to the number of yarns in the braid. In the subsequent equation development, the governing equations for each mode will be derived from a dimensional perspective and then nondimensionalized and formulated entirely in terms of dimensionless parameters.

2.4 Nondimensional Composite Parameters

The twelve dimensional parameters may be reduced to nine nondimensional parameters by incorporating the nondimensionalizing quantities. In reality, if it were feasible to assess the cross-section of each yarn experimentally, the number of dimensional parameters describing the composite could be reduced by one. Instead of including both the yarn density and linear density, the cross-sectional area could be substituted. However, the yarn density and linear density are easier to determine and may be incorporated with the yarn packing factor to represent the cross-sectional area of the yarn using the relationship

$$A_{y_0} = \frac{\rho_L}{\rho \, YPF} \qquad (2.4 - 1)$$

Care must be taken to insure that consistent dimensions are utilized in the computation. Textile manufacturers have traditionally represented linear density with units of denier. One denier is defined to be one gram per 9000 meters.

Once the yarn cross-sectional area is known, the yarn width may be determined by employing the relationship

$$y_w = \sqrt{\frac{A_{y_0}}{YAR}} \qquad (2.4 - 2)$$

The yarn thickness may then be determined using the equation

$$y_t = \frac{A_{y_0}}{y_w} \qquad (2.4 - 3)$$

Once the yarn thickness is known, the mean braid radius may be found by subtracting the yarn thickness from one-half the outer braid diameter.

$$r_{b_0} = \frac{D_{b_{\infty}}}{2} - y_t \qquad (2.4 - 4)$$

The mean braid radius may be incorporated with the number of yarns to find the transverse dimension of the fundamental braid unit by employing the relationship

$$X_0 = \frac{2\pi r_{b_0}}{N_c} \qquad (2.4 - 5)$$

The axial dimension of the fundamental braid unit may be found from the braid density using the equation

$$Y_0 = \frac{1}{2 \, ppi_0} \qquad (2.4 - 6)$$

The inner braid radius may be found by subtracting the yarn thickness from the mean braid radius

$$r_{b_{i0}} = r_{b_0} - y_t \qquad (2.4 - 7)$$

Comparing the inner braid radius with the core radius indicates whether or not the core is initially in contact with the braid.

The corresponding nondimensional parameters may be found by combining dimensional parameters. The wall thickness ratio represents the ratio of the braid wall thickness to the mean braid diameter and is given by

$$WTR_0 = \frac{2y_t}{r_{b_0}} \qquad (2.4 - 8)$$

The core/inner braid radius ratio is used to assess the mode of the composite and is simply given by

$$CIBR_0 = \frac{r_{c_0}}{r_{b_{i_0}}} \qquad (2.4 - 9)$$

The braid or helix angle is given by

$$\tan\theta_0 = \frac{X_0}{Y_0} \qquad (2.4 - 10)$$

The modulus ratio represents the stiffness of the core compared to the braid yarns and is given by

$$RMOD = \frac{E_c}{E_y} \qquad (2.4 - 11)$$

The braid cover factor is a ratio of the projected yarn surface area to the mean braid surface area. It may be found by considering first the yarn volume fraction which is defined by the ratio of the yarn volume to the braid volume. Isolating one-quarter of the fundamental braid unit and ignoring any bending in the yarns, the volume fraction may be represented by the yarn volume divided by the volume of the quarter diamond that the yarn occupies. In terms of braid parameters,

$$V_{y_0} = \frac{L_0\left(\frac{y_w}{2}\right)y_t}{\frac{1}{2}X_0Y_0(2y_t)} \qquad (2.4 - 12)$$

Simplifying the expression,

$$V_{y_0} = \frac{L_0 y_w}{2X_0Y_0} \qquad (2.4 - 13)$$

Since

$$X_0 = L_0 \sin\theta_0 \qquad (2.4 - 14)$$

and

$$Y_0 = L_0 \cos\theta_0 \tag{2.4 - 15}$$

the yarn volume fraction may be equivalently represented by the expressions

$$V_{y_0} = \frac{y_w}{2 X_0 \cos\theta_0} = \frac{y_w}{2 Y_0 \sin\theta_0} \tag{2.4 - 16}$$

When computing the cover factor, the projected yarn surface area must be determined by subtracting overlapping yarn areas. For one-quarter of the fundamental braid unit, the total surface area is

$$A_{b_0} = \frac{1}{2} X_0 Y_0 \tag{2.4 - 17}$$

The projected yarn surface area corresponding to braid area is given by

$$A_{p_0} = L_0 \left(\frac{y_w}{2}\right) - \frac{\left(\frac{y_w}{2}\right)^2}{\sin 2\theta_0} \tag{2.4 - 18}$$

Manipulating the previous expression

$$A_{p_0} = \frac{L_0 y_w}{2} - \frac{y_w^2}{8 \sin\theta_0 \cos\theta_0} \tag{2.4 - 19}$$

or

$$A_{p_0} = \frac{1}{2}\left[X_0 Y_0 - \left(X_0 - \frac{y_w}{2\cos\theta_0}\right)\left(Y_0 - \frac{y_w}{2\sin\theta_0}\right)\right] \tag{2.4 - 20}$$

Since the cover factor is the ratio of the projected yarn surface area to the corresponding braid surface area

$$CF_0 = \frac{\frac{1}{2}\left[X_0 Y_0 - \left(X_0 - \frac{y_w}{2\cos\theta_0}\right)\left(Y_0 - \frac{y_w}{2\sin\theta_0}\right)\right]}{\frac{1}{2} X_0 Y_0} \tag{2.4 - 21}$$

Simplifying the expressing,

$$CF_0 = 1 - \left(1 - \frac{y_w}{2 X_0 \cos\theta_0}\right)\left(1 - \frac{y_w}{2 Y_0 \sin\theta_0}\right) \tag{2.4 - 22}$$

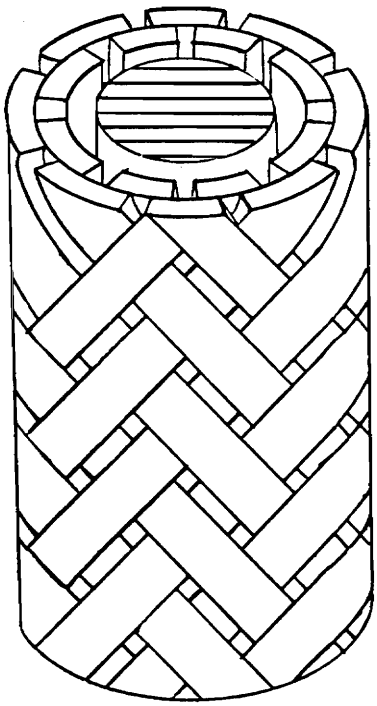
Substituting the yarn volume fraction

$$CF_0 = 1 - (1 - V_{y_0})^2 \tag{2.4 - 23}$$

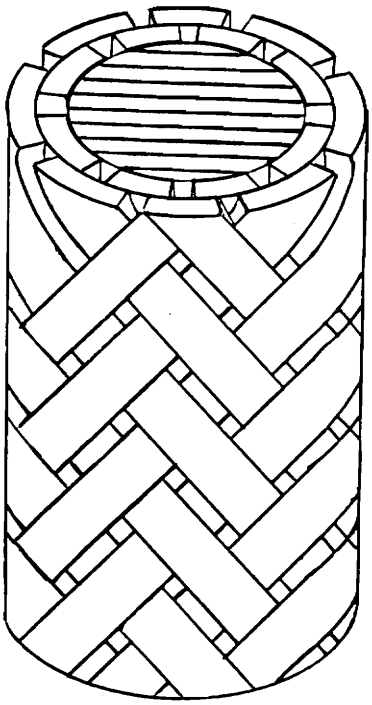
2.5 Mode Transition Criteria

The mechanical behavior of the composite is a synergistic response that may be characterized by four distinct modes of operation. The quantities that determine the mode are the relationship between the inner braid radius and the core radius and the status of the braid yarns. The relationship between the inner braid radius and the core radius is represented nondimensionally by the core/inner braid radius ratio. This quantity represents the ratio of the core radius to the inner braid radius. When the core and braid are separated by some finite space, as in modes one and four, this parameter is some value less than one. When the core and braid are in contact with one another, as in modes two and three, this parameter is identically one. The status of the braid refers to the geometric configuration of the yarns. If the yarns are arranged so that there is some space between them, the braid is said to be open. Under the action of axial deformation, the yarns will pivot upon each other freely. While axial extension is accompanied by a corresponding reduction in braid radius, there is no yarn strain associated with the braid deformation and consequently no tension evolves in the yarns or braid. Once the braid radius contracts enough that the yarns touch each other, the braid is said to be locked. In this condition, any additional axial extension must be accompanied by yarn strain. In modes one and two the braid is open while in modes three and four the braid is locked.

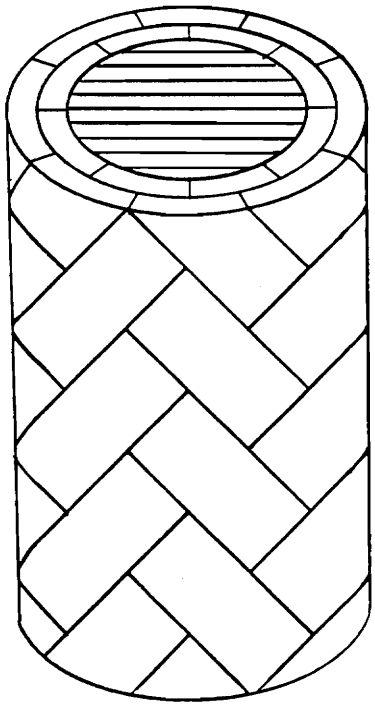
The nondimensional parameters that describe the status of the braid are the helix angle and cover factor. The cover factor is a measure of the projected surface area of the braid covered by the yarns. In modes one and two, the helix angle is some value greater than the locking angle and since spaces exist between the yarns, the cover factor is less than one. In modes three and four, the helix angle is identically equal to the locking angle and since the yarns are touching each other and locked, the cover factor is identically equal to one. Figure 5 schematically illustrates the four modes of operation as a function of core/inner braid radius ratio and cover factor. Table 2 summarizes the dimensional and



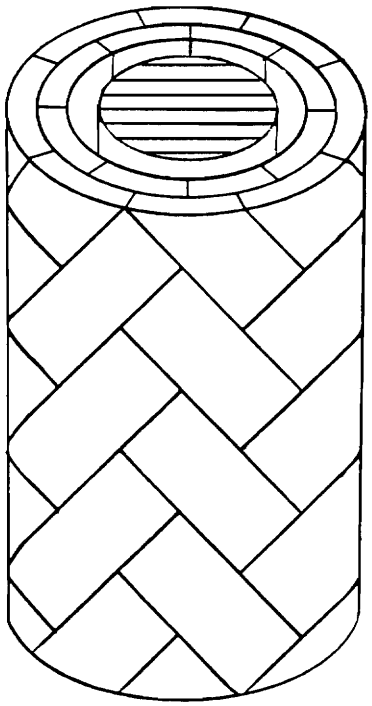
Mode 1



Mode 2



Mode 3



Mode 4

Figure 5. Modes of Operation

Table 2. Mode Determination Criteria

Mode	Dimensional Criteria	Nondimensional Criteria
Mode 1	core radius < inner braid radius braid angle > locking angle	Core/Inner Braid Radius ratio < 1 Cover Factor < 1
Mode 2	core radius = inner braid radius braid angle > locking angle	Core/Inner Braid Radius ratio = 1 Cover Factor < 1
Mode 3	core radius = inner braid radius braid angle = locking angle	Core/Inner Braid Radius ratio = 1 Cover Factor = 1
Mode 4	core radius < inner braid radius braid angle = locking anlge	Core/Inner Braid Radius ratio < 1 Cover Factor =1

nondimensional parameters that define each mode of operation.

While the relationship between the inner braid radius and core radius is governed by equilibrium considerations and material properties, the locking criteria is solely a function of geometry. To derive the locking criteria, one-quarter of a single braid unit cell is considered. As illustrated in Figure 6, the braid is locked when the yarns touch each other. Since the yarn width is measured normal to the yarn axis, the triangles created by the solid lines in Figure 6 are similar and the locking criteria, formulated in terms of the yarn width and braid unit length is

$$\tan \theta_L = \frac{L - \sqrt{L^2 - y_w^2}}{y_w} \qquad (2.5 - 1)$$

Nondimensionally, this equation becomes

$$\tan \theta_L = \sqrt{B} - \sqrt{B - 1} \qquad (2.5 - 2)$$

where

$$B = \frac{(1+\varepsilon_y)^2}{\overline{y_w}^2 \sin^2 \theta_0} \qquad (2.5 - 3)$$

The nondimensional yarn width is defined as the yarn width divided by the initial transverse dimension of the fundamental braid unit cell. Formulating the locking angle in term of these parameters insures that if there is no yarn strain, the leg length of the braid unit cell remains constant and since the yarn width is assumed to be invariant, the locking angle also remains constant. This condition prevails in mode one as the braid extends without any accompanying yarn strain.

2.6 Modeling Overview

To model the mechanical response of the composite, axial strain is chosen as the controlling independent variable. Utilizing geometric and equilibrium considerations coupled with material properties, all associated parameters are uniquely determined based on the mode of operation. Within the model itself the initial mode is determined based on the composite parameters. As the axial strain changes these parameters, the transition

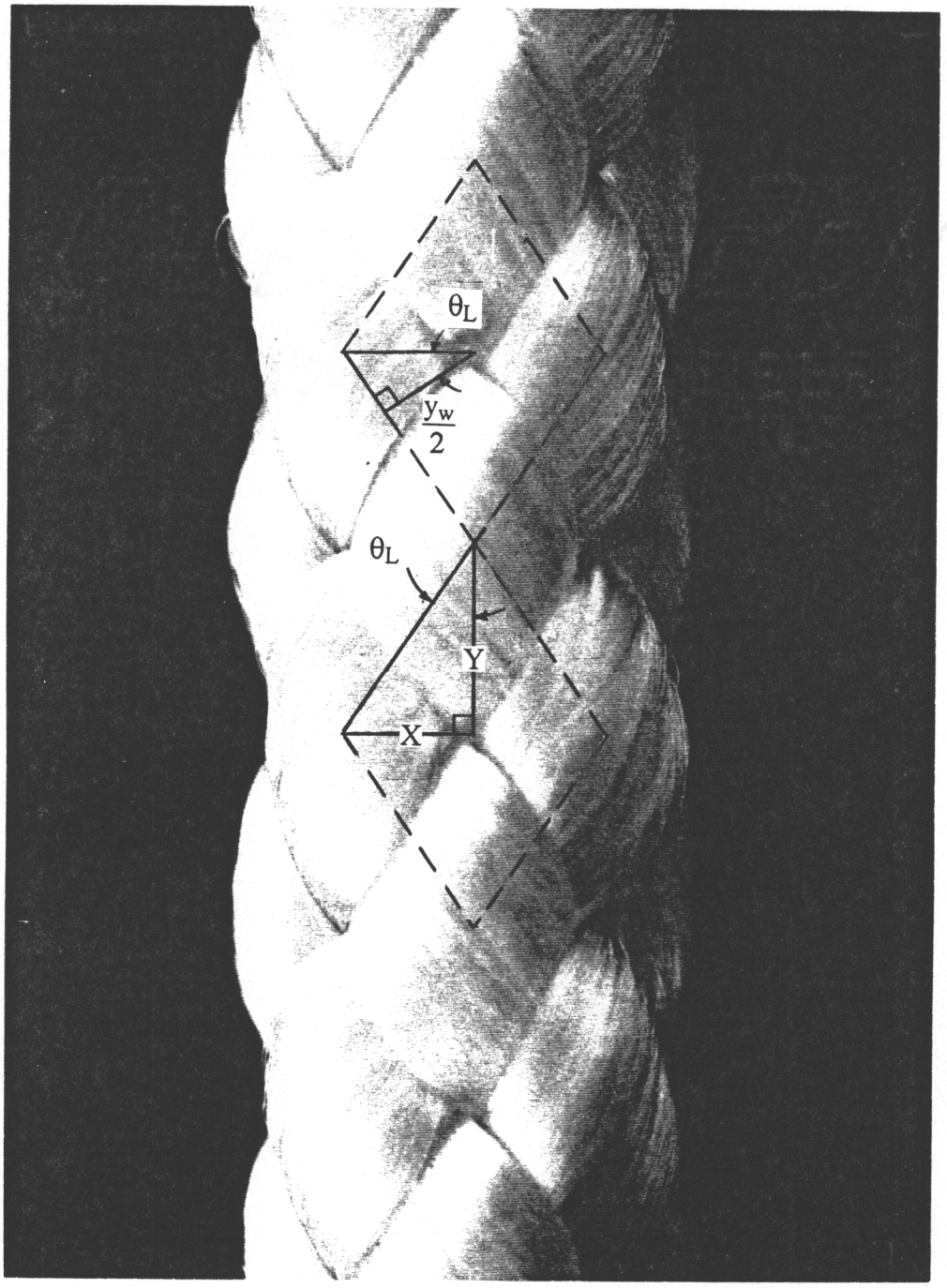


Figure 6. Locked Braid

criteria dictate the subsequent modes of operation. At each axial strain value, a mode guess is made and the governing equations describing that mode are evaluated along with the mode transition criteria. Assessing the core/inner braid radius ratio and braid angle enable the assumed mode of operation to be validated. If the transition criteria indicate that the axial strain corresponds to a different mode, the appropriate mode is selected and the transition criteria and associated parameters are re-evaluated. This procedure is repeated until the appropriate mode is established.

As noted in Table 1 and in the subsequent equation development, the subscript "0" indicates an initial parameter while a bar over a variable name denotes a nondimensional quantity.

2.7 Mode One Equation Development

In mode one, the core is not in contact with the braid and the braid itself is open. Both constituents behave independently and the braid extends freely while only the core develops any resistance to axial extension. If axial strain is uniform, then isolating a single braid unit,

$$Y = Y_0(1+\varepsilon_y) \tag{2.7 - 1}$$

If there is no yarn strain, then the length of each leg of the braid unit is constant and

$$X^2+Y^2 = X_0^2+Y_0^2 = L^2 \tag{2.7 - 2}$$

Substituting for Y and solving for X,

$$X = \sqrt{X_0^2 - Y_0^2(2\varepsilon_z+\varepsilon_z^2)} \tag{2.7 - 3}$$

The braid or helix angle is defined as

$$\tan\theta = \frac{X}{Y} \tag{2.7 - 4}$$

Expressing the braid angle as a function of the initial braid angle and axial strain only,

$$\tan\theta = \sqrt{\frac{1}{(1+\varepsilon_z)^2\cos^2\theta_0} - 1} \tag{2.7 - 5}$$

The mean circumference of the braid can be related to the single braid unit by the

expression

$$2\pi r_b = N_c X \tag{2.7 - 6}$$

where N_c is defined to be the number of yarns in the braid.

Solving for the current mean braid radius from the previous equation,

$$r_b = \frac{N_c X}{2\pi} \tag{2.7 - 7}$$

The nondimensional mean braid radius is defined as

$$\overline{r_b} = \frac{r_b}{r_{b_0}} \tag{2.7 - 8}$$

and may be represented as a function of only the initial braid angle and axial strain by the equation

$$\overline{r_b} = \sqrt{1 - \frac{2\varepsilon_z + \varepsilon_z^2}{\tan^2\theta_0}} \tag{2.7 - 9}$$

The inner braid radius may be found by subtracting the yarn thickness from the mean braid radius.

$$r_{b_i} = r_b - y_t \tag{2.7 - 10}$$

Nondimensionally,

$$r_{b_i} = \frac{r_b - y_t}{r_{b_0}} = \overline{r_b} - \overline{y_t} \tag{2.7 - 11}$$

where the nondimensional yarn thickness is defined as the yarn thickness divided by the mean braid radius.

If the core is assumed to be linearly elastic with a constant Poisson's ratio, the radial contraction as a function of the axial strain is given by

$$\varepsilon_r = -\nu\varepsilon_z \tag{2.7 - 12}$$

The radius of the core may be calculated using the relationship

$$r_c = r_{c_0}(1 + \varepsilon_r) \tag{2.7 - 13}$$

or nondimensionally,

$$r_c = \frac{r_c}{r_{b_0}} = \frac{r_{c_0}}{r_{b_0}}(1 + \varepsilon_r) \tag{2.7 - 14}$$

Letting

$$\overline{r_{c_0}} = \frac{r_{c_0}}{r_{b_0}} \qquad (2.7 - 15)$$

$$\overline{r_c} = \overline{r_{c_0}}(1+\varepsilon_r) \qquad (2.7 - 16)$$

If the core radius remains less than the inner braid radius and the braid angle exceeds the locking angle then the composite operates in mode one for the given axial stain.

2.8 Mode Two Equation Development

In mode two, the braid remains open but is in contact with the core. Hence, any axial extension must also be accompanied by a radial compression of the core. To generate a compressive force, a fiber strain must evolve in the yarns. In mode one, the behavior of the composite is completely determined by considering the geometric constraints governing the behavior of the braid and the material properties of the core. In mode two, the braid and core are in contact and the appropriate constraint that governs the behavior of the composite is an equilibrium of forces at the surface of contact between the braid and core. Instead of basing the analysis on geometric constraints and material properties alone, an equilibrium analysis predicated on a force balance is employed.

For modeling purposes, the yarns are assumed to generate a uniform pressure at the mean braid radius balanced by the stress at the surface of the core. Imposing the equilibrium constraints, the pressure generated at the mean braid radius must balance the radial stress at the outer surface of the core when the inner braid radius is equal to the core radius. To satisfy both these prerequisites simultaneously, an iterative solution technique is employed that determines the yarn tension based on an estimation of the yarn strain. This tension permits a calculation of the pressure generated by the braid and exerted on the core. The pressure is assumed to be uniformly distributed over the entire surface of the core. In fact, a uniform distribution only results when the braid cover factor equals unity. When the cover factor is less than one, as it is in mode two, the mean pressure only approximates the actual force distribution over the surface of the core. The accuracy of this approximation

depends on the value of the cover factor. As the cover factor approaches unity, the approximation becomes exact.

Based on the constitutive relationships for the core, this pressure results in a displacement profile that determines the radius of the core. From the yarn strain and axial strain, the mean braid radius and inner braid radius may be calculated. The accuracy of the assumed yarn strain is assessed by evaluating the agreement between the core radius and the inner braid radius. The estimation of yarn strain is refined by comparing the radii values and the solution is repeated until the agreement between the radii values falls within some predefined tolerance.

Implementing this solution technique to establish the governing equations for mode two, an initial value is assumed for the yarn strain. For a linear model of the yarn,

$$\sigma_y = E_y \varepsilon_y \qquad (2.8 - 1)$$

and since the yarn is porous, the corresponding tension for a uniaxial state of stress is given by

$$T_y = \sigma_y A_{y_0} YPF \qquad (2.8 - 2)$$

As a first approximation, the yarn is regarded as a linearly elastic material. However, the capability to incorporate a nonlinear material may be added while retaining the same form as the previous equation by adding a nonlinear correction factor. For a nonlinear model of the yarn, a characteristic modulus is established and a table defining the stress-strain properties of the yarn is incorporated. At any strain value, the ratio of the actual stress divided by the extrapolated linear stress value at the same strain based on the characteristic modulus determines a nonlinear strain correction factor. This formulation also affords a measure of the yarn's nonlinearity by inspecting the deviation of the nonlinear correction factor from unity. Incorporating this formulation,

$$\sigma_y = E_y \varepsilon_y \varepsilon_{y_{corr}} \qquad (2.8 - 3)$$

where ε_{ycorr} is the nonlinear correction factor calculated from a table of yarn properties.

The yarn tension may be calculated from the expression

$$T_y = \sigma_y A_{y_0} YPF \qquad (2.8 - 4)$$

The pressure generated by the yarn tension is a function of the braid geometry and core radius. A single yarn wound helically about a cylinder of radius r_b at an angle θ to the axis of the cylinder is illustrated in Figure 7 and may be described by the equation

$$\mathbf{r}(t) = r_b \cos(t)\,\mathbf{i} + r_b \sin(t)\,\mathbf{j} + r_b\, t \cot(\theta)\,\mathbf{k} \qquad (2.8 - 5)$$

The radial component of the tension may be found be employing the definition of curvature. In cylindrical coordinates, curvature is the absolute rate at which the angle ϕ changes with respect to the arc length, s.

$$K = \left| \frac{d\phi}{ds} \right| \qquad (2.8 - 6)$$

The normal or radial component of the tension at any point is given by

$$dN = T_y\, d\phi \qquad (2.8 - 7)$$

Omitting the absolute value notation,

$$d\phi = K\, ds \qquad (2.8 - 8)$$

Substituting for $d\phi$ and integrating over some finite arc length from L_0 to L, the radial component of the tension that creates a pressure is given by

$$N = \int_{L_0}^{L} dN = \int_{L_0}^{L} T_y K\, ds \qquad (2.8 - 9)$$

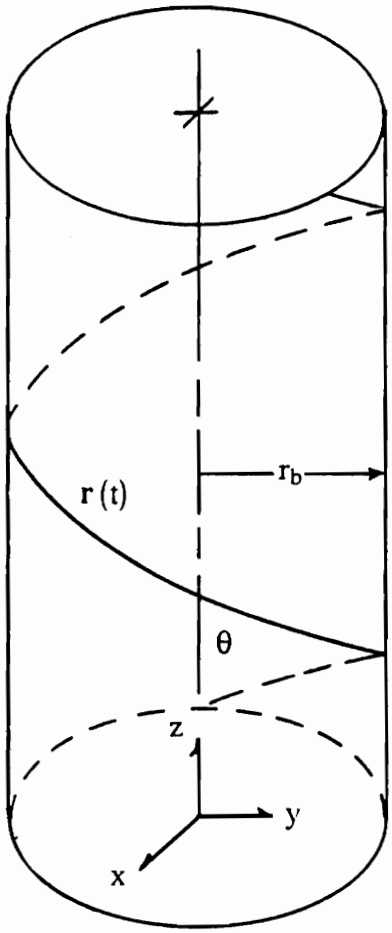
For a three-dimensional curve, the radius of curvature, K, is given by

$$K = \frac{|\dot{\mathbf{r}}(t)|^3}{|\dot{\mathbf{r}}(t) \times \ddot{\mathbf{r}}(t)|} \qquad (2.8 - 10)$$

Evaluating this expression for the helically wound yarn yields

$$K = \frac{\sin^2\theta}{r_b} \qquad (2.8 - 11)$$

Since the radius of curvature and tension are constant everywhere along the yarn, the normal component of the tension is given by



$$\mathbf{r}(t) = r_b \cos(t)\,\mathbf{i} + r_b \sin(t)\,\mathbf{j} + r_b\, t \cot(\theta)\,\mathbf{k}$$

Figure 7. Helically Wound Yarn

$$N = T_y K \left(\Delta L\right) \tag{2.8 - 12}$$

Isolating a single leg of the fundamental braid unit

$$N = T_y K \; L \tag{2.8 - 13}$$

Since a single yarn of length L is actually shared by two adjacent braid units, the area over which this normal force is distributed is equivalent to one-half the area of the diamond that forms the fundamental braid unit and is given by

$$A = L X \cos\theta = X Y \tag{2.8 - 14}$$

For a uniform pressure distribution,

$$P = \frac{N}{A} \tag{2.8 - 15}$$

Substituting expressions for the normal force and corresponding area, the pressure becomes

$$P = \frac{T_y K \; L}{L X \cos\theta} \tag{2.8 - 16}$$

Substituting for the curvature, K, and the transverse braid unit dimension, X, the expression for the mean pressure reduces to

$$P = \frac{T_y \tan\theta}{r_b L} \tag{2.8 - 17}$$

For equilibrium, the radial stress at the outer radius of the core must balance the pressure generated by the yarn tension, so

$$\sigma_r = -P \tag{2.8 - 18}$$

From the constitutive relationships for a linearly elastic material in cylindrical coordinates,

$$\sigma_r = \frac{E_c}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_r + \nu(\varepsilon_\theta + \varepsilon_z)\right] \tag{2.8 - 19}$$

Before this expression can be evaluated, a relationship must be established between the radial and tangential strains. From their definitions,

$$\varepsilon_r = \frac{\partial u_r}{\partial r} \tag{2.8 - 20}$$

and

$$\varepsilon_\theta = \frac{u_r}{r} + \frac{1}{r}\frac{\partial u_\theta}{\partial \theta} \qquad (2.8 - 21)$$

If the core is considered to be an axisymmetric, linearly elastic cylinder, then there is no variation in the tangential direction and all shearing components vanish. An equilibrium analysis on an infinitesimal element in cylindrical coordinates, making the small angle approximation that $\sin(\theta) = \theta$, and neglecting the highest order derivatives yields

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \qquad (2.8 - 22)$$

Consistent with the model, the boundary conditions on this differential equation are

$$u_r = 0 \quad \text{at } r = 0 \qquad (2.8 - 23)$$

and

$$\sigma_r = -P \quad \text{at } r = r_c \qquad (2.8 - 24)$$

Substituting the constitutive relationships for stress in term of strain and subsequently the definitions of strain into the governing differential equation allows the equilibrium equation to be formulated solely in terms of the radial displacement. Hence, if the axial strain is assumed to be uniform and constant, the previous equation becomes

$$\frac{d^2u_r}{dr^2} + \frac{1}{r}\frac{du_r}{dr} - \frac{1}{r^2}u_r = 0 \qquad (2.8 - 25)$$

Recognizing this second order homogeneous differential equation as an Euler equation, the solution is of the form

$$u_r = \beta r^n \qquad (2.8 - 26)$$

where β represents an arbitrary constant determined by the boundary conditions. Differentiating the fundamental solution and substituting back into the differential equation yields

$$\beta r^{n-2}\left(n^2-1\right) = 0 \qquad (2.8 - 27)$$

Solving the characteristic equation yield roots of +1 and -1, so the general solution is of the

form

$$u_r = \beta_1 r + \frac{\beta_2}{r} \tag{2.8 - 28}$$

Subject to the boundary condition that the radial displacement at the center of the core be zero,

$$\beta_1(0) + \beta_2\left(\frac{1}{0}\right) = 0 \tag{2.8 - 29}$$

Since the solution must be bounded,

$$\beta_2 = 0 \tag{2.8 - 30}$$

and

$$u_r = \beta_1 r \tag{2.8 - 31}$$

Hence the radial displacement profile is linear.

Subject to the second boundary condition demanding that the radial stress balance the pressure generated by the yarns, the displacement profile may be found to be

$$u_r = -\left[\frac{P(1+\nu)(1-2\nu)}{E_c} + \nu\varepsilon_z\right] r \tag{2.8 - 32}$$

Based on this equation, without any external pressure only the Poisson contraction influences the radial displacement profile. Furthermore, an incompressible material with a Poisson's ratio of one half and a constant axial strain will exhibit a radial displacement profile that is independent of pressure. It should be noted however, that incompressibility may be represented by a Poisson's ratio of one half only for infinitesimal strains. Most importantly, since the radial displacement profile is linear and a function of only the radius and core material properties for a constant axial strain, the radial and tangential strains are equivalent based on their definitions and the assumption of symmetry.

Therefore,

$$\varepsilon_r = \varepsilon_\theta \tag{2.8 - 33}$$

and substituting this relationship into the constitutive equation for radial stress,

$$\sigma_r = \frac{E_c}{(1+\nu)(1-2\nu)}(\varepsilon_r + \nu\varepsilon_z) \tag{2.8 - 34}$$

Substituting the pressure for the radial stress and solving for the radial strain yields

$$\varepsilon_r = -\frac{P(1+\nu)(1-2\nu)}{E_c} - \nu\varepsilon_z \qquad (2.8 - 35)$$

The preceding relationship could also be derived by substituting the radial displacement profile into the strain definition and differentiating.

The core radius may be determined by employing the relationship

$$r_c = r_{c_0}(1+\varepsilon_r) \qquad (2.8 - 36)$$

To calculate the corresponding inner braid radius,

$$Y = Y_0(1+\varepsilon_z) \qquad (2.8 - 37)$$

and

$$L = L_0(1+\varepsilon_y) \qquad (2.8 - 38)$$

Since

$$X^2+Y^2 = L^2 \qquad (2.8 - 39)$$

Substituting for Y and L and solving for X yields

$$X = \sqrt{L_0^2(1+\varepsilon_y)^2 - Y_0^2(1+\varepsilon_z)^2} \qquad (2.8 - 40)$$

Relating the mean braid radius to the braid unit employs the equation

$$r_b = \frac{N_c X}{2\pi} \qquad (2.8 - 41)$$

and the inner braid radius may be found by subtracting the yarn thickness.

Nondimensionalizing the previous quantities yields expressions that are solely functions of the initial braid angle, axial strain, and yarn strain. The corresponding nondimensional expression are

$$\overline{Y} = \frac{1+\varepsilon_z}{\tan\theta_0} \qquad (2.8 - 42)$$

$$\overline{L} = \frac{1+\varepsilon_y}{\sin\theta_0} \qquad (2.8 - 43)$$

and

$$\overline{X} = \sqrt{\frac{(1+\varepsilon_y)^2}{\sin^2\theta_0} - \frac{(1+\varepsilon_z)^2}{\tan^2\theta_0}} \qquad (2.8 - 44)$$

As noted previously, the nondimensional transverse dimension of the fundamental braid unit cell is identically equal to the nondimensional braid radius.

If the composite is in mode two, the inner braid radius and the core radius should be identical yielding a core/inner braid radius ratio of one. If the initial guess for the yarn strain does not result in agreement between the radii based on the equilibrium analysis, then a new yarn strain is estimated and the solution procedure is repeated until the agreement between the radii values falls within some predefined tolerance. To insure mode two operation, the braid angle must also remain greater than the locking angle.

2.9 Mode Three Equation Development

Once the braid locks on itself while still in contact with the core, mode three operation commences. In this mode, the braid remains locked and any axial extension is accompanied by yarn strain. This analysis is predicated on geometric constraints imposed by the locked braid and material properties. An equilibrium analysis based on a force balance is no longer viable since a portion of the pressure generated by the braid yarns is supported by the braid itself. Hence, the core experiences only a portion of the total yarn pressure.

Basing the analysis on the axial strain and isolating a single braid unit,

$$Y = Y_0(1+\varepsilon_z) \qquad (2.9 - 1)$$

Nondimensionally,

$$\overline{Y} = \frac{1+\varepsilon_z}{\tan\theta_0} \qquad (2.9 - 2)$$

Since the yarn width and axial strain are known and the braid is also locked (or jammed), the braid angle is given dimensionally by the equation,

$$\tan\theta_L = \frac{1}{\sqrt{\left(\frac{2Y}{y_w}\right)^2 - 1}} \qquad (2.9 - 3)$$

Formulated nondimensionally,

$$\tan\theta_L = \frac{1}{\sqrt{\left[\frac{2(1+\varepsilon_z)}{\overline{y_w}\tan\theta_0}\right]^2 - 1}} \qquad (2.9 - 4)$$

Since

$$\tan\theta = \frac{X}{Y} = \frac{\overline{X}}{\overline{Y}} \qquad (2.9 - 5)$$

the equilibrium X dimension is given by

$$X = \frac{Y}{\sqrt{\frac{2Y^2}{y_w} - 1}} \qquad (2.9 - 6)$$

or nondimensionally by

$$\overline{X} = \frac{1}{\sqrt{\left(\frac{2}{\overline{y_w}}\right)^2 - \left(\frac{\tan\theta_0}{1+\varepsilon_z}\right)^2}} \qquad (2.9 - 7)$$

The length of a leg of the braid unit is given by

$$L = \sqrt{X^2+Y^2} \qquad (2.9 - 8)$$

and nondimensionally by

$$\overline{L} = \sqrt{\overline{X}^2+\overline{Y}^2} \qquad (2.9 - 9)$$

The yarn strain may be found by employing the relationship

$$\varepsilon_y = \frac{L - L_0}{L_0} \qquad (2.9 - 10)$$

From the previously developed relationships,

$$r_{b_i} = r_b - y_t \qquad (2.9 - 11)$$

and

$$\overline{r_{b_i}} = \overline{r_b} - \overline{y_t} \qquad (2.9 - 12)$$

or since $\overline{r_b} = \overline{X}$,

$$\overline{r_{b_i}} = \overline{X} - \overline{y_t} \qquad (2.9 - 13)$$

Since the core is in contact with the braid, its radius is given by the inner braid radius and the radial strain is

$$\varepsilon_r = \frac{r_c - r_{c_0}}{r_{c_0}} \qquad (2.9 - 14)$$

2.10 Mode Four Equation Development

In mode four, like mode three, the braid remains locked but the Poisson contraction of the core causes it to withdraw from the inner wall of the braid. Hence, the braid and core act independently as they do in mode one.

The same equations developed for mode three apply to mode four with the exception that the core radius is no longer equal to the inner braid radius. Since there is no external pressure applied to the core radially, its radius can be characterized by the equation

$$r_c = r_{c_0}(1+\varepsilon_r) \qquad (2.10 - 1)$$

From the constitutive relationships for the core,

$$\varepsilon_r = -\nu\varepsilon_z \qquad (2.10 - 2)$$

Substituting for the radial strain,

$$r_c = r_{c_0}(1-\nu\varepsilon_z) \qquad (2.10 - 3)$$

Nondimensionally,

$$\overline{r_c} = \frac{r_{c_0}}{r_{b_0}}(1-\nu\varepsilon_z) \qquad (2.10 - 4)$$

2.11 Mode Summary

In each mode, axial strain is the independent variable. For each strain value an appropriate mode is guessed and the governing equations are evaluated to solve for the fundamental parameters including braid angle, mean braid radius, and associated strains. These parameters are then checked to insure that the proper mode of operation was selected. If a contradiction arises and the transition criteria dictate another mode, the composite parameters are re-evaluated in the new mode. This process continues until the proper mode is established.

2.12 Output Parameters

Once the mode, braid angle, and associated strains are known, the geometric parameters and forces that characterize the composite and each of its constituents may be found. The yarn stress may be computed directly from the yarn strain. For a linear yarn, the stress is simply given by

$$\sigma_y = E_y \varepsilon_y \qquad (2.12 - 1)$$

For a nonlinear yarn, the stress may be computed by interpolating from a table of properties. Once the stress is known, a nonlinear correction factor may be determined by dividing the stress by the product of the yarn strain and a characteristic modulus defined by the user. Hence

$$\sigma_y = E_y \varepsilon_y \varepsilon_{y_{con}} \qquad (2.12 - 2)$$

This formulation affords the user the ability to assess the degree of nonlinearity in the yarn's behavior by inspecting the correction factor variations. For a linearly elastic fiber, the correction factor is uniformly one.

Dimensionally, the yarn tension may be found by employing the relationship

$$T_y = YPF\, A_{y_0} E_y \varepsilon_y \varepsilon_{y_{con}} \qquad (2.12 - 3)$$

Nondimensionalizing the tension by the tension in a single yarn at 100 percent strain,

$$\overline{T_y} = YPF\, \varepsilon_y \varepsilon_{y_{con}} \qquad (2.12 - 4)$$

The yarn volume fraction may be expressed by the relationship

$$V_y = \frac{y_w}{2X\cos\theta} \qquad (2.12 - 5)$$

Rewriting the equation in terms of the initial yarn volume fraction,

$$\frac{V_y}{V_{y_0}} = \frac{X_0 \cos\theta_0}{X\cos\theta} \qquad (2.12 - 6)$$

Substituting the nondimensional mean braid radius for the nondimensional transverse dimension of the fundamental braid unit

$$V_y = \frac{V_{y_0} \cos\theta_0}{\overline{r_b}\cos\theta} \qquad (2.12 - 7)$$

Updating the cover factor based on the yarn volume fraction

$$CF = 1 - (1 - V_y)^2 \qquad (2.12 - 8)$$

The component of the total braid tension in the axial direction may be found by employing the equation

$$T_b = N_c YPF\, A_{y_0} E_y\, \varepsilon_y\, \varepsilon_{y_{corr}} \cos\theta \qquad (2.12 - 9)$$

Nondimensionalizing the braid tension by the tension in an equivalent number of yarns at 100 percent strain,

$$\overline{T_b} = YPF\, \varepsilon_y\, \varepsilon_{y_{corr}} \cos\theta \qquad (2.12 - 10)$$

or substituting the nondimensional yarn tension

$$\overline{T_b} = \overline{T_y} \cos\theta \qquad (2.12 - 11)$$

The axial core stress may be found utilizing the constitutive relationship

$$\sigma_z = \frac{E_c}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_z + \nu(\varepsilon_r + \varepsilon_\theta)\right] \qquad (2.12 - 12)$$

The axial core tension may be written as

$$T_c = CPF\, A_{c_0}\, \sigma_z \qquad (2.12 - 13)$$

Substituting for the axial stress and employing the relationships

$$A_{c_0} = \pi r_{c_0}^2 \qquad (2.12 - 14)$$

and

$$\varepsilon_r = \varepsilon_\theta \qquad (2.12 - 15)$$

the core tension becomes

$$T_c = \frac{CPF\, \pi\, r_{c_0}^2\, E_c}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_z + 2\nu\varepsilon_r\right] \qquad (2.12 - 16)$$

Nondimensionalizing the core tension

$$\overline{T_c} = \frac{\frac{CPF\, \pi\, r_{c_0}^2\, E_c}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_z + 2\nu\varepsilon_r\right]}{N_c A_{y_0} E_y} \qquad (2.12 - 17)$$

Letting

$$YVF = \frac{N_c A_{y_0}}{2\pi r_{b_0}^2} \qquad (2.12 - 18)$$

and substituting nondimensional quantities, the core tension becomes

$$\overline{T_c} = \frac{CPF(RMOD)\bar{r}_{c_0}^2}{2(YVF)(1+\nu)(1-2\nu)}[(1-\nu)\varepsilon_z + 2\nu\varepsilon_r] \qquad (2.12 - 19)$$

The axial composite tension is simply given by the sum of the axial components from the braid and core. Dimensionally,

$$T_{comp} = T_c + T_b \qquad (2.12 - 20)$$

and nondimensionally,

$$\overline{T_{comp}} = \overline{T_c} + \overline{T_b} \qquad (2.12 - 21)$$

If the total composite length is specified, the displacement corresponding to any value of axial strain may be found from the relationship

$$Disp = L_{comp}\,\varepsilon_z \qquad (2.12 - 22)$$

When dimensional output is desired from a nondimensional model formulation, the initial outer braid diameter, yarn modulus, and composite length must be specified.

2.13 Model Implementation

The formulation of the theoretical model lends itself to implementation as a simulation program. The controlling independent variable, axial strain is incorporated in a loop and conditional statements allow the appropriate mode of operation to be selected based on the transition criteria. Once the mode is chosen, the governing equations for that mode are evaluated and the model parameters are updated. Subsequently the mode of operation is verified by checking the updated mode transition criteria.

2.14 Program Features

The previous equations are implemented in a simulation program written in QuickBasic* that may be found in Appendix A. The majority of the code is devoted to a preprocessor that allows either a dimensional or nondimensional formulation and also

permits the user to interactively modify the input parameters. Prior to initiating the simulation, several conditional checks are incorporated to insure that the model parameters represent a feasible geometry. There is also a capability to model the yarns as linear or nonlinear materials. In the case of a nonlinear yarn model, the stress-strain characteristics must be specified in a data file. The program also affords the user the option to select the strain range for the simulation. The simulation can be terminated once the yarns fail if a nonlinear yarn model is used or may continue to a preset strain value. Composite failure is defined by a yarn stress equal to zero for some nonzero yarn strain . Dimensional input parameters are detailed in Table 3 while nondimensional input parameters are listed and defined in Table 4.

In the processing unit, the conditional statements that determine the mode of operation and associated governing equations are implemented. All computations are carried out nondimensionally to reduce notational complexity.

In the postprocessor, output files are generated that characterize the composite as well as its constituent materials at each strain interval. Four output files are generated by the program. Three detail the composite parameters associated with each value of axial strain while the remaining file summarizes the trial parameters. Within the program temporary files with the extension "DAT" are created which are subsequently written to data files specified by the user.

The file "GEO.DAT" contains nondimensional geometric parameters including the axial strain, radial core strain, yarn strain, braid angle, locking angle, cover factor, inner braid radius, and core radius. A final parameter, GAP, is simply the difference between the nondimensional inner braid radius and core radius. The file "FORCE.DAT" contains mode data and nondimensional force parameters. It includes axial strain, mode of operation, axial core tension, axial braid tension, axial composite tension, and the nonlinear yarn correction factor. The file "DIMOUT.DAT" contains dimensional output parameters.

Table 3. Dimensional Input Parameters

Braid Properties

Quantity	Notation		Units
	Text	Program	
Yarn Density	ρ	rhobraid	gm / cm^3
Linear Yarn Density	ρ_L	rhoLbraid	denier [gm / 9000 m]
Yarn Aspect Ratio	y_t/y_w	YAR	dimensionless
Yarn Packing Factor	YPF	YPF	dimensionless
Number of Yarns in Braid	N_C	N_C	yarns
Initial Braid Braid Density	ppi0	ppi0	picks / inch
Initial Outer Braid Diameter	D_{bo0}	Dbraid0o	mm
Yarn Modulus	E_y	YarnMod	Pa

Core Properties

Quantity	Notation		Units
	Text	Program	
Initial Core Diameter	D_{C0}	Dcore0	mm
Core Modulus	E_C	CoreMod	Pa
Core Poisson's Ratio	ν	V	dimensionless
Core Packing Factor	CPF	CPF	dimensionless

Table 4. Nondimensional Input Parameters

Quantity	Notation		Definition	Range
	Text	Program		
Initial Wall Thickness Ratio	$2y_t/r_{b0}$	WTR	$\frac{2(\text{Yarn Thickness})}{\text{Mean Braid Radius}}$	0 - 2
Initial Core/Inner Braid Radius Ratio	r_{c0}/r_{b0}	CIBR	$\frac{\text{Core Radius}}{\text{Inner Braid Radius}}$	0 - 1
Yarn Aspect Ratio	y_w/y_t	YAR	$\frac{\text{Yarn Thickness}}{\text{Yarn Width}}$	Unrestricted
Yarn Packing Factor	YPF	YPF	$\frac{\text{Yarn Fiber Volume}}{\text{Total Yarn Volume}}$	0 - 1
Core Packing Factor	CPF	CPF	$\frac{\text{Core Fiber Volume}}{\text{Total Core Volume}}$	0 - 1
Initial Braid Angle	θ_0	angle0	Yarn Helix Angle	0 - 90 deg
Initial Braid Cover Factor	CF_0	F0	$\frac{\text{Projected Yarn Surface Area}}{\text{Mean Braid Surface Area}}$	0 - 1
Modulus Ratio	E_c/E_y	RMOD	$\frac{\text{Core Modulus}}{\text{Yarn Modulus}}$	Unrestricted
Core Poisson's Ratio	ν	V	$-\frac{\text{Radial Strain}}{\text{Axial Strain}}$	< 0.5

It includes composite displacement, mode of operation, inner braid radius, core radius, axial core tension, axial braid tension, and the total axial composite tension. The remaining output file, "PARAMTR.DAT", is essentially a model parameter summary. It includes the date that the trial was generated, a brief description, and the output filename for the dimensional data specified by the user. The summary also notes whether the yarn was characterized as a linear or nonlinear material. If a nonlinear analysis was utilized, the data file containing the yarn stress-strain properties is listed. Subsequently, all nondimensional and dimensional input parameters are listed. Finally, if the simulation was terminated at yarn failure, the value of axial strain at which the braid yarns failed is specified.

