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Pgs: 168-173

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COMPOSITE FIBRE-RESINE LAMINA AND ANALYTICAL SOLUTION FOR STUDY OF LIGAMENT

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Abstract

The objective of this work is to study ligament system with the composite fibre-resin lamina which is not exactly but matches nearer to the ligament structure. The skeletal ligaments are short bands of tough fibrous connective tissue which are same as composite material. This paper presents analytical study of a composite Fibre-Resin lamina and orthotropic stress -strain relationship formulation for composite material.

Keywords: Anterior Cruciate Ligament, anistropic material, orthotropic material

1. Introduction

The knee is essentially made up of four bones. The femur, which is the large bone in your thigh, attaches by ligaments to your tibia. Just below and next to the tibia is the fibula, which runs parallel to the tibia. The

Vol.2 Issue.4,
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Pgs: 168-173

patella, (kneecap) slides on the knee joint as the knee bends. There are also a number of ligaments, cartilages and muscles which strengthen and support the knee. The knee can be thought of as basically having four ligaments holding it in place, one at each side, to stop the bones sliding sideways, and two crossing over in the middle to stop the bones sliding forwards and backwards [3].

- Medial collateral ligament (MCL) – runs along the inner part of the knee and prevents bending inwards.
- Lateral collateral ligament (LCL) – runs along the outer part of the knee and prevents bending outwards
- Anterior cruciate ligament (ACL) – lies in the middle of the knee. It prevents the tibia sliding forwards in front of the femur. It also provides rotational stability to the knee.
- Posterior cruciate ligament (PCL) - works in conjunction with the ACL. It prevents the tibia sliding backwards under the femur.

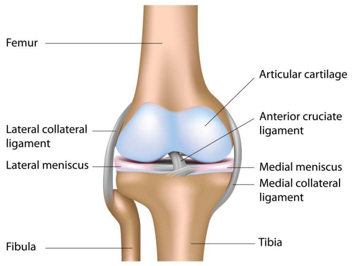

Figure 1: anterior view of right knee

The ACL is the major intra-articular ligament of the knee and is critical to normal kinematics and stability. The ACL controls motion by connecting the femur to the tibia and stabilizing the joint, preventing abnormal types of motion. Its main functions are to support and strengthen the knee and prevent excessive anterior translation of the femur that could cause a dislocation and fracture of bones in the knee joint. The ACL is a dense, highly organized, cable-like tissue composed of collagens (types I, III, and V), elastin, proteoglycans, water, and cells. The human ACL has an average length of 27–32 mm and a cross-sectional area of 44.4–57.5 mm^2. Ligaments have a hierarchical structure with different levels of organization including collagen molecules, fibrils, fibril bundles, and fascicles that run parallel to the long axis of the tissue. The collagen fibrils in ligaments display a periodic change in direction called a crimp pattern. In ACL, this crimp pattern repeats every 45–60 mm . The fascicles contain collagen fibrils, proteoglycans, and elastin. The ligament is surrounded by a sheath of vascularized epiligament . An additional level of structure exists in the ACL, the collagenous network is twisted by approximately 180° from the femoral attachment site to the tibial attachment site. The ACL also contains antromedial and posterolateral bands[2]

2) Mechanical properties of ACL

Biological soft tissues sustain large deformations, rotations and displacements, have a highly non-linear behaviour, posses anisotropic mechanical properties and show a clear time and strain rate dependency. Their typical anisotropic behaviour is caused by several collagen fiber families (usually one or two fibers coincide at each point) that are arranged in a matrix of soft material named ground substance, Typical examples of fibered soft biological tissues are blood vessels, tendons, ligaments, cornea and car- tillage. Ligaments are composite, anisotropic structures exhibiting non-linear time and history dependent viscoelastic properties[3].

a) Stress-strain relationship:

Ligaments display triphasic behavior when exposed to strain. First there is a region where the ligament exhibits a low amount of stress per unit strain, this is called the non-linear or toe region. This region is followed by an area noted for its increase in stress per unit strain, called the linear region. The last region displays a slight decrease in stress per unit strain and marks the failure of the ligament, this is the yield and failure region. The presence of this unique behaviour is due to the components of the ligament and their arrangement in the tissue. When force is first applied to the tissue it is transferred to the collagen fibrils. This results in lateral contraction of fibrils, the release of water, and the straightening of the crimp pattern in the collagen fibrils. Once the crimp pattern is straightened, the force is applied directly to the collagen molecules. The collagen triple helix is stretched and interfibrillar slippage occurs between cross links. This results in an increase in stress per unit strain. Finally, the collagen fibers in the ligament fail by defibrillation causing a decrease in stress per unit strain and tissue failure[2].

