An Investigation to the Effects of Impact Strength on Laminated Notched Composites used in Prosthetic Sockets Manufacturing

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Abstract. The sockets used in prostheses manufacturing are normally made from materials of high strength/weight ratio for durability and comfort wearing purposes. The sockets may be subjected to impact loading and cause a fracture due to this loading if the material has a low toughness energy. Therefore, the current work is directed to investigate experimentally the determination of impact energy and the toughness of different types of fibers and resins to assess their effectiveness in sustaining the impact loading. Samples were prepared according to the ASTM standard using the fiberglass, Kevlar and carbon fibers with three types of resins araldite, polyester and Orthocryl lamination resin 80:20 with 2-3% hardener. All types of fibers are mat types and 12 layers were manufactured with thickness approximately 4 mm. The layers of the samples were arranged (4 perlon+4 kevlar+4 perlon), (4 perlon+4 glass+ 4 perlon), (4 perlon+4 carbon+4 perlon) and three mixed samples (3perlon+2 kevlar+2 perlon+2 carbon+3 perlon), (3 perlon+2 kevlar+2 perlon+2 carbon+3 perlon), and (3 perlon+2 kevlar+2 perlon+3 carbon+2 perlon). The sample with the lamination (4 perlon+4 kevlar+4 perlon) layers has shown a good ultimate stress= 124.7 MPa, and modulus of elasticity = 25.6 GPa with an acceptable of impact energy 13.7 Joule, toughness 147.9 KJ/m 2 and a fracture toughness of 65.77 MN/m 3/2 using the orhocrylic resin.

Keywords: Impact, Laminate, Strength, Prostheses, Sockets.

1. Introduction
Due to the increasing of amputees because of the accidents, and congenital deformity in the developed countries and in addition to that, the diseases and wars in the developing countries. Therefore, rapid needs for improving the materials to be used in manufacturing the sockets prostheses and orthoses for people of special needs. The researchers directed their work to discover new lamination systems to meet the amputee’s requirements. Many researchers worked on this topic to prepare materials which has high strength/weight ratio and durable without side effects on the amputees. M.J. Jweeg et al. [1]
investigated numerically and experimentally a below knee prosthesis and developing different laminations of composite material and different lamination schemes and used the CT scan for the dynamic analysis of the sockets. They tried different materials and laminations using the orthocryl resin. M.J. Jweeg et al. [2] achieved analytical and experimental study for the syme’s sockets. Stresses and deformations were calculated using different types of laminations of composites. They compared their results with a socket manufactured from a polypropylene materials. The composites have shown a superior characterization with a high strength/weight ratio and good fatigue strength. A related work on the characterization of composite materials used in manufacturing the prostheses sockets may be found in the literatures [3-8]. The impact tests findings and the stresses developed are important to be defined in the application considered in this work, sockets manufacturing and in many other engineering applications such as the aviation systems [9-12]. This is because that the sockets may be subjected to impact loading during the gait cycle of the patient which causes a damage in the prosthesis, therefore, the survey should include the works related to this topic. In general, the composite materials may subject to delamination when the matrix subjects to impact loading which has a negative effect on the mechanical properties of the laminate. Therefore, the material requires a careful manufacturing process and the possibility of the damage may be taken into considerations especially for those used by the special needs people. Many researches go deeply in the effects of damage in composite materials to avoid the risks in the case of the possibility of damages due to different of sources such as the impact loading [13-15]. On the basis of the results of tensile, bending and impact tests of the samples to be used in the rehabilitation centers, the prostheses engineers may give a decision on the acceptable material by the stress analysis of the sockets taking into consideration the normal contact pressure between the socket and the patient stump does not exceed approximately 250 KPa [16-18].

In this work, different composites and types of resins will be used in the experimental investigation for 12 types of laminates with different schemes of laminations. Tensile, bending and impact tests will be achieved in addition to the theoretical investigation to calculate the toughness and the fracture toughness of the samples. A conclusion will be stated on the basis of the results to be used in the design of the socket prostheses.