Once the simulation is completed, the program affords the user the option to restart the simulation modifying only the model parameters, change only the simulation range and convergence parameters, or restart the entire program.

3.0 EXPERIMENTAL MODEL VALIDATION

3.1 Introduction

In an attempt to verify the theoretical model and underlying assumptions, a number of experimental trials were carried out to test the agreement between theory and experiment. In these trials, commercially available braided Dacron* cords were modified by replacing the original core with an elastomer taken from bungi cords. Several specimens are illustrated in Figure 8. An actual cross-section from an experimental specimen is shown in Figure 9. For the computer based simulations, the core was modeled as a cylinder but actually consisted of a series of elastic strands. The number of strands dictated the dimension of the equivalent radius for the core. Tension tests were performed with an Instron machine on the composites and their constituent materials. Utilizing the experimental data, computer based simulations were performed in an attempt to validate the model.

It should be noted that several secondary factors became immediately apparent during the experimental testing. Both the yarns and elastomers exhibited various degrees of creep and hysteresis which the theoretical model did not accommodate. In an attempt to minimize the influence of these factors, all tests were carried out at the same cross-head speed of five inches per minute and only first cycle loading data was utilized. While the elastomer was always loaded axially and deformed at the same rate as the cross-head, the yarns were oriented at different angles in different samples and consequently, their deformation rates varied with braid angle. However, in the tests performed on the yarns, tensile response showed no apparent rate dependence for cross-head speeds between one and ten inches per minute. Since the tensile tests revealed that the yarns had a very small elastic region, neither the yarns nor the composites were preconditioned in order to avoid any plastic yielding.

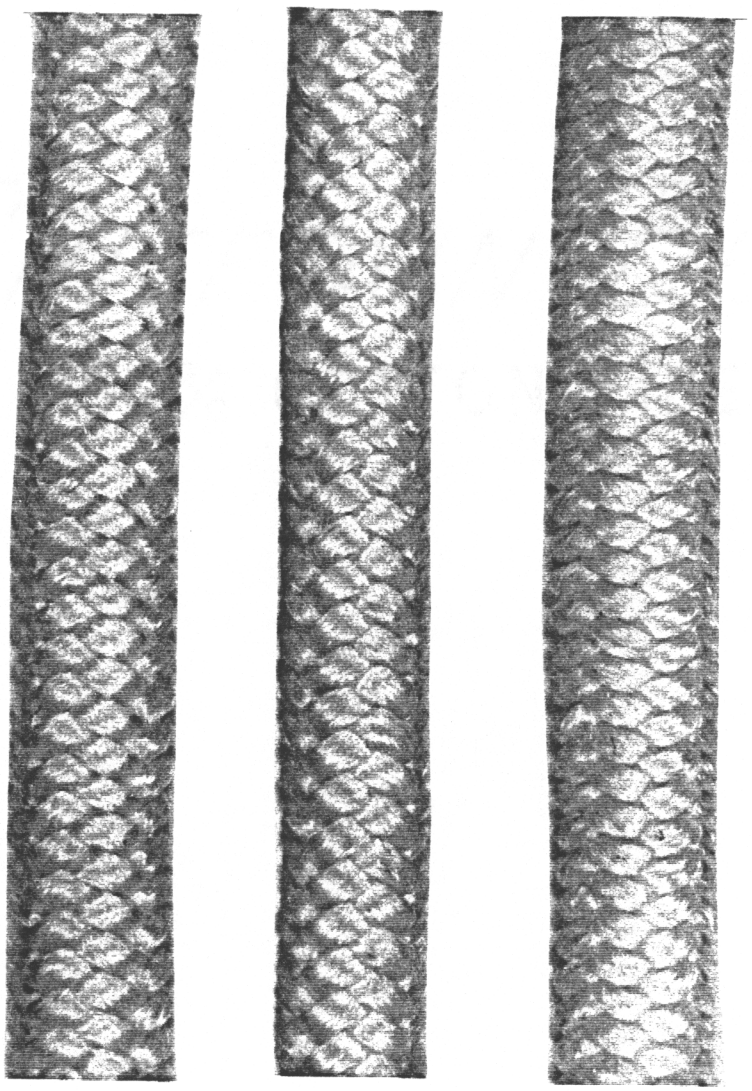


Figure 8. Braided Dacron* Composites with Different Core Diameters

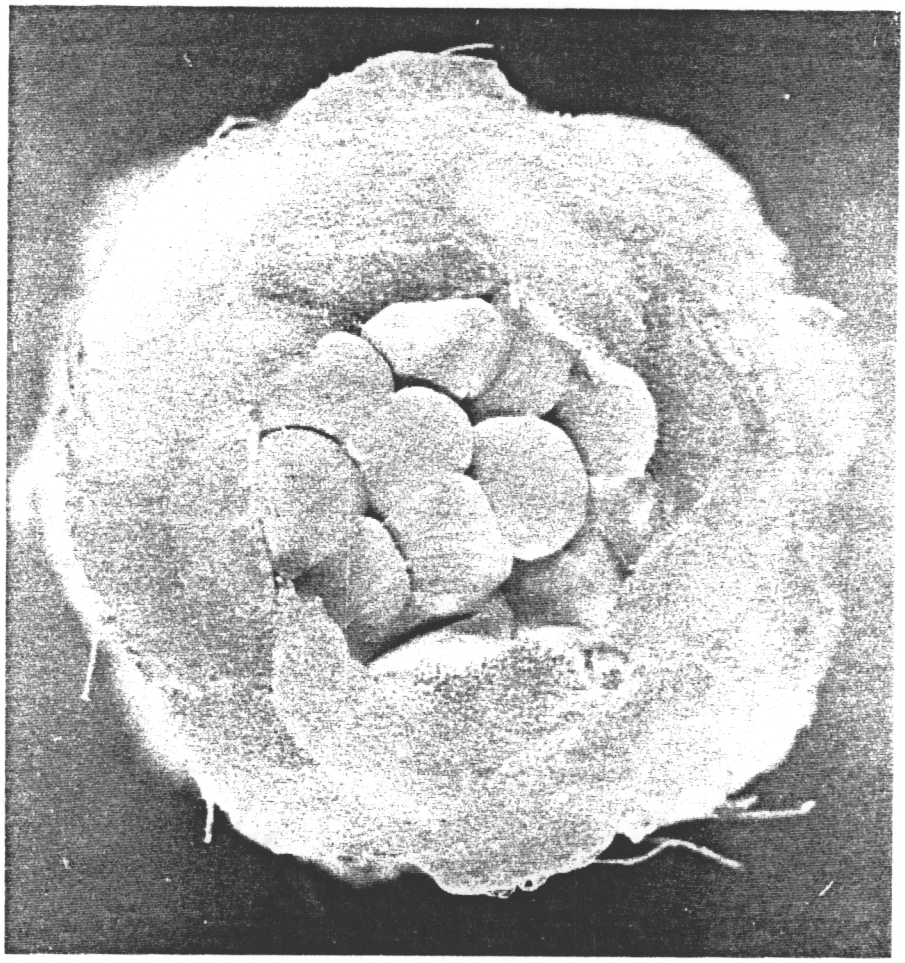


Figure 9. Actual Composite Cross-Section

3.2 Core and Yarn Property Determination

Preliminary to simulating the composites, core and yarn properties had to be established. Although the manufacturer would not specify the identity or material properties of the elastomer in the bungi cords, axial tension tests revealed that the modulus decreased from 6.0 to 2.0 MPa over a strain range of 50 percent. Poisson's ratio was found to be approximately 0.30. Since the core's contribution to the composite is most apparent in the toe-region at lower strains, the higher modulus value was utilized for the simulations. To obtain the Dacron* fiber properties, uniaxial tension tests were performed on the yarns and the resulting data was converted from force-displacement to stress-strain by incorporating the yarn cross-sectional area and total length. The yarn specimens were taken from the actual Dacron* braids and mounted with epoxy on LetraMax 4000 Ruling Mechanical Board, a heavy duty type of cardboard, as illustrated in Figure 10. In order to minimize end effects associated with force-displacement data, samples with 25 and 30 centimeter lengths were tested that had radius/length ratios on the order of 1/1000. After the data was normalized by sample length and converted to stress-strain, no apparent differences arose, indicating that end effects were negligible. Since the yarn properties are experimentally determined, the fiber consolidation technique does not need to be included in the model formulation. The experimental yarn data will include the influence of the fiber orientation within the yarns.

During the experimental testing, two types of crimp were noted in the braid yarns. The macro-crimp, apparent at the yarn level and visible to the naked eye, resulted from the yarns' interlaced configuration within the braid. The micro-crimp, introduced to the fibers comprising the yarns during the fabrication process, was present even in yarns that appeared visibly straight.

To verify the braid mechanics and yarn properties, several experimental tests and computer based simulations were run on the braided Dacron* alone without a core. In the

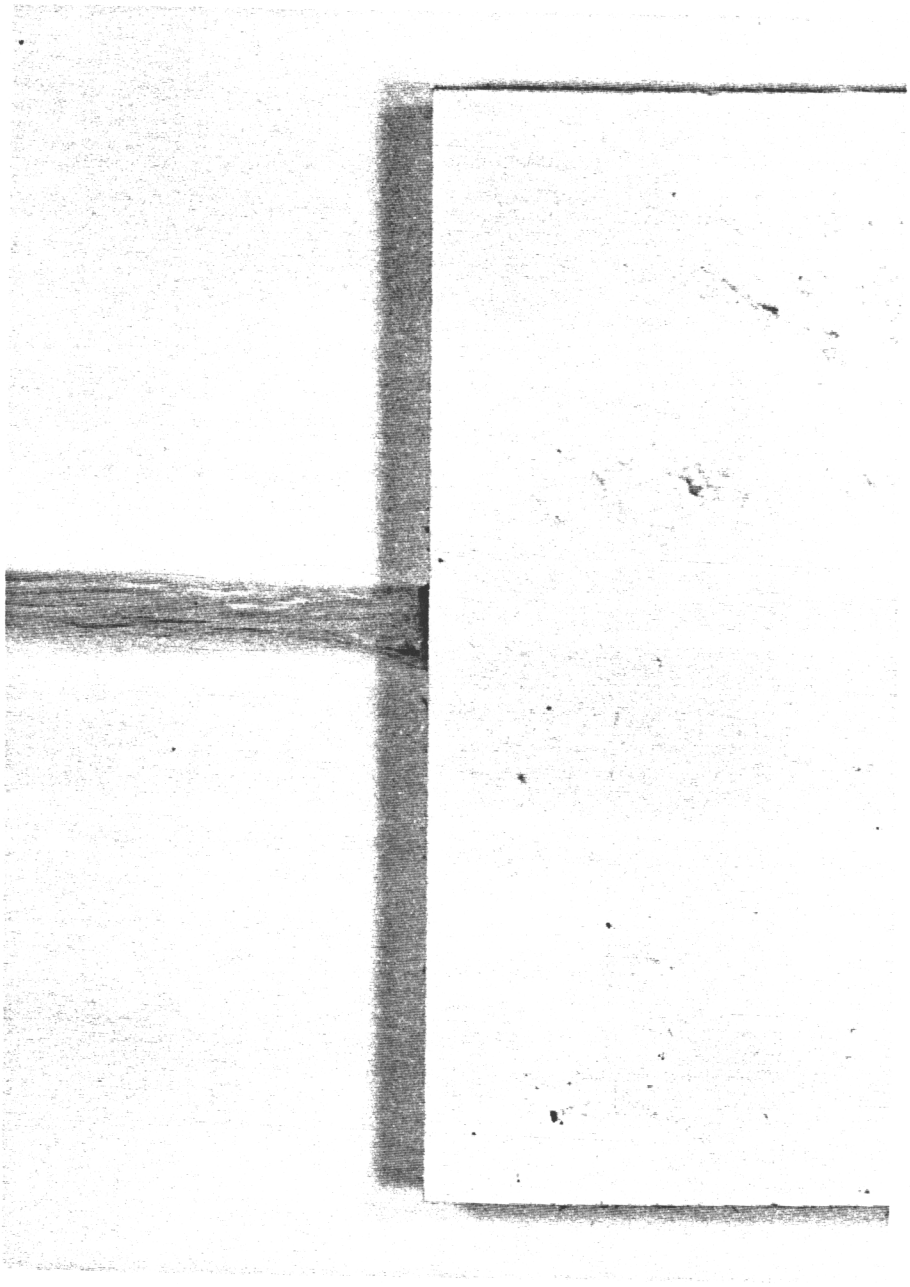


Figure 10. Yarn Mounting Technique for Experimental Testing

initial testing designed to determine the fiber properties, the yarns were pulled nearly straight in an attempt to eliminate the apparent macro-crimp. The resulting Dacron* properties may be found in Figure 11 and are designated by the legend title "Without Crimp". The very small toe-region results from micro-crimp retained at the fiber level even after the yarn had been pulled visibly straight. Yet the simulations based on these yarn properties predicted a much stiffer composite response in the region of elastic yarn deformation and premature mode transitions as evidenced by the theoretical braid response based on yarn properties without any apparent crimp in Figure 12.

These observations made it apparent that the crimp set in the Dacron* yarns was essential to the model and subsequent tests were conducted on the yarns allowing them to hang under their own weight and that of the fixturing cardboard. This retained much of the macro-crimp and was reflected in the tension tests and is illustrated in Figure 11 by the curve designated fiber properties "With Crimp". However, in the uniaxial tension tests without the constraints imposed by the other yarns in the braid, all the macro-crimp initially pulled out at very low forces. The micro-crimp associated with the fibers themselves then pulled out resulting in a small transitional toe-region from the macro crimp dominated region to the region of elastic behavior. The elastic region is characterized by a very high modulus but spans less that ten percent of the strain range for the fiber behavior. Once the strain levels exceeded the elastic limits of the Dacron*, the fibers began to yield. This yielding was initially characterized by a rather low modulus that steadily increased until failure, resulting in an upward concavity in the plastic region illustrated by the Dacron* fiber property curves in Figure 11. Subsequent simulations with yarn properties that incorporated crimp still revealed excessive stiffness within the elastic region of the yarn behavior accompanied by a delayed mode transition as illustrated in Figure 12. In all samples however, the transition from elastic to plastic regions and the plastic behavior predicted by theory appeared to agree well with experiment.

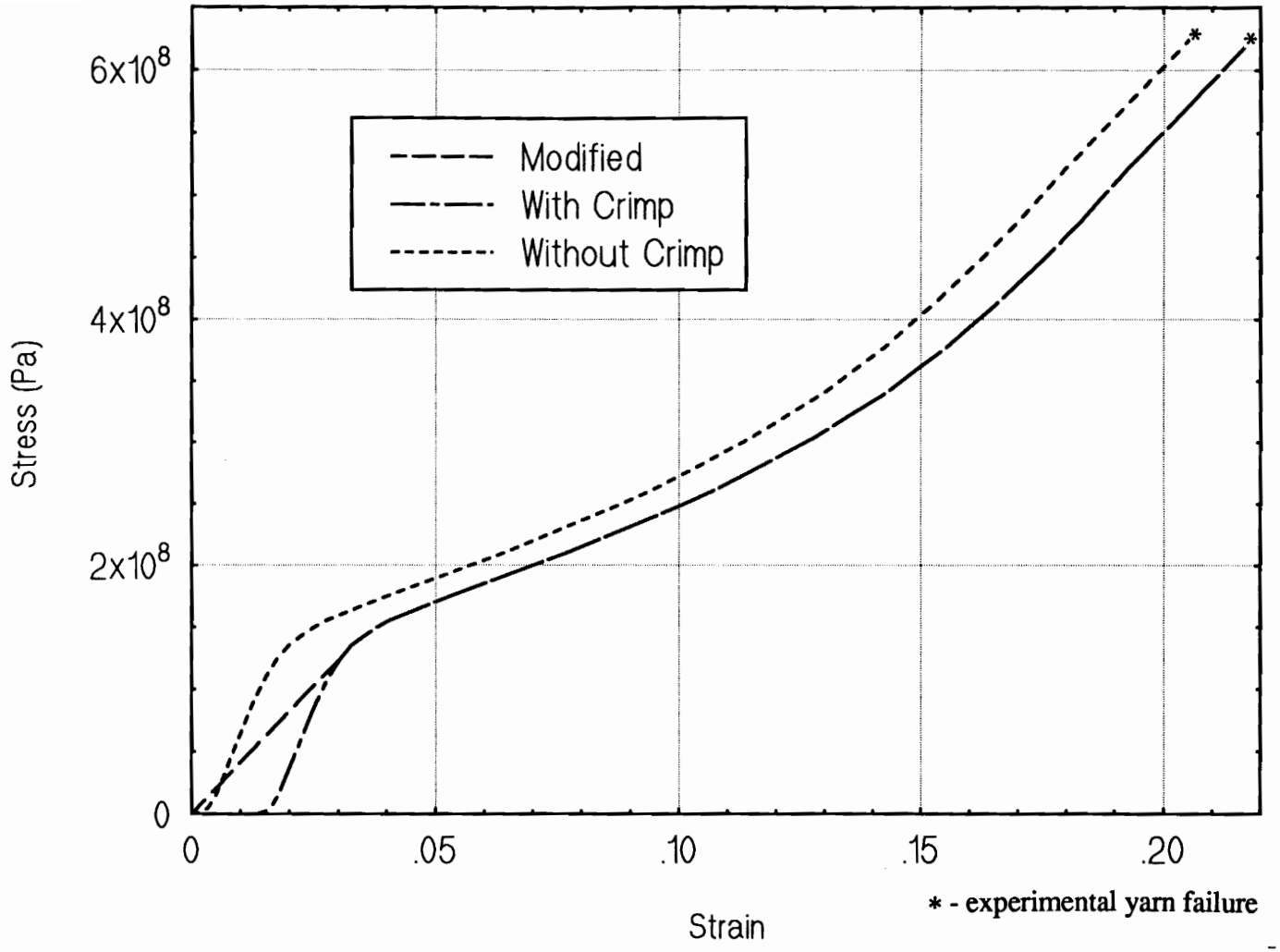


Figure 11. Dacron* Fiber Properties

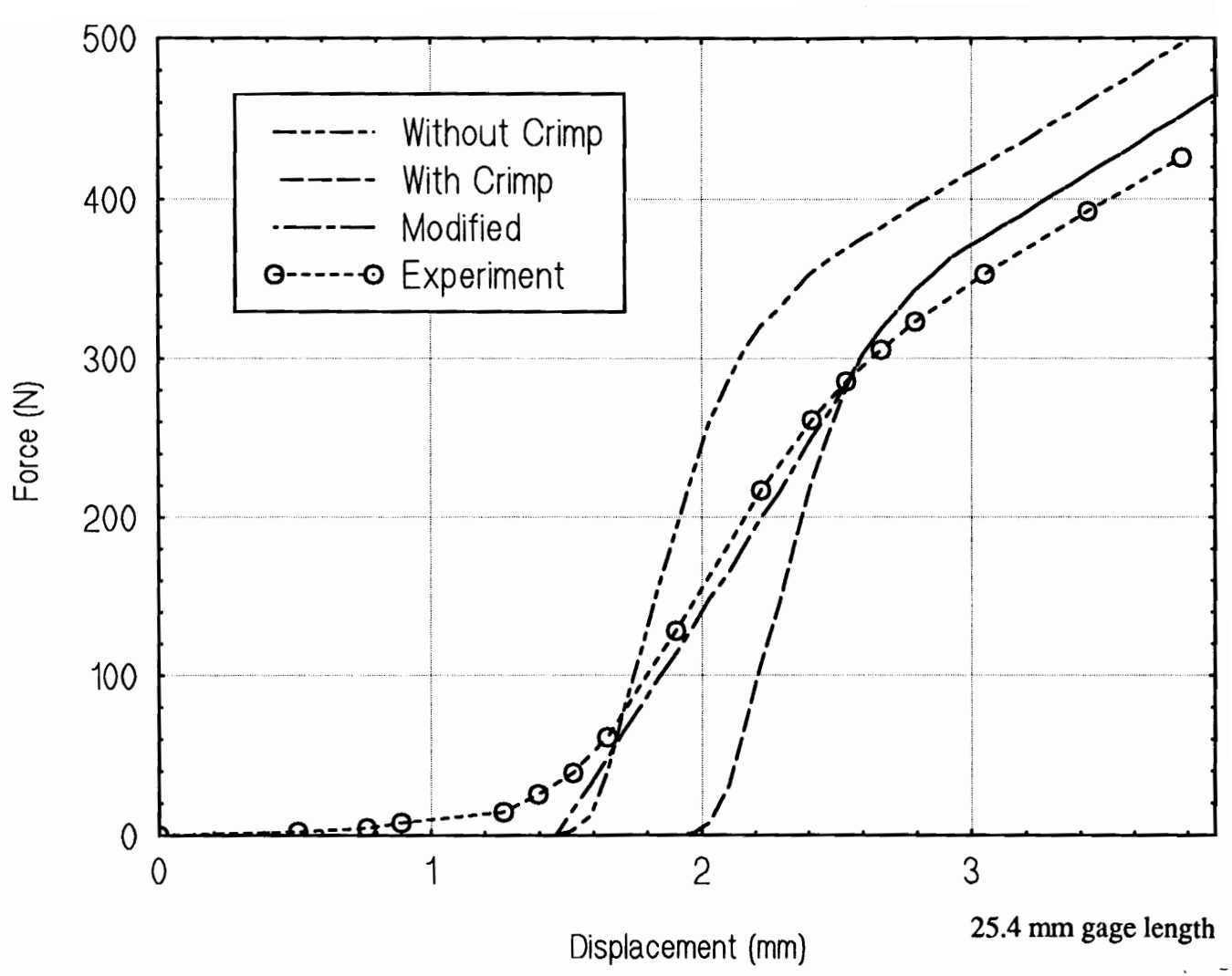


Figure 12. Experimental Verification - Braid Only

Based on the apparent composite behavior, it was hypothesized that for small strains, the yarns did not behave as if they were in a state of uniaxial tension. Instead, the constraints imposed by the other yarns in the braid caused the crimp to pull out within the region of elastic behavior instead of immediately prior to it. In a real braid, the yarns impede each other's straightening and consequently, elastic stretching and straightening are not discrete phenomenon as they appear in a uniaxial tension test but are intimately connected. Consequently, the Dacron* fiber properties were modified incorporating both the crimp dominated and elastic behavior regions. This was accomplished by using a linear interpolation from the initial point of the fiber properties curve to the knee where yielding began. The fiber properties modified to reflect the hypothesized yarn behavior are illustrated in Figure 11 and are designated by the curve labeled "Modified" fiber properties. The resulting braid simulations using the modified fiber properties showed excellent agreement with the experimental data as evidenced by Figure 12.

The parameters characterizing the braid alone are summarized in Table 5 which was generated by the simulation program. Figure 13 reflects the extrapolated braid response to failure based on the simulation's yarn failure criteria. Figure 14 illustrates the theoretical mode transitions associated with the braid's behavior. Since the braid has no core, the mode transition is directly from one to four once the braid locks.

3.3 Experimental Composite Testing

Utilizing the modified fiber properties to characterize the braid yarns, several simulations were run on different classes of composites that were created by changing the relative size of the core components. To acquire the experimental data, the composites were mounted with a 50 percent strain extensometer. Each specimen was 300 mm long. To facilitate testing, the composite ends were mounted between two pieces of heavy duty cardboard in the same fashion as the individual yarns. This technique enabled the flat Instron grips to uniformly secure the braided yarns and core. To check the significance of

Table 5. Model Parameter Summary - Braid Only

```
                    DATE : 05/19/91
        MODEL DESCRIPTION : SPECIMEN 3B (BRAID ONLY)
NONLINEAR ANALYSIS
YARN PROPERTY FILENAME : A:MODIFY.DAC
                NONDIMENSIONAL PARAMETERS
WALL THICKNESS RATIO = 0.5896
CORE/INNER BRAID RADIUS RATIO = 0.0000
YARN ASPECT RATIO = 0.5000
YARN PACKING FACTOR = 0.5000
CORE PACKING FACTOR = 0.0000
INITIAL BRAID ANGLE =  32.610 DEG
INITIAL BRAID COVER FACTOR = 0.9882
CORE/YARN MODULUS RATIO =   0.00000
CORE POISSON'S RATIO = 0.0000
                DIMENSIONAL PARAMETERS
NUMBER OF YARNS IN BRAID =  16.000
YARN DENSITY =  1.3800 [GM/CM^3]
LINEAR YARN DENSITY =  2000.00 [DENIER]
YARN MODULUS =   2867.770 [MPa]
INITIAL BRAID DENSITY =   15.200 [PICKS PER INCH]
INITIAL OUTER BRAID DIAMETER =   3.525 [MM]
INITIAL CORE DIAMETER =   0.000 [MM]
CORE MODULUS =      0.000 [MPa]
YARN FAILURE AT  35.50 % AXIAL STRAIN
```

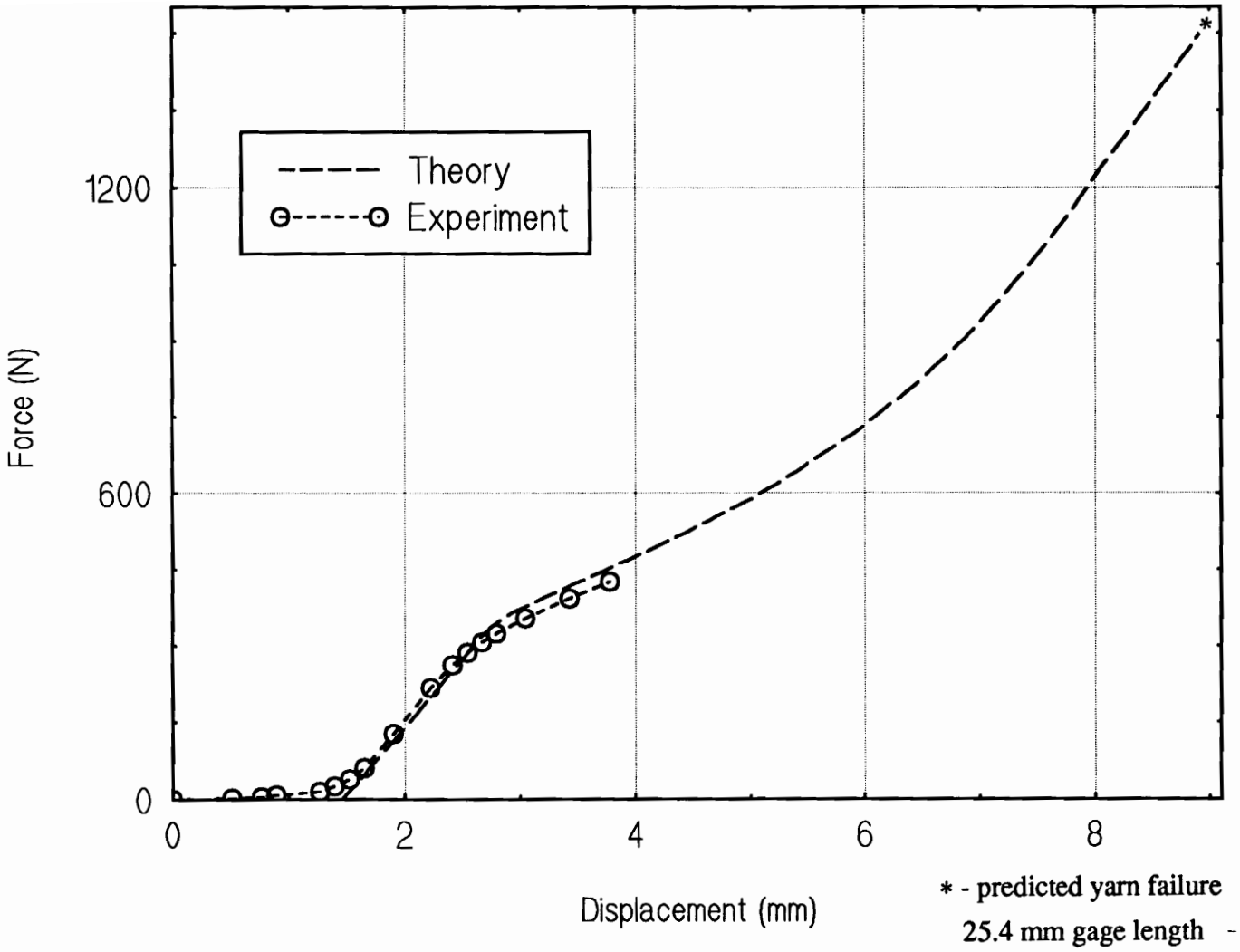


Figure 13. Experimental Verification and Failure Prediction - Braid Only

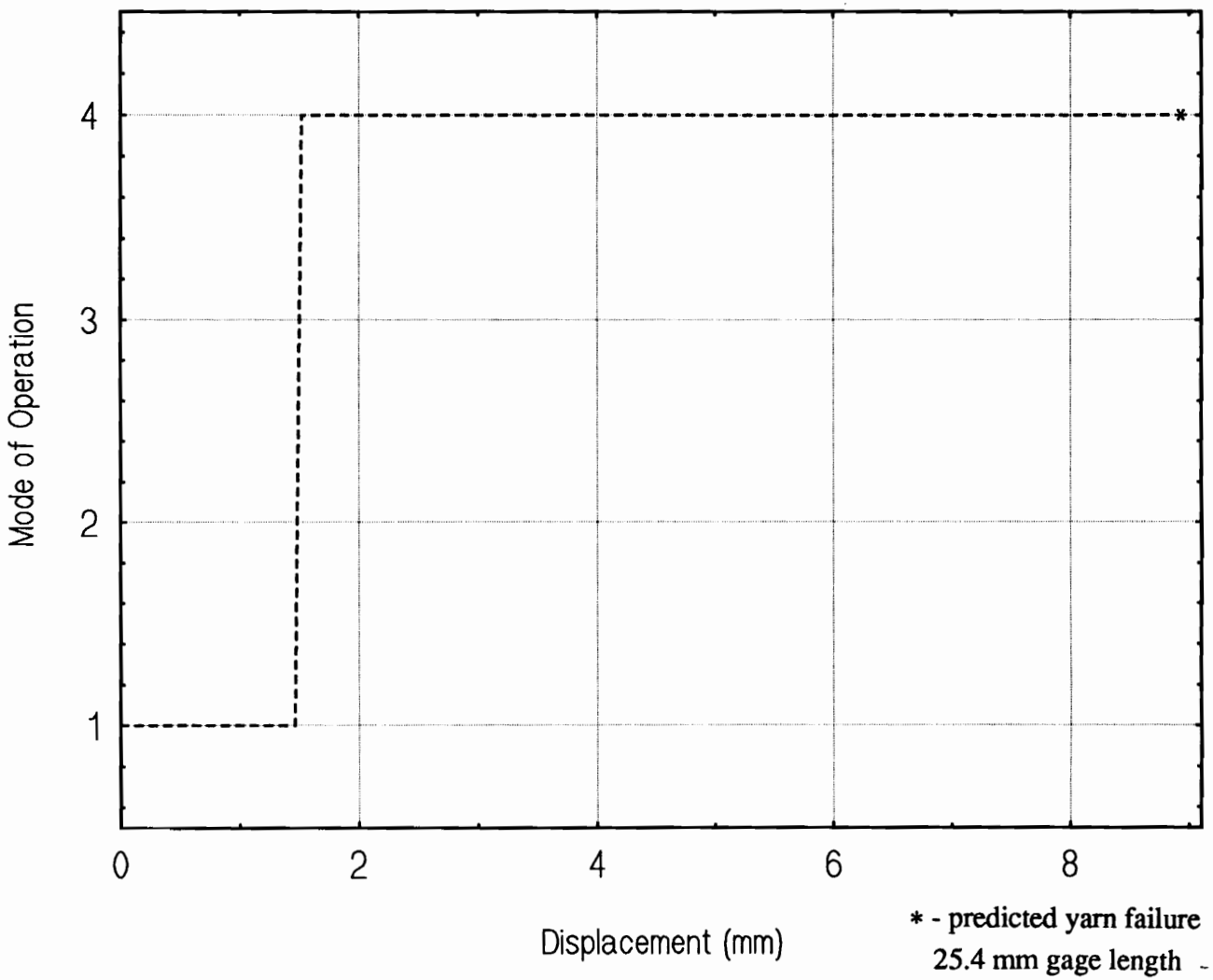


Figure 14. Theoretical Mode Transitions - Braid Only

end effects, strain and end displacement data were acquired simultaneously. When the extensometer was carefully mounted, no significant differences arose between the strain and displacement data. This indicated that end effects were negligible and that the assumption of uniform axial strain was valid. Nevertheless, to insure the best accuracy, extensometer based strain data was utilized for comparisons of theory and experiment. The results of the experimental data are illustrated in Figure 15. Displacement values were calculated from extensometer strain data based on a composite length of 25.4 mm (1 inch). Force data was recorded directly from the load cell. Experimental composite specimens are designated by a number and letter. The number designates the number of elastic strands that comprise the core while the letter distinguishes specimens with the same number of core strands. Each specimen consists of the same Dacron* braid fabricated with sixteen 2000 denier yarns. Increasing the core size effectively acts to extend the toe-region by increasing the initial braid density. Each experimental series is characterized by a toe-region followed by a relatively stiff region that results from the elastic behavior of the yarns. Beyond the elastic response is a region characterized by a lower modulus associated with plastic deformation. Since each of the composites has the same braid and a very low modulus core material, their mechanical response curves exhibit similar slopes. Within each class of samples, composite parameters varied slightly but overall agreement between experimental specimens was quite good and the specimen representing the approximate mean composite properties was chosen for comparison with the computer based simulation.

3.4 Theoretical and Experimental Comparison

The results from simulation and experiment are illustrated in Figures 16, 19, and 22 for specimens with four, eight, and twelve strand cores respectively. The model parameters used to characterize each composite specimen are summarized in Tables 6, 7, and 8. These tables, like Table 5, were generated by the simulation program. Figures 17,

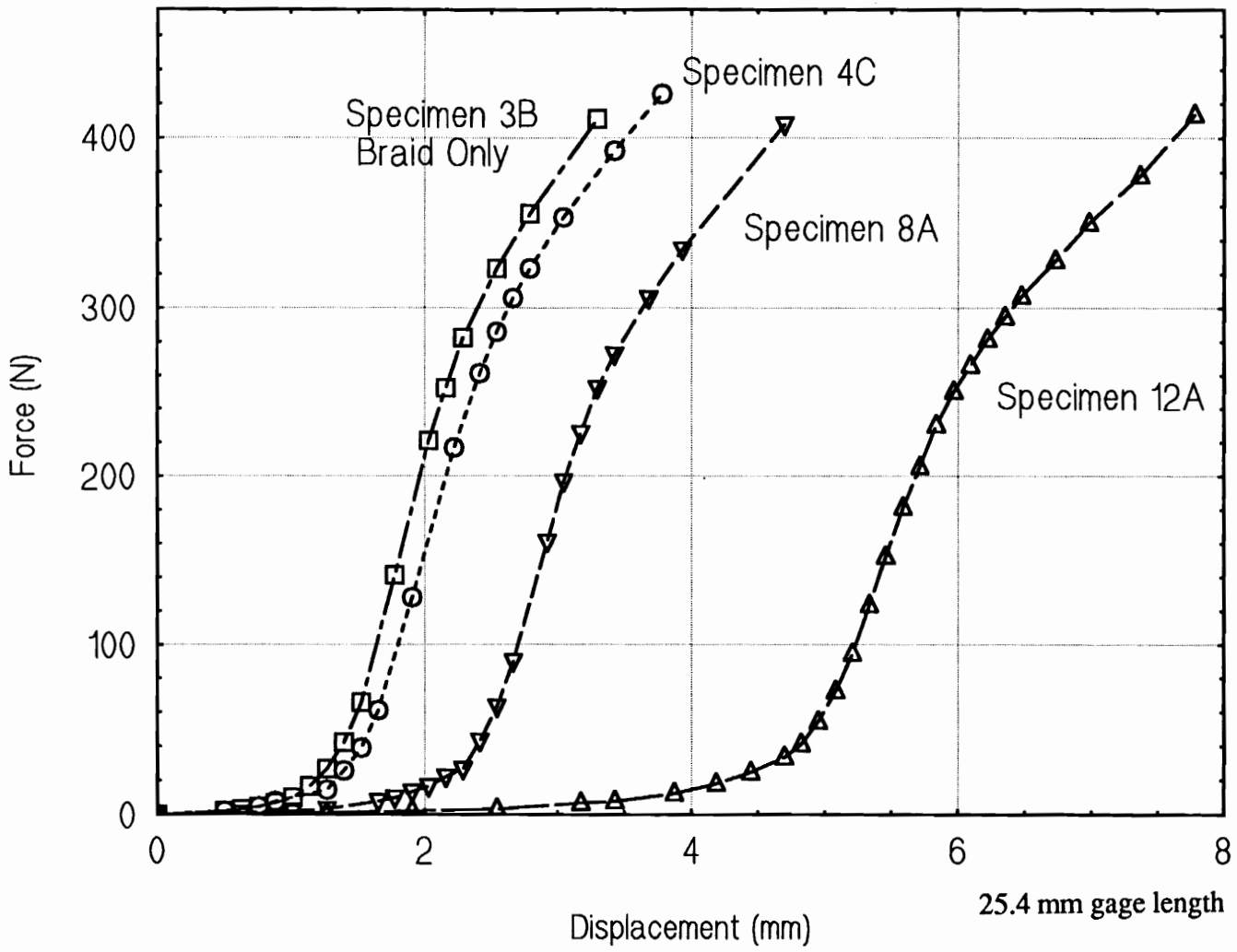


Figure 15. Experimental Data

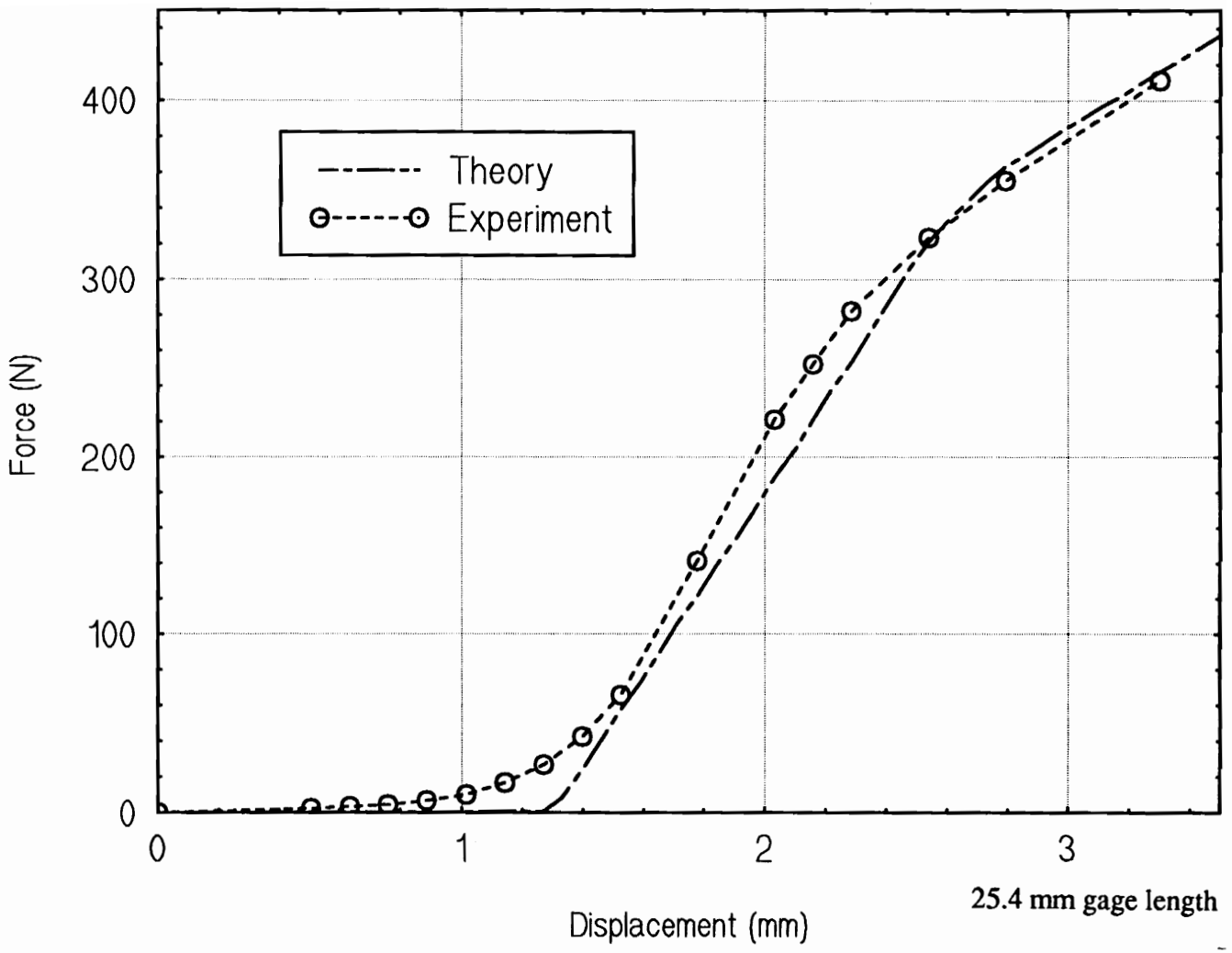


Figure 16. Experimental Verification - Specimen 4C

Table 6. Model Parameter Summary - Specimen 4C

```
                    DATE : 05/17/91
        MODEL DESCRIPTION : SPECIMEN 4C
NONLINEAR ANALYSIS
YARN PROPERTY FILENAME : A:MODIFY.DAC
                NONDIMENSIONAL PARAMETERS
WALL THICKNESS RATIO = 0.5995
CORE/INNER BRAID RADIUS RATIO = 0.6827
YARN ASPECT RATIO = 0.5000
YARN PACKING FACTOR = 0.5000
CORE PACKING FACTOR = 1.0000
INITIAL BRAID ANGLE =  32.685 DEG
INITIAL BRAID COVER FACTOR = 0.9913
CORE/YARN MODULUS RATIO =   0.00209
CORE POISSON'S RATIO = 0.3000
                DIMENSIONAL PARAMETERS
NUMBER OF YARNS IN BRAID =  16.000
YARN DENSITY =  1.3800 [GM/CM^3]
LINEAR YARN DENSITY =  2000.00 [DENIER]
YARN MODULUS =   2867.770 [MPa]
INITIAL BRAID DENSITY =   15.500 [PICKS PER INCH]
INITIAL OUTER BRAID DIAMETER =   3.480 [MM]
INITIAL CORE DIAMETER =   1.280 [MM]
CORE MODULUS =      6.000 [MPa]
YARN FAILURE AT  35.00 % AXIAL STRAIN
```

