Study of The Reliability of A Composite Used In The Knee Prosthesis

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ABSTRACT— In orthopedic surgery, the effectiveness of the implants used, such as hip and knee prostheses, depends mainly on their geometries and the type of loading to which they are subjected. In this work a probabilistic approach is chosen to study the reliability of a composite structure used in the manufacture of knee prostheses. The purpose of integrating reliability concepts is to consider uncertainty in several aspects including loading and material properties. The reliability index β is an excellent indication of durability and safety for given operating conditions. β is obtained using failure probability and a mechanical model. The critical stress intensity factor (Kc) is adopted as a criterion to the maximum limit of a numerically calculated KI. The results presented are discussed according to the length of the crack (a), and the limit load used.

KEYWORDS— Reliability analysis, critical stress intensity factor, crack length, load, reliability index

I. Introduction

The aging of the population, accidents at work and daily traffic offer composites manufacturers a strong potential for development [1]. As in many other industries, it is primarily for their lightness and strength that composites are used in health. Bone implants prostheses of all kinds, screws and stems to repair a fracture, but also instrumentation. Composites, which are often blends of fibers and polymer resins, offer ever more solutions to surgeons and doctors. They can replace metals and plastics, or even offer new properties. But these advances remain discreet and the volumes of composites used in the health remain smaller compared to those consumed by the aeronautics and by the automobile. The health care sector represents only a tiny percentage of the global composites market, which is close to 60 billion euros [2]. Composite materials based on glass-fiber reinforced acrylic resin remain the most widely used in the orthopedic prosthetic appliance manufacturing industry for people with disabilities. They allow meeting all the requirements of shape and cadence by successive layers to have laminates that must not have any defect, nor undergo treatment likely to hide the defects [3]. Biomechanical research uses approaches in geometric modeling, mechanics and experimental analysis close to the mechanics of structures and materials. However, many locks exist upstream and downstream to characterize and customize the geometry, the materials whose behavior varies according to the laws of remodeling still poorly known, as well as the mechanical loadings. The purpose of integrating the concepts of reliability is to consider uncertainty in several aspects, such as loadings and material properties [4].

In this work, a probabilistic analysis is chosen to study the reliability limits of a composite structure under loading. The reliability index β is calculated on a plate which has a crack and which is subjected to a compressive force. The critical stress intensity factor (K_C) is adopted as a criterion to the maximum limit of a numerically calculated K_I.

II. Mechanical model

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Knee prostheses are often used in compression. The stress σ resistant to compression force F is given by the following equation considering only a compressive force exerted on a plate having a crack of length a.

$$\sigma = \frac{F}{s.B}$$ (1), *s*: length plate, *B*: width plate.

In the existence of a crack of size a, according to the methods of the Linear Elastic Fracture Mechanics (*LEFM*), the stress intensity factor is specified by:

$$K_I = \sigma \cdot (\pi \cdot a)^{0.5} \cdot Y$$ (2)

Where Y is the geometrical factor given by the next formula:

$$Y = 1.12 - 0.231\left(\frac{a}{w}\right) + 10.55\left(\frac{a}{w}\right)^2 - 21.72\left(\frac{a}{w}\right)^3 + 30.39\left(\frac{a}{w}\right)^4$$ (3)

The final mechanical model adopted to state the rupture of a composite structure subjected to compression force and having a defect length (a) is illustrated in equation 4:

$$K_I = \frac{F}{s.B} \cdot (\pi \cdot a)^{0.5} \cdot Y$$ (4)

III. Reliability analysis based on PHIMECA Software

For each sizing rule, a failure scenario is defined using a performance function *G (Xi) =R(Xi) -S(Xi)*, with *Xi* the basic random variables, and *R(Xi)* the resistance and *S(Xi)* solicitation. The inequality *G (Xi)> 0* indicates a security state, however *G (Xi) <0* explains a state of failure. Knowing the variables involved in writing a failure scenario is often only statistical information. The goal is then to assess a probability P_f, that of being in a failure situation. The probability of failure P_f as shown in Figure 1 is the probability of being in D_f [5].