2. Theoretical Considerations

2.1. Energy Release Rate

Consider Fig. 1 in which a specimen of length L and a notch with a crack length a is subjected to a tensile force F. The crack will be extended due to axial load to \( (a + \delta a) \). The compliance of the specimen is defined as the reciprocal of the stiffness and can be written as follows,

\[
\text{Comp.} = \frac{\delta x}{F} \tag{1}
\]

Where, \( \frac{\delta x}{F} \) is the reciprocal of the slop of the load extension diagram.

The load displacement diagram is shown in Fig. 2. It behaves linearly elastic, the area oad represents the elastic strain energy with crack length a, while the area obd represents the elastic strain energy with crack length \( (a + \delta a) \) and the area oab is the release elastic strain energy.

The strain energy is given by,

\[
U = \frac{1}{2} F \times x \quad (\text{Strain energy per unit volume (N.m/m}^3))
\]

The strain energy may be expressed in terms of the compliance as follows, from Eq. (1),

\[
\delta x = \text{Comp.} \delta F
\]

And the energy release due to the crack extension is given by,

\[
U = \frac{1}{2} F \delta x \tag{3}
\]

Or, using Eq. (2) and Eq. (3), gives,

\[
U = \frac{1}{2} \text{Comp.} F^2 \tag{4}
\]

For a small crack extension \( \delta a \), the strain energy \( U \) can be found experimentally for the considered sheet shown in Fig. 1, using the charpy test as shown in Fig. 3.
Fig. 1. A notched specimen subjected to an axial load F.

Fig. 2. Load extension diagram

(a) Simply supported beam

(b) ASTM E23 Beam Stander Sample
2.2. **Toughness of the material** $G_c (J/m^2)$

Toughness of the material is defined as follows,

$$G_c = \frac{1}{b} \frac{\delta U}{\delta a}$$

Using Eq. (4), Eq. (5) becomes,

$$G_c = \frac{1}{b} \frac{1}{2} F^2 \left( \frac{\delta \text{Comp.}}{\delta a} \right)$$

Substitution of $F^2 = \frac{2U}{\text{Comp.}}$ From Eq. (4) into Eq. (6) gives,

$$G_c = \frac{U}{b \text{Comp.} \frac{\delta \text{Comp.}}{\delta (a/h)}}$$

Where, $\frac{\delta \text{Comp.}}{\delta (a/h)}$ are found from the load extension diagram for different crack lengths. Or, $G_c = \frac{U}{b \text{Comp.} \frac{\delta \text{Comp.}}{\delta (a/h)}}$

Or,

$$U = G_c (b \text{Comp.})$$

Eq. (8) represents a straight line and the slope of this straight line gives the specimen toughness of the specimen. The strain energy $U$ is found from plotting stress-strain diagram and the Comp. which is called the geometric shape factor and $\left( \frac{\delta \text{Comp.}}{\delta a} \right)$ is found experimentally.

2.3. **Fracture Toughness**

Toughness is a material property gives an indication of how much the material can absorb energy before damage occurrence. This is one of the important factors to be considered before the judgement on the type of material to be used in the socket prostheses manufacturing. The fracture toughness is obtained by using Irwin Theory, [19], which states that the stresses near the crack is directly proportional to root square of the crack depth $\sqrt{\pi a}$ and the stress intensity $K_{Ic}$ is given by,

$$K_{Ic} = y \cdot \sigma \sqrt{\pi a}$$

Where, $\sigma$ is the applied stress and $y$ is the coefficient of the geometry shape and $K_{Ic}$ is critical fracture toughness of the material. $K_{Ic}$ is related to the material toughness as follows,

$$K_{Ic} = \sqrt{\frac{E}{G_c}}$$

Where, $E$ is the modulus of elasticity of the material.
3. Experimental Work
To achieve the experimental program, the following types of samples should be prepared,

i. Tensile test specimen to obtain the load deflection diagrams which will be achieved according to the standard ASTM D638 from which the compliance of the material is obtained, [20-23], in addition to calculate the tensile strength of the specimen.

ii. Bending tests to obtain the modulus of elasticity of the samples which are performed according to the standard (ASTM D790).

iii. Charpy impact test specimen prepared according the standard ASTM E23.