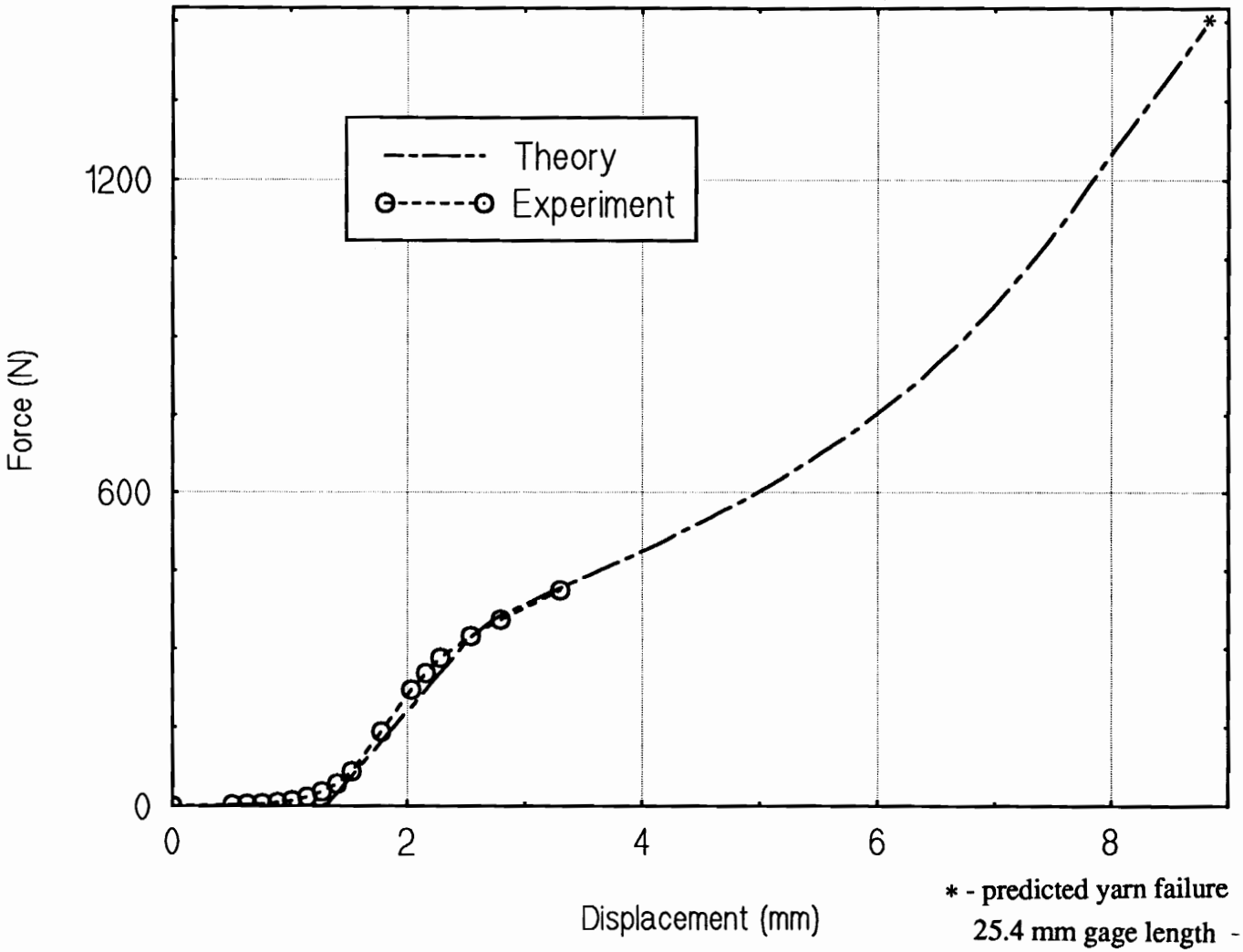


Figure 17. Experimental Verification and Failure Prediction - Specimen 4C

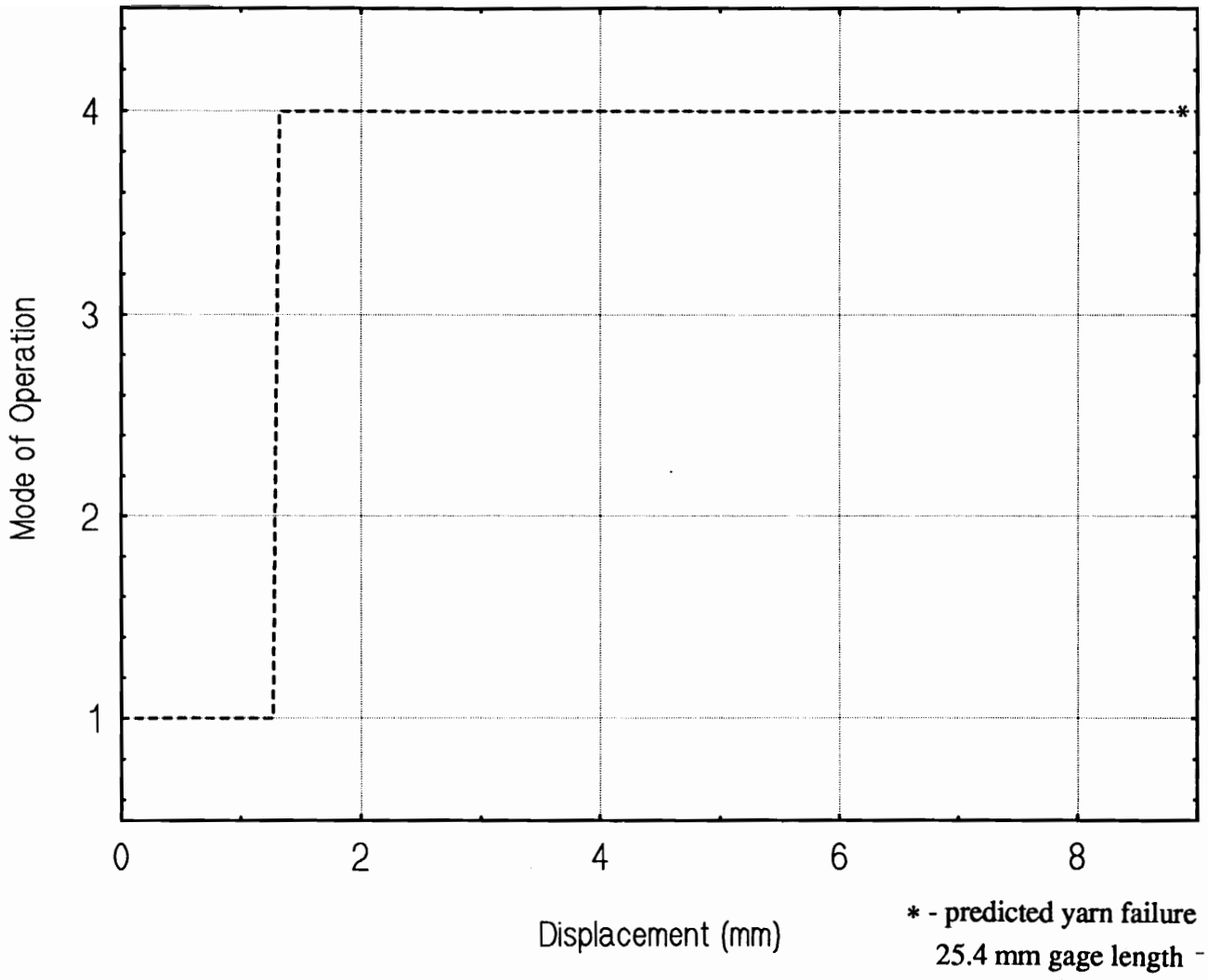


Figure 18. Theoretical Mode Transitions - Specimen 4C

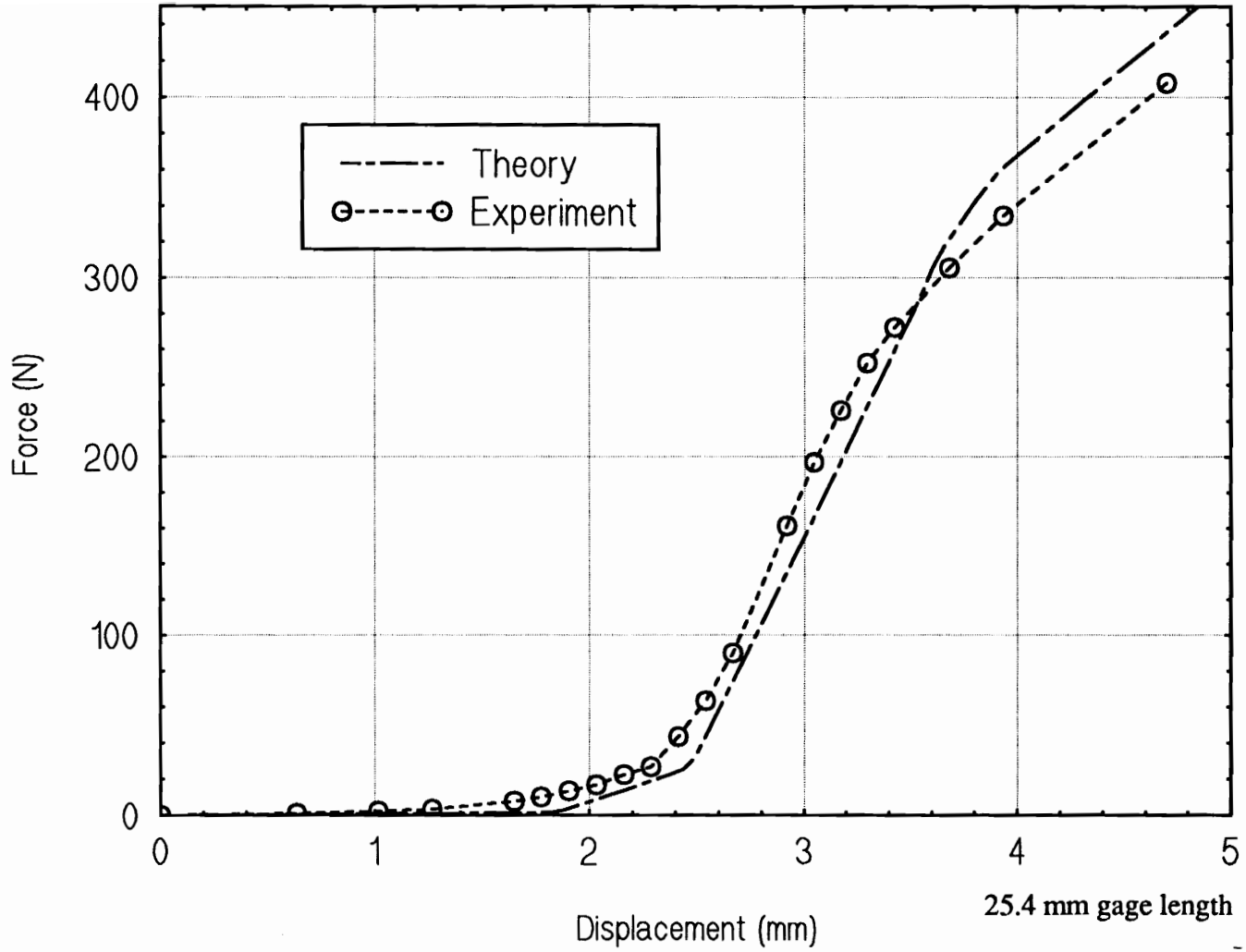


Figure 19. Experimental Verification - Specimen 8A

Table 7. Model Parameter Summary - Specimen 8A

```
                    DATE : 05/17/91
        MODEL DESCRIPTION : SPECIMEN 8A
NONLINEAR ANALYSIS
YARN PROPERTY FILENAME : A:MODIFY.DAC
                NONDIMENSIONAL PARAMETERS
WALL THICKNESS RATIO = 0.5540
CORE/INNER BRAID RADIUS RATIO = 0.8115
YARN ASPECT RATIO = 0.5000
YARN PACKING FACTOR = 0.5000
CORE PACKING FACTOR = 1.0000
INITIAL BRAID ANGLE =  36.469 DEG
INITIAL BRAID COVER FACTOR = 0.9849
CORE/YARN MODULUS RATIO =   0.00209
CORE POISSON'S RATIO = 0.3000
                DIMENSIONAL PARAMETERS
NUMBER OF YARNS IN BRAID =  16.000
YARN DENSITY =  1.3800 [GM/CM^3]
LINEAR YARN DENSITY =  2000.00 [DENIER]
YARN MODULUS =   2867.770 [MPa]
INITIAL BRAID DENSITY =   16.500 [PICKS PER INCH]
INITIAL OUTER BRAID DIAMETER =   3.700 [MM]
INITIAL CORE DIAMETER =   1.700 [MM]
CORE MODULUS =      6.000 [MPa]
YARN FAILURE AT  41.00 % AXIAL STRAIN
```

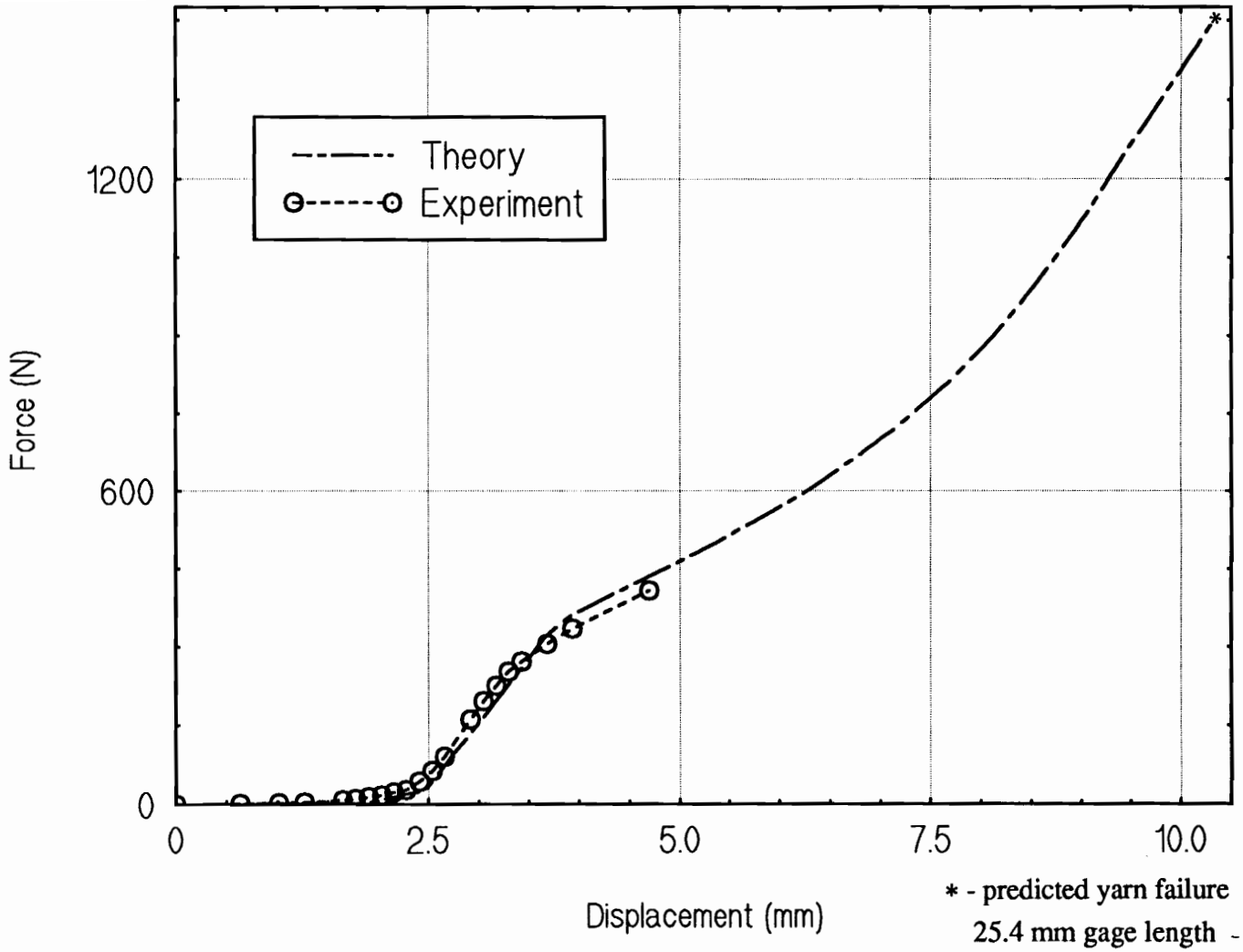


Figure 20. Experimental Verification and Failure Prediction - Specimen 8A

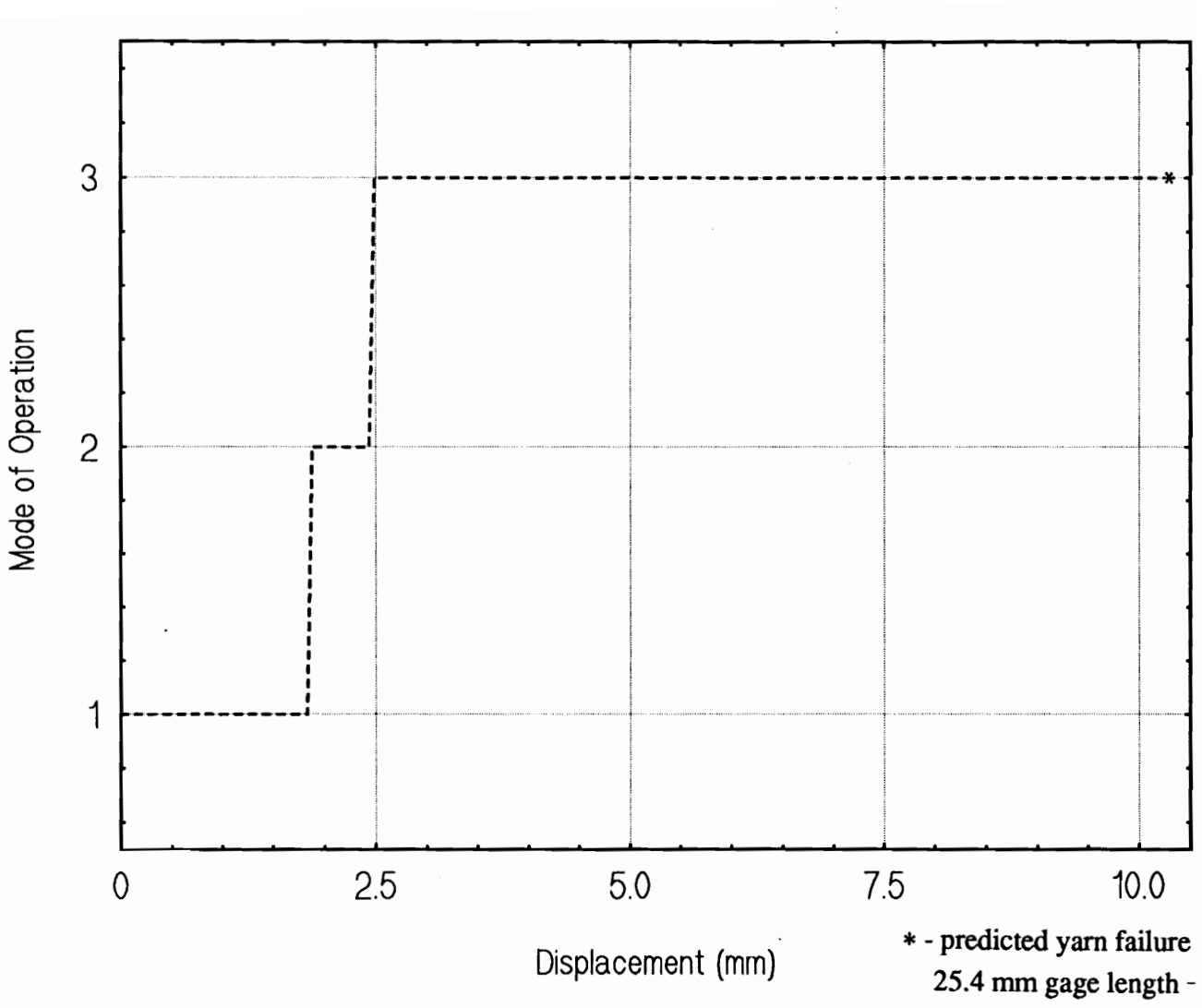


Figure 21. Theoretical Mode Transitions - Specimen 8A

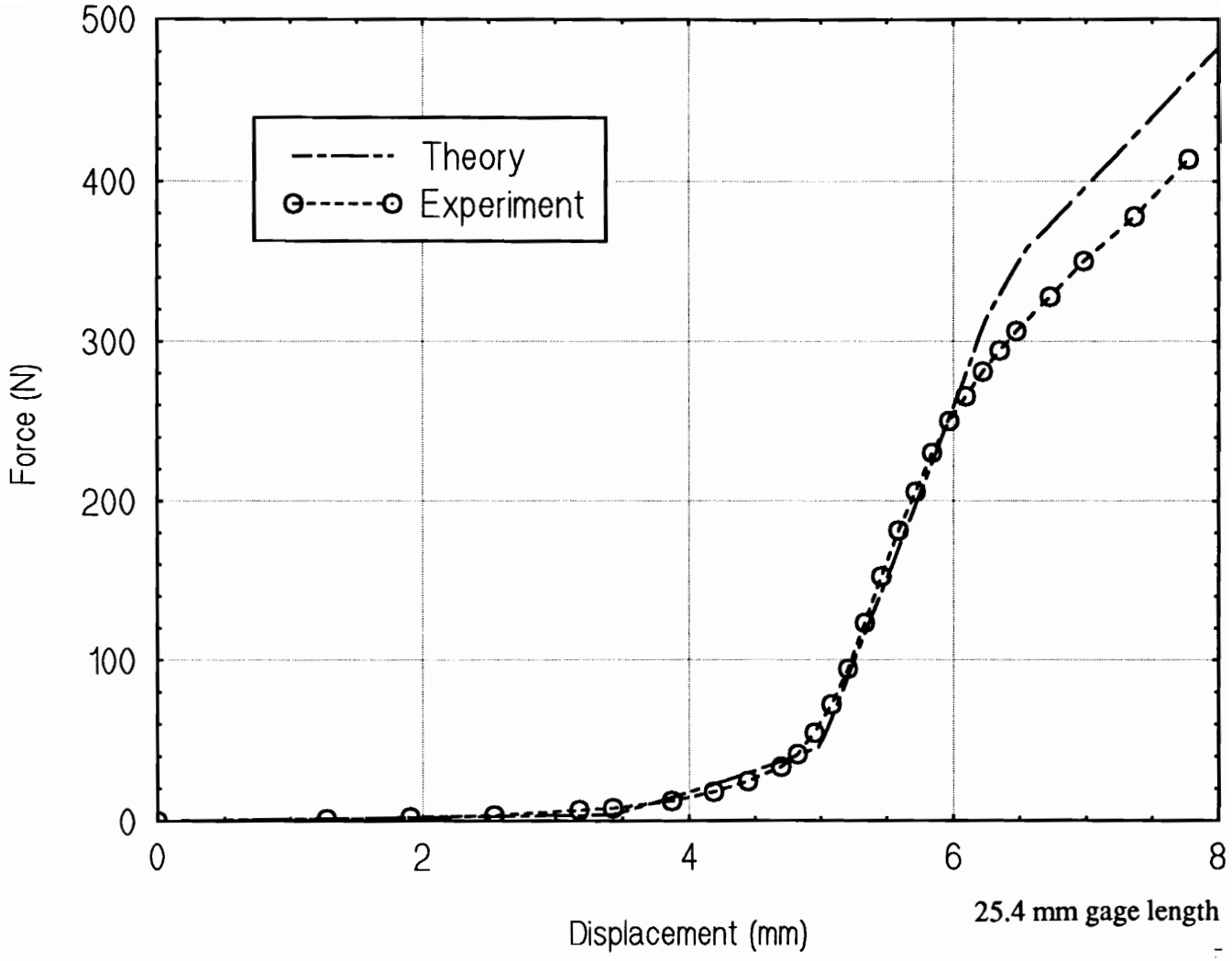


Figure 22. Experimental Verification - Specimen 12A

Table 8. Model Parameter Summary - Specimen 12A

```
                    DATE : 05/17/91
        MODEL DESCRIPTION : SPECIMEN 12A
NONLINEAR ANALYSIS
YARN PROPERTY FILENAME : A:MODIFY.DAC
                NONDIMENSIONAL PARAMETERS
WALL THICKNESS RATIO = 0.4958
CORE/INNER BRAID RADIUS RATIO = 0.7927
YARN ASPECT RATIO = 0.5000
YARN PACKING FACTOR = 0.5000
CORE PACKING FACTOR = 1.0000
INITIAL BRAID ANGLE =  43.106 DEG
INITIAL BRAID COVER FACTOR = 0.9817
CORE/YARN MODULUS RATIO =   0.00209
CORE POISSON'S RATIO = 0.3000
                DIMENSIONAL PARAMETERS
NUMBER OF YARNS IN BRAID =  16.000
YARN DENSITY =  1.3800 [GM/CM^3]
LINEAR YARN DENSITY =  2000.00 [DENIER]
YARN MODULUS =   2867.770 [MPa]
INITIAL BRAID DENSITY =   18.700 [PICKS PER INCH]
INITIAL OUTER BRAID DIAMETER =   4.040 [MM]
INITIAL CORE DIAMETER =   1.930 [MM]
CORE MODULUS =      6.000 [MPa]
YARN FAILURE AT  54.40 % AXIAL STRAIN
```

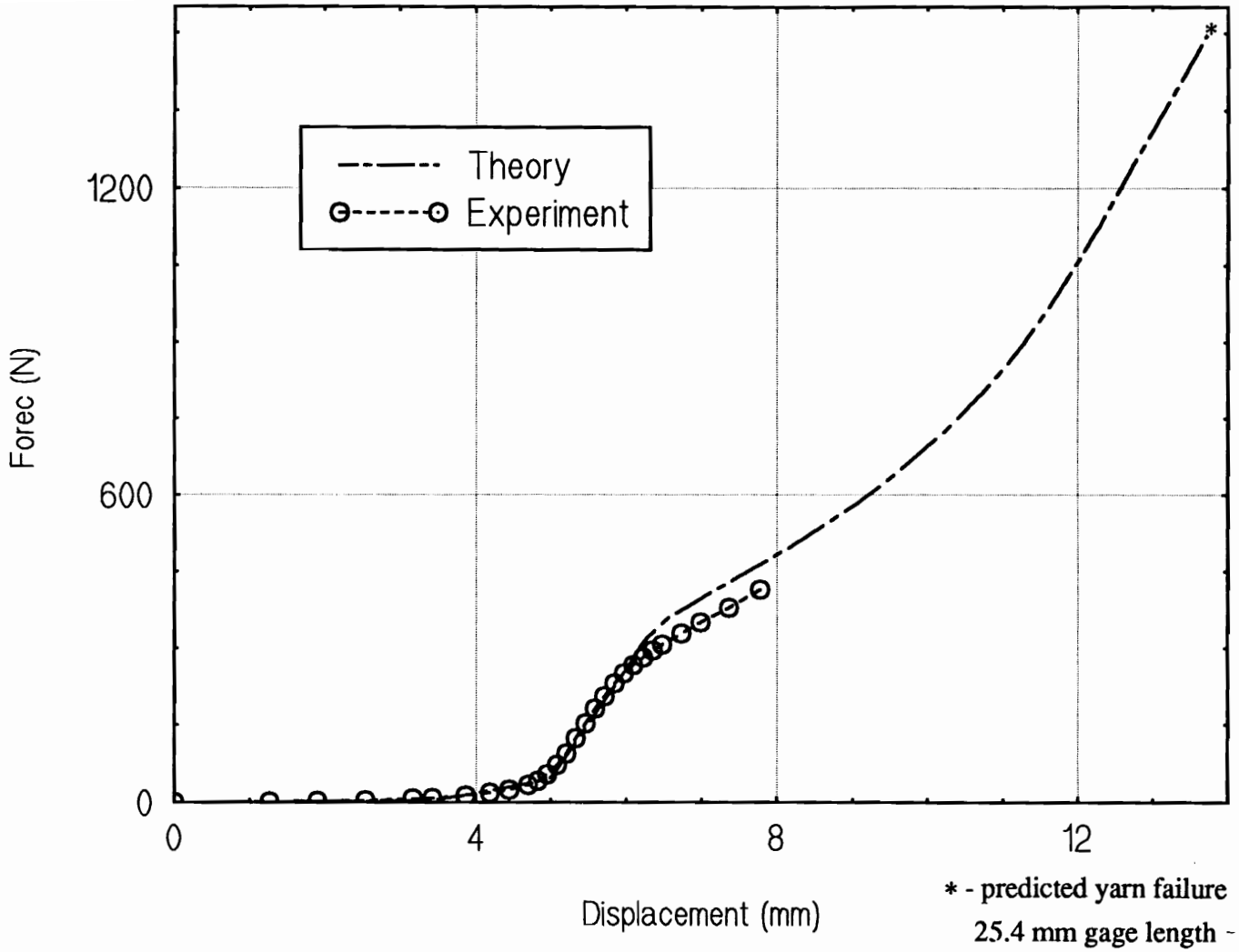


Figure 23. Experimental Verification and Failure Prediction - Specimen 12A

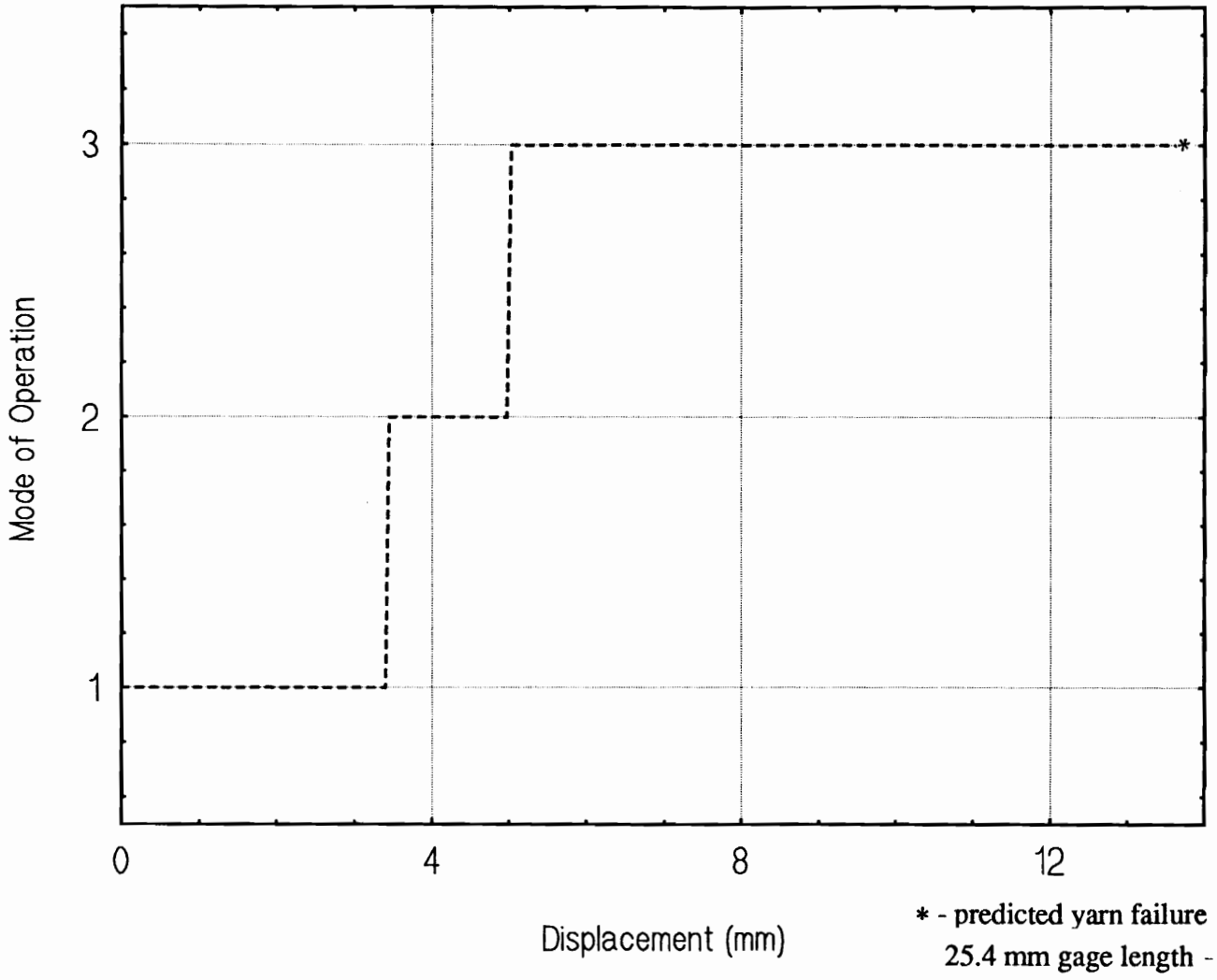


Figure 24. Theoretical Mode Transitions - Specimen 12A

20, and 23 predict failure for each of the specimens. Experimental failure data was not obtained because the specimens could not be adequately secured in the grips with the existing fixturing. As previously noted, all dimensional displacement data is based on nominal specimen lengths of 25.4 millimeters. Converting the displacement data back to strain values can be accomplished by dividing the displacement values by the specimen length. The theoretical modes of operation as a function of axial strain are also illustrated for each specimen in Figures 18, 21, and 24.

In all of the simulations, transitional regions and slopes within each region are accurately predicted. For both the braid only (Specimen 3B) and the four core sample (Specimen 4C), the mode transition is directly from one to four, indicating that the braid never contacts the core. Consequently, the slope transition in the toe-region is rather abrupt for the theoretical curves. Both the eight core (Specimen 8A) and twelve core (Specimen 12A) simulations exhibit mode two and three behavior resulting in more gradual and smoother slope transitions within the toe-regions.

While overall agreement between theory and experiment is rather exceptional, several minor discrepancies must be noted. Most apparently, the simulations exhibit consistently lower forces than the experiments within the toe-regions. This phenomenon most probably stems from neglecting friction in the braid and assuming that the yarn aspect ratio remains constant. Among these contributing factors, variations in the yarn aspect ratio are likely to dominate friction.

Over the range of the composite's behavior, there is the potential for significant variation in the yarn aspect ratio. Experimentally, the yarn aspect ratio is measured at locking and assumed to be constant. In reality two locking angles exist and the yarn aspect ratio may be different for these angles. If the aspect ratios are substantially different and the composite is initially near its maximum braid angle and deforms enough to reach its minimum braid angle, a single parameter may not be sufficient to characterize the yarn

aspect ratio.

Changes in the yarn aspect ratio stem from the braid dynamics. Two competing factors influence its value at any time. Because the yarns are actually interlaced, there is a measure of inherent crimp. As the composite elongates, the yarns attempt to straighten themselves but are constrained by each other. This phenomenon tends to compress the yarns radially and reduce the yarn thickness while increasing the width. This effect acts to drive the yarn aspect ratio down. The competing factor is the influence of the tangential compression developed as the yarns approach the locking point. Since the yarns are flexible, as they begin to jam compressive forces develop between the yarns that tend to drive the yarn width down and the yarn thickness up. This effect acts to increase the yarn aspect ratio. The equilibrium of these competing factors determines the yarn aspect ratio at any time. Incorporating these effects would prove immensely difficult and would demand including the particular lacing pattern used to fabricate the braid as well as three dimensional yarn properties. For the experimental specimens, the effects of a dynamic yarn aspect ratio are apparent only within the toe-region and are rather negligible secondary factors. This generalization however, cannot be extended to all composites. The effects of variations in yarn aspect ratio will be more apparent for composites with flexible, loosely consolidated yarns. Composites with stiffer, more rigid yarns may show little if any variation in yarn aspect ratio.

The other apparent discrepancy regards the force levels in the plastic region of deformation. The simulations consistently predict slightly higher forces than the experiments evidence. This phenomenon most likely stems form the assumption that all of the crimp pulls out in the elastic region. While this assumption is largely justified based on the experimental trials, it also appears that some of the crimp is retained and pulls out in the plastic region. Retaining some of the crimp in the plastic region would effectively act to lower the apparent yarn modulus and result in lower force levels. The impact of this

phenomenon is also rather negligible for the composites examined here but again, this generalization cannot be extended to all composites.

3.5 Experimental Limitations

While the experimental results presented here lend strong credibility to the model, they are essentially only a documentation of braid dynamics for a particular braid configuration. Although the primary experimental objective was to verify the composite behavior, the extraordinarily low core/yarn modulus ratio resulted in an almost imperceptible core contribution to the composite's behavior.

One of the most critical assumptions in the model formulation is the extension of linear constitutive equations based on infinitesimal strains to finite deformations. Unfortunately, the very low modulus ratio imposed by the available materials resulted in a rather insignificant contribution from the elastomer in modes one, three, and four. Only in mode two is the influence of the elastomer apparent. Yet even in mode two, the rather abrupt slope transitions in the composites' behavior predicted by the simulations stem from the extraordinarily low modulus ratio. In fact, the core modulus is low enough that the Poisson ratio associated with the core is almost inconsequential to the composite behavior except as it closely approaches one-half.

To more thoroughly validate the model and underlying assumptions, a series of tests should be run on a composite with a core/yarn modulus ratio that is at least an order of magnitude larger than the modulus ratio of 0.002 in the experimental series documented here. This would afford the ability to evaluate the assumption of linear core behavior. Of course, it can be concluded that for very low core/yarn modulus ratios, the application of linear elastic theory is sufficient.

In the experimental verification, the composite parameters most difficult to accurately assess and consequently the most uncertain parameters were yarn packing factor and yarn aspect ratio. In an attempt evaluate them, the composite samples were pulled to

locking and set in epoxy. Subsequently, cross sections were cut and measured to estimate these parameters. Simulations revealed that these parameters have little effect on the slope of the composite's behavior but primarily influence the transition regions. In a dimensional formulation, the yarn packing factor controls only the relative size of the yarn and its porosity. Larger yarns tend to lock sooner and consequently result in earlier mode transitions. Since the yarn denier and density are fixed, decreasing the yarn packing factor serves only to increase the volume that a fixed quantity of material occupies, resulting in larger yarns. The net effect is that lowering the yarn packing factor moves the entire composite tensile response to the left. Conversely, a higher yarn packing factor results in more compact, smaller yarns that lock later than their larger counterparts, moving the entire composite response curve to the right.

The yarn aspect ratio is a measure of the ratio of yarn thickness, measured radially, to yarn width, measured tangentially. It is experimentally measured at the locking point and assumed to be constant although it may vary in modes one and two. Decreasing this ratio results in yarns that are wider at their locking point and consequently jam earlier. A higher yarn aspect ratio increases the yarn thickness, and while it may result in the braid contacting the core earlier accompanied by an earlier transition to mode two, it will also delay locking, contributing to a later transition to mode 3. Hence decreasing the yarn aspect ratio moves the composite response to the left while increasing it moves the entire response to the right and may simultaneously extend the transitional toe-region.

4.0 NONDIMENSIONAL PARAMETER INFLUENCES ON COMPOSITE RESPONSE

4.1 Introduction

Although the ability to fabricate different experimental specimens was limited, several trial cases were designed to analyze widely varying composites while also exploring and further verifying the model. In an attempt to reach generalized conclusions, nondimensional formulations were used to describe the composites. Output was also processed nondimensionally. Dimensional data is referenced only when the nondimensional trends are superficially misleading. While each model is limited to a single class of composites, the nondimensional formulation affords the ability to qualitatively identify trends among similar classes of composites. To reduce the complexity associated with interpreting trends in the data, all constituent materials were modeled as linearly elastic. Parameter summaries for the various models may be found in Appendix B.

The base model selected for comparison is summarized in Table 9. The initial parameters and strain range were selected in order to illustrate the full range of the composite's behavior. While the strain range of 200 percent may seem artificially large, it is not impossible to attain for these composites and the same quantitative behavior may be illustrated over a smaller strain range with the appropriate initial parameters. The parameters that describe the initial condition of the base model are also feasible values that represent a real class of composites quite similar to the experimental specimens.

4.2 Core Effects on Composite Response

The characteristic that distinguishes this class of composites from traditional circular braids is its elastic core. To identify the differences between a circular braid alone and a braid encompassing an elastic core, a comprehensive analysis was performed to determine the particular effects of the core on the composite's behavior and its influences on the composite parameters over the range of the composite's behavior.

Table 9. Model Parameter Summary - Base Model

```
                    DATE : 04/29/91
          MODEL DESCRIPTION : BASE MODEL
                 CASE NUMBER : 001
LINEAR ANALYSIS
                  NONDIMENSIONAL PARAMETERS
WALL THICKNESS RATIO = 0.2500
CORE/INNER BRAID RADIUS RATIO = 0.8000
YARN ASPECT RATIO = 0.3330
YARN PACKING FACTOR = 1.0000
CORE PACKING FACTOR = 1.0000
INITIAL BRAID ANGLE =  50.000 DEG
INITIAL BRAID COVER FACTOR = 0.9500
CORE/YARN MODULUS RATIO =   0.02500
CORE POISSON'S RATIO = 0.3000
                  DIMENSIONAL PARAMETERS
NUMBER OF YARNS IN BRAID =  16.707
YARN MODULUS =   5000.000 [MPa]
INITIAL BRAID DENSITY =   18.110 [PICKS PER INCH]
INITIAL OUTER BRAID DIAMETER =   5.000 [MM]
INITIAL CORE DIAMETER =   3.111 [MM]
CORE MODULUS =    125.000 [MPa]
```

To determine the function of the core a nondimensional case study was implemented that simulates the same braided composite with and without a core. As illustrated in Figure 25, the core provides a smooth transition within the toe-region from low to high modulus. Instead of the abrupt transition for the braid without a core, the braid tension component with the core reflects a more gradual transition. The composite response illustrated in Figure 25 is the sum of the braid and core tension components and illustrates a very smooth transition from low to high modulus. Figure 26 details these variations within the toe-region. It should be noted that although both the yarn and core are modeled as linearly elastic materials, the composite response is distinctly nonlinear and strongly resembles soft-tissue behavior. The yarn response is initially nonlinear in the toe-region but approaches a linear limits at higher strains. The core exhibits a linear or nearly linear response within each mode but the slope of this response varies from mode to mode. In modes one and four it behaves as it would independently since there is no contact between the braid and core. In modes two and three however, the pressure created by the braid coupled with the Poisson contraction effectively work to reduce the apparent modulus of the core. Once the braid locks on itself and begins to support its own compressive load, the slope of the core response gradually increases until it no longer contacts the braid and enters mode four operation.

To better understand the mechanics of the composite response, the variations in several model parameters were investigated. Figure 27 illustrates that the addition of the core actually delays the point at which the braid locks and mode three operation commences. The presence of the core maintains a larger braid angle and simultaneously decreases the locking angle. As a consequence, the core effectively delays jamming in the braid. This phenomenon results from the yarn strain introduced to the braid as it compresses the core. Figure 28 illustrates that the presence of the core also results in smoother transitions in braid radius. This is also a consequence of the yarn strain