b) *Anisotropic properties*

Because of its fiber reinforced nature, it would appear that the ACL is anisotropic, or that the modulus of the material depends on the direction in which it is pulled. Conversely, isotropic materials have moduli that are independent of the loading angle.

c) Viscoelasticity

Ligament viscoelasticity controls viscous dissipation of energy and thus the potential for injury or catastrophic failure. Viscoelasticity under different loading conditions is likely related to the organization and anisotropy of the tissue.

2) Analytical study

Due to the stress-strain properties, the analytical solution is developed baesd on proposed solution (P. Boresi)[1]. to study ACL response due to composite nature of ligament. Advance Mechanics of Material(P. Boresi and Richard J.Schmidt) proposed the solution for unidirectional model of a lamina of a section of an airplane wing composed of fibres and resin. The volume fraction is consider for the determination of stress strain relations of the lamina.

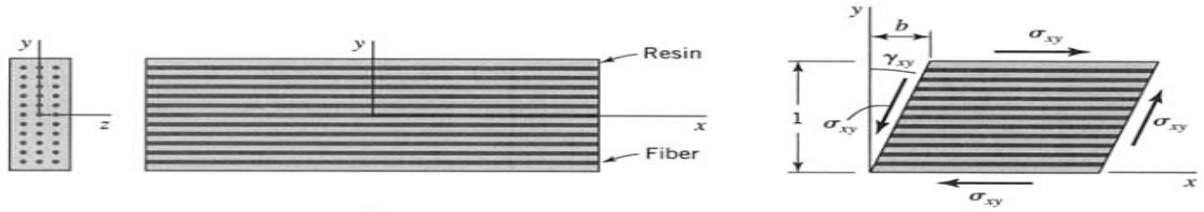

Fig.2 Fiber-Resin lamina, fiber: resin volume fraction = f, resin volume fraction=1-f

The modulus of elasticity and Poisson's ratio of Fibre and Resin be denoted as EF,μF and ER since the lamina is thin, the effective state of stress in lamina is approximately one of plane stress in the x-y plane of the laminate. stress strain relations for the fibres and resins are

$$\varepsilon_{xxF} = \frac{1}{E_F}\left(\sigma_{xxF} - \nu_F \sigma_{yyF}\right)$$

$$\varepsilon_{yyF} = \frac{1}{E_F}\left(\sigma_{yyF} - \nu_F \sigma_{xxF}\right) \quad \text{(a)}$$

$$\varepsilon_{xxR} = \frac{1}{E_R}\left(\sigma_{xxR} - \nu_R \sigma_{yyR}\right)$$

$$\varepsilon_{yyR} = \frac{1}{E_R}\left(\sigma_{yyR} - \nu_R \sigma_{xxR}\right)$$

Where (σ_{xxF}, σ_{yyF}), (σ_{xxR}, σ_{yyR}), (ε_{xxF}, ε_{yyF}), and (ε_{xxR} $\varepsilon_{yy,}$) denote stress and strain components in the fiber (F) and resin (R), respectively.Since the fibers and resin are bonded, the effective lamina strain ε_{xx} is the same as that in the fibers and in the resin; that is, in the x direction,

$$\varepsilon_{xx} = \varepsilon_{xxF} = \varepsilon_{xxR} \quad \text{(b)}$$

In the y direction, the effective lamina strain εyy is proportional to the amount of fiber per unit length in the y direction and the amount of resin per unit length in the y direction. Hence,

$$\varepsilon_{yy} = f\varepsilon_{yyF} + (1-f)\varepsilon_{yyR} \quad \text{(c)}$$