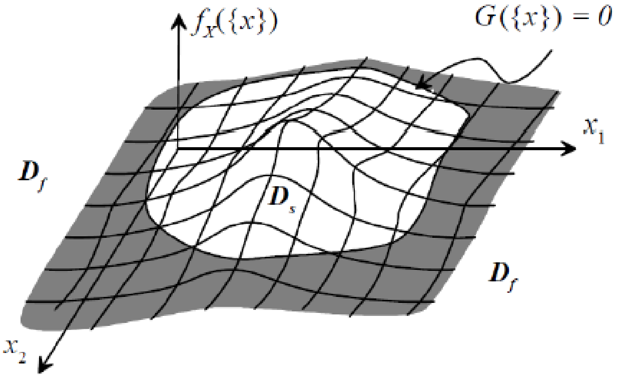

Fig. 1 Probability density function f_X *(Xi)* [5]

Failure probability P_f is established by equation (5), where *P[G(X)≤0]* is the probability operator and *Φ(-β)* is the cumulative Gaussian probability function [6]:

$$P_f = P[G(X) \leq 0] = \Phi(-\beta)$$
(5)

Consequently, the limit state function used in this work is detailed in Equation (6). This limit state is selected to agree to the expected safety margin distinct by the difference between the material critical toughness (K_C) and a specified service operational level selected by K_I value. The limit state *G* is measured to assess the reliability index.

$$G = K_C - \frac{F}{s.B} \cdot (\pi \cdot a)^{0,5} \cdot \left[1.12 - 0.231\left(\frac{a}{w}\right) + 10.55\left(\frac{a}{w}\right)^2 - 21.72\left(\frac{a}{w}\right)^3 + 30.39\left(\frac{a}{w}\right)^4 \right] \quad (6)$$

The reliability software PHIMECA [7] is used to compute reliability index *β*. This factor is defined as the inverse of the probability of failure which is expressed here in this study function of crack length and compression force. The range for K_C values is taken from literature analysis dealing with fiberglass composites structures. It is found that thoughness are within the lying from 20 to 60MPa.√m. In the case of PMMA alone, K_C varies between 0.7 and 1.6MPa.√m [8].

Figure 2 illustrates the variation in the reliability index as a function of crack length and the critical toughness K_C. Discontinuous horizontal lines here limit the margin or limit function *(G(x)=0)* that separates the security domain when *G(x)>0* of the failure domain when *G(x)<0*. Three levels of tenacity of composites structure resistance are considered (low: 20; medium: 40 and high: 60MPa.√m) and as projected the trends are subsequent comparable behaviors and the reliability index decreases with increasing crack length. It should be noted that *β* equal to 3 corresponding to $P_f \approx 1.3\ 10^{-3}$ is a value in which the considered structure is in a failure domain. On the other hand, for a value of *β* greater than 4.25 and $P_f \approx 1.6\ 10^{-5}$, the structure works in the safety domain.

In the first case for K_C=20MPa.√m, the reliability analysis indicates that the security domain is far from the actual service values. This curve shows the falling values of *β* most of them in the region of failure. For the case 2, K_C= 40MPa.√m, when crack length is fewer than 2 mm, the reliability index reached the safe limit (*β*=4.25). Finally, in case 3 (K_C= 60 MPa.√m), the structure works in the safety field when the length of the crack does not exceed 4.5 mm.