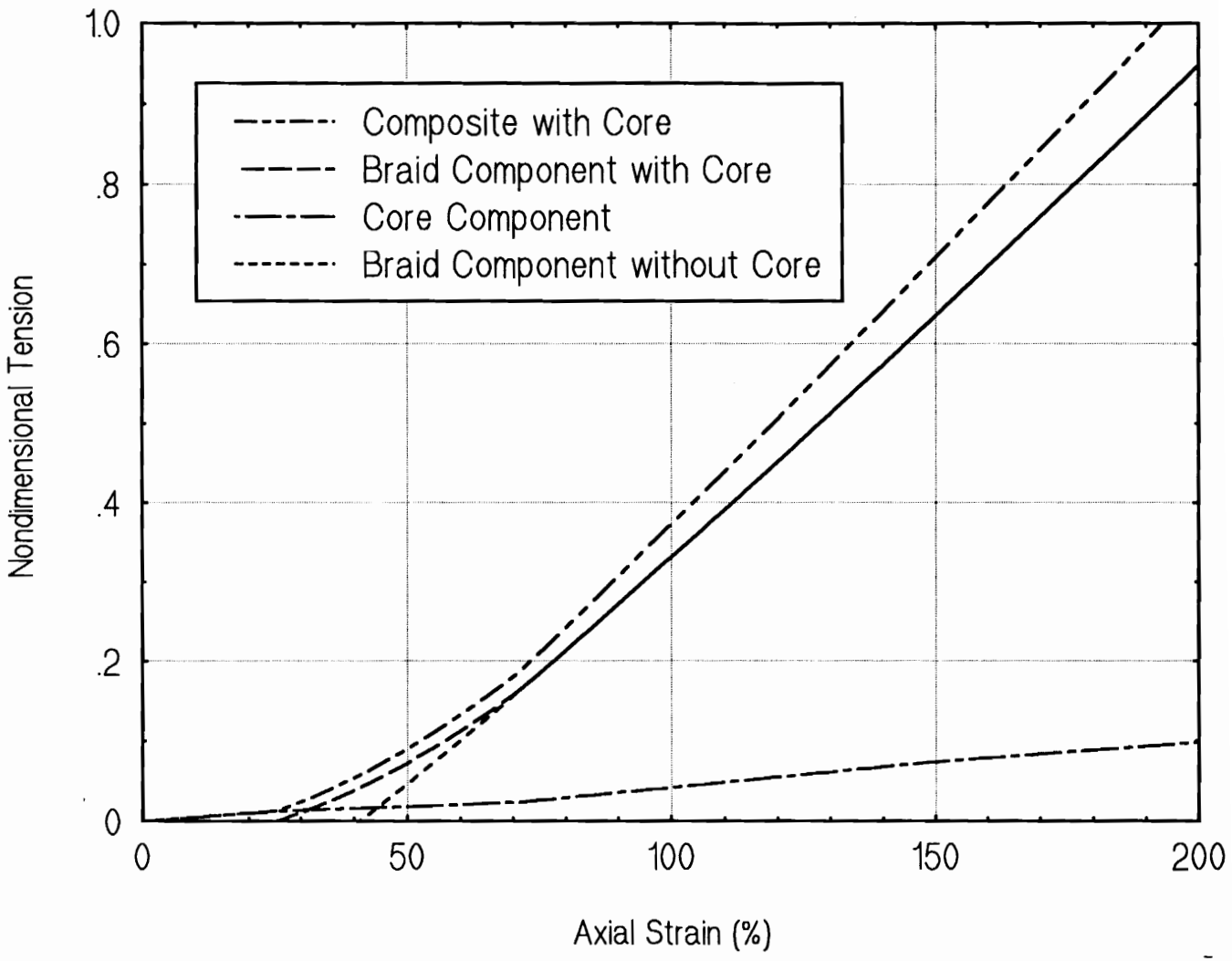


Figure 25. Core Effects on Composite and Component Tension Variations

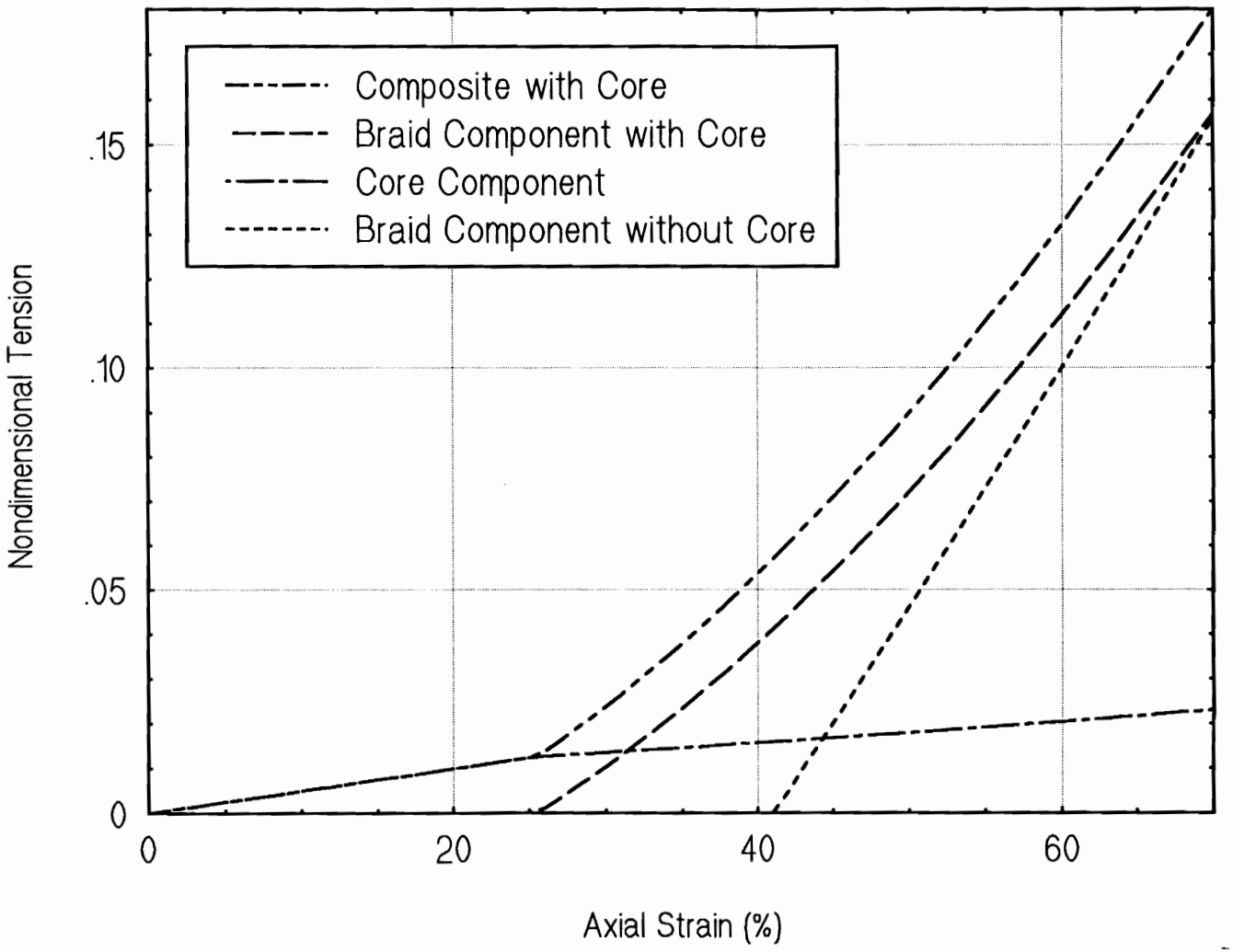


Figure 26. Core Effects on Composite and Component Toe-Region Tension Variations

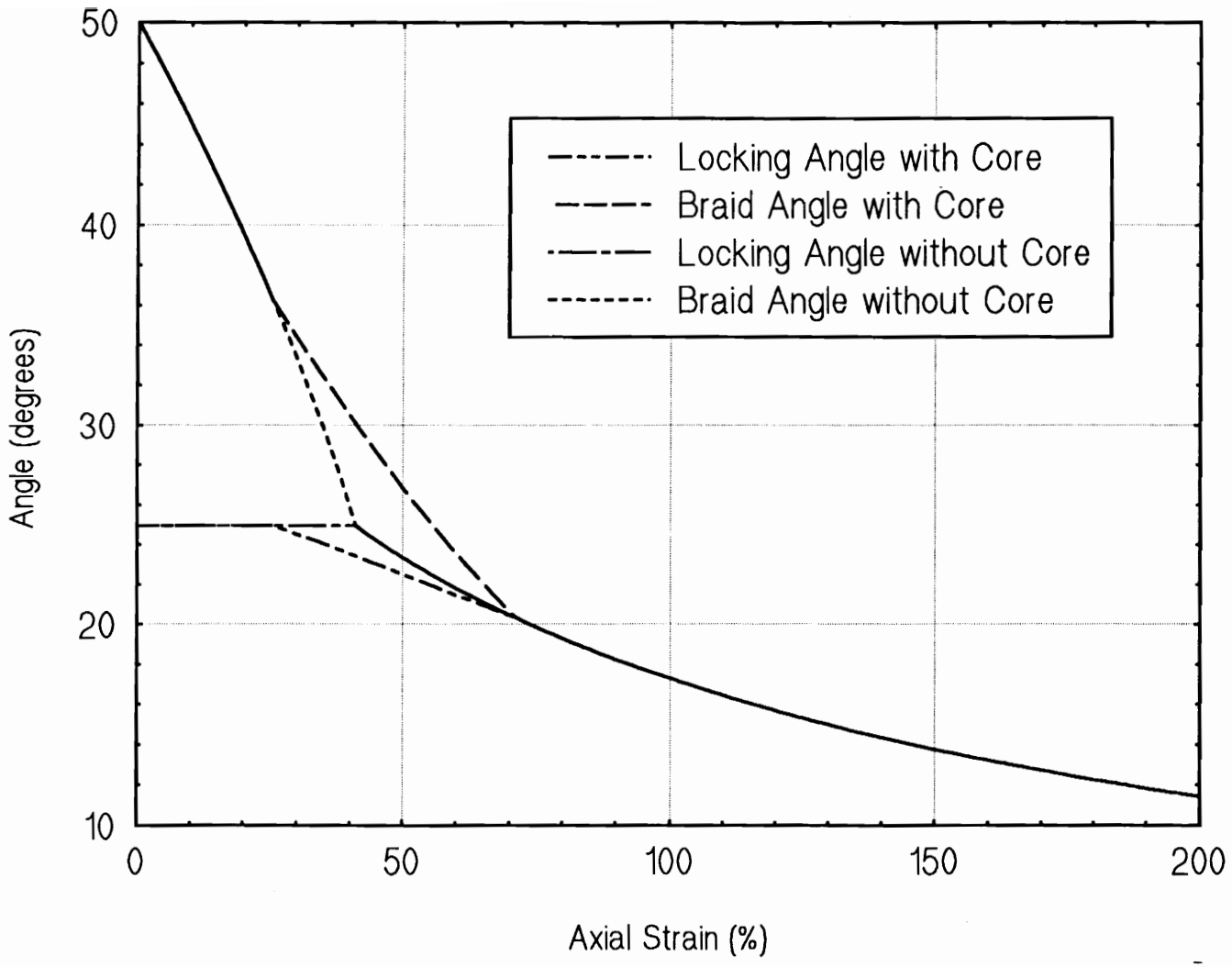


Figure 27. Core Effects on Braid Angle and Locking Angle Variations

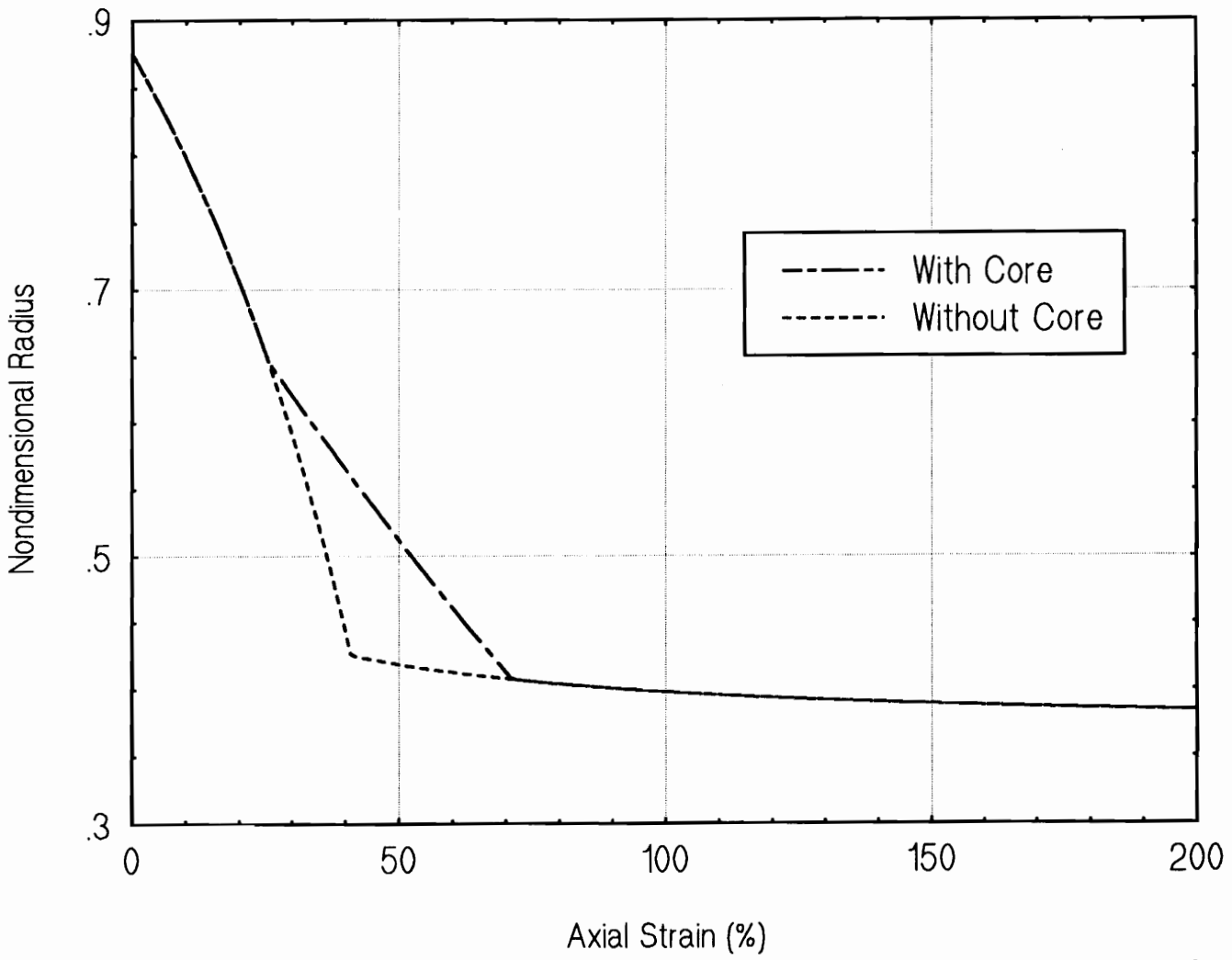


Figure 28. Core Effects on Inner Braid Radius Variations

introduced by the radial compression of the core. The relationship between the core and inner braid radius coupled with the braid angle define the mode variations illustrated in Figure 29. Yet while the braid remains open longer with the addition of the core component, its tension is greater than its counterpart without a core in both mode two and the initial portion of mode three. As the braid supports a larger component of its own radial load in the latter stages of mode three and the core simultaneously withdraws from the inner braid wall, the behavior of the braid with and without a core approaches the same asymptotic limit as illustrated in Figure 25. In modes one and four, the braids act independently of the core and consequently illustrate the same mechanical responses.

Figure 30 depicts cover factor variations consistent with the previous data. The presence of the core delays locking and maintains a cover factor less than one for a greater strain range. It is also interesting to note that the cover factor is not strictly increasing with axial strain but actually has a distinct minimum that is less that its initial value. In reality two locking angles exist, one minimum and one maximum. If the braid is compressed enough axially in its initial condition, its braid angle will approach its maximum locking angle and the associated cover factor will be very close to unity. As the braid extends, the cover factor may actually decrease initially until the minimum locking angle is approached at which point the cover factor will again begin increasing until it approaches unity.

4.3 Braid Angle Influences on Composite Response

Among the most important composite parameters is the initial braid angle. This parameter can also be closely controlled in the fabrication process and is consequently of great interest. To explore composite response as a function of initial braid angle, a series of different helix angles were chosen while all other nondimensional parameters where held constant. Figure 31 illustrates that decreasing the helix angle effectively shortens the toe-region and results in a relatively stiffer composite. A smaller initial braid angle causes the braid to lock earlier and since the yarns are aligned closer to the braid axis, the radial

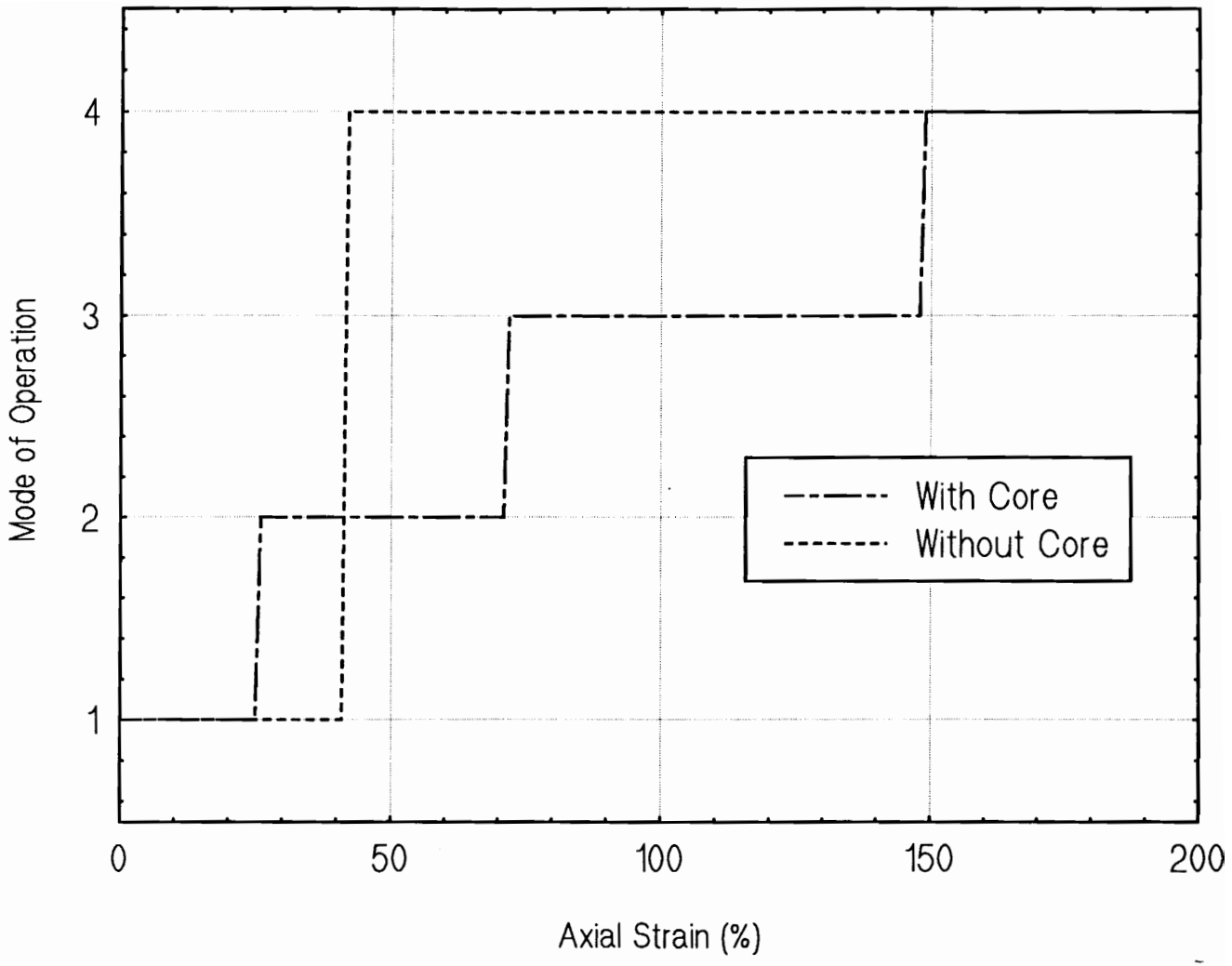


Figure 29. Core Effects on Mode Transitions

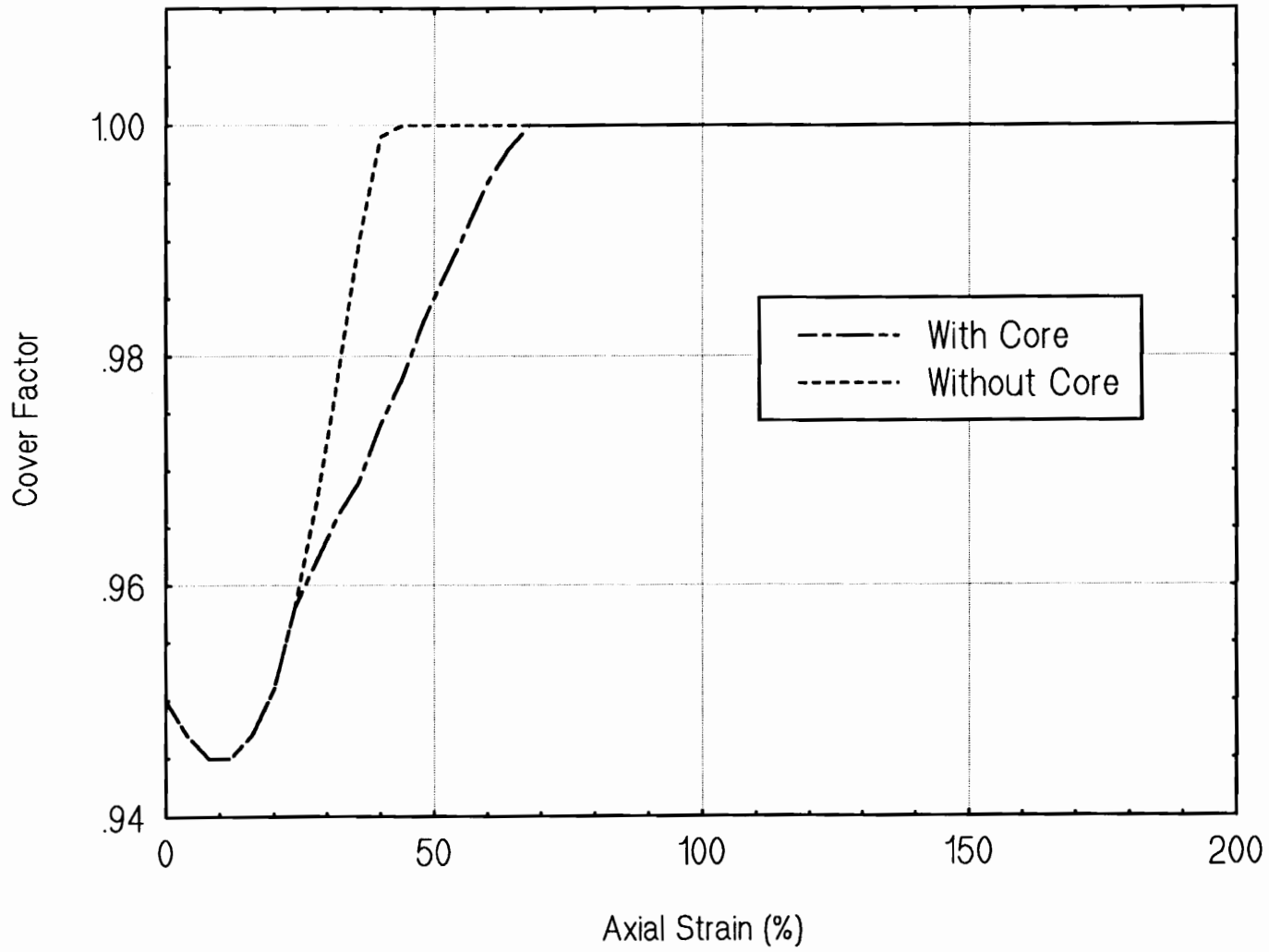


Figure 30. Core Effects on Cover Factor Variations

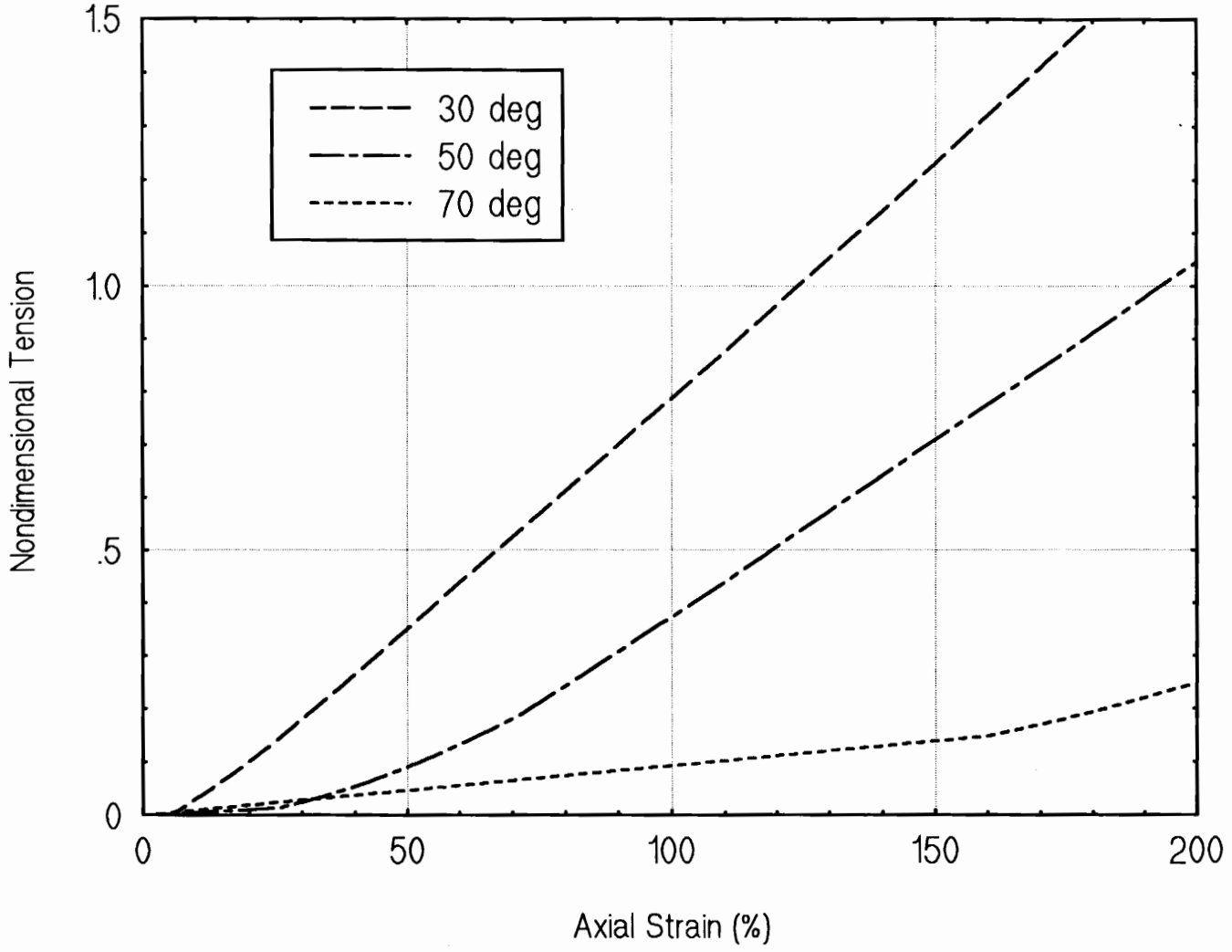


Figure 31. Nondimensional Composite Tension Variations for Different Initial Braid Angles

component of the braid tension is smaller. Consequently a greater yarn strain is required to attain the same radial pressure to compress the core in mode two. For smaller braid angles, a relatively larger component of the yarn strain also contributes to a higher axial composite tension. To maintain the same cover factor as the braid angle decreases, the number of yarns in the braid must increase to compensate for the decreasing braid density. Since the nondimensional tension data incorporates the number of yarns comprising the braid, it is slightly misleading in the toe region. Consequently, the dimensional data for specimens with a 5.0 millimeter initial outer braid diameter and yarn modulus of 5000 MPa is included and illustrated in Figure 32. Both nondimensional and dimensional toe-region tension variations are detailed in Figures 33 and 34. The dimensional composite tensile responses are identical in mode one since the cores are the same.

Examining the inner braid and core radii variations for different initial braid angles reveals that a larger initial braid angle delays locking and effectively stretches the composite's behavior over a larger strain interval as illustrated in Figures 35 and 36. It is interesting to note that the braid radius variation in mode one is distinctly nonlinear while it is nearly linear in mode two. An abrupt transition in the rate of change of the braid radius results as the braid locks, moving into mode three. The braid radius variation in modes three and four is nearly linear and smoothly continuous. In modes two and three the inner braid and core radii are identical since the braid and core are in contact with each other. The core radius variations have the same slope in modes one and four regardless of initial angle since the core's behavior in these modes is independent of the braid.

Figures 37 and 38 illustrate variations in the braid and locking angles. Reducing the initial braid angle effectively results in locking at a lower axial strain, moving the entire response to the left and truncating the strain range for mode one and mode two operation. Coupling the radii variations with the braid angle data defines the mode transitions illustrated in Figure 39.

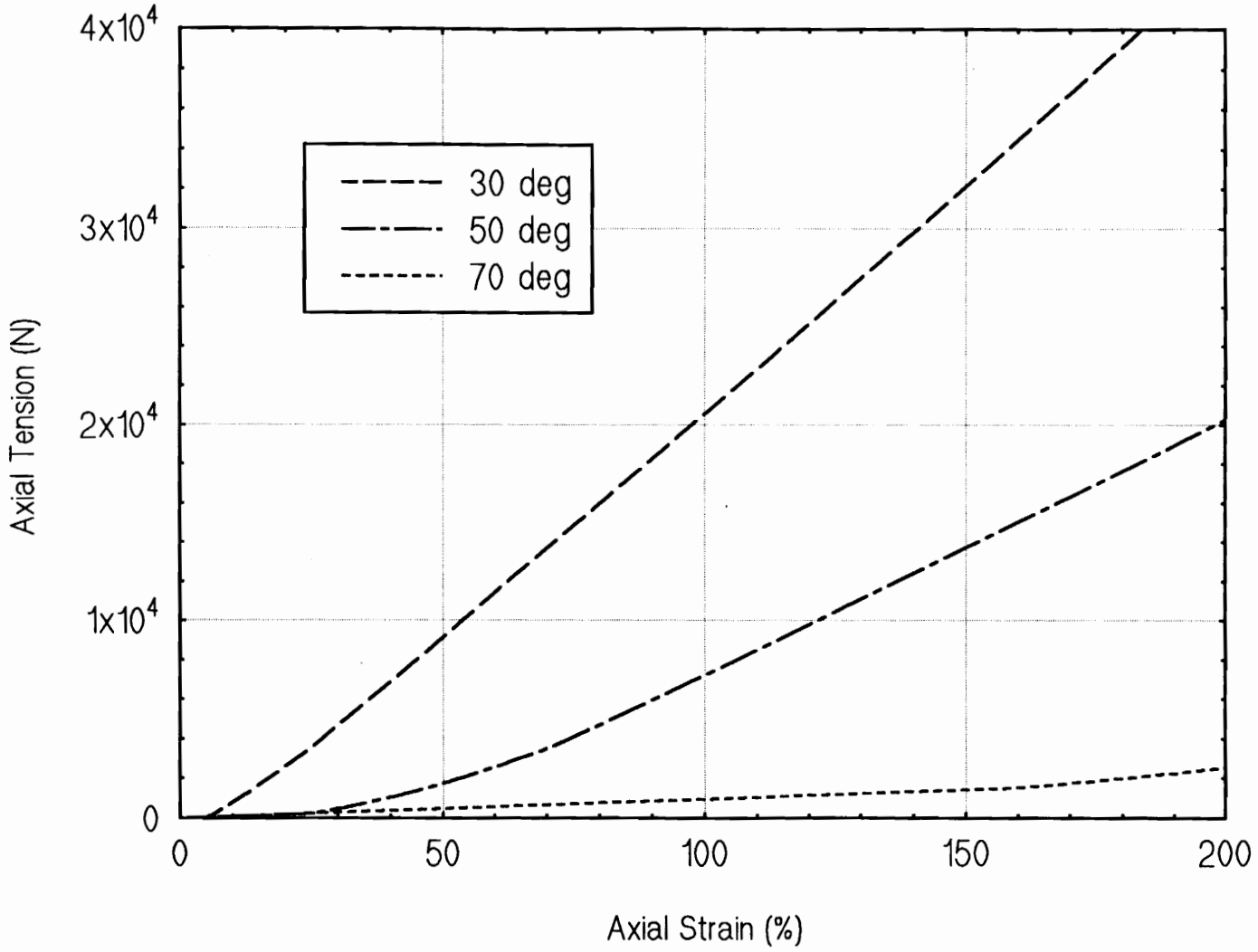


Figure 32. Dimensional Composite Tension Variations for Different Initial Braid Angles

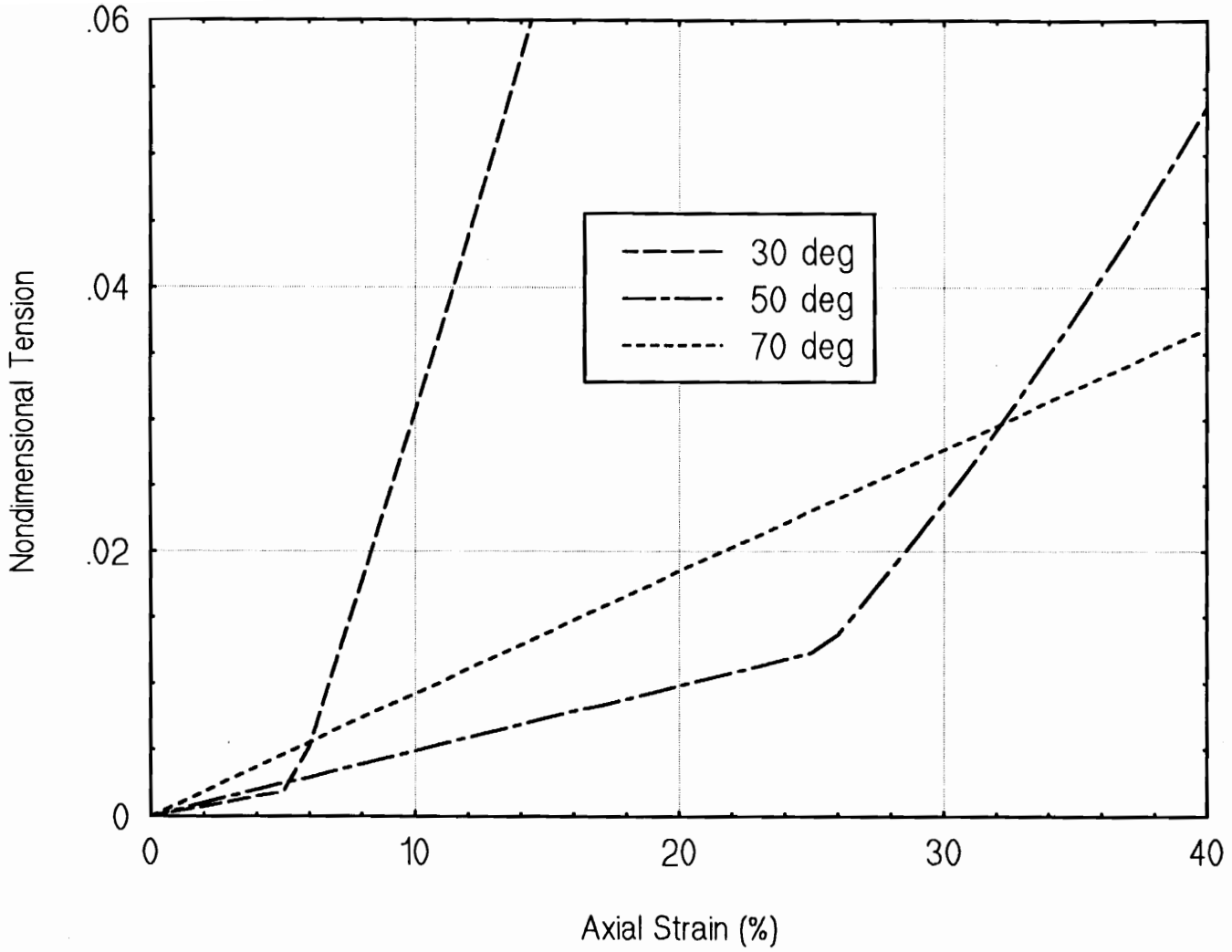


Figure 33. Nondimensional Composite Toe-Region Tension Variations for Different Initial Braid Angles

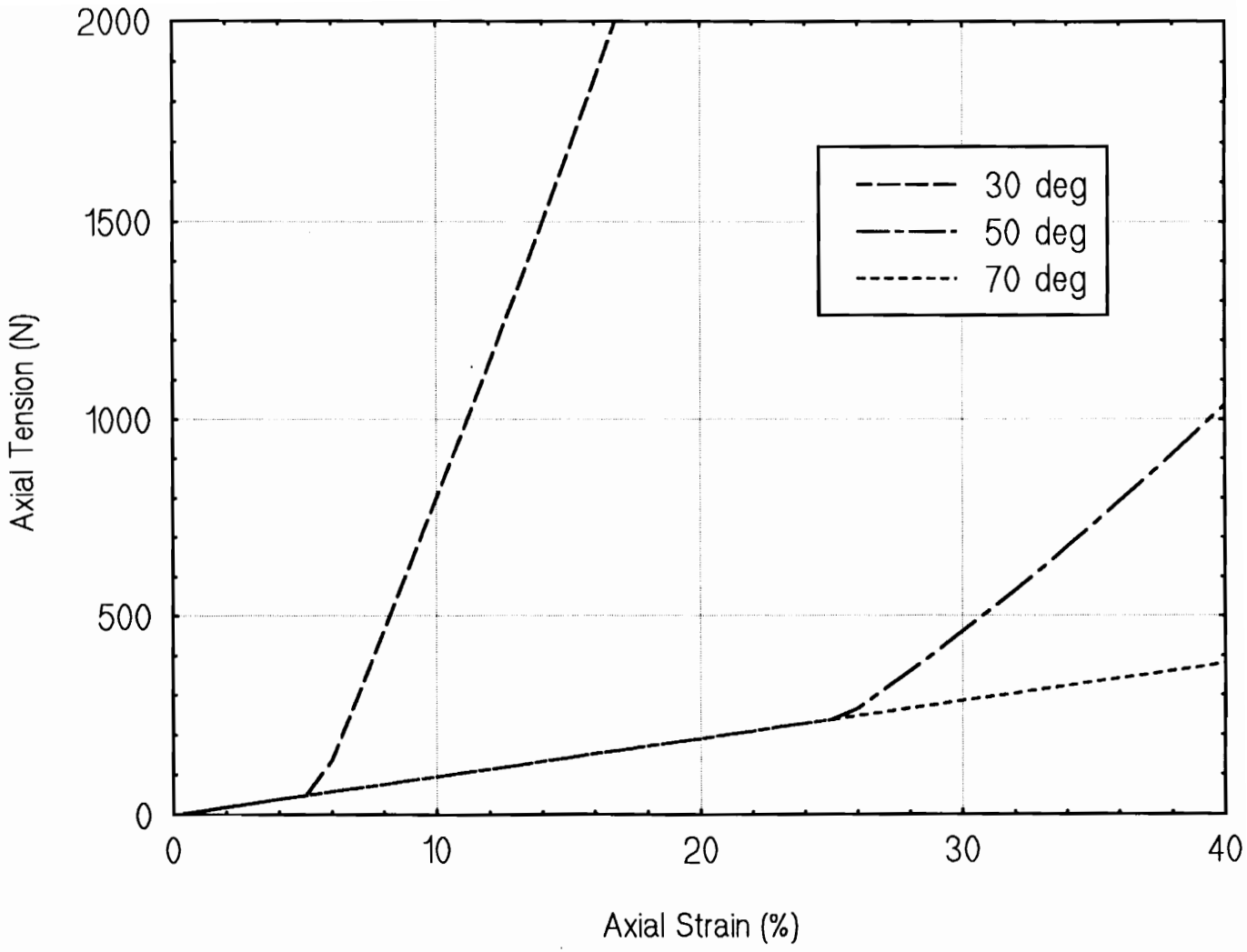


Figure 34. Dimensional Composite Toe-Region Tension Variations for Different Initial Braid Angles

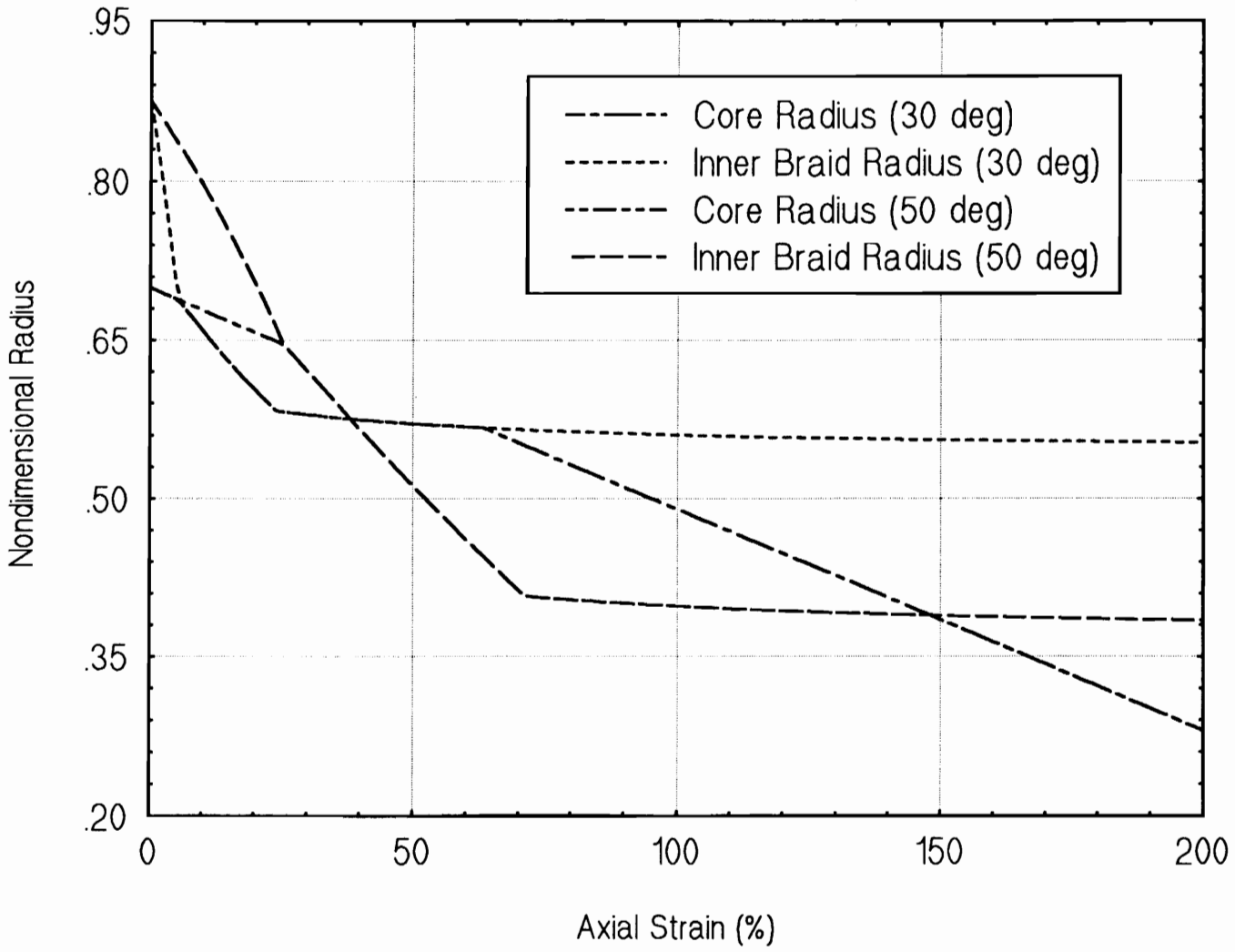


Figure 35. Radii Variations for 30 and 50 Degree Initial Braid Angles

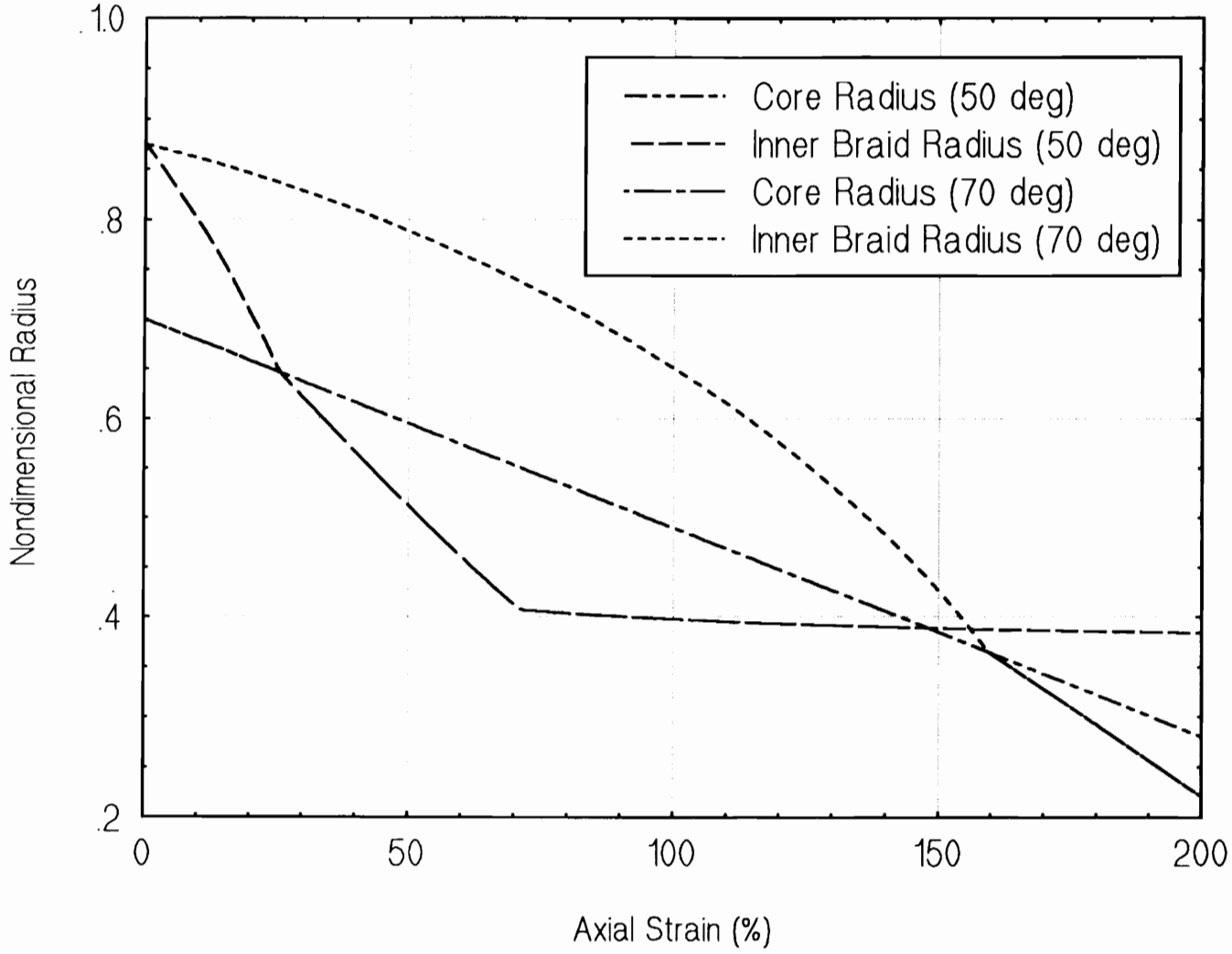


Figure 36. Radii Variations for 50 and 70 Degree Initial Braid Angles

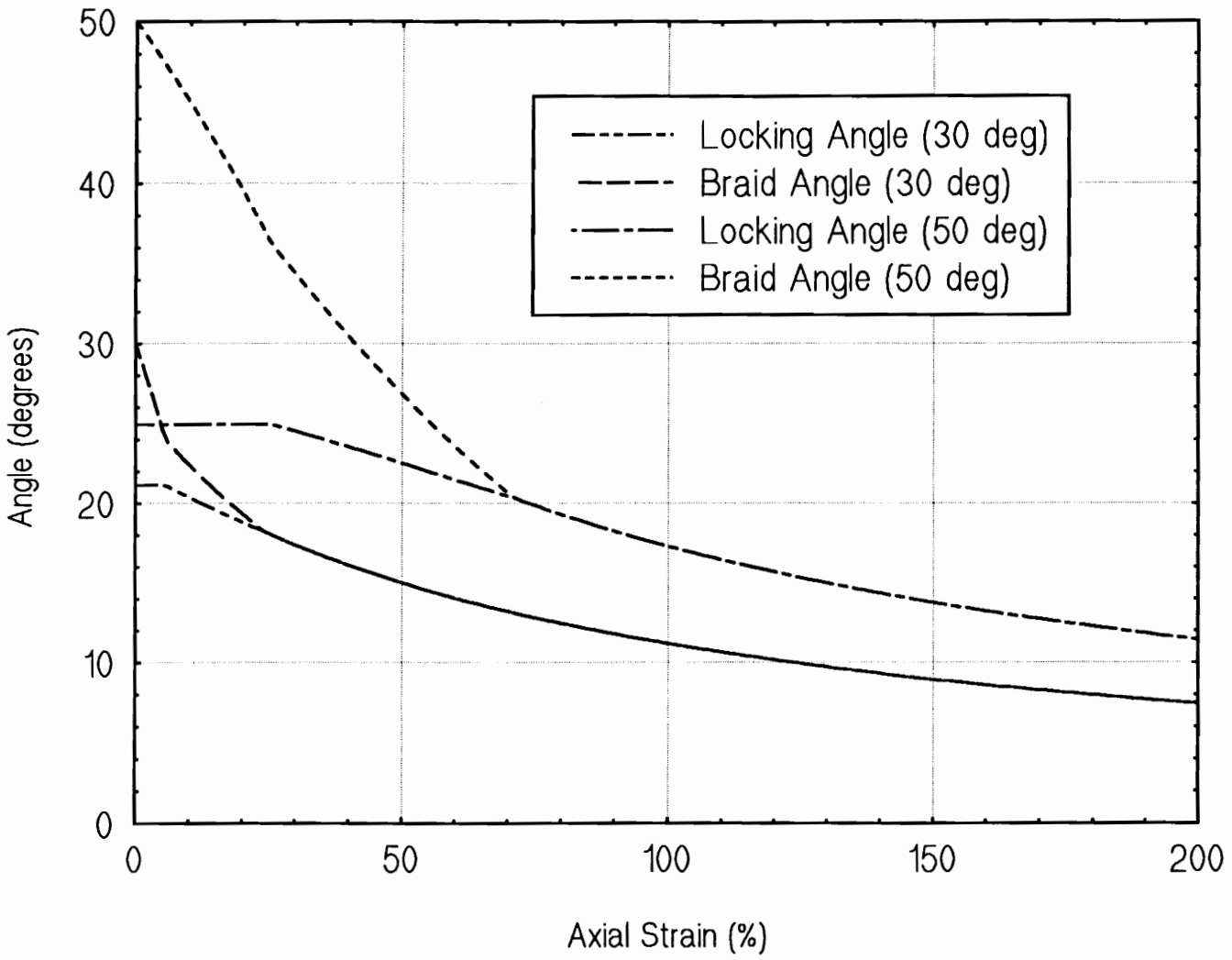


Figure 37. Braid Angle and Locking Angle Variations for 30 and 50 Degree Initial Braid Angles

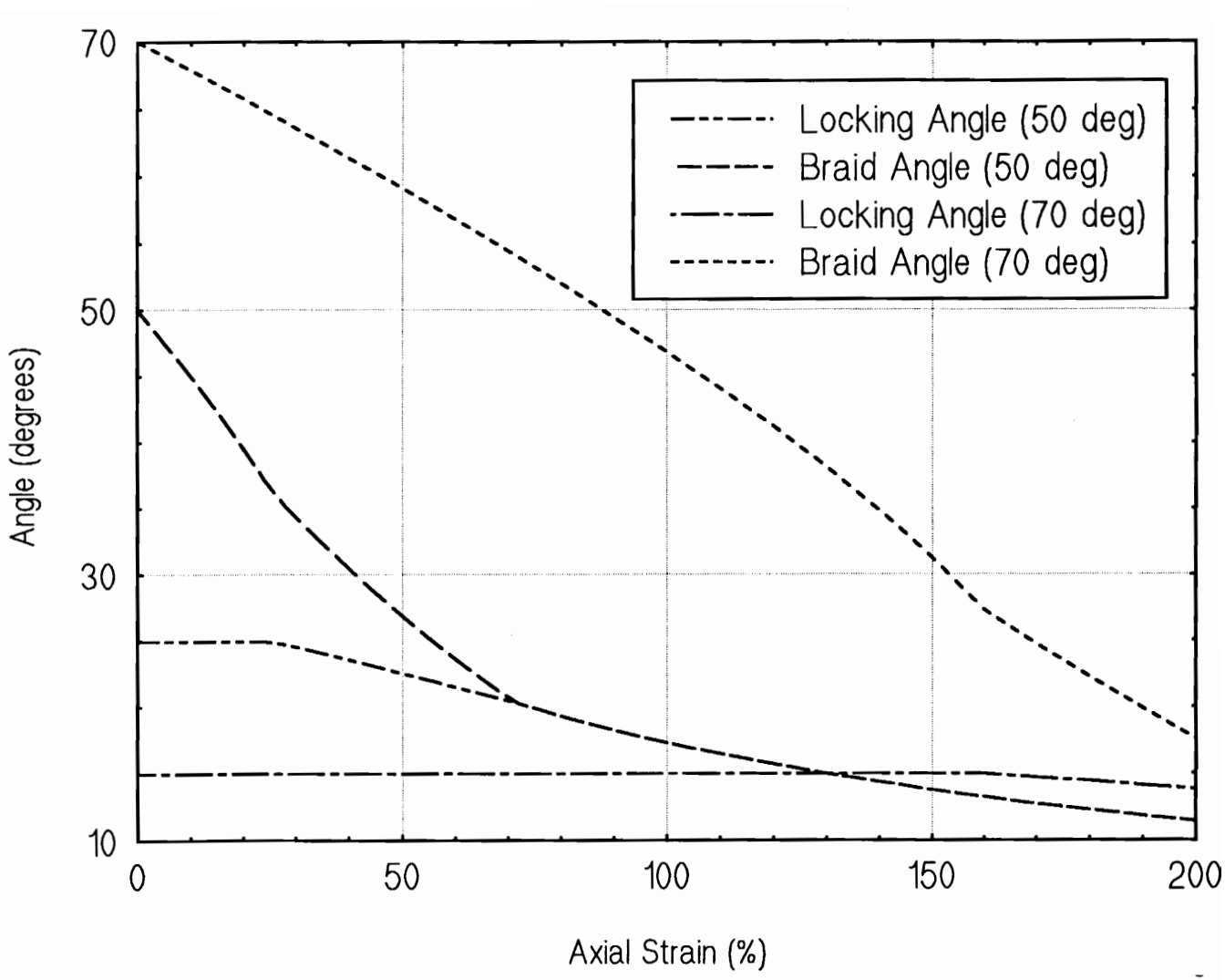


Figure 38. Braid Angle and Locking Angle Variations for 50 and 70 Degree Initial Braid Angles

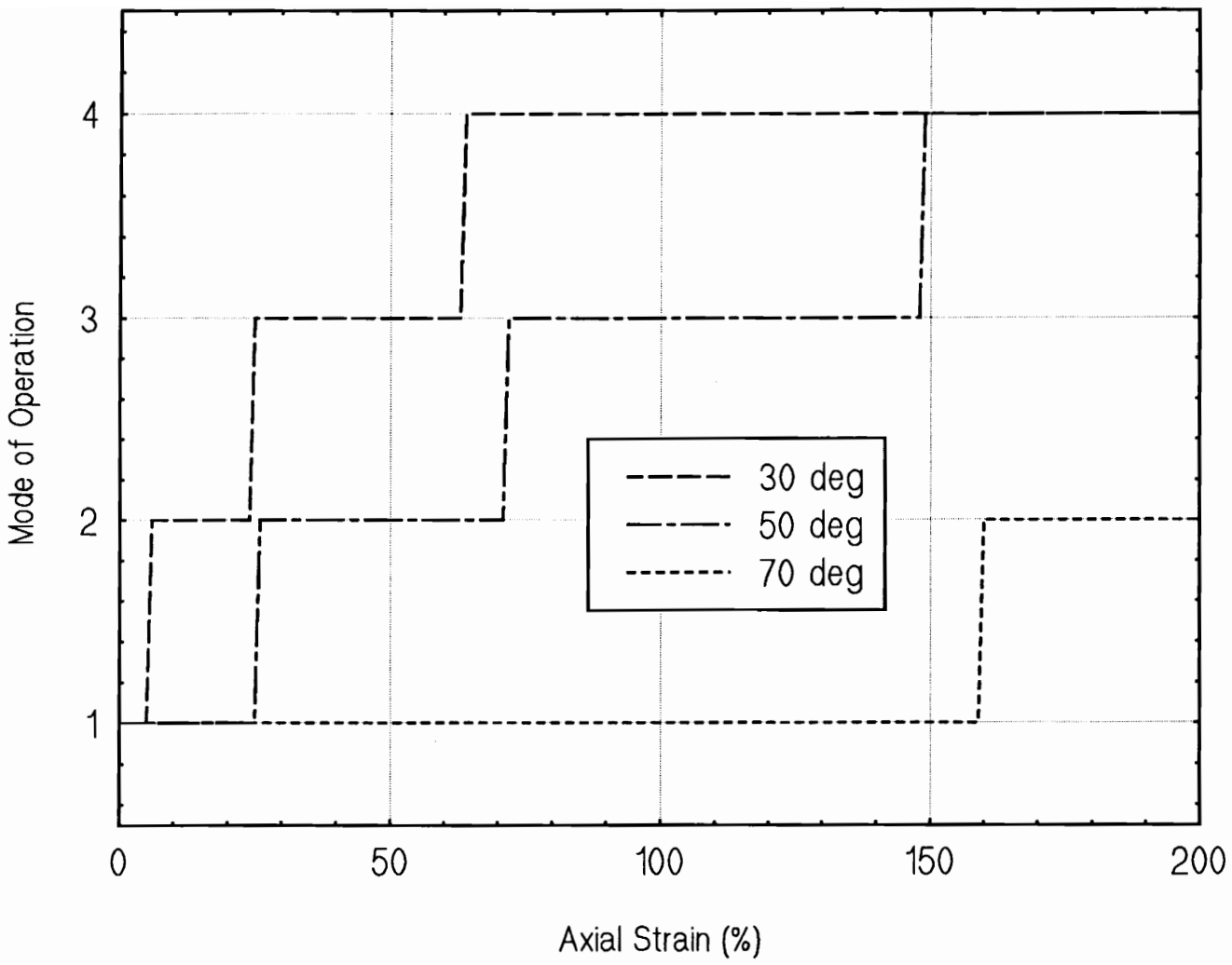


Figure 39. Mode Transitions for Different Initial Braid Angles

Figure 40 depicts variations in the cover factor for different initial angles. For an initial angle of 70 degrees, the braid is very near its maximum locking angle and consequently, the cover factor initially decreases with axial strain and shows a distinct minimum. An initial angle of 30 degrees however, is very near the minimum locking angle and consequently, the cover factor is strictly increasing with axial strain until it reaches unity. For an initial angle of 50 degrees, the cover factor decreases only modestly before increasing to approach unity.

