**viscoelastic modeling of porcine ligaments**

**Bruno Mello Silveira**

Stephanie Aguiar Salles de Barros

Departamento de Engenharia Mecânica - PPEMM - CEFET/RJ; Av. Maracanã, 229 – RJ – Brazil. bruno.silveira@aluno.cefet-rj.br, stephanie.barros@aluno.cefet-rj.br

Rodrigo Ribeiro Pinho Rodarte

Programa de Pós-graduação em Engenharia Mecânica e Tecnologia de Materiais - PPEMM - CEFET/RJ; Av. Maracanã, 229 – RJ – Brazil. Instituto Nacional de Traumatologia e Ortopedia – INTO -Av. Brazil, 500, RJ, Brazil. rodrigo.rodarte@aluno.cefet-rj.br

**Paulo Pedro Kenedi**

Programa de Pós-graduação em Engenharia Mecânica e Tecnologia de Materiais - PPEMM - CEFET/RJ; Av. Maracanã, 229 – RJ – Brazil. Departamento de Engenharia Mecânica – CEFET/RJ - Av. Maracanã, 229 – RJ – Brazil. paulo.kenedi@cefet-rj.br

**Abstract.** Viscoelastic quasi-linear analytical models, as Fung, was implemented through the utilization of experimental results obtained from several porcine ligaments as: lateral collateral ligament (LCL), anterior cruciate ligament (ACL), posterior cruciate ligament (PCL) and medial collateral ligament (MCL). To implement quasi-linear viscoelastic models for soft tissues, as the Fung one, was necessary the utilization of a programming language, as C Sharp, and Object-oriented programming to deal with the model’s mathematical demands, as the convolution calculations. Moreover, those technologies allow to reduce the code execution time which was one of the main problems. Despite this benefit, was necessary to implement the numerical methods used in process. The models’ results show the stress evolution in relaxation tests. Although, the preliminary results show a good correlation between experimental and analytical models, showing a noticeable change in ligaments stiffness after the experimental implementation of relaxation tests.

**Keywords:** knee ligaments, analytic model, viscoelasticity, Fung

1. Introduction

The purpose of these paper is to explain how to implement quasi-linear viscoelastic models for soft tissues. For that, it is necessary the utilization of a programming language to deal with the model’s mathematical demands, as the convolution, integral and derivative calculations, and with the complex logics to be dealt with. In that research, is used C Sharp.

1. Fung’s quasi-linear viscoelastic model

The quasi-linear viscoelastic model, proposed by (Fung, 1993), applies the non-linearity stress-strain relation expressing the stress in two parts: the reduced relaxation function, which depends only on time, and elastic response, which depends on strain. To be easier while calculating the stress, the elastic response can be expressed depending only on time, because, in that research, the strain is considered depending on this, as will be shown below.

This model is commonly used for soft tissue, as it can represent the tissue with good approximation. The constants needed for the equations is obtained experimentally, however, like any model, the Fung’s model has limitations, since for distinct relaxations and strain levels, different values for those constants are found.

Moreover, two considerations were made: consider and disregard ramp time. While considering, is possible to calculate the variables A and B, shown below in elastic response equation, with those, multiple relaxations can be assumed. Is that research, is assumed just two relaxations.

* 1. Mathematical equation

(Fung, 1993) propose equations for elastic response, reduced relaxation function and stress considering one relaxation, although, as tow relaxations will be considered, it is necessary to reformulate these equations as will be presented under.

* + 1. Strain

To describe the strain, the equation 1 is used when considering ramp time and equation 2, when not.

|  |  |
| --- | --- |
| , | (1) |

In equation 1, the parameters and represent, respectively, ramp time and strain rate applied in experiment, with used when strain increase and , when decrease. Furthermore, the parameters , , and are the limit time for each equation, indicating when the strain behavior changes.

|  |  |
| --- | --- |
| , | (2) |

In equation 2, represents the constant stain applied in experiment.

With that, is possible to calculate the derivative that will be used in the stress calculations step. The equation 3 and 4 are the derivative in time of, respectively, equation 1 and 2.

|  |  |
| --- | --- |
| , | (3) |
| , | (4) |

* + 1. Elastic response

|  |  |
| --- | --- |
| , | (5) |

|  |  |
| --- | --- |
| , | (6) |

|  |  |
| --- | --- |
| , | (7) |

|  |  |
| --- | --- |
| , | (8) |

* + 1. Reduced relaxation funcion

|  |  |
| --- | --- |
| , | (9) |

|  |  |
| --- | --- |
| , | (10) |

* + 1. Stress

|  |  |
| --- | --- |
| , | (11) |
| , | (12) |
| , | (13) |

1. numerical implementation

Interface gráfica do usuário

Descrição gerada automaticamente com confiança média

(single space line, size 10)

Figure 1. Schematic diagram of the control strategy.

(single space line, size 10)

The figures, as well as their captions, must be centered in the breadth-wise direction. The captions of the figures should not be longer than 3 lines, centered and in Times New Roman size 10.

One blank line must be left before and after each figure.

The legend for the data symbols as well as the labels for each curve should be included into the figure. Lettering should be large enough for ease reading. All units must be expressed in the S.I. (metric) system.

Color figures and high-quality photographs can be included in the manuscript. To reduce the file size and preserve the graphic resolution, figures must be saved into GIF (figures with less than 16 colors) or JPEG (for higher color density) files before being inserted in the manuscript.

Tables must be referred to either as “Table 1” in the middle of a phrase or as “Table 1” in the beginning of a sentence. The tables themselves as well as their titles must be centered in the breadth-wise direction. The titles of the tables should not be longer than 3 lines. The font style and size used in the tables must be similar (both in size and style) to those used in the text body. Units must be expressed in the S.I. (metric) system. Explanations, if any, should be given at the foot of the tables, not within the tables themselves.

One blank line must be left before and after each table.

The style of table borders is left free. An example is given in Table 1.

Cross references for equations, figures and tables are used in this template. The corresponding labels are Equation, Figure, and Table, respectively.

(single space line, size 10)

Table 1. Experimental results for flexural properties of CFRC-4HS and CFRC-TWILL composites.

Span/depth ratio = 35:1. Average results of 7 specimens.

(single space line, size 10)

|  |  |  |
| --- | --- | --- |
| **Composite Properties** | **CFRC-TWILL** | **CFRC-4HS** |
| Flexural Strength, MPa(1) | 209 ± 10 | 180 ± 15 |
| Flexural Modulus, GPa(1) | 57.0 ± 2.8 | 18.0 ± 1.3 |
| Mid-span deflection at the failure stress, mm | 2.15 ± 1.90 | 6.40 ± 0.25 |

(1) measured at 25°C

1. Acknowledgements

This optional section must be placed before the list of references.

1. References

Fung, Y. 1993. Biomechanics: Mechanical Properties of Living Tissues. Springer New York, University of Michigan.

1. Responsibility notice

The authors are the only responsible for the printed material included in this paper.