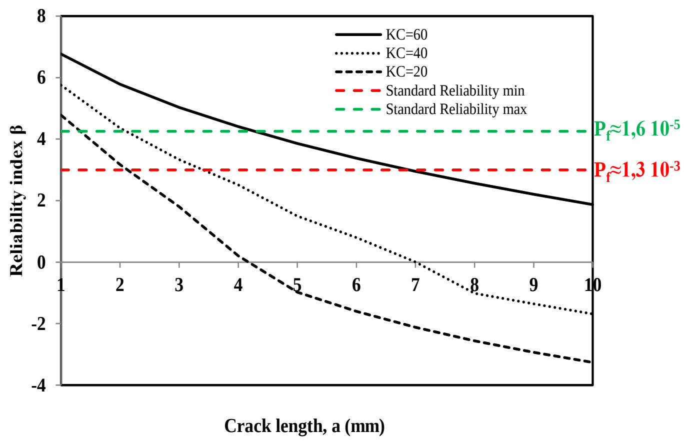

Fig. 2 Reliability index in composites structure as a function of the crack length and critical toughness K_C (MPa. √ m).

Figure 3 illustrates the variation of the reliability index *β* as a function of the compression force and the critical toughness K_C. According to the literature, the compression forces exerted on knee prostheses vary between 800 and 3000 N [9].

The reliability index is calculated each time in three cases K_C different. The horizontal lines here separates the security domain; where *G(x)>0* from the failure domain where *G(x)<0*. For the first case K_C= 20 MPa.√m. It is obvious that whatever the value of the load considered the structure always belongs to the domain of failure where *β* is equal to 3 is the probability of failure is large. In the second case, K_C = 40 MPa√m, the structure is safe if the applied load is less than 650 N. And finally, concerning the third case K_C = 60 MPa√m, the structure is in the safety domain as long as the applied load is less than 1000 N.

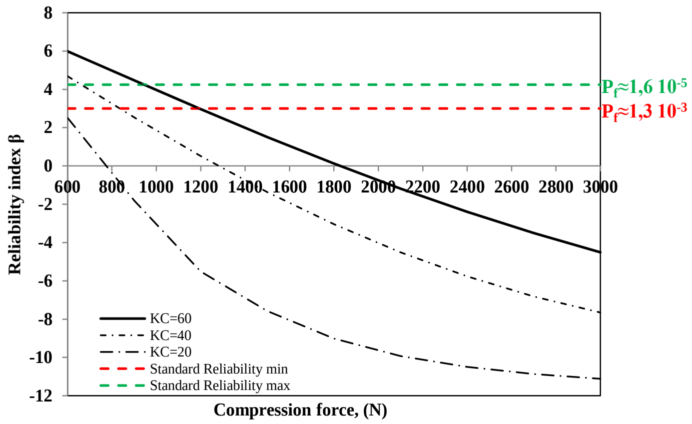

Fig. 3 Reliability index in composites structure as a function of the compression force and critical toughness K_C (MPa. √ m).

IV. Conclusions

A reliability analysis applied on a cracked composite plate, based on FORM/SORM approach and implanted in the software PHIMECA, is illustrated. The developed mechanical model for plaque resistance is constructed using fracture mechanics critical stress intensity factor *(K_C)* which is used as a limit design assessment. Simulations of the reliability index β used compression force, and crack length as a function of 3 levels of K_C.

In view of increased crack length, β decreased progressively as anticipated for the whole tenacity cases. It is recognized that fracture toughness and reliability give comparable properties in terms of material resistance to cracking. When K_C = 40MPa.√m, the structure is safe only if the length of the crack does not exceed 2 mm. In the case where K_C = 60MPa.√m, the plate considered belongs to the safety domain only if the length of the crack is less than 4.5 mm.

This study also made it possible to calculate the reliability index as a function of the compression load applied in three levels of toughness. In level 1, when K_C = 20MPa.√m, the reliability analysis showed that whatever the value of the applied load the plate is still working in the failure domain i.e. β close to 3. In the second level K_C = 40MPa.√m, the analyzed structure is safe only if the load is less than 650N. Finally in the third level of toughness, K_C = 60MPa.√m, the safety domain is reached when the applied load is less than 1000N.

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