Figure 41 illustrates variations in radial core strain as a function of initial angle. The slope of this curve in mode one and mode four operation is given by the negative of the Poisson ratio for the core. Deviations from this line occur in modes two and three where the compressive pressure of the core assists the Poisson contraction of the core. As the composite enters mode three operation, a progressively larger portion of the compressive load is borne by the braid itself and consequently the core strain remains nearly constant as the Poisson contraction just exceeds the radial expansion of the core associated with the decreasing compressive pressure from the braid.

Figure 42 illustrates variations in yarn strain which reflect the same trends as the axial component of the braid tension. A larger initial braid angle delays locking and consequently increases the range over which the yarn strain is zero. A lower braid angle demands a greater yarn strain to accommodate the same amount of axial extension. Consequently the slope of the composite tension curve associated with a smaller initial braid angle is greater.

While the braid angle is the single most flexible parameter in braid fabrication and consequently of the greatest practical significance, other composite parameters can also be varied. In order to explore the influence of the other nondimensional parameters, several additional trials were explored. The data presentation associated with those cases will be limited to composite tension and mode of operation variations.

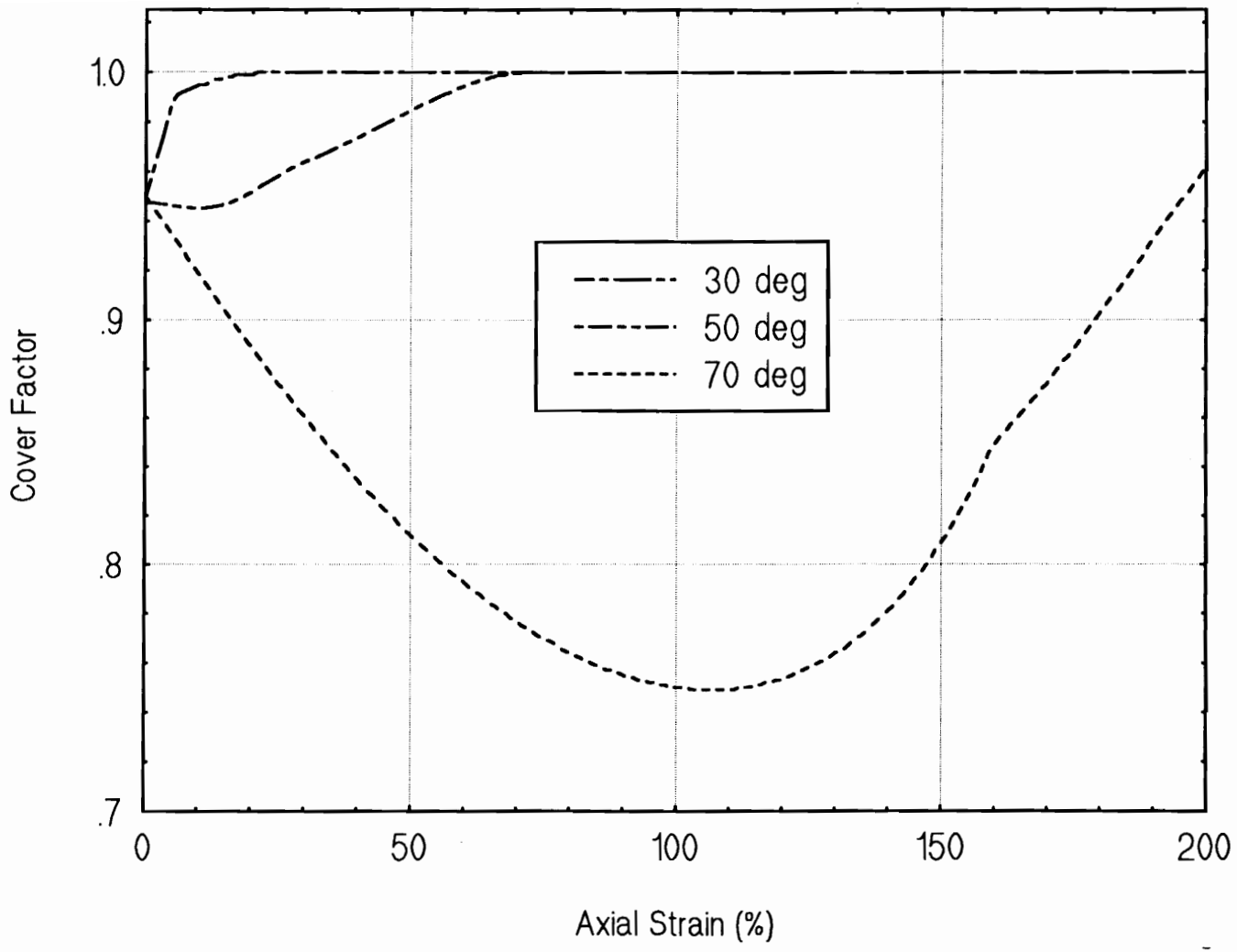


Figure 40. Cover Factor Variations for Different Initial Braid Angles

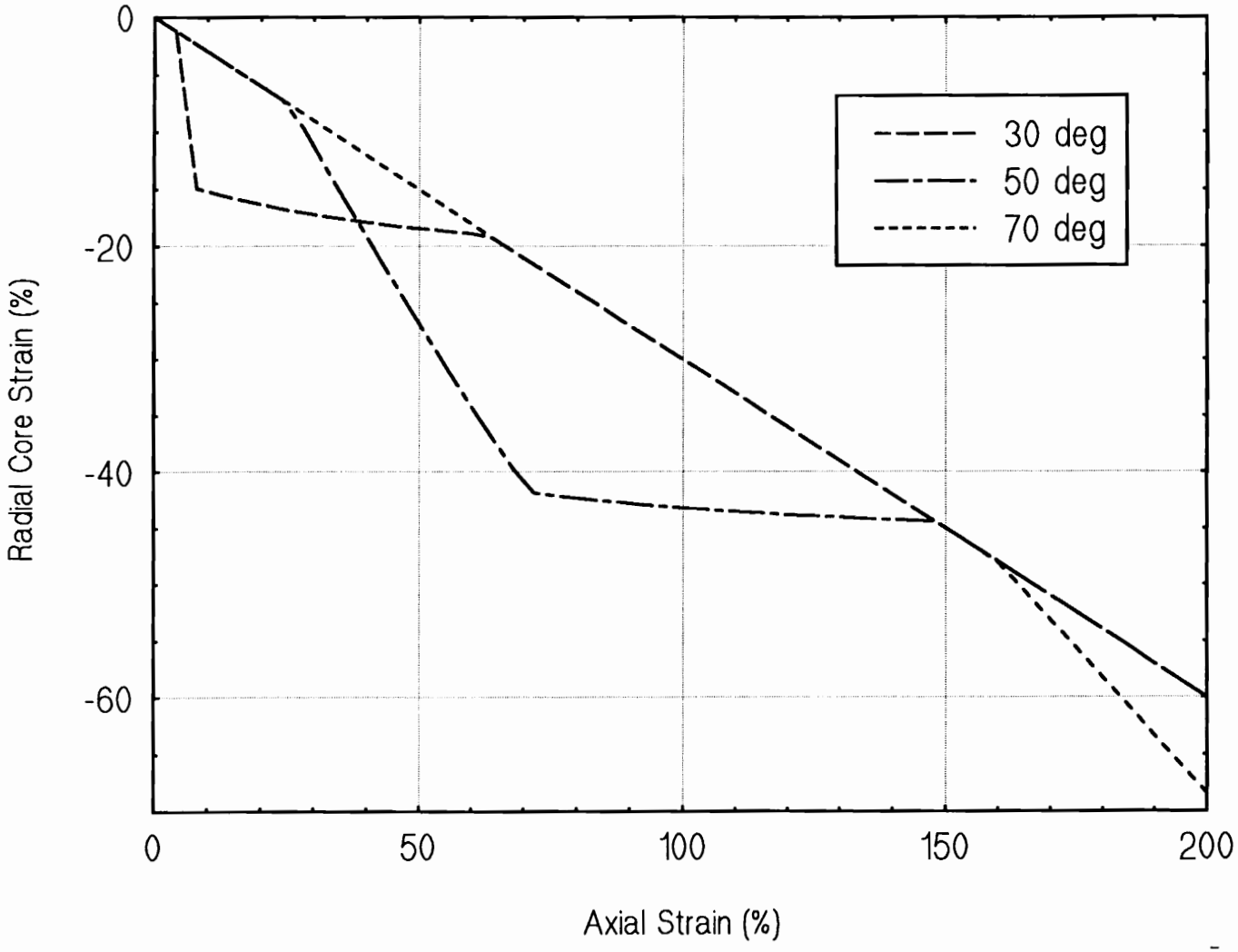


Figure 41. Radial Core Strain Variations for Different Initial Braid Angles

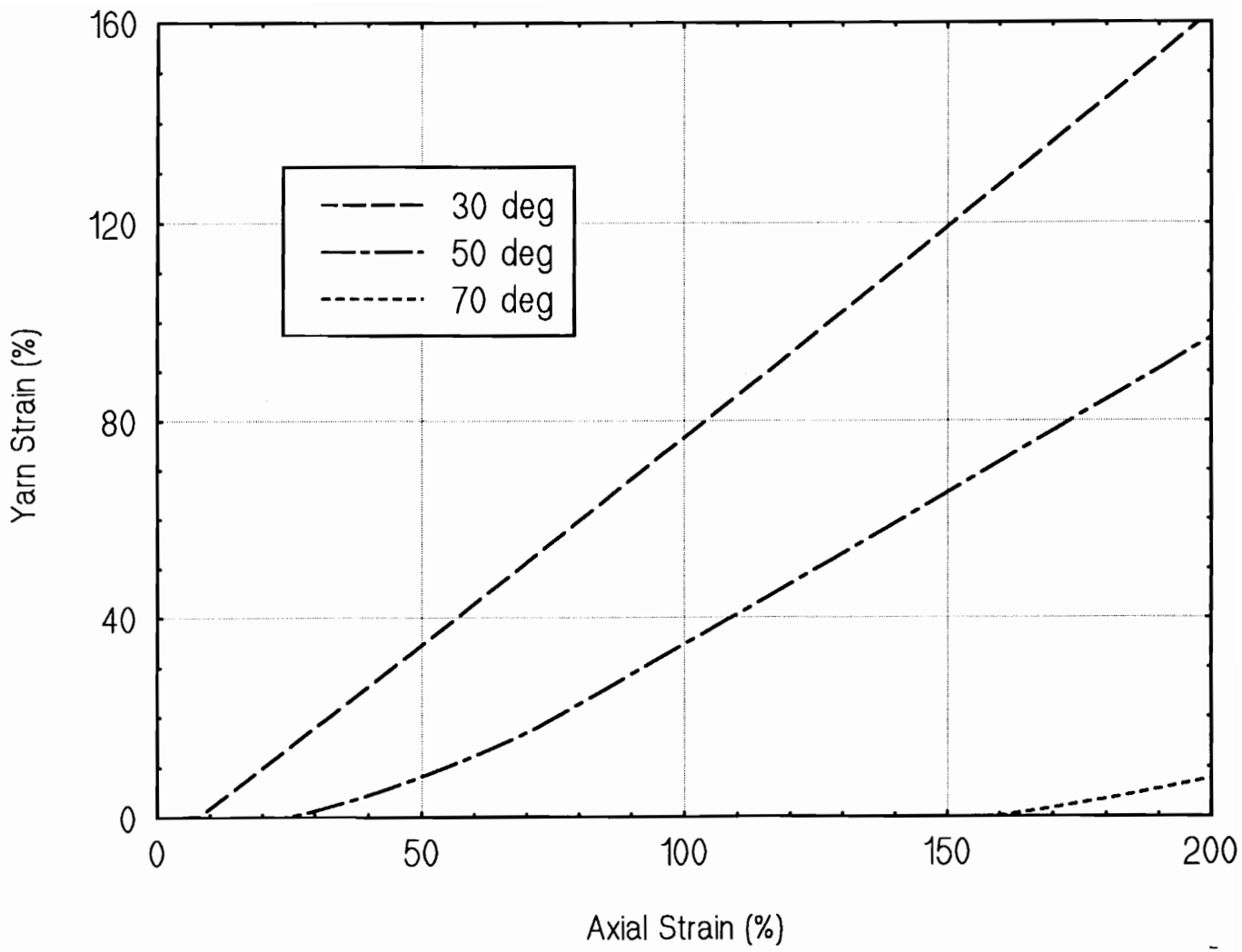


Figure 42. Yarn Strain Variations for Different Initial Braid Angles

4.4 Poisson Ratio Influences on Composite Response

The significance of the value chosen to represent the Poisson ratio for the core also depends on the modulus ratio and is only apparent in modes two and three when the braid and core are in contact with each other. If the modulus ratio is rather low, then the Poisson contraction of the core becomes less significant to the composite response except as the Poisson ratio approaches one-half. Since the base model has a core modulus that is only two and a half percent of the yarn modulus, there is little discernable difference in composite tension for Poisson ratios ranging from 0.0 to just less than 0.5 as illustrated in Figure 43. However, the mathematical singularity in the stress function for linearly elastic materials with a Poisson's ratio of one-half results in a distinct discontinuity as the Poisson ratio approaches that value. Figure 44 depicts toe-region tension variations and better illustrates this phenomenon. The discontinuity in the composite's tensile response stems from the core's contribution to the composite tension. As the Poisson ratio nears one-half, the core's rate of radial contraction approaches a constant that is independent of external pressure. While the compressive load does not effect the core radius, it does influence the axial tension. In mode two, the core supports the entire pressure generated by the yarns. This acts to decrease the axial core tension in mode two as the Poisson ratio approaches one-half. Once the braid locks however, it begins to support its own compressive load. The locking transition is most apparent as the Poisson ratio closely approaches one-half since the core withdraws from the inner braid wall as the braid locks. This means that the radial pressure generated by the yarns is suddenly removed. This discrete change results in a discontinuity in the core's tensile response that is reflected in the composite's behavior.

For infinitesimal strains, a Poisson ratio of one-half represents incompressibility. Yet assigning the Poisson ratio a value of one-half to represent incompressibility for finite strain is grossly erroneous. As reflected by Figure 45, maintaining incompressibility for an elastic, homogeneous cylinder would demand updating the Poisson ratio with axial strain.

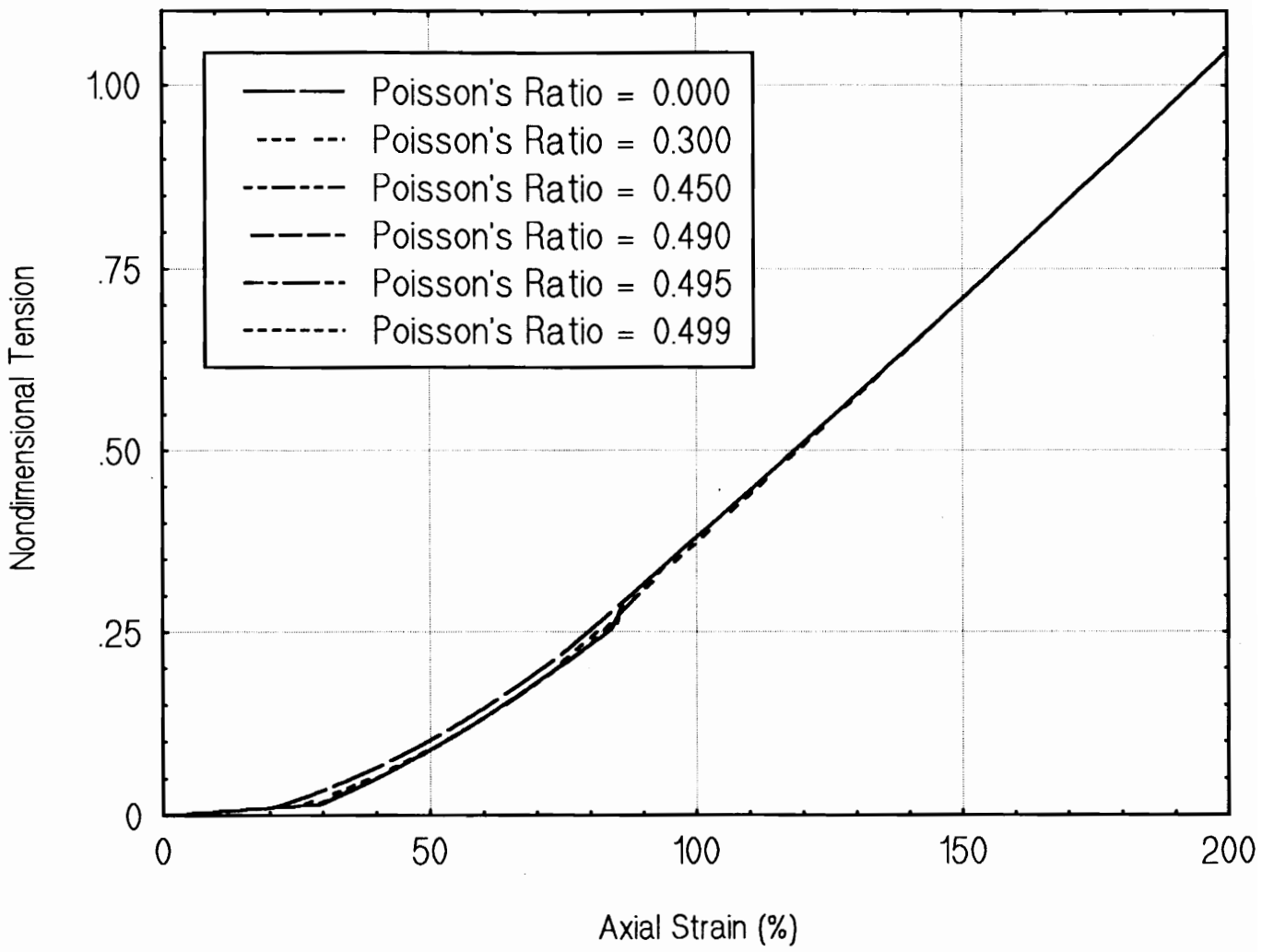


Figure 43. Nondimensional Composite Tension Variations for Different Core Poisson Ratios

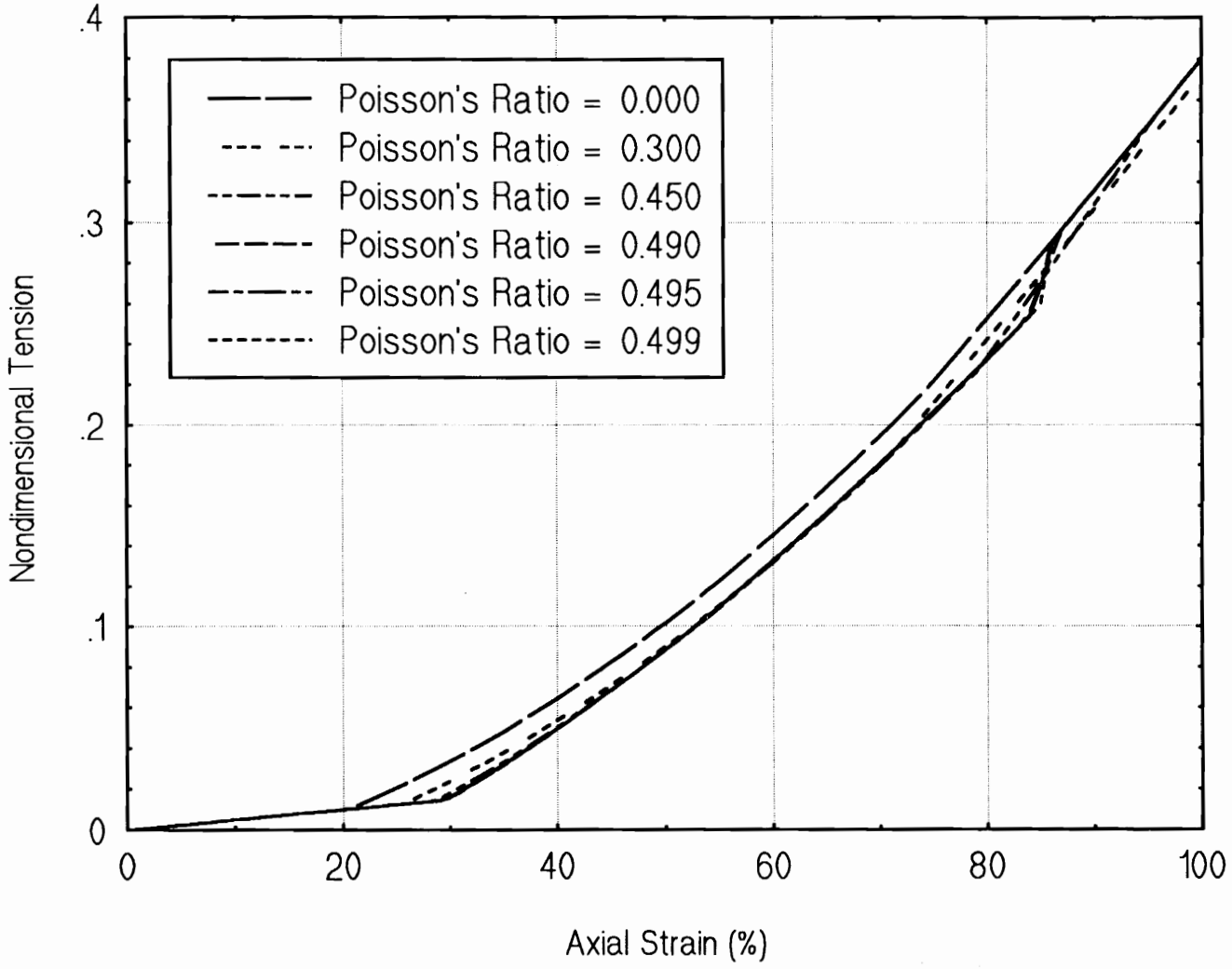


Figure 44. Nondimensional Composite Toe-Region Tension Variations for Different Core Poisson Ratios

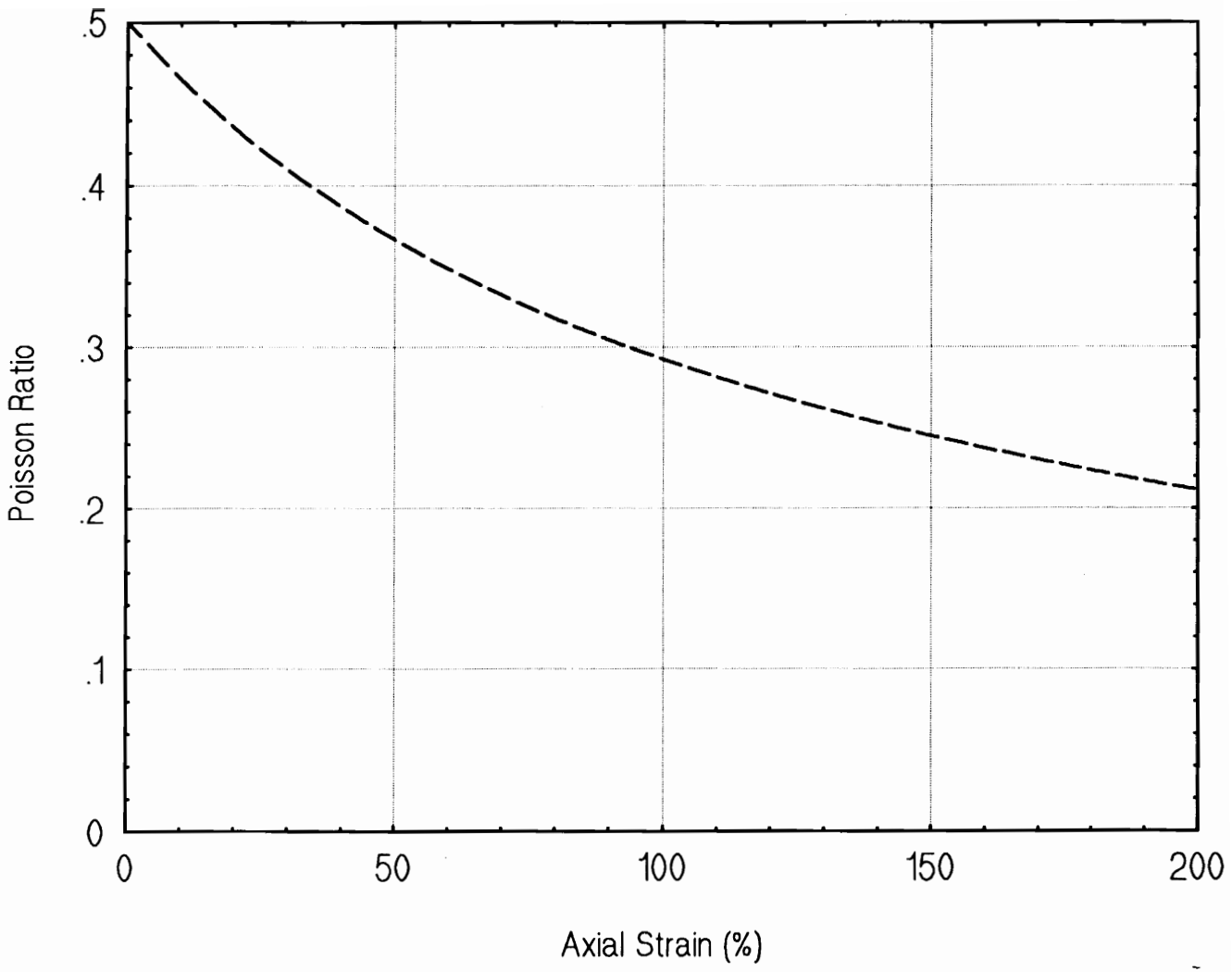


Figure 45. Poisson Ratio Variations with Axial Strain for an Incompressible Cylinder

Only for stains very near zero does one-half actually represent incompressibility. In the experimental series, the core modulus was so low that the value chosen for the Poisson ratio became almost insignificant. However, based on experimental data obtained from the elastomer, a value of 0.3 was chosen. This value however, could range from 0.0 to just less than 0.5 without appreciably affecting the experimental simulations.

Figure 46 illustrates that the Poisson ratio has subtle effects on the mode transitions. As the Poisson ratio decreases, less radial contraction associated with the axial core strain results in an earlier transition to mode two and delayed transition to mode four, effectively increasing the stain range over which the braid and core are in contact. Additionally, as the Poisson ratio approaches one-half, mode three operation vanishes, indicating that the core withdraws from the inner braid wall at the same time the braid locks.

4.5 Wall Thickness Ratio Influences on Composite Response

Figure 47 depicts variations in nondimensional composite tension for different wall thickness ratios. As the wall thickness ratio decreases while all other nondimensional parameters are held constant, the number of yarns in the braid linearly increases to maintain the yarn aspect ratio. Decreasing the wall thickness ratio also reduces the yarn volume and increases the size of the core to maintain the same core/inner braid radius ratio. The reduced yarn volume demands a slightly greater yarn strain rate in mode two but the yarn strain values do not vary significantly among different composites at the same axial strain values in mode two and are identical in modes three and four. The nondimensional contribution of the core also becomes more significant as the core grows larger. Since the nondimensional braid tensile components vary only slightly, it is the core's contribution that results in a nondimensional composite tension that increases as the wall thickness ratio decreases. Yet as Figure 48 illustrates, the increased fiber volume associated with a higher wall thickness ratio actually increases the dimensional composite tension. Figure 49

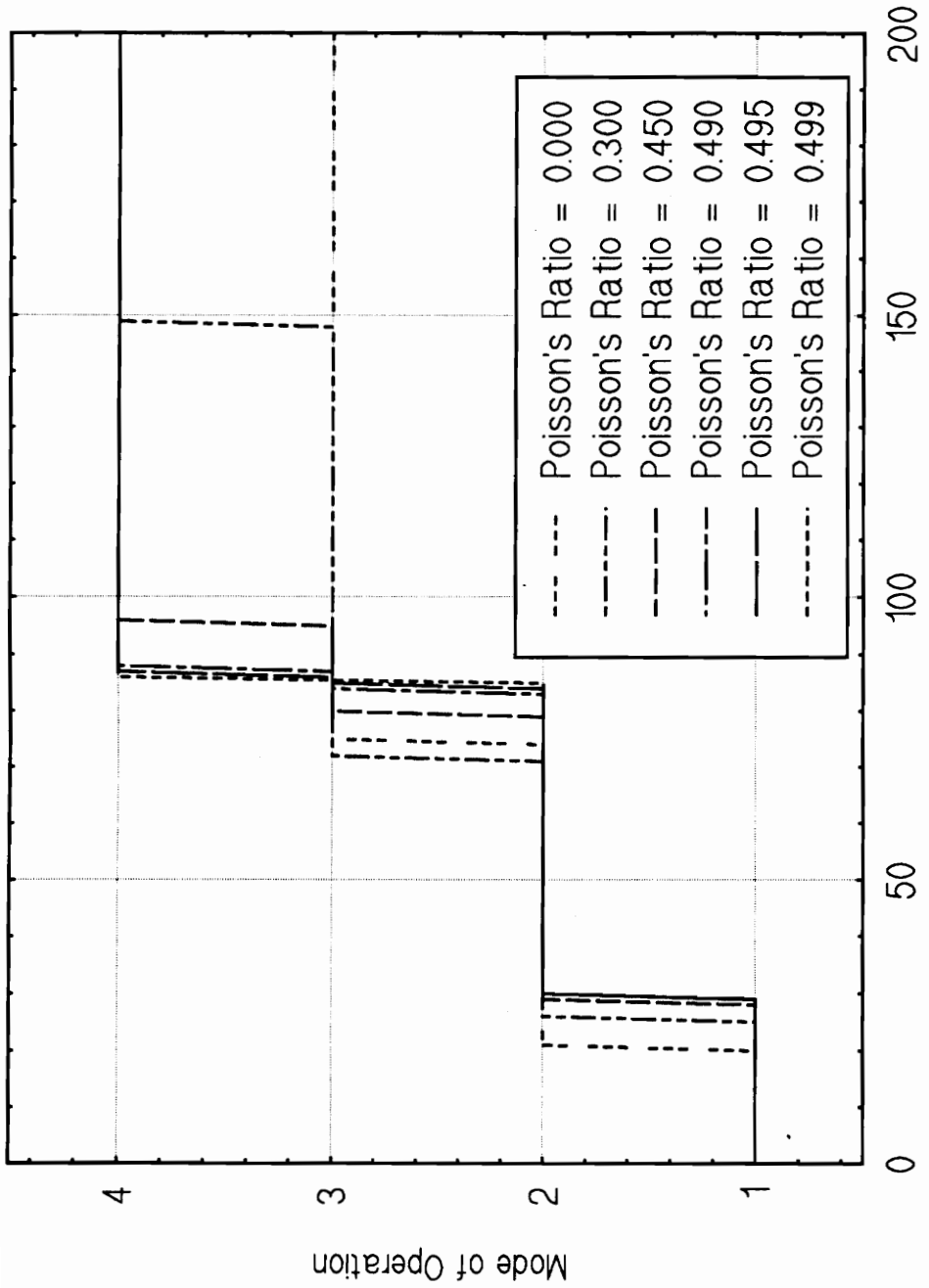


Figure 46. Mode Transitions for Different Core Poisson Ratios

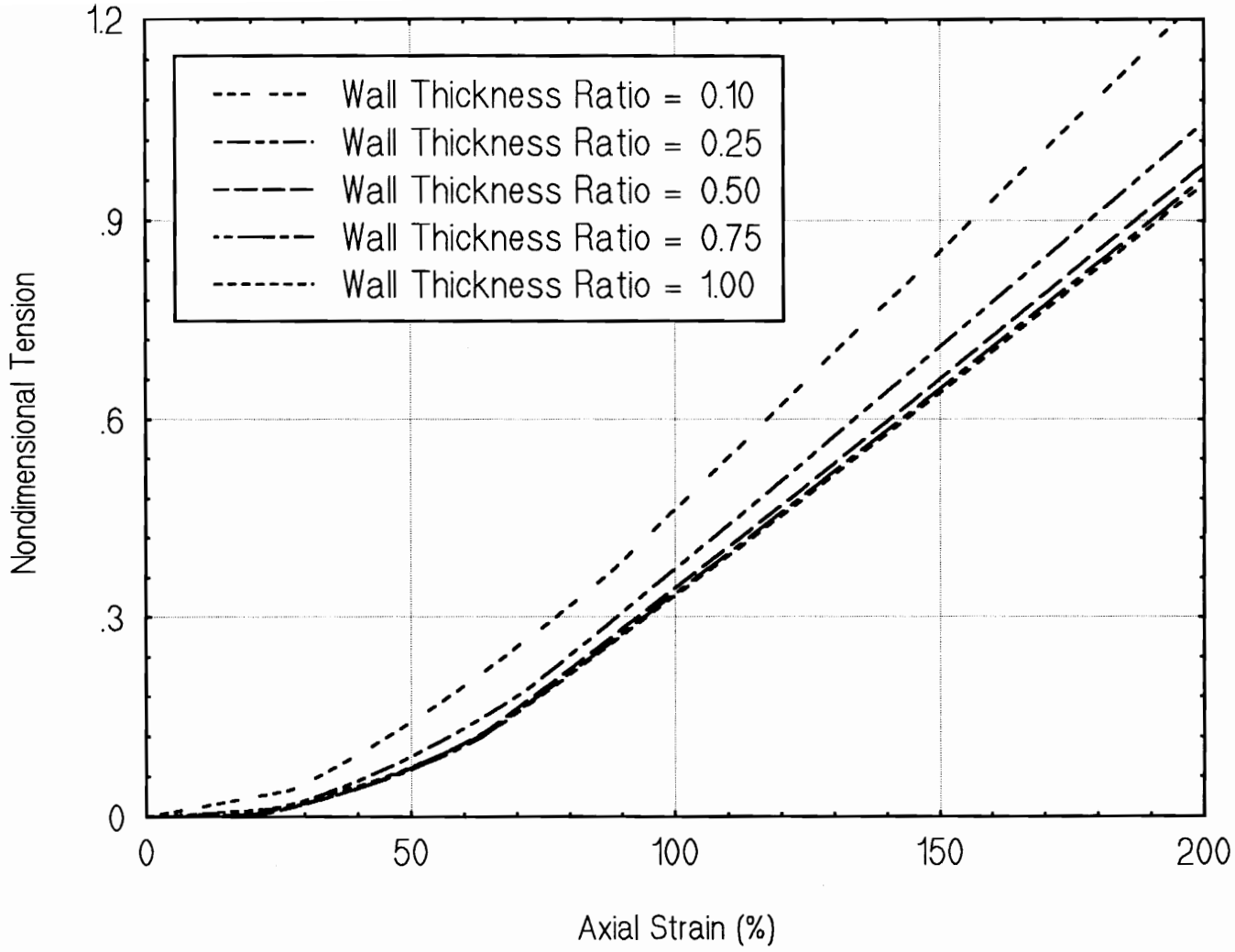


Figure 47. Nondimensional Composite Tension Variations for Different Wall Thickness Ratios

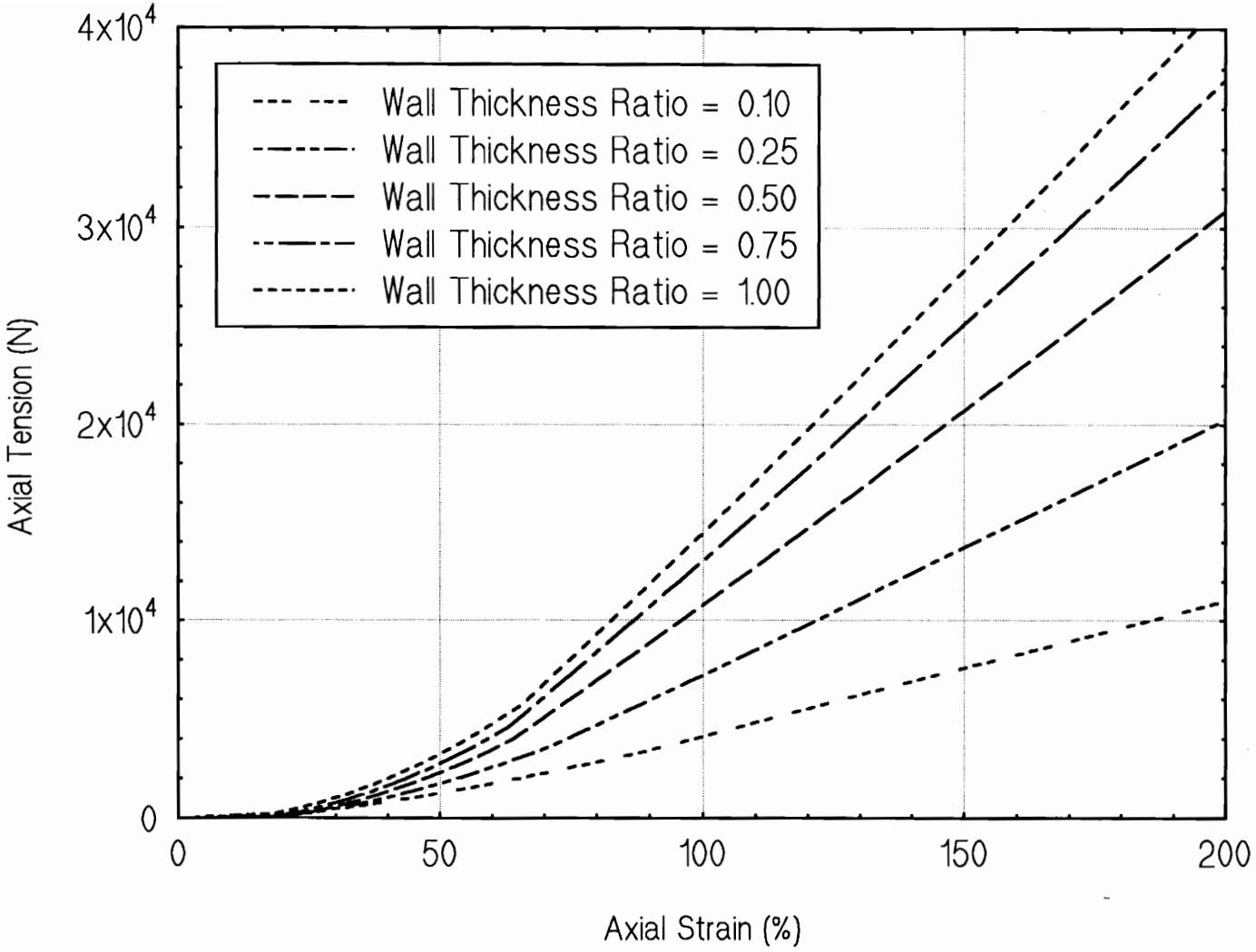


Figure 48. Dimensional Composite Tension Variations for Different Wall Thickness Ratios

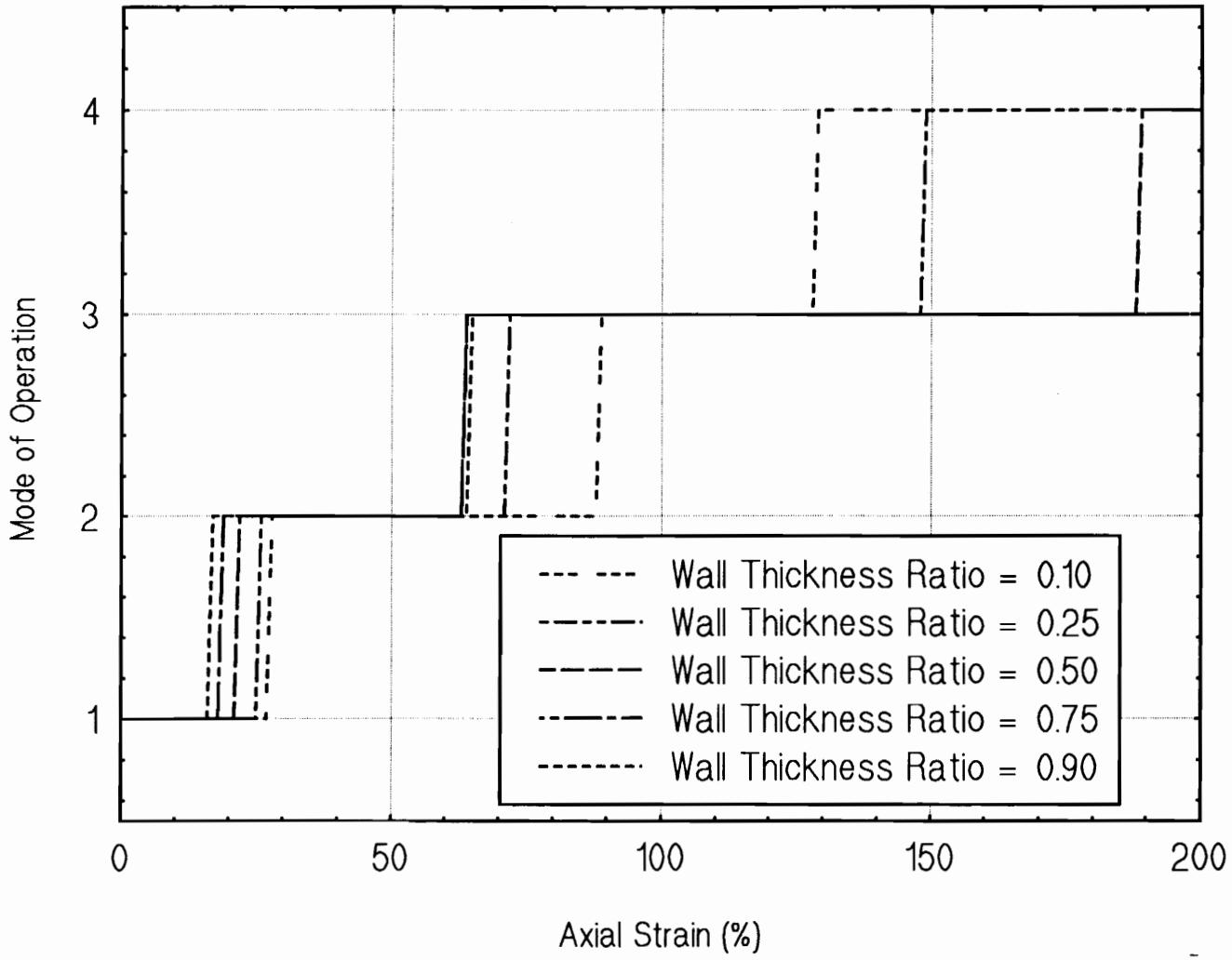


Figure 49. Mode Transitions for Different Wall Thickness Ratios

indicates that a lower wall thickness ratio also acts to delay transitions from mode one to two and from mode two to three while it accelerates the transition to from mode three to four. This phenomenon stems from the fact that a smaller braid thickness results in later contact with the core and an earlier withdrawal of the core from the inner braid wall.