Also, by equilibrium of the lamina in the x direction, the effective lamina stress σ_{xx} is

$$\sigma_{xx} = f\sigma_{yyF} + (1-f)\sigma_{xxR} \quad \text{(d)}$$

In the y direction, the effective lamina stress σ_{yy} is the same as in the fibers and in the resin, that is,

$$\sigma_{yy} = \sigma_{yyF} = \sigma_{yyR} \qquad \text{(e)}$$

Solving Eqs. (a) through (e) for ε_{xx} and ε_{yy} in terms of σ_{xx} and σ_{yy}, we obtain the effective stress-strain relations for the lamina as

$$\varepsilon_{xx} = \frac{1}{E}(\sigma_{xx} - \nu\sigma_{yy})$$

$$\varepsilon_{yy} = \frac{1}{E}(\beta\sigma_{yy} - \nu\sigma_{xx})$$

where

$$E = fE_F + (1-f)E_R$$

$$\nu = f\nu_F + (1-f)\nu_R \qquad \text{(g)}$$

$$\beta = f(1-f)[(1-\nu_R^2\frac{E_F}{E_R} + (1-\nu_F^2)\frac{E_R}{E_F} + 2\nu_F\nu_R + \frac{1-f}{f} + \frac{f}{1-f}]$$

To determine the shear stress-strain relation, we apply a shear stress o, to a rectangular element of the lamina (Figure.1b), and we calculate the angle change y, of the rectangle. By Figure.1b, the relative displacement b of the top of the element is

$$b = f\gamma_F + (1-f)\gamma_R \qquad \text{(h)}$$

Where γ_F and γ_R are the angle changes attributed to the fibers and the resin, respectively; that is,

$$\gamma_F = \frac{\sigma_{xy}}{G_F} \ , \ \gamma_R = \frac{\sigma_{xy}}{G_R} \qquad \text{(i)}$$

And G_F and G_R are the shear moduli of elasticity of the fiber and resin, respectively. Hence, the change γ_{xy}, in angle of the element (the shear strain) is, with Eqs. (h) and (i),

$$\gamma_{xy} = 2\varepsilon_{xy} = b = [\frac{fG_R + (1-f)G_F}{G_F G_R}]\sigma_{xy} \qquad \text{(j)}$$

By Eq.(j), the shear stress-strain relation is

$$\sigma_{xy} = G\gamma_{xy} = 2G\varepsilon_{xy} \qquad \text{(k)}$$

where

$$G = \frac{G_F G_R}{fG_R + (1-f)G_F}$$

Vol.2 Issue.4,

April 2014.

Pgs: 168-173

Thus, by Eqs. (f), (g), (k), and (l), we obtain the stress-strain relations of the lamina, in the form of Eqs.as

$$\sigma_{xx} = C_{11}\varepsilon_{xx} + C_{12}\varepsilon_{yy}$$

$$\sigma_{yy} = C_{12}\varepsilon_{xx} + C_{22}\varepsilon_{yy} \qquad \text{(m)}$$

$$\sigma_{xy} = C_{33}\gamma_{xx}$$

$$C_{11} = \frac{\beta E}{\beta - \nu^2} \quad , \quad C_{21} = \frac{\nu E}{\beta - \nu^2} \quad , \quad C_{22} = \frac{E}{\beta - \nu^2} \quad , \quad C_{33} = G \qquad \text{(n)}$$

3. Analytical calculation:

Material property is given as , Glass fiber:- EF=72.4GPa,GF=27.8GPa,poissons ratio=0.30 Epoxy resin:- EF=3.50GPa,GF=1.35GPa,poissons ratio=0.30 The volume fraction of fiber is f=0.70

□ = [0.7 × 72.4+0.3 × 3.50] = 51.73 GPa;

□ = [0.7 × 0.3 + 0.3 × 0.3] = 0.3

β = 0.70 x (1-0.70){((1-0.302) (72.4/3.50)) + (($1\text{-}0.30^2$) (3.50/72.4)) + (2 x 0.3 x 0.3) + ((1-0.70)/(0.70)) + ((0.70)/ (1-0.70))}

β = 4.9325

G = (27.8x1.35)/((0.70x1.35)+((1-0.70)(27.8))

G= 4.042003231

C11=52.6914

C12=3.2047

C22=10.6824

C33=4.0420

4. Conclusion:

From the above derivation this is proved, the lamina is independent from both dimension as well as force. It's better to consider anisotropic property rather than composite nature of ligament.

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