4.6 Core/Inner Braid Radius Ratio Influences on Composite Response

Changing the core/inner braid radius ratio effectively sizes the core. Figure 50 illustrates that for a sufficiently small core, the braid will never contact the core and consequently, the composite response is characterized by rather abrupt transitions that resemble the braid alone without a core. As the radius ratio approaches unity however, the composite response begins closer to mode two operation and the transition within the toe-region becomes smoother. While the yarn strain is higher for composites with larger cores at the same axial strain value only in mode two, it is the increased contribution from the larger core which results in a composite tensile response that increases with a larger core/inner braid radius ratio.

For a sufficiently small radius ratio the braid will lock without ever contacting the core. This results in a mode transition directly from one to four as illustrated in Figure 51. For radius ratios approaching unity, the composite begins closer to mode two operation and delays the transition from mode three to four. For larger cores, the braid is in contact with the core longer and the composite response is much smoother.

4.7 Yarn Aspect Ratio Influences on Composite Response

Although critical to the mode transitions in the dimensional analysis, both the composite tension and mode transitions are independent of yarn aspect ratio in the nondimensional formulation as evidenced by Figures 52 and 53 respectively. Regardless of the value chosen for the yarn aspect ratio, the curves remain superimposed on one another. The wall thickness ratio and core/inner braid radius ratio govern the nondimensional response and changing the yarn aspect ratio only alters the number of

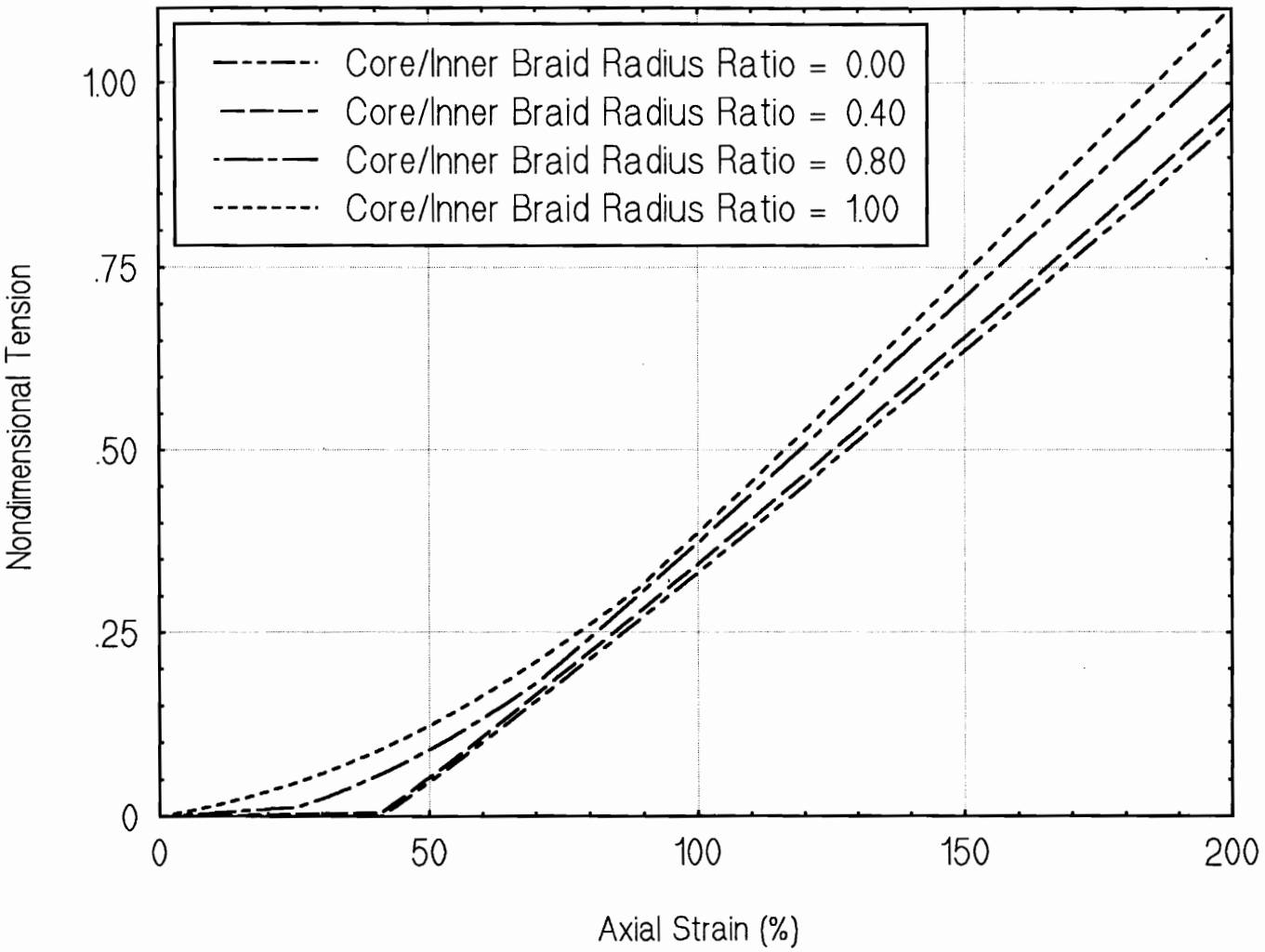


Figure 50. Nondimensional Composite Tension Variations for Different Core/Inner Braid Radius Ratios

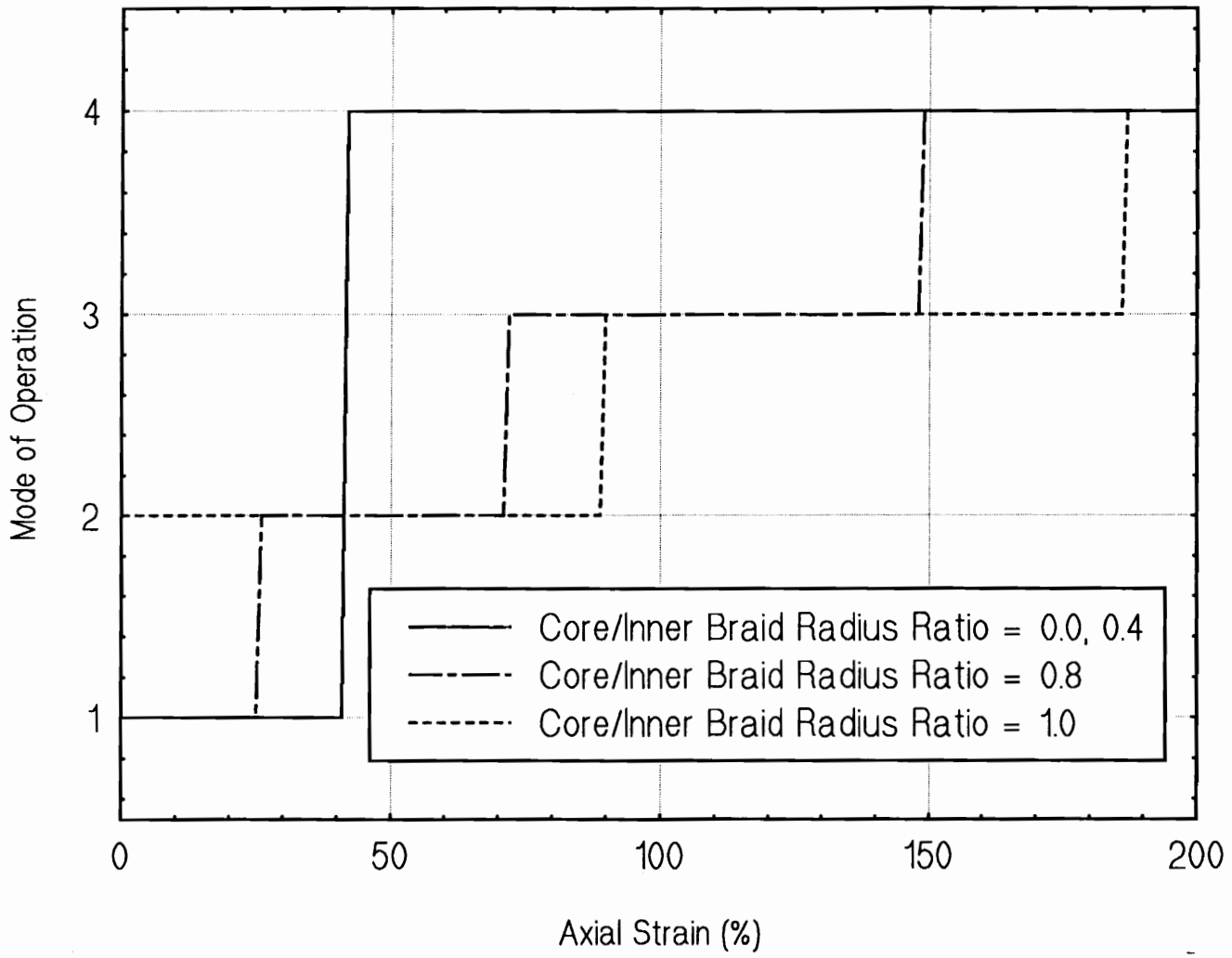


Figure 51. Mode Transitions for Different Core/Inner Braid Radius Ratios

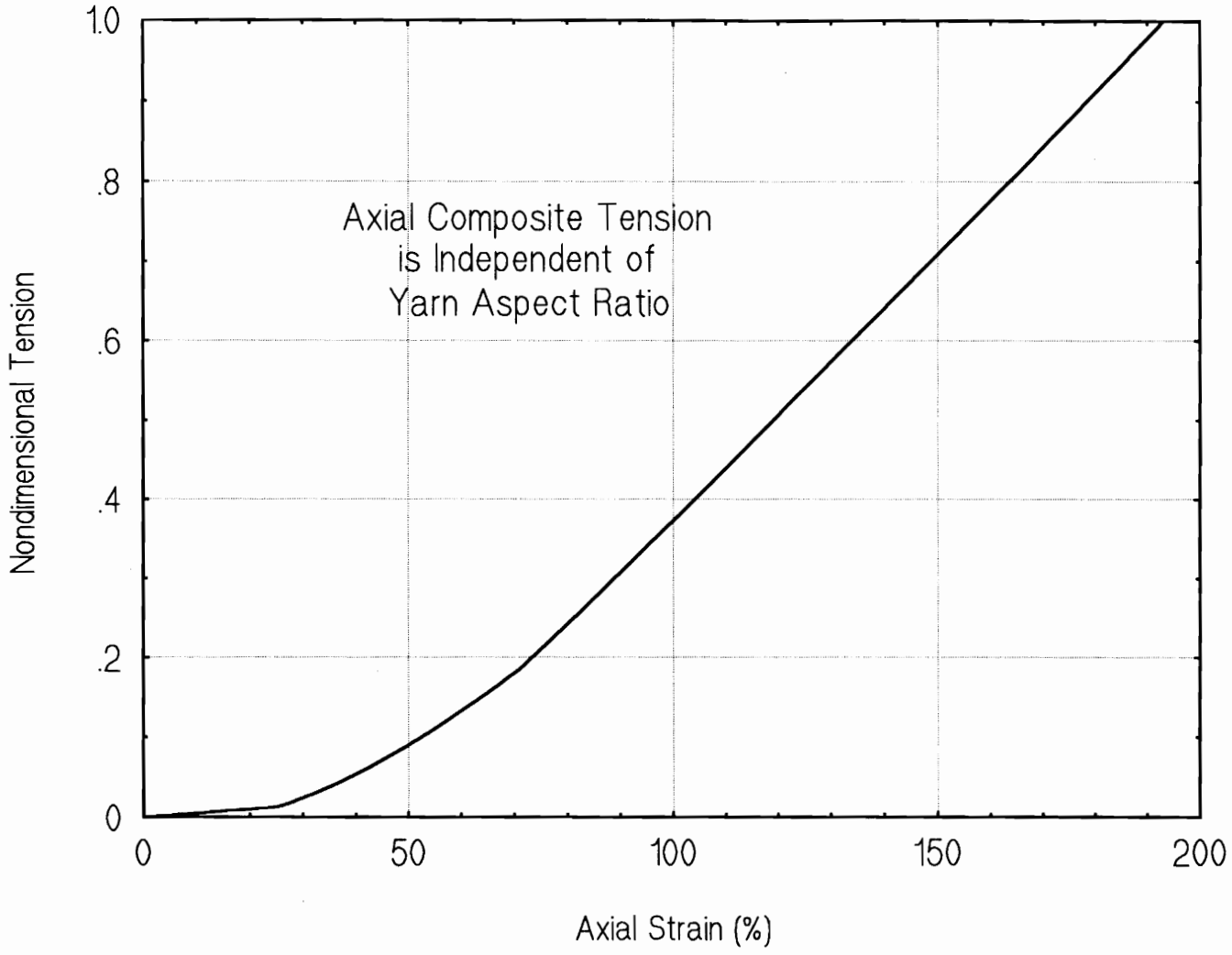


Figure 52. Nondimensional Composite Tension Variations for Different Yarn Aspect Ratios

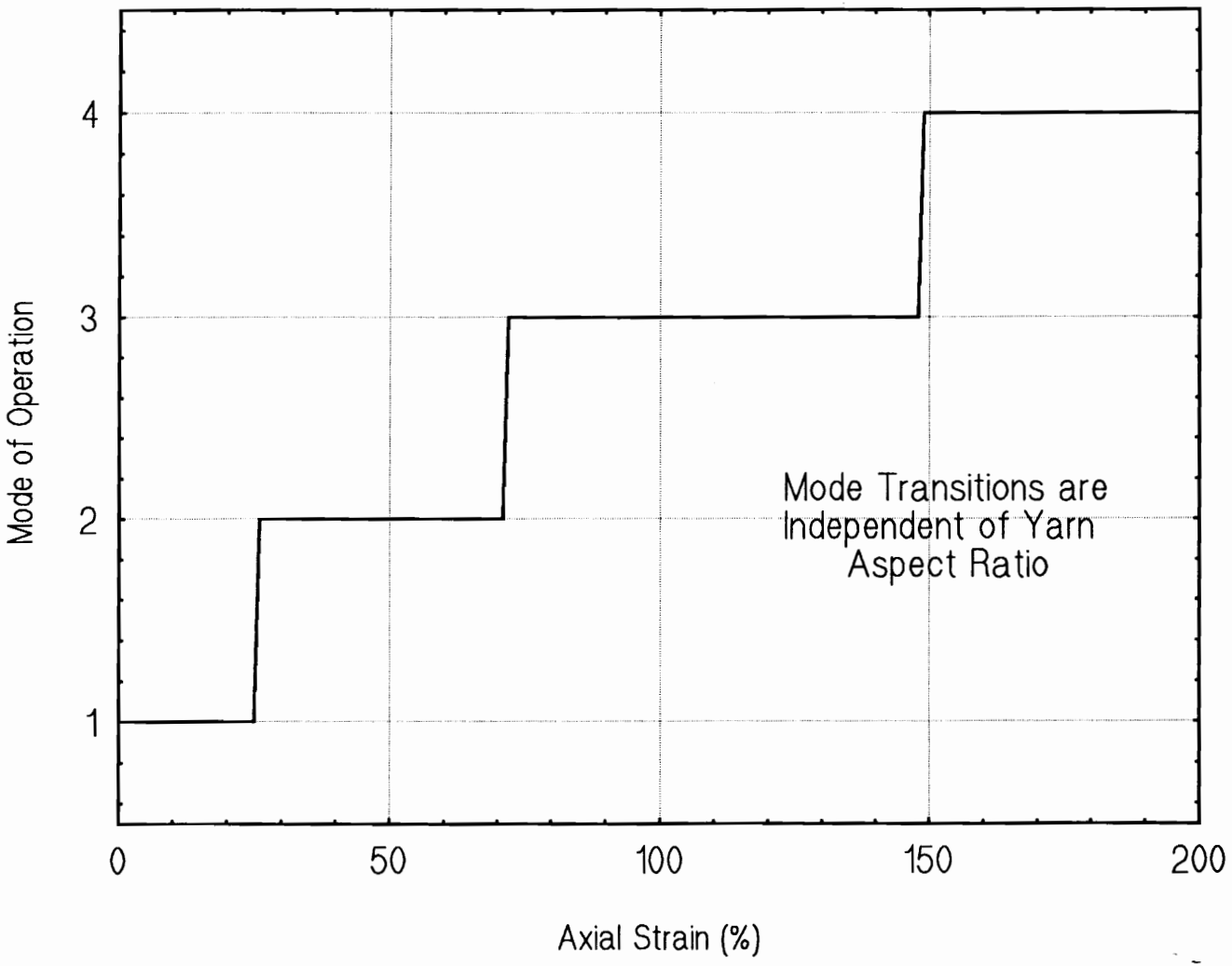


Figure 53. Mode Transitions for Different Yarn Aspect Ratios

carriers and braid density associated with the nondimensional parameters. As the yarn aspect ratio decreases, the yarn width must increase since the yarn thickness is held constant by the wall thickness ratio. This results in fewer yarns comprising the braid and a decreased braid density. Yet the total fiber volume and yarn orientation remain constant regardless of the yarn aspect ratio. Hence the strain associated with a single yarn is the same for composites with different yarn aspect ratios. Composites with a lower yarn aspect ratio, having fewer yarns with larger cross-sections, exhibit the same response as composites with a higher yarn aspect ratio, having a greater number of yarns with smaller cross-sections.

4.8 Yarn Packing Factor Influences on Composite Response

Changing the yarn packing factor has a more appreciable effect on both the composite tension and mode transitions. While the composite tension is proportional to the yarn packing factor as illustrated in Figure 54, the mode of operation shows subtle variations. The point at which the braid contacts the core remains unchanged and consequently the transition from mode one to two is identical regardless of packing factor. While subtle differences in the yarn strain variations are apparent only in mode two, it is the yarn's porosity governed by the yarn packing factor that results in discernable differences among the composite tensile responses. Since a lower packing factor results in more porous yarns, the tension developed for the same yarn strain decreases with the packing factor. Consequently, to achieve the same compressive load, a larger strain is required for a more porous yarn with a lower packing factor than its denser counterpart with the same dimensions. This results is delayed locking for yarns with a lower packing factor and a later transition to mode three. The transition from mode three to four is governed by the core and remains unchanged. These trends are illustrated in Figure 55.

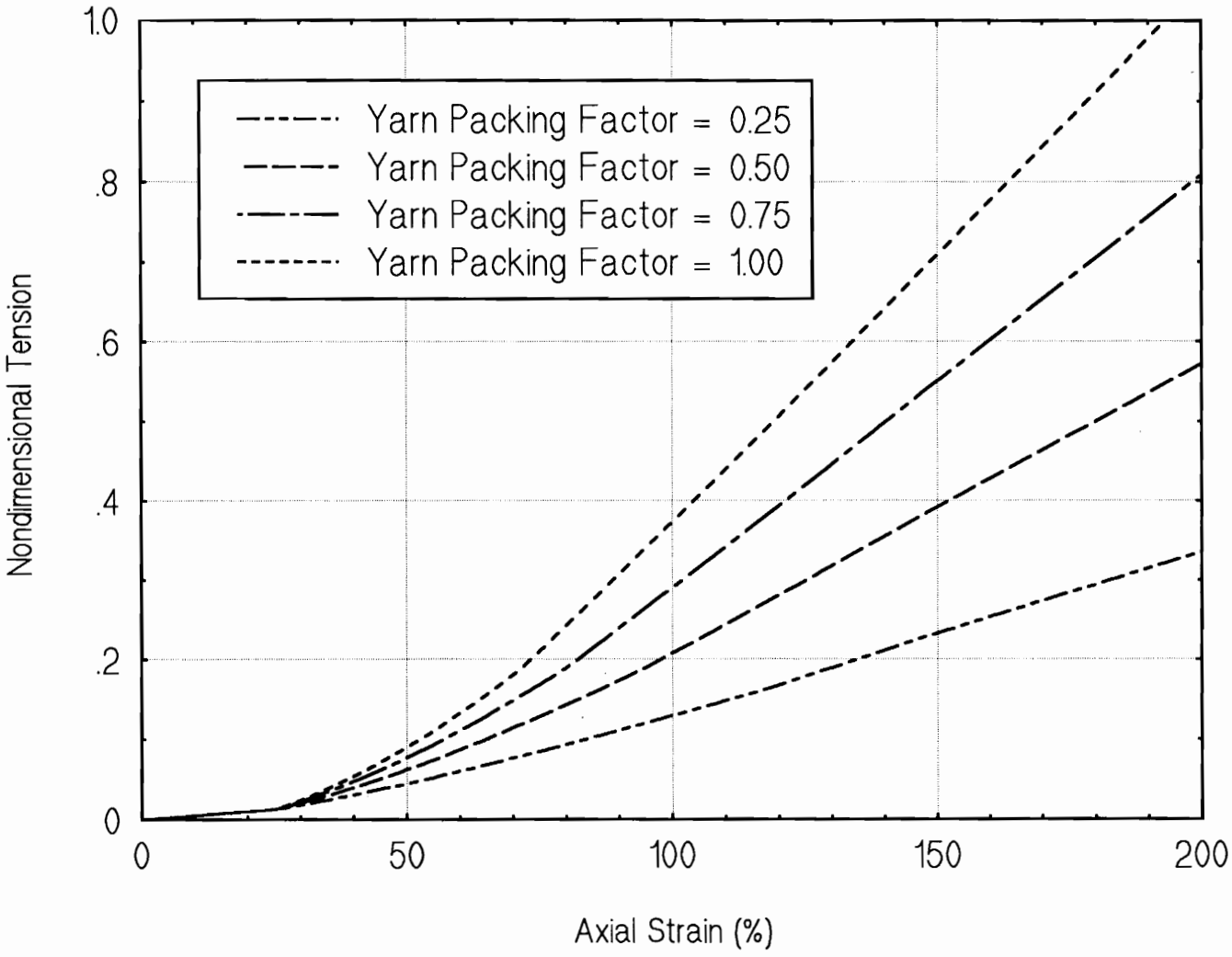


Figure 54. Nondimensional Composite Tension Variations for Different Yarn Packing Factors

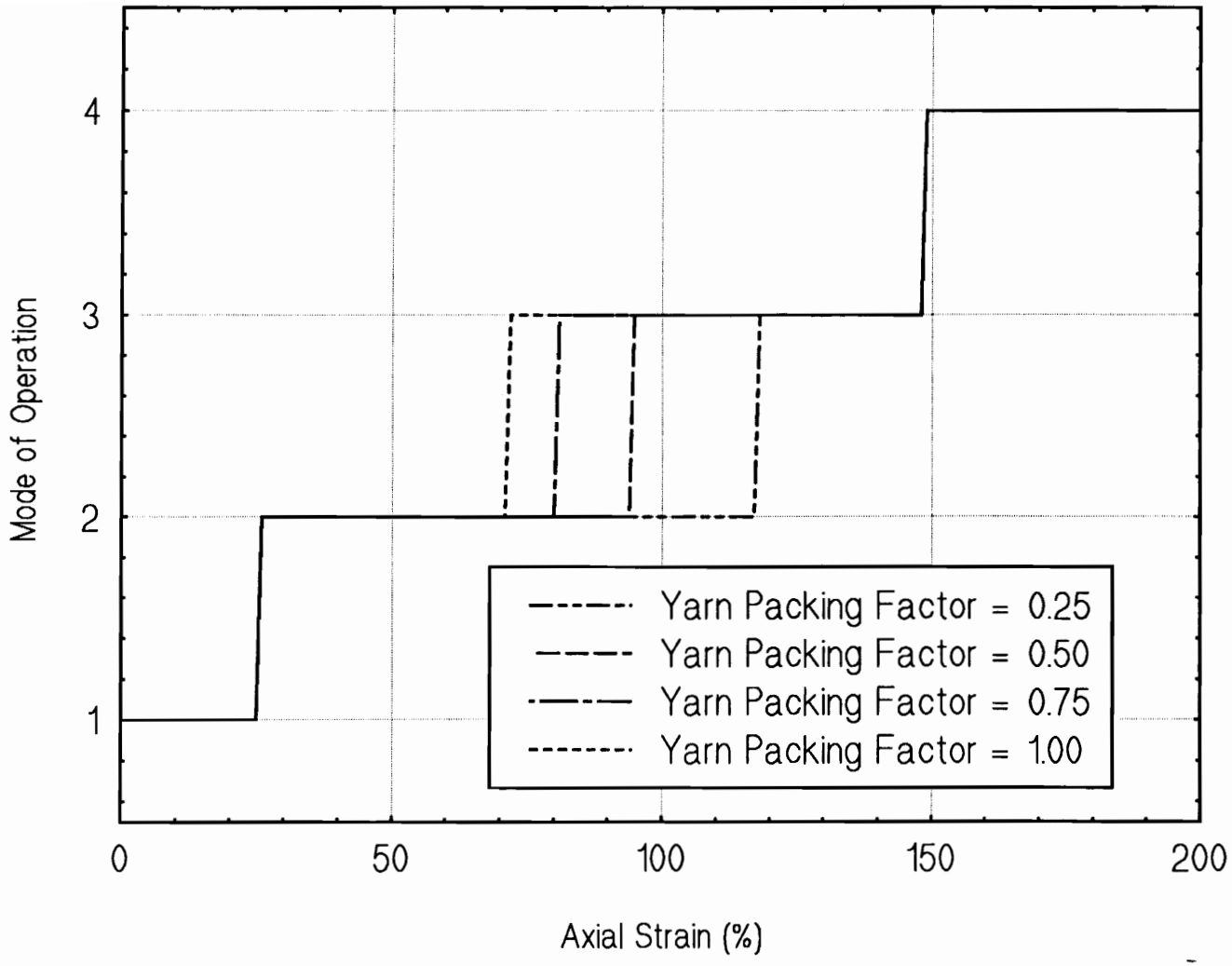


Figure 55. Mode Transitions for Different Yarn Packing Factors

4.9 Core Packing Factor Influences on Composite Response

Changing the core packing factor alters only the core's porosity. Since the packing factor is assumed to be constant, it does not effect the core's size, elastic modulus, or Poisson ratio. Yet as a consequence of the greater porosity associated with a lower packing factor, the core component of the tension contributed to the composite decreases, decreasing the composite tension as illustrated in Figure 56. However, since the material properties and rate of contraction remain unchanged, the mode transitions are independent of core packing factor for cores of the same size as evidenced by Figure 57.

4.10 Cover Factor Influences on Composite Response

Altering the initial cover factor while maintaining the same initial braid angle acts to change the point at which the braid locks. While the nondimensional composite tension curves illustrated in Figure 58 indicate that the composite tension rises with a decreasing cover factor, this trend does not reflect the dimensional tension variations because the nondimensional tension is normalized by the number of yarns in the braid. While the yarns maintain identical configurations, a lower cover factor decreases the number of yarns in the braid and appears to artificially increase the core's contribution to the composite tension. This trend is reflected in Figure 58. The dimensional data in Figure 59 illustrates that increasing the cover factor among similarly sized composites with the same material properties actually increases the composite tension as would be intuitively anticipated. The increased number of carriers acts to increase the dimensional tension. Figure 60 illustrates that a higher initial cover factor also accelerates locking and results in earlier transitions to modes three and four. While the point where the braid contacts the core remains unchanged, evidenced by identical transitions form mode one to two, the duration of the mode two operation is directly dependent of the number of yarns. The lower cover factor acts to delay the locking point, extending the region of mode two behavior.

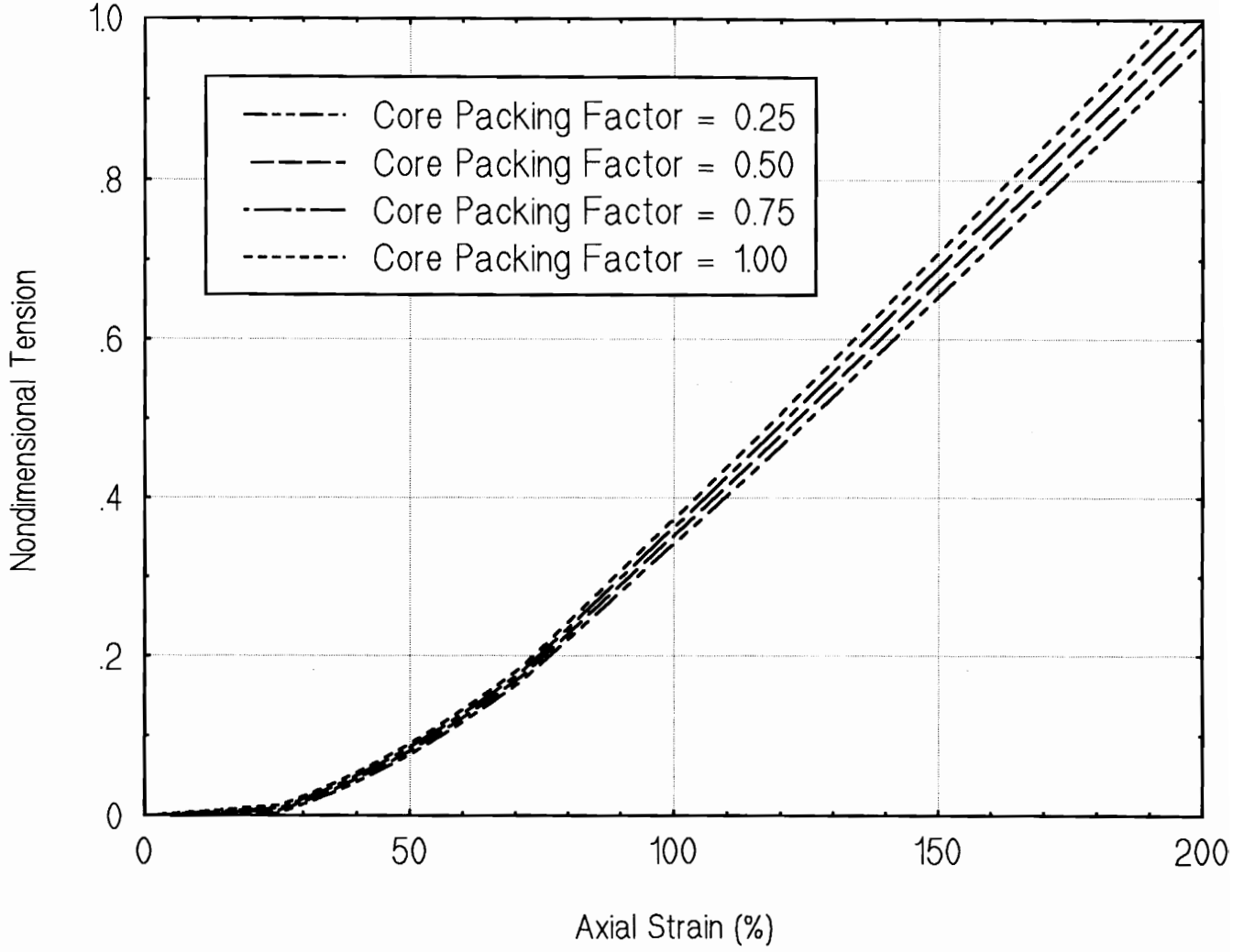


Figure 56. Nondimensional Composite Tension Variations for Different Core Packing Factors

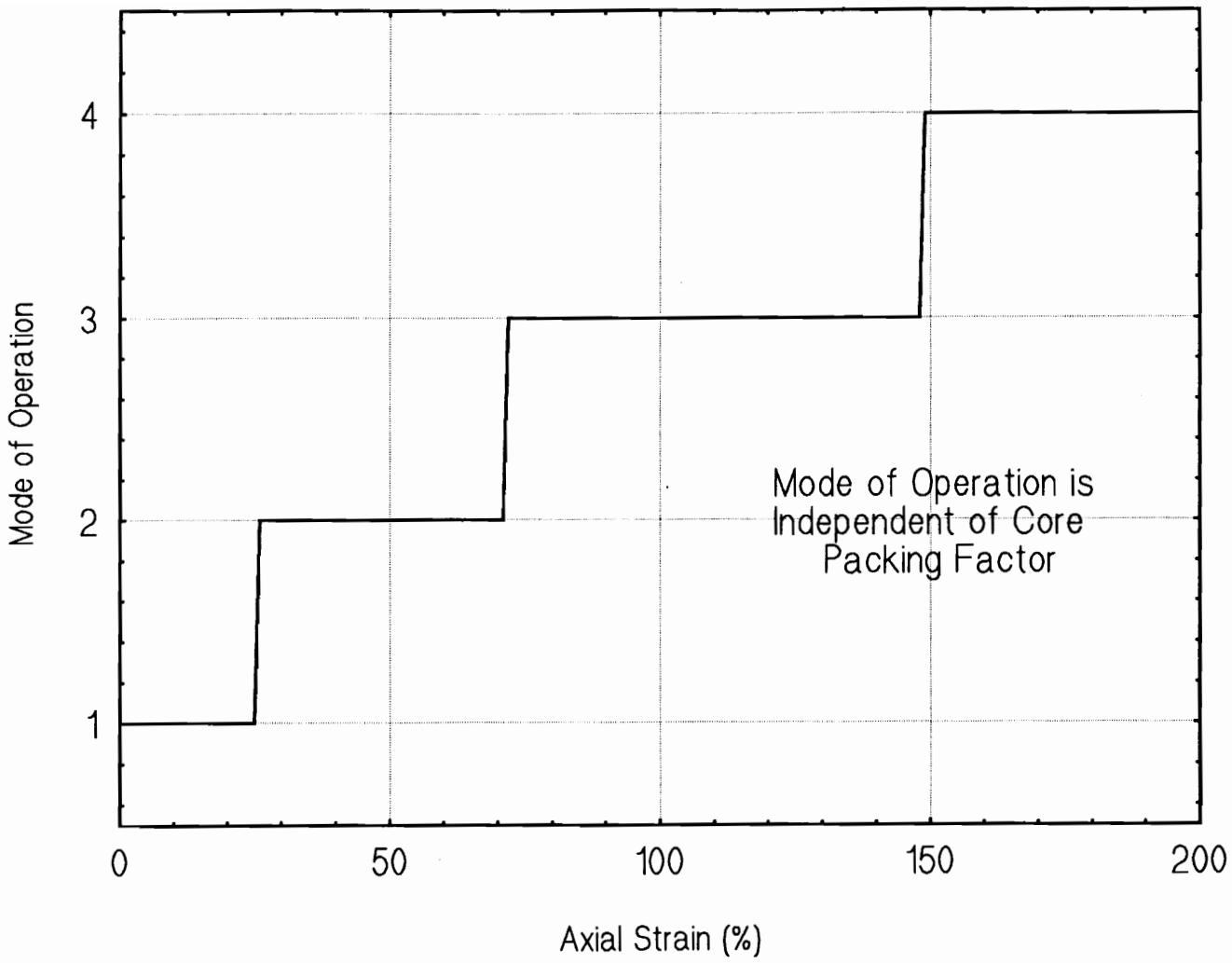


Figure 57. Mode Transitions for Different Core Packing Factors

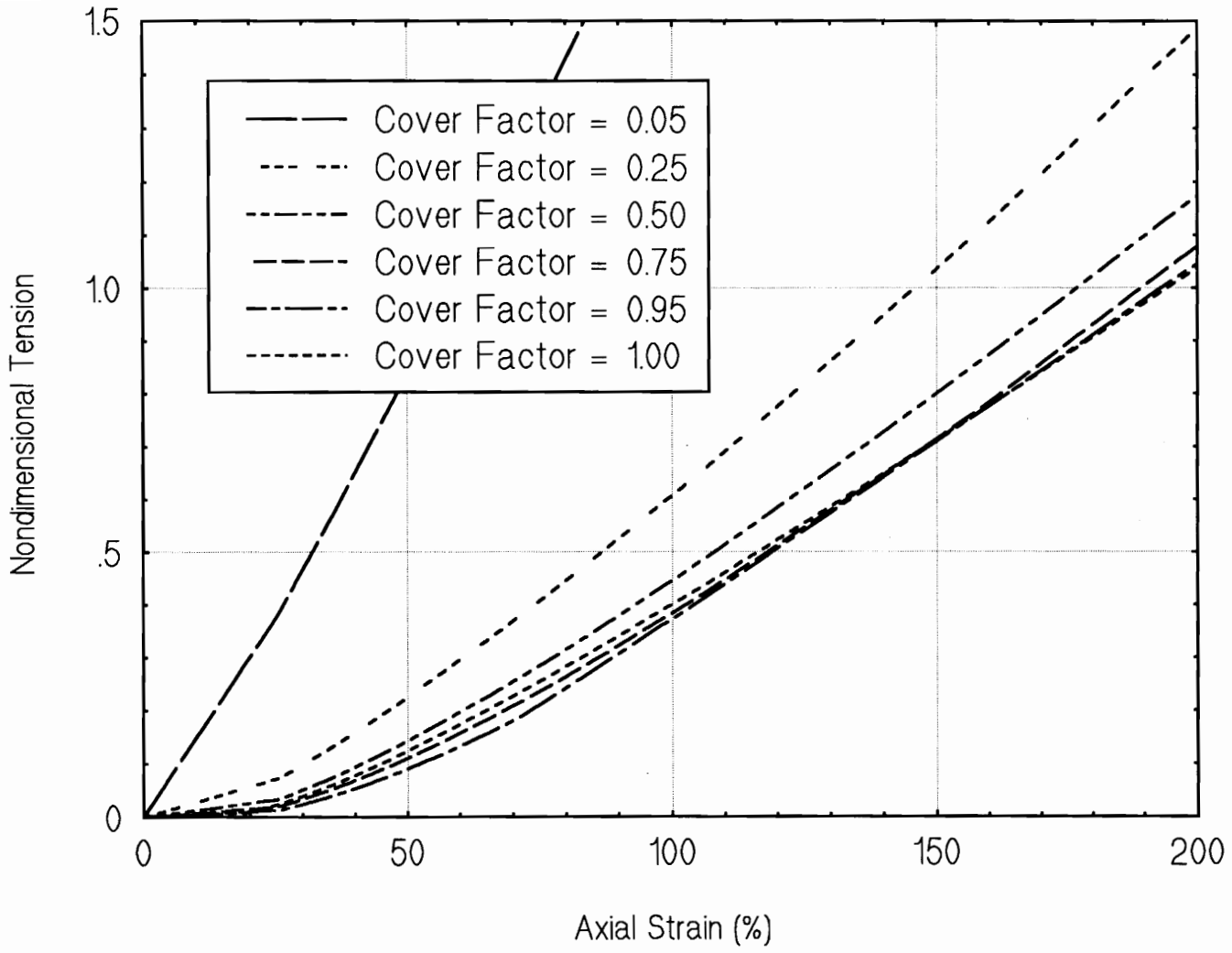


Figure 58. Nondimensional Composite Tension Variations for Different Initial Cover Factors

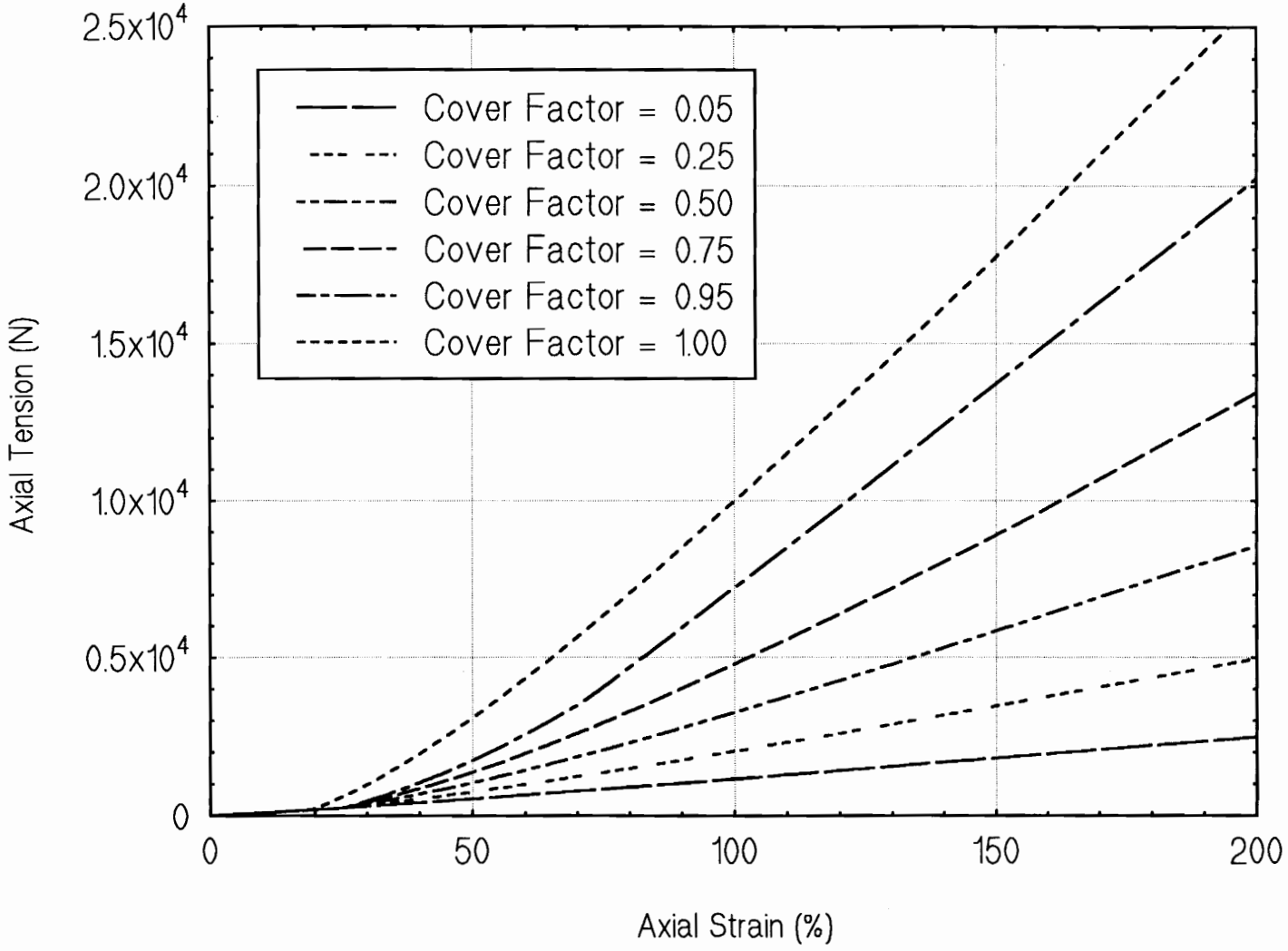


Figure 59. Dimensional Composite Tension Variations for Different Initial Cover Factors

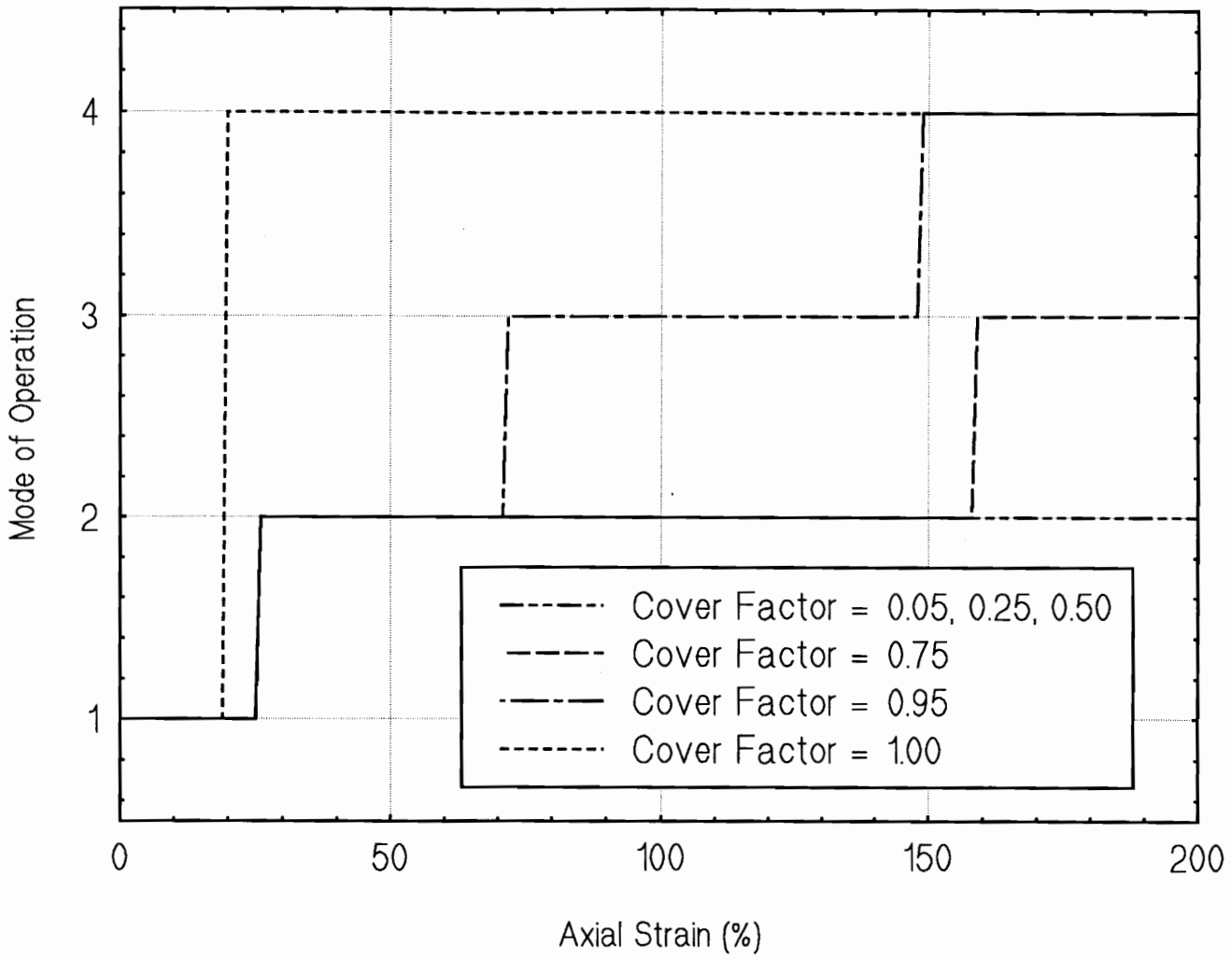


Figure 60. Mode Transitions for Different Initial Cover Factors

As the initial cover factor approaches unity, the braid angle approaches its extreme locking angles. If the initial braid angle is less than or equal to 45 degrees, the braid is at its minimum locking angle and the locked braid will not extend without inducing yarn strain. If the initial braid angle is greater than 45 degrees, the braid is at its maximum locking angle and will freely extend until it reaches its minimum locking angle. Since the initial braid angle is 50 degrees, it defines the maximum locking angle and the composite will exhibit mode one operation as the cover factor initially decreases before increasing to approach unity again. The initial braid angle's compliment of 40 degrees defines the minimum locking angle. Since the initial braid angle and locking angle are quite close, mode one behavior is rather brief and the braid locks without ever contacting the core. As a consequence, the composite with an initial cover factor equal to unity moves directly from mode one to four.

4.11 Modulus Ratio Influences on Composite Response

The modulus ratio serves to control the size of the toe-region and shape of the composite tensile response curve. For very low core/yarn modulus ratios, the toe-region is quite apparent. As the modulus ratio increases above several percent and approaches unity, the composite response becomes nearly linear and the toe-region characterized by a relatively low modulus disappears as evidence by Figure 61. Toe-region characteristics are detailed in Figure 62. Mode transitions are illustrated in Figure 63. Without the core, the composite moves from mode one to four. As the modulus ratio increases, the transition from mode two to three is delayed since a larger radial pressure is required to compress a stiffer core. Although the modulus ratio influences the yarn strain only in mode two, it acts to increase the yarn strain which serves to delay locking. Since the transition to mode four is governed by the yarn properties and the core's Poisson ratio, it remains unchanged.

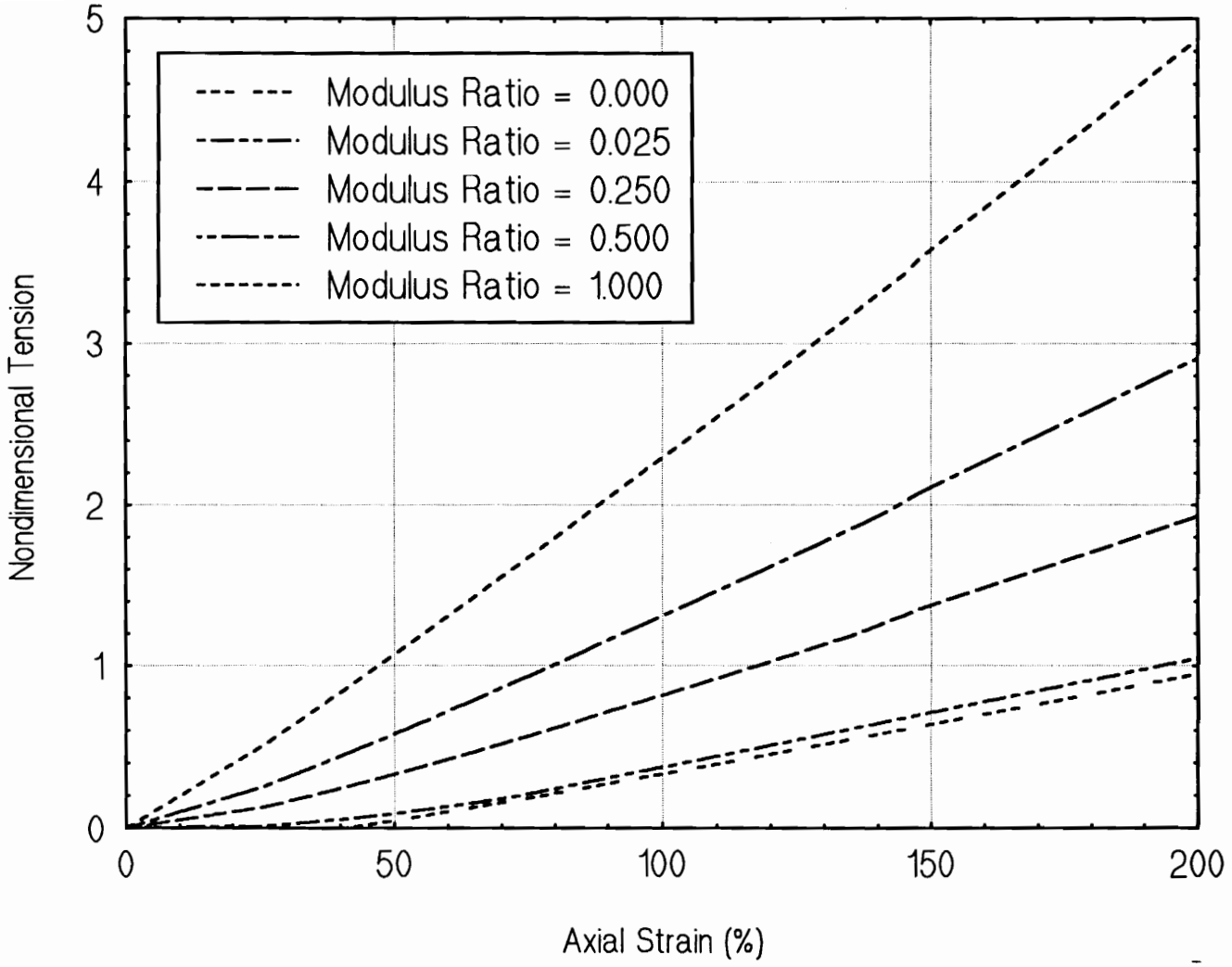


Figure 61. Nondimensional Composite Tension Variations for Different Core/Yarn Modulus Ratios

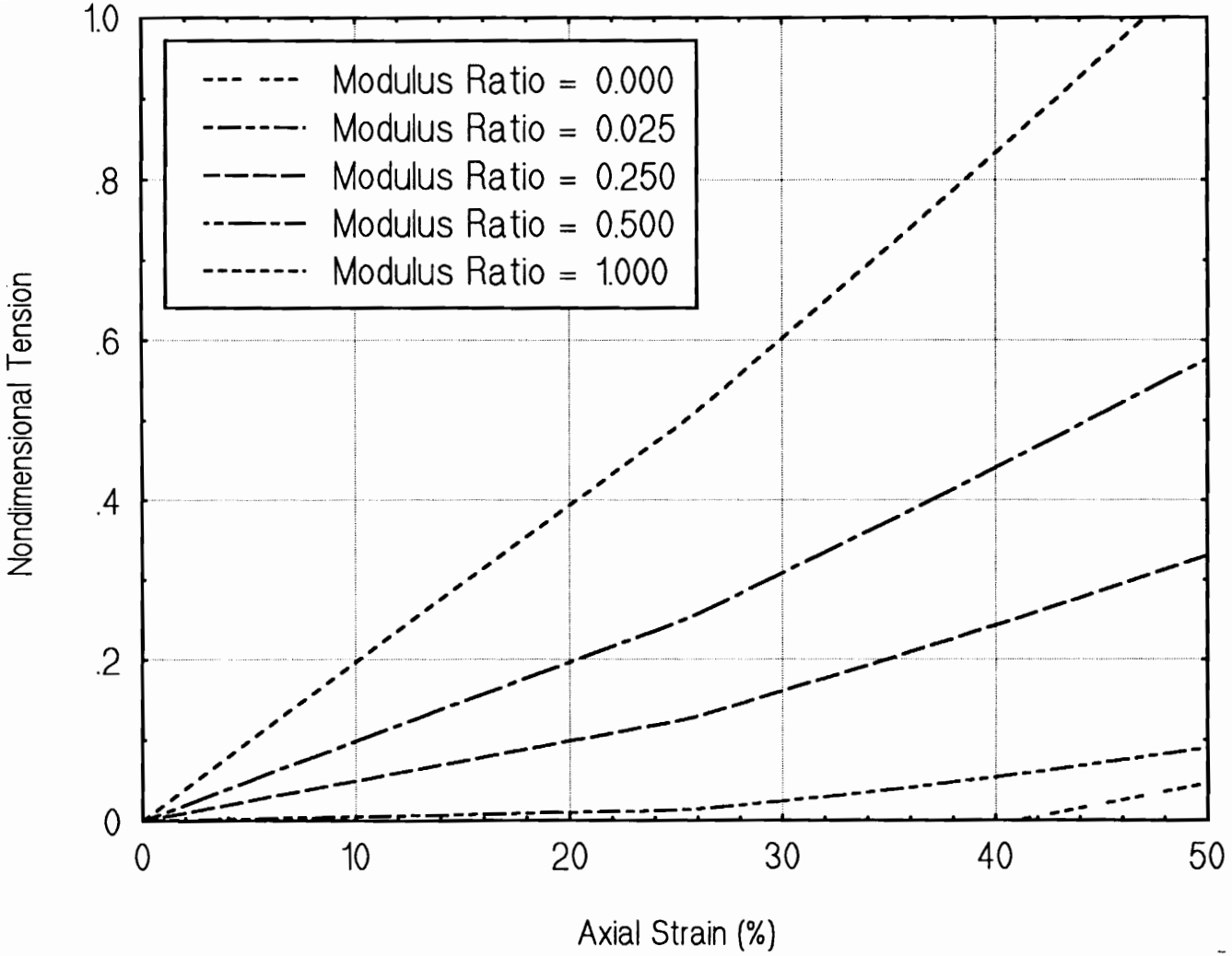


Figure 62. Nondimensional Composite Toe-Region Tension Variations for Different Core/Yarn Modulus Ratios

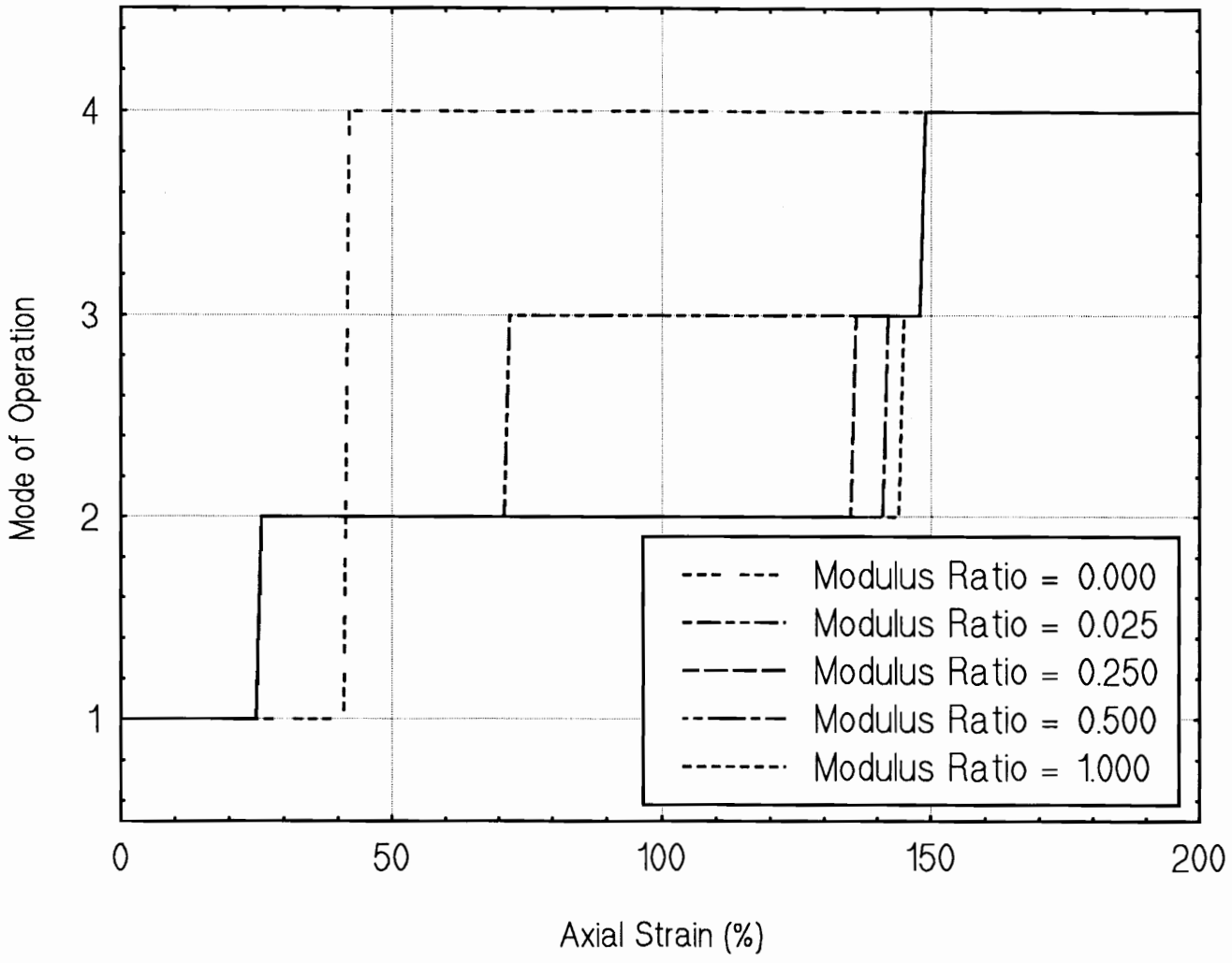


Figure 63. Mode Transitions for Different Core/Yarn Modulus Ratios

5.0 SUMMARY AND CONCLUSIONS

5.1 Introduction

This endeavor was undertaken by first establishing a theoretical model and then running experimental trials in an attempt to assess the validity of the model. While the model afforded some flexibility that enabled some of the initial assumptions to be relaxed, the theoretical development independent of and prior to the experimental evaluation made the experimental verification a rigorous test of the model's validity. While the experimental verification was limited to a single class of braids with various sized cores, the agreement between theory and experiment was quite good, strongly endorsing the fundamental assumptions of the model regarding braid mechanics. Yet extending this theory to broader classes of composite circular braids would demand additional testing. Most significantly, the assumption of linearly elastic core behavior would have to be verified with modulus ratios larger than those in the experimental series. Although the core undergoes finite deformation, its contribution to the composite's response is most significant at lower strains for low modulus ratios. While the linearly elastic theory used to model the core deteriorates as the strain level increases, it accurately describes the core's behavior at lower strains where its contribution to the composite's response is most significant. Reformulating the description of the core to include nonlinear behavior over finite deformation intervals would demand extensive revision of the existing model.

It should be noted that the distinct toe-region exhibited by the composites is a direct consequence of the low modulus ratio and raising the modulus ratio significantly above several percent would defeat the design purposes. Since the core's contribution is most appreciable at lower strains and less apparent at higher strains, linearly elastic theory is sufficient for low modulus ratios. In applications demanding very stiff materials however, a core material stiffer than the braid yarns may be desirable. Many braided ropes and cords for sailing employ this strategy and exhibit no significant toe-region.

5.2 Observations

The experimental series is essentially a documentation of braid dynamics and lends strong credibility to the model. The most significant assumption in the model development is the premise regarding a constant yarn aspect ratio. While this assumption is quite good for stiff yarns that maintain their shape, it becomes more tenuous for yarns consisting of loosely consolidated fibers that easily deform. In the experimental series however, the Dacron* yarns were very flexible and consisted of many individual fibers. Yet the assumption of a constant yarn aspect ratio proved quite good. A more sophisticated model that incorporates a dynamic yarn aspect ratio would be far more complicated and demand a more detailed description of both the yarns and the braiding pattern. Given this difficulty and the almost negligible influence that the changes in yarn aspect ratio had on composite tension, reformulating the model would not be justified by the marginally improvement in accuracy.

Although yarn crimp cannot be introduced if the yarn fibers are modeled linearly, a nonlinear yarn formulation can include the influence of crimp on the composite's response. While this is probably the most efficient strategy, it lends itself to an experimental rather than a theoretical approach. Including crimp in the model explicitly would demand incorporating the braiding pattern in the formulation as well as yarn bending within the braid. This would rather dramatically increase the model's complexity but would decrease the reliance on experimental yarn properties.

5.3 Extensions and Recommendations

A far more productive endeavor would be to incorporate the effects of creep and hysteresis in the model so that loading and unloading over several cycles could be predicted. As the model stands, it can be used to predict first cycle or steady state response if material properties are given. Predicting transient response would be rather complex but incorporating an assessment of plastic strain to update material properties could be

accomplished without great difficulty. Simply modifying and rewriting the data file that defines the yarn properties would be sufficient.

The most beneficial undertaking would be additional experimental verification over a strain range that extends to failure. The existing equipment and fixturing available for the experimental analysis restricted the strain range and did not permit testing to failure. However, tests with specimens of twelve and fifteen inch lengths mounted with a two inch extensometer showed that end displacement data and strain data from the extensometer were nearly identical if the tension tests were conducted with care. Consequently, reliable failure data could be obtained using end displacement if a means of securely mounting the circular specimens were available. The rather significant radial contraction associated with the large axial deformations makes this a challenging task.

5.4 Conclusions

Concisely summarizing the previous discussions and noting possible extensions,

- o Good agreement between theory and experiment verifies the fundamental braid mechanics.
- o The core provides smooth transitions and elastic recovery.
- o A low modulus ratio is essential to the toe-region.
- o Modeling assumptions are reasonable.
- o Experimental verification is presently limited to a single class of composites
- o Improving the model by incorporating variations in the yarn aspect ratio or explicitly including crimp in the formulation would dramatically increase complexity.
- o Incorporating plastic deformation would be more profitable.
- o Viscoelastic properties could also be included.
- o The greatest asset would be additional testing to failure enabling broader generalizations and a more thorough verification of assumptions.

REFERENCES

1. Popper P, "Braiding" in *Encyclopedia of Composites*, VCH Publishers, 1989, p. 130.

2. Himmelfarb D, *The Technology of Cordage Fibres and Rope*, Leonard Hill [Books] Limited, 9 Eden Street, N.W. 1, London, 1957.

3. "Computers Weave Materials for the Space Age", *New Scientist*, 122(1): 28, 1989.

4. Drouin R, Dore R, Thiry P, Jean-Francois C, "Modelling of a Composite Prosthesis for Quasi Cylindrical Ligaments," Universite de Montreal/Ecole Polytechnique, 26th Annual ORS, Atlanta, Georgia, February 5-7, 1980.

5. Ibid.

BIBLIOGRAPHY

1. Ahfeld SK, Larson RI, Collins HR, "Anterior Cruciate Reconstruction in the Chronically Undatable Knee Using an Expanded Plytetrafluorethylene (PTFE) Prosthetic Ligament," *Am J Sports Med*, 15: 326-330, 1987.

2. Birman IS, Libgober A, *Contemporary Mathematics - Braids*, American Mathematical Society, v 78, Providence, Rhode Island, 1988.

3. Bolton CW, Bruchman B, "Mechanical and Biological Properties of the Gore-Tex Expanded Polytetrafluoroethylene (PTFE) Prosthetic Ligament," *Aktuel Probl Chir Orthop* 26: 40-51, 1983.

4. Bolton CW, Bruchman WC, "The Gore-Tex Expanded Polytetrafluoroethylene Prosthetic Ligament. An in vitro and in vivo evaluation," *Clin Orthop* 196: 202-213, 1985.

5. Butler HC, "Teflon as a Prosthetic Ligament in Repair of Ruptured Anterior Cruciate Ligaments," *Am J Vet Res* 25: 55-59, 1964.

6. Butler DL, "Mechanical Properties of Transplants for the Anterior Cruciate Ligament," *Trans Orthop Res Soc* 4: 81, 1979.

7. "Computers Weave Materials for the Space Age", *New Scientist*, 122(1): 28, 1989.

8. Cowart VS, "Several Choices Available for Repair of Ligamental Tears in the Knee," *JAMA*, 263(2): 197,1990.

9. Drouin R, Dore R, Thiry P, Jean-Francois C, "Modelling of a Composite Prosthesis for Quasi Cylindrical Ligaments," Universite de Montreal/Ecole Polytechnique, 26th Annual ORS, Atlanta, Georgia, February 5-7, 1980.

10. Fung YC, *Biomechanics - Mechanical Properties of Living Tissue*, Springer-Verlag, New York, 1981.

11. Glousman R, Shields C Jr, Kerlan R, et al, "Gore-Tex Prosthetic Ligament in Anterior Cruciate Deficient Knees," *Am J Sports Med*, 16(4): 321-326, 1988.

12. Grood ES, Noyes FR, "Cruciate Ligament Prosthesis: Strength, Creep and Fatigue Properties," *J Bone Joint Surg* 58A: 1083-1088, 1976.

13. Gupta BN, Brinker WO, "Anterior Cruciate Ligament Prosthetis in the Dog," *J Am Vet Med Assoc* 154: 1057-1061, 1969.

14. Hansen VL, *Braids and Coverings - Selected Topics*, Cambridge University Press, New York, 1989.

15. Himmelfarb D, *The Technology of Cordage Fibres and Rope*, Leonard Hill [Books] Limited, 9 Eden Street, N.W. 1, London, 1957.

16. Indelicato PA, Pascaler MS, Hugel MO, "Early Experience with the Gore-Tex Polytetrafluoroethylene Anterior Cruciate Ligament Prosthetis," *Am J Sports Med*, 17: 55-62, 1989.

17. Jenkins DHR, McKibbin B, "The Role of Flexible Carbon-Fibre Implants as Tendon and Ligament Substitutes in Clinical Practice," *J Bone Joint Surg* 62B: 497-499, 1980.

18. Johnson FL, "Use of Braided Nylon as Prosthetic Anterior Cruciate Ligament of the Dog," *J Am Vet Med Assoc*, 137: 646-647, 1960.

19. Kennedy JC, "Application of Prothetics to Anterior Cructiate Ligament Reconstruction and Repair," *Clin Orthop* 172: 125-128, 1983.

20. Ko, Fk, "Braiding" in *Engineered Materials Handbook*, ASM International, Metals Park, Ohio, 1987, pp. 519-528.

21. Li W, Kang T, El Shiekh A, "Structural Mechanics of 3D Braided Preforms for Composites. Part 1. Geometry of Fabric Produced by 4-Step Process," NASA Conference Publicaton 3001, FIBER-TEX 87, Greenville, SC, November 1987.

22. Lubell A, "Mixed Reviews for Artificial Ligaments," *The Physician and Sportsmedicine*, 18(1): 44, 1990.

23. Muller W, *The Knee - Form, Function, and Ligament Reconstruction*, Springer-Verlag, New York, 1983.

24. Noyes FR, Butler DL, Grood ES, et al, "Biomechanical Analysis of Human Ligaments Grafts Used in Kness Ligament Repairs and Reconstructions," *J Bone Joint Surg* 66A: 344-352, 1984.

25. Pastore CM, "A Processing Science Model for Three-Dimensional Braiding," Ph.D. thesis, Drexel University, Philadelphia, 1988.

26. Popper P, "Braiding" in *Encyclopedia of Composites*, VCH Publishers, 1989, pp. 130-147.

27. Reiligmann H, *Textile Technology - Machine Braids*, All-Textile Employers Association, Frankfort, KY, 1981.

28. Schulitz KP, Drahl H, Stein WH, *Late Reconstructions of Injured Ligaments of the Knee*, Springer-Verlag, New York, 1978.

29. Silver FH, *Biological Materials: Structure, Mechanical Properties and Modeling of Soft Tissues*, New York University Press, New York, 1987.

30. Simpson DC, *Modern Trends in Biomechanics*, Butterworth and Company Limited, London, 1970.

31. Tremblay GR, Laurin CA, Drouin G, "The Challange of Prosthetic Cruciate Ligament Replacement," *Clin Orthop* 147: 88-92, 1980.

32. Yang CN, Ge ML, *Braid Group, Knot Theory, and Statistical Mechanics*, World Scientific, New Jersey, 1989.

Appendix A

```
'C:\THESIS\CMPMODL.BAS
'07/30/91


DECLARE FUNCTION PROPERTY# (XP#, X#(), Y#(), NDATA!, FLAG#, FAIL#)

'                    BRAIDED YARN/ELASTOMER COMPOSITE MODEL

'       THIS PROGRAM IS DESIGNED TO SIMULATE THE MECHANICAL RESPONSE OF
'        A COMPOSITE CONSISTING OF BRAIDED YARNS ENCOMPASSING AN
'        ELASTIC CORE.  THE FORMULATION ACCOMODATES BOTH DIMENSIONAL
'        AND NONDIMENSIONAL PARAMETERS, PERMITTING DESIGN AND
'        EVALUATION CAPABILITIES.

        DEFDBL A-I, O-Z

        DIM EYDAT(1000), SIGYDAT(1000)

        M$ = CHR$(9)

        CONST PI = 3.141592, CONVincm = 2.54, CONVmmcm = .1, CONVPalbs =
.000144988#, CONVmcm = 100!

        CLS

'                              PREPROCESSOR

START:
        PRINT "      BRAIDED YARN/ELASTOMER COMPOSITE SIMULATION "
        PRINT
        PRINT "    NOTE THAT IF A NONLINEAR ANALYSIS IS DESIRED, THE "
        PRINT " YARN PROPERTIES MUST BE SPECIFIED IN AN ASCII DATA FILE
"
        PRINT "   WITH THE NUMBER OF ORDERED PAIRS AS THE FIRST ENTRY "
        PRINT "  FOLLOWED BY THE STRAIN [Dimensionless] AND STRESS [Pa]
"
        PRINT "                VALUES IN ADJACENT COLUMNS. "
        PRINT

        PRINT "     EXISTING TRIAL CASES : "
        PRINT
        FILES "C:\THESIS\PARAMTR.*"
        PRINT
        DO UNTIL LEN(TRIAL$) = 3

         PRINT " PLEASE DESIGNATE THE PRESENT CASE NUMBER BY ENTERING A
"
         PRINT "  THREE DIGIT NUMBER WITH LEADING ZEROS.  IF THE CASE IS
"
         PRINT "  NOT TO BE SAVED, ENTER 000. "
         INPUT TRIAL$
```

```
        LOOP

INPUTS:
        PRINT " PLEASE DESIGNATE THE TYPE OF INPUT PARAMETERS BY
SELECTING "
        PRINT "               THE APPROPRIATE OPTION:    "
        PRINT "               (1) DIMENSIONAL          "
        PRINT "               (2) NONDIMENSIONAL       "
        INPUT INPUTOPT
        PRINT

        SELECT CASE INPUTOPT

        CASE 1
'                          DIMENSIONAL FORMULATION

'                            MODEL PARAMETERS

DIMENSIONAL:

        PRINT "               BRAID PROPERTIES "
        PRINT
        PRINT " ENTER THE YARN DENSITY [GM/CM^3] "
        INPUT rhobraid
        PRINT
        PRINT " ENTER THE LINEAR DENSITY OF THE YARN [DENIER] "
        INPUT rhoLbraid
        PRINT
        PRINT " FOR MODELING PURPOSES, THE YARN CROSS-SECTION IS "
        PRINT "          ASSUMED TO BE RECTANGULAR. "
        PRINT
        PRINT " ENTER THE YARN ASPECT RATIO DEFINED BY "
        PRINT "    ( Yarn Thickness / Yarn Width )          "
        INPUT YAR
        PRINT
        PRINT " ENTER THE YARN PACKING FACTOR DEFINED BY "
        PRINT "        ( Fiber Volume / Yarn Volume )  "
        PRINT "                RANGE ( 0 - 1 )       "
        INPUT YPF
        PRINT
        PRINT " ENTER THE NUMBER OF YARNS INCORPORATED IN THE BRAID "
        INPUT Nc
        PRINT
        PRINT " ENTER THE INITIAL BRAID DENSITY QUANTIFIED BY THE "
        PRINT "              NUMBER OF PICKS PER INCH "
        INPUT ppi0
        PRINT
        PRINT " ENTER THE INITIAL OUTER BRAID DIAMETER [MM] "
        INPUT Dbraid0o
        PRINT
```

```
        PRINT "                CORE PROPERTIES      "
        PRINT
CORE:
        PRINT " IS THE BRAID INITIALLY IN CONTACT WITH THE CORE? "
        PRINT "          (1) YES          "
        PRINT "          (2) NO           "
        INPUT COREOPT
        PRINT

        SELECT CASE COREOPT

        CASE 1

          CIBR = 1

        CASE 2

          PRINT " ENTER THE INITIAL CORE DIAMETER [MM] "
          INPUT Dcore0
          PRINT

        CASE ELSE

          GOTO CORE

        END SELECT

        PRINT " ENTER THE CORE MODULUS [Pa] "
        INPUT CoreMod
        PRINT
        PRINT " ENTER POISSON'S RATIO FOR THE CORE "
        INPUT V
        PRINT
        PRINT " ENTER THE CORE PACKING FACTOR DEFINED BY "
        PRINT "   ( Core Fiber Volume / Core Volume )        "
        PRINT "             RANGE ( 0 - 1 )              "
        INPUT CPF
        PRINT

'             UNIT CONVERSION AND INITIAL PARAMETER CALCULATIONS

        Ay0 = rhoLbraid / (rhobraid * 9000 * 100 * YPF)

        yarnwidth = SQR(Ay0 / YAR)

        yarnthickness = Ay0 / yarnwidth

        rbraid0 = (Dbraid0o * CONVmmcm / 2) - yarnthickness

        X0 = 2 * PI * rbraid0 / Nc
```

```
        Y0 = (1 * CONVincm) / (2 * ppi0)

        THETA0 = ATN(X0 / Y0)

        rbraid0i = rbraid0 - yarnthickness

        IF COREOPT = 1 THEN

          rcore0 = rbraid0i

          Dcore0 = 2 * rcore0

        ELSEIF COREOPT = 2 THEN

          rcore0 = Dcore0 * CONVmmcm / 2

        END IF

        IF rcore0 > rbraid0i THEN

          PRINT " INITIAL PARAMETERS RESULT IN AN IMPOSSIBLE BRAID
GEOMETRY "
          PRINT "   INITIAL CORE RADIUS IS GREATER THAN THE BRAID RADIUS
"
          PRINT "    PLEASE CHECK AND RE-ENTER THE COMPOSITE PARAMETERS
"
          PRINT "                    HIT RETURN TO CONTINUE "
          INPUT ESTRING$
          PRINT
          GOTO DIMENSIONAL

        END IF

        WTR = 2 * yarnthickness / rbraid0

        IF (WTR < 0) OR (WTR > 2) THEN
          PRINT "   IMPOSSIBLE WALL THICKNESS RATIO "
          PRINT USING "          WTR = ##.#### "; WTR
          PRINT "       FEASIBLE RANGE ( 0 - 2 )  "
          PRINT " PLEASE CHECK AND RE-ENTER PARAMETERS "
          PRINT "       HIT RETURN TO CONTINUE "
          INPUT ESTRING$
          PRINT
          GOTO DIMENSIONAL
        END IF

        CIBR = rcore0 / rbraid0i

        IF (CIBR < 0) OR (CIBR > 1) THEN
          PRINT " IMPOSSIBLE CORE/INNER BRAID RADIUS RATIO "
          PRINT USING "              CIBR = ##.#### "; CIBR
```

```
  PRINT "          FEASIBLE RANGE ( 0 - 1 )   "
  PRINT "   PLEASE CHECK AND RE-ENTER PARAMETERS "
  PRINT "           HIT RETURN TO CONTINUE "
  INPUT ESTRING$
  PRINT
  GOTO DIMENSIONAL
END IF

angle0 = THETA0 * 180 / PI

IF (angle0 < 0) OR (angle0 > 90) THEN
  PRINT "     IMPOSSIBLE INITIAL BRAID ANGLE "
  PRINT USING "          INITIAL ANGLE = ###.### "; angle0
  PRINT "      FEASIBLE RANGE ( 0 - 90 deg )   "
  PRINT "   PLEASE CHECK AND RE-ENTER PARAMETERS "
  PRINT "            HIT RETURN TO CONTINUE "
  INPUT ESTRING$
  PRINT
  GOTO DIMENSIONAL
END IF

YVF = Nc * Ay0 / (2 * PI * rbraid0 ^ 2)

VY0 = YVF / (WTR * COS(THETA0))

IF (VY0 < 0) OR (VY0 > 1) THEN
  PRINT " IMPOSSIBLE BRAID YARN VOLUME FRACTION "
  PRINT USING "        VOLUME FRACTION = ##.#### "; VY0
  PRINT "         FEASIBLE RANGE ( 0 - 1 )   "
  PRINT "  PLEASE CHECK AND RE-ENTER PARAMETERS "
  PRINT "          HIT RETURN TO CONTINUE "
  INPUT ESTRING$
  PRINT
  GOTO DIMENSIONAL
END IF

F0 = 1 - (1 - VY0) ^ 2

IF (F0 < 0) OR (F0 > 1) THEN
  PRINT "  IMPOSSIBLE INITIAL BRAID COVER FACTOR "
  PRINT USING "          COVER FACTOR = ##.#### "; F0
  PRINT "         FEASIBLE RANGE ( 0 - 1 )   "
  PRINT "  PLEASE CHECK AND RE-ENTER PARAMETERS "
  PRINT "          HIT RETURN TO CONTINUE "
  INPUT ESTRING$
  PRINT
  GOTO DIMENSIONAL
END IF

CASE 2
```

```
'                          NONDIMENSIONAL FORMULATION

'                               MODEL PARAMETERS

NONDIMENSIONAL:

        PRINT
        PRINT " ENTER THE INITIAL WALL THICKNESS RATIO DEFINED BY "
        PRINT "     ( 2 * Yarn Thickness / Mean Braid Radius )   "
        PRINT "                   RANGE ( 0 - 2 )       "
        INPUT WTR
        PRINT

        PRINT "   ENTER THE INITIAL CORE/INNER BRAID RADIUS RATIO
DEFINED BY "
        PRINT "      Core Radius / ( Mean Braid Radius - Yarn Thickness
) "
        PRINT "                         RANGE ( 0 - 1 )"
        INPUT CIBR
        PRINT

        PRINT " ENTER THE YARN ASPECT RATIO DEFINED BY "
        PRINT "     ( Yarn Thickness / Yarn Width )    "
        INPUT YAR
        PRINT

        PRINT " ENTER THE INITIAL YARN PACKING FACTOR DEFINED BY "
        PRINT "           ( Fiber Volume / Yarn Volume )    "
        PRINT "                RANGE ( 0 - 1 )        "
        INPUT YPF
        PRINT

        PRINT " ENTER THE CORE PACKING FACTOR DEFINED BY "
        PRINT "     ( Core Fiber Volume / Core Volume ) "
        PRINT "              RANGE ( 0 - 1 ) "
        INPUT CPF
        PRINT

        PRINT " ENTER THE INITIAL BRAID ANGLE IN DEGREES "
        INPUT angle0
        PRINT

        PRINT " ENTER THE INITIAL BRAID COVER FACTOR DEFINED BY "
        PRINT "    THE FRACTION OF THE PROJECTED BRAID AREA   "
        PRINT "                COVERED BY THE YARN "
        PRINT "                  RANGE ( 0 - 1 )   "
        INPUT F0
        PRINT

        PRINT " ENTER THE MODULUS RATIO DEFINED BY "
        PRINT "    ( Core Modulus / Yarn Modulus )   "
```

```
        INPUT RMOD
        PRINT

        PRINT " ENTER POISSON'S RATIO FOR THE CORE "
        INPUT V
        PRINT

        CASE ELSE

        GOTO INPUTS

        END SELECT

YARN:
        PRINT "   THIS PROGRAM MODELS THE YARN AS EITHER "
        PRINT "   A LINEAR OR NONLINEAR ELASTIC MATERIAL "
        PRINT " PLEASE ENTER THE APPROPRIATE CHOICE FOR THE "
        PRINT "          TYPE OF ANALYSIS DESIRED     "
        PRINT "               (1) LINEAR       "
        PRINT "               (2) NONLINEAR    "
        INPUT YARNOPT
        PRINT

        SELECT CASE YARNOPT

        CASE 1

          IF INPUTOPT = 1 THEN

            PRINT " ENTER THE YARN MODULUS [Pa] "
            INPUT YarnMod
            PRINT

          END IF

          EYCORR = 1

        CASE 2

          PRINT " FOR A NONLINEAR ANALYSIS, THE YARN PROPERTIES SHOULD "
          PRINT "  BE SPECIFIED IN A DATA FILE DEFINED BY THE USER, AS A
"
          PRINT "  TABLE OF STRAIN [DIMENSIONLESS] - STRESS [PA] VALUES.
"
          PRINT "  THE FIRST VALUE IN THE TABLE SHOULD BE THE NUMBER OF"
          PRINT "  ORDERED PAIRS DEFINING THE MATERIAL PROPERTIES. "
          PRINT
          PRINT " ENTER THE NAME OF THE FILE THAT DEFINES THE YARN "
          PRINT "  PROPERTIES.  INCLUDE DRIVE AND SUBDIRECTORY "
          PRINT "  DESIGNATIONS IF NECESSARY. "
          INPUT DATAFILE$
```

```
          PRINT
MODULUS:
          PRINT " FOR THE NONDIMENSIONAL ANALYSIS A CHARACTERISTIC "
          PRINT "           MODULUS MUST BE DEFINED. "
          PRINT " PLEASE SPECIFY THE DESIRED OPTION "
          PRINT "          (1) ARBITRARY MODULUS "
          PRINT "          (2) AVERAGE MODULUS "
          INPUT MODOPT
          PRINT

          OPEN DATAFILE$ FOR INPUT AS #7

          INPUT #7, NDATA

          FOR I = 1 TO NDATA

            INPUT #7, EYDAT(I), SIGYDAT(I)

          NEXT I

          CLOSE #7

          SELECT CASE MODOPT

            CASE 1

            PRINT " ENTER THE CHARACTERISTIC YARN MODULUS [Pa]. "
            INPUT YarnMod
            PRINT

            CASE 2

            YarnMod = (SIGYDAT(NDATA) - SIGYDAT(1)) / (EYDAT(NDATA) -
EYDAT(1))

            CASE ELSE

            GOTO MODULUS

          END SELECT

          CASE ELSE

          GOTO YARN

        END SELECT

'                          PARAMETER CONVERSION

        THETA0 = angle0 * PI / 180
```

```
RCB = CIBR * (1 - (WTR / 2))

YT = WTR / 2

VY0 = 1 - SQR(1 - F0)

YVF = VY0 * WTR * COS(THETA0)

YW = 2 * VY0 * COS(THETA0)

A = (1 + (1 / (TAN(THETA0)) ^ 2)) * ((1 + EY) ^ 2) / (YW ^ 2)

IF INPUTOPT = 1 THEN

RMOD = CoreMod / YarnMod

END IF

                CHECK PARAMETER FEASIBILITY
IF A < 1 THEN

  PRINT "     IMPOSSIBLE GEOMETRIC CONFIGURATION  "
  PRINT "    YARN WIDTH EXCEEDS UNIT BRAID LENGTH "
  PRINT " PLEASE CHECK AND RE-ENTER MODEL PARAMETERS "
  PRINT "           HIT RETURN TO CONTINUE "
  INPUT ESTRING$
  PRINT
  IF INPUTOPT = 1 THEN

    GOTO NONDIMENSIONAL

  ELSEIF INPUTOPT = 2 THEN

    GOTO DIMENSIONAL

  END IF

END IF

THETALOCK1 = ATN(SQR(A) - SQR(A - 1))

THETALOCK2 = ATN(1 / (SQR(A) - SQR(A - 1)))

IF THETALOCK1 <= THETALOCK2 THEN

  THETALOCKMIN = THETALOCK1
  THETALOCKMAX = THETALOCK2

ELSEIF THETALOCK1 > THETALOCK2 THEN
```

```
            THETALOCKMIN = THETALOCK2
            THETALOCKMAX = THETALOCK1

          END IF

          CHECK = RCB + WTR / 2

          IF CHECK > 1 THEN

            PRINT " CORE RADIUS AND WALL THICKNESS EXCEED MEAN BRAID
RADIUS "
            PRINT "       PLEASE CHECK AND RE-ENTER MODEL PARAMETERS "
            PRINT "                  HIT RETURN TO CONTINUE "
            INPUT ESTRING$
            PRINT
            IF INPUTOPT = 1 THEN

              GOTO NONDIMENSIONAL

            ELSEIF INPUTOPT = 2 THEN

              GOTO DIMENSIONAL

            END IF

          END IF

FAILURE:
          IF YARNOPT = 2 THEN

            PRINT " PLEASE INDICATE IF THE SIMULATION SHOULD BE TERMINATED
"
            PRINT "                   AT YARN FAILURE "
            PRINT "                      (1) YES      "
            PRINT "                      (2) NO       "
            INPUT FLAG
            PRINT

            IF (FLAG <> 1) AND (FLAG <> 2) THEN GOTO FAILURE

          END IF

          IF YARNOPT = 1 THEN

            FLAG = 2

          END IF

          IF (THETA0 < THETALOCKMIN) OR (THETA0 > THETALOCKMAX) THEN
```

```
          PRINT " INITIAL PARAMETERS RESULT IN AN IMPOSSIBLE BRAID
GEOMETRY "
          PRINT "              BRAID IS BEYOND LOCKING POINT "
          PRINT "      PLEASE CHECK AND RE-ENTER COMPOSITE PARAMETERS "
          PRINT "                  HIT RETURN TO CONTINUE "
          INPUT ESTRING$
          PRINT

          IF INPUTOPT = 1 THEN

            GOTO DIMENSIONAL

          ELSEIF INPUTOPT = 2 THEN

            GOTO NONDIMENSIONAL

          END IF

        END IF

SIMPARAMETERS:

        PRINT " COMPOSITE MECHANICAL PROPERTY SIMULATION PARAMETERS "
        PRINT
        PRINT " ENTER THE STRAIN RANGE FOR THE SIMULATION IN PERCENT "
        PRINT "                [minimum, maximum] "
        INPUT eminimum, emaximum
        PRINT

        EMIN = eminimum / 100
        EMAX = emaximum / 100 + .001

        PRINT " ENTER THE STRAIN STEP SIZE FOR THE SIMULATION AS A
PERCENT "
        INPUT strainstep
        PRINT

        DE = strainstep / 100

        PRINT " ENTER THE CONVERGENCE TOLERANCE FOR THE MODEL "
        PRINT "         (SUGGESTED VALUE : 0.000001) "
        INPUT ERRORMAX
        PRINT

        PRINT " ENTER THE MAXIMUM NUMBER OF ITERATIONS TO CONVERGENCE "
        PRINT "              (SUGGESTED VALUE : 50) "
        INPUT IMAX
        PRINT

DIMOUT:
        PRINT " WOULD YOU LIKE TO PROCESS THE OUTPUT DIMENSIONALLY? "
```

```
        PRINT "                          (1) YES    "
        PRINT "                          (2) NO     "
        INPUT OUTOPT
        PRINT

POSTDIM:
        SELECT CASE OUTOPT

          CASE 1

          IF INPUTOPT = 2 THEN

            PRINT " ENTER THE INITIAL OUTER BRAID DIAMETER [MM] "
            INPUT Dbraid0o
            PRINT

              rbraid0 = (Dbraid0o * CONVmmcm / 2) / (1 + (WTR / 2))

            PRINT " ENTER THE YARN MODULUS [Pa] "
            INPUT YarnMod
            PRINT

          END IF

          PRINT " ENTER THE TOTAL LENGTH OF THE COMPOSITE [MM] "
          INPUT RLength
          PRINT

          CRLength = RLength * CONVmmcm

          CASE 2

          CASE ELSE

            GOTO DIMOUT

          END SELECT

VERIFICATION:

        PRINT "              PARAMETER VERIFICATION   "
        PRINT

        IF INPUTOPT = 1 THEN

          CLS

          IF YARNOPT = 1 THEN

            PRINT "  LINEAR ANALYSIS "
            PRINT
```

```
          ELSEIF YARNOPT = 2 THEN

            PRINT "  NONLINEAR ANALYSIS "
            PRINT

          END IF

          PRINT "                    CURRENT DIMENSIONAL PARAMETERS "
          PRINT

          Nc = 8 * PI * YVF * YAR / (WTR ^ 2)

          ppi0 = CONVincm * TAN(THETA0) * YW * YAR / (WTR * rbraid0)

          Dbraid0o = rbraid0 * (2 + WTR) / CONVmmcm

          Dcore0 = 2 * RCB * rbraid0 / CONVmmcm

          PRINT USING "  (1) YARN DENSITY = ##.#### [GM/CM^3] ";
rhobraid
          PRINT USING "  (2) LINEAR YARN DENSITY = #####.## [DENIER] ";
rhoLbraid
          PRINT USING "  (3) YARN MODULUS = ######.### [MPa] "; YarnMod
/ 1000000!
          PRINT USING "  (4) YARN ASPECT RATIO = #.#### "; YAR
          PRINT USING "  (5) YARN PACKING FACTOR = #.#### "; YPF
          PRINT USING "  (6) NUMBER OF YARNS IN BRAID = ###.### "; Nc
          PRINT USING "  (7) INITIAL BRAID DENSITY = ####.### [PICKS PER
INCH] "; ppi0
          PRINT USING "  (8) INITIAL OUTER BRAID DIAMETER = ###.### [MM]
"; Dbraid0o
          PRINT USING "  (9) INITIAL CORE DIAMETER = ###.### [MM] ";
Dcore0
          PRINT USING " (10) CORE MODULUS = ######.### [MPa] "; CoreMod
/ 1000000!
          PRINT USING " (11) CORE POISSON'S RATIO = #.#### "; V
          PRINT USING " (12) CORE PACKING FRACTION = #.#### "; CPF
          PRINT
          PRINT "          ASSOCIATED NONDIMENSIONAL PARAMETERS    "
          PRINT
          PRINT USING "       WALL THICKNESS RATIO = #.#### "; WTR
          PRINT USING "       CORE/INNER BRAID RADIUS RATIO = #.#### ";
CIBR
          PRINT USING "       INITIAL BRAID ANGLE = ###.### DEG "; angle0
          PRINT USING "       INITIAL BRAID COVER FACTOR = #.#### "; F0
          PRINT USING "       CORE/YARN MODULUS RATIO = ###.##### "; RMOD
          PRINT
          PRINT "  IF YOU WISH TO MODIFY ANY OF THE CURRENT DIMENSIONAL
"
```

```
    PRINT " PARAMETERS, PLEASE ENTER THE APPROPRIATE OPTION NUMBER
"
    PRINT " (HIT RETURN IF THE EXISTING PARAMETERS ARE ACCEPTABLE)
"
    INPUT CHECK

  SELECT CASE CHECK

    CASE 0

    CASE 1

    PRINT " ENTER THE YARN DENSITY [GM/CM^3] "
    INPUT rhobraid

    CASE 2

    PRINT " ENTER THE LINEAR DENSITY OF THE YARN [DENIER] "
    INPUT rhoLbraid

    CASE 3

    PRINT " ENTER THE CHARACTERISTIC YARN MODULUS [Pa] "
    INPUT YarnMod

    CASE 4

    PRINT " FOR MODELING PURPOSES, THE YARN CROSS-SECTION IS "
    PRINT "          ASSUMED TO BE RECTANGULAR. "
    PRINT
    PRINT " ENTER THE YARN ASPECT RATIO DEFINED BY "
    PRINT "    ( Yarn Thickness / Yarn Width )          "
    INPUT YAR

    CASE 5

    PRINT " ENTER THE YARN PACKING FACTOR DEFINED BY "
    PRINT "        ( Fiber Volume / Yarn Volume )  "
    PRINT "                RANGE ( 0 - 1 )       "
    INPUT YPF

    CASE 6

    PRINT " ENTER THE NUMBER OF YARNS INCORPORATED IN THE BRAID "
    INPUT Nc

    CASE 7

    PRINT " ENTER THE INITIAL BRAID DENSITY QUANTIFIED BY THE "
    PRINT "              NUMBER OF PICKS PER INCH "
    INPUT ppi0
```

```
          CASE 8

          PRINT " ENTER THE INITIAL OUTER BRAID DIAMETER [MM] "
          INPUT Dbraid0o

          CASE 9

CORECHECK:
          PRINT " IS THE BRAID INITIALLY IN CONTACT WITH THE CORE? "
          PRINT "          (1) YES          "
          PRINT "          (2) NO           "
          INPUT COREOPT

          SELECT CASE COREOPT

          CASE 1

            CIBR = 1

          CASE 2

            PRINT " ENTER THE INITIAL CORE DIAMETER [MM] "
            INPUT Dcore0

          CASE ELSE

          GOTO CORECHECK

          END SELECT

          CASE 10

          PRINT " ENTER THE CORE MODULUS [Pa] "
          INPUT CoreMod

          CASE 11

          PRINT " ENTER POISSON'S RATIO FOR THE CORE "
          INPUT V

          CASE 12

          PRINT " ENTER THE CORE PACKING FACTOR DEFINED BY "
          PRINT "    ( Core Fiber Volume / Core Volume )          "
          PRINT "              RANGE ( 0 - 1 )                 "
          INPUT CPF

          CASE ELSE

          GOTO VERIFICATION
```

```
          END SELECT

          IF (CHECK <> 0) THEN

          '      UNIT CONVERSION AND INITIAL PARAMETER CALCULATIONS

          Ay0 = rhoLbraid / (rhobraid * 9000 * 100 * YPF)

          yarnwidth = SQR(Ay0 / YAR)

          yarnthickness = Ay0 / yarnwidth

          rbraid0 = (Dbraid0o * CONVmmcm / 2) - yarnthickness

          X0 = 2 * PI * rbraid0 / Nc

          Y0 = (1 * CONVincm) / (2 * ppi0)

          THETA0 = ATN(X0 / Y0)

          rbraid0i = rbraid0 - yarnthickness

          IF COREOPT = 1 THEN

            rcore0 = rbraid0i

            Dcore0 = 2 * rcore0

          ELSEIF COREOPT = 2 THEN

            rcore0 = Dcore0 * CONVmmcm / 2

          END IF

          IF rcore0 > rbraid0i THEN

          PRINT " INITIAL PARAMETERS RESULT IN AN IMPOSSIBLE BRAID
GEOMETRY "
          PRINT "  INITIAL CORE RADIUS IS GREATER THAN THE BRAID RADIUS
"
          PRINT "   PLEASE CHECK AND RE-ENTER THE COMPOSITE PARAMETERS "
          PRINT "                  HIT RETURN TO CONTINUE "
          INPUT ESTRING$
          PRINT
          GOTO VERIFICATION

          END IF

          WTR = 2 * yarnthickness / rbraid0
```

```
  CIBR = rcore0 / rbraid0i

  angle0 = THETA0 * 180 / PI

  YVF = Nc * Ay0 / (2 * PI * rbraid0 ^ 2)

  VY0 = YVF / (WTR * COS(THETA0))

  F0 = 1 - (1 - VY0) ^ 2

  RCB = CIBR * (1 - (WTR / 2))

  YT = WTR / 2

  YW = 2 * VY0 * COS(THETA0)

IF (WTR < 0) OR (WTR > 2) THEN
  PRINT "   IMPOSSIBLE WALL THICKNESS RATIO "
  PRINT USING "          WTR = ##.#### "; WTR
  PRINT "       FEASIBLE RANGE ( 0 - 2 )  "
  PRINT " PLEASE CHECK AND RE-ENTER PARAMETERS "
  PRINT "         HIT RETURN TO CONTINUE "
  INPUT ESTRING$
  PRINT
  GOTO VERIFICATION
END IF

IF (CIBR < 0) OR (CIBR > 1) THEN
  PRINT " IMPOSSIBLE CORE/INNER BRAID RADIUS RATIO "
  PRINT USING "               CIBR = ##.#### "; CIBR
  PRINT "          FEASIBLE RANGE ( 0 - 1 )  "
  PRINT "   PLEASE CHECK AND RE-ENTER PARAMETERS "
  PRINT "           HIT RETURN TO CONTINUE "
  INPUT ESTRING$
  PRINT
  GOTO VERIFICATION
END IF

IF (angle0 < 0) OR (angle0 > 90) THEN
  PRINT "     IMPOSSIBLE INITIAL BRAID ANGLE "
  PRINT USING "          INITIAL ANGLE = ###.### "; angle0
  PRINT "      FEASIBLE RANGE ( 0 - 90 deg )  "
  PRINT "   PLEASE CHECK AND RE-ENTER PARAMETERS "
  PRINT "          HIT RETURN TO CONTINUE "
  INPUT ESTRING$
  PRINT
  GOTO VERIFICATION
END IF


IF (VY0 < 0) OR (VY0 > 1) THEN
```

```
    PRINT " IMPOSSIBLE BRAID YARN VOLUME FRACTION "
    PRINT USING "       VOLUME FRACTION = ##.#### "; VY0
    PRINT "        FEASIBLE RANGE ( 0 - 1 )  "
    PRINT "  PLEASE CHECK AND RE-ENTER PARAMETERS "
    PRINT "         HIT RETURN TO CONTINUE "
    INPUT ESTRING$
    PRINT
    GOTO VERIFICATION
  END IF

  IF (F0 < 0) OR (F0 > 1) THEN
    PRINT "  IMPOSSIBLE INITIAL BRAID COVER FACTOR "
    PRINT USING "         COVER FACTOR = ##.#### "; F0
    PRINT "        FEASIBLE RANGE ( 0 - 1 )  "
    PRINT "  PLEASE CHECK AND RE-ENTER PARAMETERS "
    PRINT "         HIT RETURN TO CONTINUE "
    INPUT ESTRING$
    PRINT
    GOTO VERIFICATION
  END IF

    GOTO VERIFICATION

    END IF

  ELSEIF (INPUTOPT = 2) THEN

    CLS

    IF YARNOPT = 1 THEN

      PRINT "  LINEAR ANALYSIS "
      PRINT

    ELSEIF YARNOPT = 2 THEN

      PRINT "  NONLINEAR ANALYSIS "
      PRINT

    END IF

    PRINT "           CURRENT NONDIMENSIONAL PARAMETERS    "
    PRINT
    PRINT USING "  (1) WALL THICKNESS RATIO = #.#### "; WTR
    PRINT USING "  (2) CORE/INNER BRAID RADIUS RATIO = #.#### ";
CIBR
    PRINT USING "  (3) YARN ASPECT RATIO = #.#### "; YAR
    PRINT USING "  (4) YARN PACKING FACTOR = #.#### "; YPF
    PRINT USING "  (5) CORE PACKING FRACTION = #.#### "; CPF
    PRINT USING "  (6) INITIAL BRAID ANGLE = ###.### DEG "; angle0
    PRINT USING "  (7) INITIAL BRAID COVER FACTOR = #.#### "; F0
```

```
          PRINT USING "  (8) CORE/YARN MODULUS RATIO = ###.##### "; RMOD
          PRINT USING "  (9) CORE POISSON'S RATIO = #.#### "; V
          PRINT

          Nc = 8 * PI * YVF * YAR / (WTR ^ 2)

          IF (OUTOPT = 1) THEN

          ppi0 = CONVincm * TAN(THETA0) * YW * YAR / (WTR * rbraid0)

          Dbraid0o = rbraid0 * (2 + WTR) / CONVmmcm

          Dcore0 = 2 * RCB * rbraid0 / CONVmmcm

          CoreMod = RMOD * YarnMod

          END IF

          PRINT "              ASSOCIATED DIMENSIONAL PARAMETERS "
          PRINT

          PRINT USING "      NUMBER OF YARNS IN BRAID = ###.### "; Nc

          IF (OUTOPT = 1) THEN

          PRINT USING "      YARN MODULUS = ######.### [MPa] "; YarnMod
/ 1000000!
          PRINT USING "      INITIAL BRAID DENSITY = ####.### [PICKS PER
INCH] "; ppi0
          PRINT USING "      INITIAL OUTER BRAID DIAMETER = ###.### [MM]
"; Dbraid0o
          PRINT USING "      INITIAL CORE DIAMETER = ###.### [MM] ";
Dcore0
          PRINT USING "      CORE MODULUS = ######.### [MPa] "; CoreMod
/ 1000000!

          END IF

          PRINT
          PRINT " IF YOU WISH TO MODIFY ANY OF THE CURRENT
NONDIMENSIONAL "
          PRINT "  PARAMETERS, PLEASE ENTER THE APPROPRIATE OPTION
NUMBER "
          PRINT "  (HIT RETURN IF THE EXISTING PARAMETERS ARE
ACCEPTABLE) "
          INPUT CHECK

        SELECT CASE CHECK

          CASE 0
```

```
          CASE 1

          PRINT " ENTER THE INITIAL WALL THICKNESS RATIO DEFINED BY "
          PRINT "    ( 2 * Yarn Thickness / Mean Braid Radius )  "
          PRINT "                  RANGE ( 0 - 2 )      "
          INPUT WTR

          CASE 2

          PRINT "   ENTER THE INITIAL CORE/INNER BRAID RADIUS RATIO
DEFINED BY "
          PRINT "      Core Radius / ( Mean Braid Radius - Yarn
Thickness ) "
          PRINT "                       RANGE ( 0 - 1 )"
          INPUT CIBR

          CASE 3

          PRINT " ENTER THE YARN ASPECT RATIO DEFINED BY "
          PRINT "    ( Yarn Thickness / Yarn Width )   "
          INPUT YAR

          CASE 4

          PRINT " ENTER THE INITIAL YARN PACKING FACTOR DEFINED BY "
          PRINT "          ( Fiber Volume / Yarn Volume )   "
          PRINT "                RANGE ( 0 - 1 )       "
          INPUT YPF

          CASE 5

          PRINT " ENTER THE CORE PACKING FACTOR DEFINED BY "
          PRINT "   ( Core Fiber Volume / Core Volume ) "
          PRINT "             RANGE ( 0 - 1 ) "
          INPUT CPF

          CASE 6

          PRINT " ENTER THE INITIAL BRAID ANGLE IN DEGREES "
          INPUT angle0

          CASE 7

          PRINT " ENTER THE INITIAL BRAID COVER FACTOR DEFINED BY "
          PRINT "    THE FRACTION OF THE PROJECTED BRAID AREA  "
          PRINT "              COVERED BY THE YARN "
          PRINT "                RANGE ( 0 - 1 )  "
          INPUT F0

          CASE 8
```

```
PRINT " ENTER THE MODULUS RATIO DEFINED BY "
PRINT "  ( Core Modulus / Yarn Modulus )  "
INPUT RMOD

CASE 9

PRINT " ENTER POISSON'S RATIO FOR THE CORE "
INPUT V

CASE ELSE

GOTO VERIFICATION

END SELECT

IF (CHECK <> 0) THEN

'                  PARAMETER CONVERSION

THETA0 = angle0 * PI / 180

RCB = CIBR * (1 - (WTR / 2))

YT = WTR / 2

VY0 = 1 - SQR(1 - F0)

YVF = VY0 * WTR * COS(THETA0)

YW = 2 * VY0 * COS(THETA0)

A = (1 + (1 / (TAN(THETA0)) ^ 2)) * ((1 + EY) ^ 2) / (YW ^ 2)


'                   CHECK PARAMETER FEASIBILITY
IF A < 1 THEN

  PRINT "     IMPOSSIBLE GEOMETRIC CONFIGURATION  "
  PRINT "    YARN WIDTH EXCEEDS UNIT BRAID LENGTH "
  PRINT " PLEASE CHECK AND RE-ENTER MODEL PARAMETERS "
  PRINT "            HIT RETURN TO CONTINUE "
  INPUT ESTRING$
  PRINT
  GOTO VERIFICATION

END IF

THETALOCK1 = ATN(SQR(A) - SQR(A - 1))

THETALOCK2 = ATN(1 / (SQR(A) - SQR(A - 1)))
```

```
        IF THETALOCK1 <= THETALOCK2 THEN

          THETALOCKMIN = THETALOCK1
          THETALOCKMAX = THETALOCK2

        ELSEIF THETALOCK1 > THETALOCK2 THEN

          THETALOCKMIN = THETALOCK2
          THETALOCKMAX = THETALOCK1

        END IF

        CHECK = RCB + WTR / 2

        IF CHECK > 1 THEN

          PRINT " CORE RADIUS AND WALL THICKNESS EXCEED MEAN COMPOSITE
RADIUS "
          PRINT "          PLEASE CHECK AND RE-ENTER MODEL PARAMETERS "
          PRINT "                    HIT RETURN TO CONTINUE "
          INPUT ESTRING$
          PRINT
          GOTO VERIFICATION

        END IF

        IF (THETA0 < THETALOCKMIN) OR (THETA0 > THETALOCKMAX) THEN

          PRINT " INITIAL PARAMETERS RESULT IN AN IMPOSSIBLE BRAID
GEOMETRY "
          PRINT "              BRAID IS BEYOND LOCKING POINT "
          PRINT "      PLEASE CHECK AND RE-ENTER COMPOSITE PARAMETERS
"
          PRINT "                   HIT RETURN TO CONTINUE "
          INPUT ESTRING$
          PRINT
          GOTO VERIFICATION

        END IF

      IF (WTR < 0) OR (WTR > 2) THEN
        PRINT "   IMPOSSIBLE WALL THICKNESS RATIO "
        PRINT USING "         WTR = ##.#### "; WTR
        PRINT "       FEASIBLE RANGE ( 0 - 2 )  "
        PRINT " PLEASE CHECK AND RE-ENTER PARAMETERS "
        PRINT "        HIT RETURN TO CONTINUE "
        INPUT ESTRING$
        PRINT
        GOTO VERIFICATION
      END IF
```

```
IF (CIBR < 0) OR (CIBR > 1) THEN
  PRINT " IMPOSSIBLE CORE/INNER BRAID RADIUS RATIO "
  PRINT USING "              CIBR = ##.#### "; CIBR
  PRINT "          FEASIBLE RANGE ( 0 - 1 )  "
  PRINT "   PLEASE CHECK AND RE-ENTER PARAMETERS "
  PRINT "           HIT RETURN TO CONTINUE "
  INPUT ESTRING$
  PRINT
  GOTO VERIFICATION
END IF

IF (angle0 < 0) OR (angle0 > 90) THEN
  PRINT "     IMPOSSIBLE INITIAL BRAID ANGLE "
  PRINT USING "          INITIAL ANGLE = ###.### "; angle0
  PRINT "      FEASIBLE RANGE ( 0 - 90 deg )  "
  PRINT "   PLEASE CHECK AND RE-ENTER PARAMETERS "
  PRINT "          HIT RETURN TO CONTINUE "
  INPUT ESTRING$
  PRINT
  GOTO VERIFICATION
END IF

IF (VY0 < 0) OR (VY0 > 1) THEN
  PRINT " IMPOSSIBLE BRAID YARN VOLUME FRACTION "
  PRINT USING "       VOLUME FRACTION = ##.#### "; VY0
  PRINT "         FEASIBLE RANGE ( 0 - 1 )  "
  PRINT "  PLEASE CHECK AND RE-ENTER PARAMETERS "
  PRINT "          HIT RETURN TO CONTINUE "
  INPUT ESTRING$
  PRINT
  GOTO VERIFICATION
END IF

IF (F0 < 0) OR (F0 > 1) THEN
  PRINT "  IMPOSSIBLE INITIAL BRAID COVER FACTOR "
  PRINT USING "          COVER FACTOR = ##.#### "; F0
  PRINT "        FEASIBLE RANGE ( 0 - 1 )  "
  PRINT "  PLEASE CHECK AND RE-ENTER PARAMETERS "
  PRINT "          HIT RETURN TO CONTINUE "
  INPUT ESTRING$
  PRINT
  GOTO VERIFICATION
END IF

  IF OUTOPT = 1 THEN

    GOTO POSTDIM

  ELSEIF OUTOPT = 2 THEN

    GOTO DIMOUT
```

```
          END IF

          END IF


          END IF


        STEPS = ((EMAX - EMIN) / DE) + 1

'                       OPEN DATA FILE FOR OUTPUT

        OPEN "C:\THESIS\GEO.DAT" FOR OUTPUT AS #3

        OPEN "C:\THESIS\FORCE.DAT" FOR OUTPUT AS #4

        PRINT #3, "   EZ     ER     EY    THETA  LOCK   COVER  RBRAIDI
RCORE     GAP "
        PRINT #3,
        PRINT #4, "   EZ   MODE       TCORE          TBRAID         TCOMP
EYCORR "
        PRINT #4,

        CLOSE #3

        CLOSE #4

        IF OUTOPT = 1 THEN

          OPEN "C:\THESIS\DIMOUT.DAT" FOR OUTPUT AS #5

          PRINT #5, "   DISP  MODE    RBRAIDI      RCORE         TCORE
TBRAID       TCOMP      "
          PRINT #5, "    (mm)            (mm)        (mm)          (N)
(N)          (N)       "
          PRINT #5,

          CLOSE #5

        END IF
```

```
'                                   PROCESSOR

'                          MECHANICAL PROPERTY SIMULATION

'                              INITIAL MODE EVALUATION

        IF (CIBR < 1) AND (THETA0 > THETALOCKMIN) THEN MODE = 1
        IF (CIBR = 1) AND (THETA0 > THETALOCKMIN) THEN MODE = 2
        IF (CIBR = 1) AND (THETA0 = THETALOCKMIN) THEN MODE = 3
        IF (CIBR < 1) AND (THETA0 = THETALOCKMIN) THEN MODE = 4

'       INITIALIZE NONLINEAR YARN STRAIN CORRECTION FACTOR

        EYCORR = 1

        FAIL = 0

        TRANSITION = 0

        FOR EZ = EMIN TO EMAX STEP DE

        PRINT USING " AXIAL STRAIN = ####.## % "; EZ * 100


SIMULATION:

       SELECT CASE MODE

       CASE 1

        '   MODE 1 - THE BRAID IS OPEN AND NOT IN CONTACT WITH THE CORE

        PRINT "  MODE  1 "

        EY = 0

        THETA = ATN(SQR((((TAN(THETA0)) ^ 2) + 1) * ((1 / (1 + EZ)) ^ 2)
- 1))

        A = (1 + (1 / (TAN(THETA0)) ^ 2)) * ((1 + EY) ^ 2) / (YW ^ 2)

        THETALOCK1 = ATN(SQR(A) - SQR(A - 1))

        THETALOCK2 = ATN(1 / (SQR(A) - SQR(A - 1)))

        IF THETALOCK1 <= THETALOCK2 THEN

          THETALOCK = THETALOCK1

        ELSEIF THETALOCK1 > THETALOCK2 THEN
```

```
          THETALOCK = THETALOCK2

        END IF

        RBRAID = SQR(1 - (2 * EZ + EZ ^ 2) / ((TAN(THETA0)) ^ 2))

        RBRAIDI = RBRAID - YT

        ER = -1 * V * EZ

        RCORE = RCB * (1 + ER)

        IF (THETA > THETALOCK) AND (RBRAIDI > RCORE) THEN

          MODE = 1

        ELSEIF (THETA > THETALOCK) AND (RBRAIDI <= RCORE) THEN

          MODE = 2
          GOTO SIMULATION

        ELSEIF (THETA <= THETALOCK) AND (RBRAIDI <= RCORE) THEN

          MODE = 3
          GOTO SIMULATION

        ELSEIF (THETA <= THETALOCK) AND (RBRAIDI > RCORE) THEN

          MODE = 4
          GOTO SIMULATION

        END IF


       CASE 2

        INDEX = 0

'       MODE 2 - BRAID IS OPEN BUT IN CONTACT WITH THE CORE

'       GUESS YARN STRAIN


        PRINT "    MODE 2  "

ITERATION:

        THETA = ATN(SQR(ABS((((TAN(THETA0)) ^ 2) + 1) * (((1 + EY) / (1
+ EZ)) ^ 2) - 1)))

        A = (1 + (1 / (TAN(THETA0)) ^ 2)) * ((1 + EY) ^ 2) / (YW ^ 2)
```

```
        THETALOCK1 = ATN(SQR(A) - SQR(A - 1))

        THETALOCK2 = ATN(1 / (SQR(A) - SQR(A - 1)))

        IF THETALOCK1 <= THETALOCK2 THEN

          THETALOCK = THETALOCK1

        ELSEIF THETALOCK1 > THETALOCK2 THEN

          THETALOCK = THETALOCK2

        END IF

        RBRAID = SQR(ABS((1 + EY) ^ 2 + (((1 + EY) ^ 2 - (1 + EZ) ^ 2) /
((TAN(THETA0)) ^ 2))))

        XSCALE = RBRAID

        YSCALE = (1 + EZ) / TAN(THETA0)

        LSCALE = SQR(XSCALE ^ 2 + YSCALE ^ 2)


'                                EQUILIBRIUM ANALYSIS

        IF (YARNOPT = 2) AND (EY <> 0) THEN

          EYCORR = PROPERTY(EY, EYDAT(), SIGYDAT(), NDATA, FLAG, FAIL) /
(EY * YarnMod)

        END IF

        TY = YPF * EY * EYCORR

        PRESSURE = TY * TAN(THETA) / (RBRAID * LSCALE)

        SIGMAR = -1 * PRESSURE

        ER = SIGMAR * YVF * (1 + V) * (1 - 2 * V) / RMOD - V * EZ

        RCORE = RCB * (1 + ER)

        RBRAIDI = RBRAID - YT

        RERROR = ABS(RBRAIDI - RCORE)

        IF RERROR > ERRORMAX THEN

          IF RCORE = RCOREOLD THEN
```

```
            SCALE = 1

          ELSEIF RCORE <> RCOREOLD THEN

            RBDIF = RBRAIDI - RBRAIDIOLD

            RCDIF = RCORE - RCOREOLD

            SCALE = ABS(RBDIF / RCDIF)

          END IF

          RBRAIDINEW = ABS((RCORE * SCALE + RBRAIDI) / (1 + SCALE))

          RBRAIDIOLD = RBRAIDI

          RCOREOLD = RCORE

          XSCALE = RBRAIDINEW + YT

          EY = ABS(SQR((XSCALE ^ 2 + YSCALE ^ 2) / (1 + (1 /
TAN(THETA0)) ^ 2)) - 1)

          INDEX = INDEX + 1

          IF INDEX > IMAX THEN

            PRINT IMAX, " ITERATIONS : NO CONVERGENCE IN MODE 2 "
            PRINT
            PRINT "                MOVING INTO MODE 3"
            MODE = 3
            GOTO SIMULATION

          END IF

          GOTO ITERATION

        END IF

'                    CHECK TO INSURE MODE 2 OPERATION

        IF (THETA > THETALOCK) AND (RERROR <= ERRORMAX) THEN

          MODE = 2

        ELSEIF (THETA <= THETALOCK) AND (RBRAIDI <= RCORE) THEN

          MODE = 3
          GOTO SIMULATION
```

```
        ELSEIF (THETA <= THETALOCK) AND (RBRAIDI > RCORE) THEN

          MODE = 4
          GOTO SIMULATION

        END IF

       CASE 3, 4

'       MODE 3 - BRAID IS JAMMED AND IN CONTACT WITH THE CORE

'       MODE 4 - BRAID IS JAMMED BUT NOT IN CONTACT WITH THE CORE

        PRINT "      MODES 3 AND 4  "

        THETA1 = ATN(YW / (2 * SQR((((1 + EZ) / TAN(THETA0)) ^ 2) - (YW
/ 2) ^ 2)))

        THETA2 = ATN((2 * SQR((((1 + EZ) / TAN(THETA0)) ^ 2) - (YW / 2)
^ 2)) / YW)

        IF THETA1 <= THETA2 THEN

          THETA = THETA1

        ELSEIF THETA1 > THETA2 THEN

          THETA = THETA2

        END IF

        THETALOCK = THETA

        YSCALE = (1 + EZ) / TAN(THETA0)

        XSCALE = YW / (2 * (SQR(1 - (YW * TAN(THETA0) / (2 * (1 + EZ)))
^ 2)))

        LSCALE = SQR(XSCALE ^ 2 + YSCALE ^ 2)

        EY = LSCALE / SQR(1 + 1 / ((TAN(THETA0)) ^ 2)) - 1

        RBRAID = XSCALE

        RBRAIDI = RBRAID - YT

        RCORE = RCB * (1 - V * EZ)

        IF RCORE >= RBRAIDI THEN
```

```
    RCORE = RBRAIDI
    ER = RCORE / RCB - 1
    MODE = 3
    PRINT "      MODE 3   "

  ELSEIF RCORE < RBRAIDI THEN

    ER = -1 * V * EZ
    MODE = 4
    PRINT "        MODE 4   "

  END IF

'                 CHECK TO INSURE MODE 3 OR 4 OPERATION

  IF (THETA <> THETALOCK) AND (RBRAIDI > RCORE) THEN

    MODE = 1
    GOTO SIMULATION

  ELSEIF (THETA <> THETALOCK) AND (RBRAIDI <= RCORE) THEN

    MODE = 2
    GOTO SIMULATION

  END IF

END SELECT
```

```
                                POSTPROCESSOR

'                               OUTPUT TO DATA FILES

        IF (YARNOPT = 2) AND (EY <> 0) THEN

          YARNSIG = PROPERTY(EY, EYDAT(), SIGYDAT(), NDATA, FLAG, FAIL)

          EYCORR = YARNSIG / (EY * YarnMod)

          IF (EY > EYDAT(NDATA)) THEN

           IF (FLAG = 1) THEN

           PRINT " YARN FAILURE - SIMULATION TERMINATED "
           PRINT

           FAIL = 1

           END IF

          IF (FAIL = 0) AND (FLAG = 2) THEN

           PRINT " YARN FAILURE - SIMULATION WILL PROCEED IGNORING
FAILURE "
           PRINT

           FAIL = 1

         END IF

           END IF

        IF (YARNSIG = 0) AND (EY > 0) THEN

           FAILSTRAIN = EZ

           IF (FLAG = 1) THEN

           PRINT " YARN FAILURE - SIMULATION TERMINATED "
           PRINT

           END IF

           IF (FAIL = 0) AND (FLAG = 2) THEN

           PRINT " YARN FAILURE - SIMULATION WILL PROCEED IGNORING
FAILURE "
           PRINT

           END IF
```

```
            FAIL = 1

          END IF

        END IF

        IF TRANSITION <> FAIL THEN

          FAILSTRAIN = EZ

        END IF

        TRANSITION = FAIL

        IF (FLAG = 1) AND (FAIL = 1) THEN GOTO TERMINATION

        TY = YPF * EY * EYCORR

        ETHETA = ER

        VY = VY0 * COS(THETA0) / (COS(THETA) * RBRAID)

        COVER = 1 - (1 - VY) ^ 2

        TCORE = RMOD * (CPF * (RCB ^ 2) / (2 * YVF)) * ((1 - V) * EZ + 2
* V * ER) / ((1 + V) * (1 - 2 * V))

        TBRAID = TY * COS(THETA)

        TCOMP = TCORE + TBRAID

        GAP = RBRAIDI - RCORE

        OPEN "C:\THESIS\GEO.DAT" FOR APPEND AS #3

        PRINT #3, USING " ###.##"; EZ * 100;
        PRINT #3, USING " ###.##"; ER * 100;
        PRINT #3, USING " ###.##"; EY * 100;
        PRINT #3, USING " ###.##"; THETA * 180 / PI;
        PRINT #3, USING " ###.##"; THETALOCK * 180 / PI;
        PRINT #3, USING " ##.###"; COVER;
        PRINT #3, USING "  #.####"; RBRAIDI;
        PRINT #3, USING "   #.####"; RCORE;
        PRINT #3, USING "  #.####"; GAP

        CLOSE #3

        OPEN "C:\THESIS\FORCE.DAT" FOR APPEND AS #4
        PRINT #4, USING " ###.##"; EZ * 100;
        PRINT #4, USING "   #"; MODE;
```

```
        PRINT #4, USING "  #######.####"; TCORE;
        PRINT #4, USING "  #######.####"; TBRAID;
        PRINT #4, USING "  #######.####"; TCOMP;
        PRINT #4, USING "       #.#####"; EYCORR

        CLOSE #4


        IF OUTOPT = 1 THEN

          ForceND = 2 * YVF * PI * rbraid0 ^ 2 * YarnMod / (CONVmcm ^ 2)

          RbraidiDIM = RBRAIDI * rbraid0 / CONVmmcm

          RcoreDIM = RCORE * rbraid0 / CONVmmcm

          TcoreDIM = TCORE * ForceND

          TbraidDIM = TBRAID * ForceND

          TcompDIM = TCOMP * ForceND

          Disp = EZ * CRLength / CONVmmcm

        OPEN "C:\THESIS\DIMOUT.DAT" FOR APPEND AS #5

        PRINT #5, USING " ###.##"; Disp;
        PRINT #5, USING "   #"; MODE;
        PRINT #5, USING "  #####.####"; RbraidiDIM;
        PRINT #5, USING "  #####.####"; RcoreDIM;
        PRINT #5, USING "  ########.##"; TcoreDIM;
        PRINT #5, USING "  ########.##"; TbraidDIM;
        PRINT #5, USING "  ########.##"; TcompDIM

        CLOSE #5

        END IF


        NEXT EZ

TERMINATION:

        PRINT " ENTER THE CURRENT DATE "
        INPUT CURRENTDATE$

        PRINT " ENTER A BRIEF MODEL DESCRIPTION "
        INPUT DESCRIPTION$

        IF OUTOPT = 1 THEN
```

```
 PRINT " ENTER THE OUTPUT COMPOSITE TENSION FILENAME "
 PRINT "  INCLUDE DRIVE DESIGNATION "
 INPUT OUTPLOT$

 DO2$ = " COPY C:\THESIS\DIMOUT.DAT " + OUTPLOT$

 SHELL DO2$

END IF

PRINT " WOULD YOU LIKE TO SAVE THE NONDIMENSIONAL OUTPUT DATA? "
PRINT "                    (1) YES "
PRINT "                    (2) NO  "
INPUT SAVEOPT
PRINT

IF SAVEOPT = 1 THEN

  PRINT " SPECIFY THE OUTPUT DRIVE DESIGNATION AND FILENAME "
  PRINT "    FOR THE NONDIMENSIONAL GEOMETRIC PARAMETERS "
  INPUT GEOFILE$
  PRINT

  DO3$ = " COPY C:\THESIS\GEO.DAT " + GEOFILE$

  PRINT " SPECIFY THE OUTPUT DRIVE DESIGNATION AND FILENAME "
  PRINT "     FOR THE NONDIMENSIONAL FORCE PARAMETERS "
  INPUT FORCEFILE$
  PRINT

  DO4$ = " COPY C:\THESIS\FORCE.DAT " + FORCEFILE$

  SHELL DO3$

  SHELL DO4$

END IF

OPEN "C:\THESIS\PARAMTR.DAT" FOR OUTPUT AS #8

  PRINT #8, "                  MODEL PARAMETER SUMMARY    "
  PRINT #8,
  PRINT #8, "                      DATE : "; CURRENTDATE$
  PRINT #8,
  PRINT #8, "         MODEL DESCRIPTION : "; DESCRIPTION$
  PRINT #8,
  PRINT #8, "          OUTPUT FILE NAME : "; OUTPLOT$
  PRINT #8,

  IF YARNOPT = 1 THEN
```

```
    PRINT #8, "  LINEAR ANALYSIS "
    PRINT #8,

  ELSEIF YARNOPT = 2 THEN

    PRINT #8, "  NONLINEAR ANALYSIS "
    PRINT #8,
    PRINT #8, USING "  YARN PROPERTY FILENAME : & "; DATAFILE$
    PRINT #8,

  END IF

  PRINT #8, "                  NONDIMENSIONAL PARAMETERS    "
  PRINT #8,
  PRINT #8, USING "  WALL THICKNESS RATIO = #.#### "; WTR
  PRINT #8,
  PRINT #8, USING "  CORE/INNER BRAID RADIUS RATIO = #.#### ";
CIBR
  PRINT #8,
  PRINT #8, USING "  YARN ASPECT RATIO = #.#### "; YAR
  PRINT #8,
  PRINT #8, USING "  YARN PACKING FACTOR = #.#### "; YPF
  PRINT #8,
  PRINT #8, USING "  CORE PACKING FACTOR = #.#### "; CPF
  PRINT #8,
  PRINT #8, USING "  INITIAL BRAID ANGLE = ###.### DEG "; angle0
  PRINT #8,
  PRINT #8, USING "  INITIAL BRAID COVER FACTOR = #.#### "; F0
  PRINT #8,
  PRINT #8, USING "  CORE/YARN MODULUS RATIO = ###.##### "; RMOD
  PRINT #8,
  PRINT #8, USING "  CORE POISSON'S RATIO = #.#### "; V
  PRINT #8,

  Nc = 8 * PI * YVF * YAR / (WTR ^ 2)

  PRINT #8, "                  DIMENSIONAL PARAMETERS     "
  PRINT #8,
  PRINT #8, USING "  NUMBER OF YARNS IN BRAID = ###.### "; Nc
  PRINT #8,

  IF OUTOPT = 1 THEN

   ppi0 = CONVincm * TAN(THETA0) * YW * YAR / (WTR * rbraid0)

   Dbraid0o = rbraid0 * (2 + WTR) / CONVmmcm

   Dcore0 = 2 * RCB * rbraid0 / CONVmmcm

   CoreMod = RMOD * YarnMod
```

```
            IF INPUTOPT = 1 THEN

              PRINT #8, USING "  YARN DENSITY = ##.#### [GM/CM^3] ";
rhobraid
              PRINT #8,
              PRINT #8, USING "  LINEAR YARN DENSITY = #####.## [DENIER]
"; rhoLbraid
              PRINT #8,

            END IF

            PRINT #8, USING "  YARN MODULUS = ######.### [MPa] "; YarnMod
/ 1000000!
            PRINT #8,
            PRINT #8, USING "  INITIAL BRAID DENSITY = ####.### [PICKS
PER INCH] "; ppi0
            PRINT #8,
            PRINT #8, USING "  INITIAL OUTER BRAID DIAMETER = ###.###
[MM] "; Dbraid0o
            PRINT #8,
            PRINT #8, USING "  INITIAL CORE DIAMETER = ###.### [MM] ";
Dcore0
            PRINT #8,
            PRINT #8, USING "  CORE MODULUS = ######.### [MPa] "; CoreMod
/ 1000000!
            PRINT #8,

         END IF

            IF FAIL = 1 THEN
              PRINT #8,
              PRINT #8, USING "  YARN FAILURE AT ###.## % AXIAL STRAIN ";
FAILSTRAIN * 100
              PRINT #8,
            END IF

            IF FAIL = 0 THEN
              PRINT #8,
              PRINT #8, USING "  NO YARN FAILURE AT ###.## % AXIAL STRAIN
"; emaximum
              PRINT #8,
            END IF

         CLOSE #8

         DO1$ = " COPY C:\THESIS\PARAMTR.DAT A:*." + TRIAL$
         SHELL DO1$

         PRINT " WOULD YOU LIKE TO RESTART THE PROGRAM? "
         PRINT "                (1) YES  "
         PRINT "                (2) NO   "
```

```
        INPUT REPEAT

        IF REPEAT = 1 THEN

         FAIL = 0
         TRANSITION = 0

         PRINT " PLEASE DESIGNATE THE NEW CASE NUMBER BY ENTERING A "
         PRINT "  THREE DIGIT NUMBER WITH LEADING ZEROS.  IF THE CASE IS
"
         PRINT "  NOT TO BE SAVED, ENTER 000. "
         INPUT TRIAL$
         PRINT

REPEATOPT:

         PRINT " WOULD YOU LIKE TO: "
         PRINT " (1) MODIFY THE MODEL PARAMETERS WITHOUT CHANGING THE "
         PRINT "       SIMULATION RANGE OR CONVERGENCE PARAMETERS "
         PRINT " (2) MODIFY THE SIMULATION RANGE AND CONVERGENCE
PARAMETERS "
         PRINT " (3) RESTART THE PROGRAM COMPLETELY "
         PRINT
         PRINT " PLEASE ENTER THE APPROPRIATE OPTION NUMBER "
         INPUT STARTOPT
         PRINT

         IF STARTOPT = 1 THEN

           GOTO VERIFICATION

         ELSEIF STARTOPT = 2 THEN

           GOTO SIMPARAMETERS

         ELSEIF STARTOPT = 3 THEN

           GOTO START

         END IF

         GOTO REPEATOPT


        END IF


        END
```

```
SUB INSTRUCTIONS

'       THIS SUBROUTINE IDENTIFIES AND DESCRIBES THE INPUT AND OUTPUT
'        FILES THAT ACCOMPANY THIS PROGRAM

'       INPUT FILES

'        YARN STRAIN [Dimensionless] - STRESS [Pa] CHARACTERISTICS -
'                        FILENAME DEFINED BY USER

'       OUTPUT FILES

'        DIMENSIONLESS GEOMETRIC PARAMETERS - C:\THESIS\GEO.DAT

'        DIMENSIONLESS FORCE PARAMETERS - C:\THESIS\FORCE.DAT

'        DIMENSIONAL PARAMETERS - C:\THESIS\DIMOUT.DAT


END SUB
```

```
      FUNCTION PROPERTY (XP, X(), Y(), NDATA, FLAG, FAIL)
        ' LINEAR INTERPOLATION FOR MATERIAL PROPERTY
        FOR I = 1 TO NDATA
          IF XP < X(I) THEN GOTO INTERPOLATION
        NEXT I
INTERPOLATION:
        IF I <= 1 THEN
          J = I + 1
        ELSEIF I > 1 THEN
          J = I - 1
        END IF

        X1 = X(J)
        X2 = X(I)
        Y1 = Y(J)
        Y2 = Y(I)
        PROPERTY = Y1 + ((Y2 - Y1) * (XP - X1) / (X2 - X1))
END FUNCTION
```

Appendix B

Appendix B

This appendix summarizes the cases designed to explore and assess the influence of various model parameters. Each summary was generated by the simulation program. The summaries include the date that the file was created, a brief description, and the case number designation. The nondimensional parameters that characterize the composite are then listed followed by the associated dimensional parameters.

MODEL PARAMETER SUMMARY

DATE : 04/29/91

MODEL DESCRIPTION : COMPOSITE WITHOUT CORE

CASE NUMBER : 002

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.0000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 0.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.00000

CORE POISSON'S RATIO = 0.0000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 0.000 [MM]

CORE MODULUS = 0.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 04/29/91

MODEL DESCRIPTION : INITIAL BRAID ANGLE = 30 DEGREES

CASE NUMBER : 003

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 30.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 22.509

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 11.820 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 04/29/91

MODEL DESCRIPTION : INITIAL BRAID ANGLE = 70 DEGREES

CASE NUMBER : 004

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 70.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 8.890

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 22.215 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 04/29/91

MODEL DESCRIPTION : CORE POISSON'S RATIO = 0.000

CASE NUMBER : 005

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.0000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 04/29/91

MODEL DESCRIPTION : CORE POISSON'S RATIO = 0.450

CASE NUMBER : 006

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.4500

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 04/29/91

MODEL DESCRIPTION : CORE POISSON'S RATIO = 0.490

CASE NUMBER : 007

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.4900

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 04/29/91

MODEL DESCRIPTION : CORE POISSON'S RATIO = 0.495

CASE NUMBER : 008

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.4950

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : INITIAL COVER FACTOR = 0.05

CASE NUMBER : 009

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.0500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 0.545

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 0.591 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : INITIAL COVER FACTOR = 0.25

CASE NUMBER : 010

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.2500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 2.883

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 3.125 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : INITIAL COVER FACTOR = 0.50

CASE NUMBER : 011

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.5000

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 6.303

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 6.832 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : INITIAL COVER FACTOR = 0.75

CASE NUMBER : 012

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.7500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 10.759

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 11.663 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : INITIAL COVER FACTOR = 1.00

CASE NUMBER : 013

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 1.0000

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 21.518

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 23.326 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : INITIAL COVER FACTOR = 0.99

CASE NUMBER : 014

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9900

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 19.367

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 20.993 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : YARN ASPECT RATIO = 0.25

CASE NUMBER : 015

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.2500

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 12.543

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 13.596 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : YARN ASPECT RATIO = 0.50

CASE NUMBER : 016

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.5000

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 25.085

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 27.192 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : YARN ASPECT RATIO = 1.0

CASE NUMBER : 017

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 1.0000

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 50.171

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 54.384 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : YARN PACKING FACTOR = 0.25

CASE NUMBER : 018

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 0.2500

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : YARN PACKING FACTOR = 0.50

CASE NUMBER : 019

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 0.5000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : YARN PACKING FACTOR = 0.75

CASE NUMBER : 020

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 0.7500

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : CORE PACKING FACTOR = 0.25

CASE NUMBER : 021

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 0.2500

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : CORE PACKING FACTOR = 0.50

CASE NUMBER : 022

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 0.5000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : CORE PACKING FACTOR = 0.75

CASE NUMBER : 023

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 0.7500

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : CORE/YARN MODULUS RATIO = 0.000

CASE NUMBER : 024

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.0000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 0.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.00000

CORE POISSON'S RATIO = 0.0000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 0.000 [MM]

CORE MODULUS = 0.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : CORE/YARN MODULUS RATIO = 0.050

CASE NUMBER : 025

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.05000

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 250.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : CORE/YARN MODULUS RATIO = 0.250

CASE NUMBER : 026

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.25000

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 1250.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : CORE/YARN MODULUS RATIO = 0.500

CASE NUMBER : 027

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.50000

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 2500.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : CORE/YARN MODULUS RATIO = 1.000

CASE NUMBER : 028

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 1.00000

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.111 [MM]

CORE MODULUS = 5000.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : CORE/INNER BRAID RADIUS RATIO = 0.40

CASE NUMBER : 029

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 0.4000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 1.556 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : CORE/INNER BRAID RADIUS RATIO = 1.00

CASE NUMBER : 030

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.2500

CORE/INNER BRAID RADIUS RATIO = 1.0000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 16.707

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 18.110 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.889 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : WALL THICKNESS RATIO = 0.100

CASE NUMBER : 031

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.1000

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 41.767

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 42.256 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 3.619 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : WALL THICKNESS RATIO = 0.500

CASE NUMBER : 032

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.5000

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 8.353

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 10.061 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 2.400 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : WALL THICKNESS RATIO = 0.750

CASE NUMBER : 033

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 0.7500

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 5.569

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 7.378 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 1.818 [MM]

CORE MODULUS = 125.000 [MPa]

MODEL PARAMETER SUMMARY

DATE : 05/06/91

MODEL DESCRIPTION : WALL THICKNESS RATIO = 1.000

CASE NUMBER : 034

LINEAR ANALYSIS

NONDIMENSIONAL PARAMETERS

WALL THICKNESS RATIO = 1.0000

CORE/INNER BRAID RADIUS RATIO = 0.8000

YARN ASPECT RATIO = 0.3330

YARN PACKING FACTOR = 1.0000

CORE PACKING FACTOR = 1.0000

INITIAL BRAID ANGLE = 50.000 DEG

INITIAL BRAID COVER FACTOR = 0.9500

CORE/YARN MODULUS RATIO = 0.02500

CORE POISSON'S RATIO = 0.3000

DIMENSIONAL PARAMETERS

NUMBER OF YARNS IN BRAID = 4.177

YARN MODULUS = 5000.000 [MPa]

INITIAL BRAID DENSITY = 6.037 [PICKS PER INCH]

INITIAL OUTER BRAID DIAMETER = 5.000 [MM]

INITIAL CORE DIAMETER = 1.333 [MM]

CORE MODULUS = 125.000 [MPa]

VITA

Robert Houston Hopper, Jr. was born in Annapolis, Maryland to Mr. and Mrs. Robert H. Hopper. He completed his secondary education at Old Mill Senior High School in Maryland and went on to Virginia Tech. There he received a bachelor's degree in Mechanical Engineering in 1989 and a master's degree in Engineering Mechanics in 1991. Robert plans to continue studies aimed towards a doctorate in Biomedical Engineering at Duke University. His long term plans include establishing his own prosthetics company to meet the needs of society.

Life is a gift and as we devote ourselves to the tasks at hand, we must never lose sight of the larger and more important issues that accompany our existence. Science without prejudice can aid in our pursuit of the truth. Yet we must use it responsibly and with the highest regard for mankind and his environment.