The materials used for manufacturing the specimens with the type of fiber, resin and the number of layers will be according to Table 1. These materials are, Knit Person, Fiber glass, woven mat, weight = 580 g/m², Kevlar fiber, woven mat, weight= 430 g/m², Carbon fiber, woven mat, weight= 450 g/m². Orthocrylic lamination resin 80: 20 with hardener, Araldite resin with hardener, and Polyester resin with a hardener.

For the preparation of the specimens, a mold is prepared of a cubic element of the size (300 × 100 × 4 mm³). The outer and inner surfaces of the mold should be smooth, and for this purpose a PVA-Polyvinyl alcohol, covers the mold to prevent the adhesive of the resin with the mold. The volume fraction is calculated as follows,

∀f = \frac{∀f}{∀resin+∀Perlon+∀f}

Similarly,

∀Perlon = \frac{∀Perlon}{∀resin+∀Perlon+∀f}

And,

∀resin = 1 - (∀Fiber + ∀Perlon)

And the density may be calculated as follows,

\rho = \frac{m}{V}

Where, m is measured by the accurate balance and the volume is measured by using a testing beaker. The vacuum shown in Fig. 4 is used to suck all the air bubbles between the PVA and the mold and to ensure an acceptable distribution of the resin in the mold, [24-26]. In order to obtain a clear picture of the effects, the volume fractions are kept approximately constant in order that the results can be analyzed easily and a recommendation for the effects of other parameters may be drawn. The Perlon, fibers and the resin volume fractions are used according to the lamination scheme planned in Table 1. Then, the samples are cut according to the international standard for testing materials, [27-30].

Table 1. Types of Laminations

| Sample | Type of Resin | Lamination Scheme                      | Perlon % | Fiber % | Resin % |
|--------|--------------|----------------------------------------|----------|---------|---------|
| S_1_a  | Polyester    | 4 Perlon+4 Kevlar Fiber+4 Perlon        | 28       | 18      | 54      |
| S_1_b  | Araldite     |                                        | 28       | 18      | 54      |
| S_1_c  | Orthocryl    |                                        | 28       | 18      | 54      |
| S_2_a  | Polyester    | 4 Perlon+4 Glass Fiber+4 Perlon         | 28       | 18      | 54      |
| S_2_b  | Araldite     |                                        | 28       | 18      | 54      |
| S_2_c  | Orthocryl    |                                        | 28       | 18      | 54      |
| S_3_a  | Polyester    | 4 Perlon+4 Carbon Fiber+4 Perlon        | 28       | 18      | 54      |
| S_3_b  | Araldite     |                                        | 28       | 18      | 54      |
| S_3_c  | Orthocryl    |                                        | 28       | 18      | 54      |
| S_4    | Orthocryl    | 3 Perlon+2 Kevlar+2 Perlon+2 Glass+3 Perlon | 28       | 18      | 54      |
| S_5    | Orthocryl    | 3 Perlon+2 Carbon+2 Perlon+2 Glass+3 Perlon | 28       | 18      | 54      |
| S_6    | Orthocryl    | 3 Perlon+2 Kevlar+2 Perlon+2 Carbon+3 Perlon | 28       | 18      | 54      |
4. Results and Discussion
The experimental program has been achieved for all the samples in Table 1. This covers mainly three types of experiments. For all the samples, the volume fractions are kept approximately the same for comparison purposes. They are 28%, 18%, and 54%, for perlon, fibre, and the resin respectively.

1. Tensile test: The composite samples were tested by using the tensile testing machine [1], Fig. 5. The stress-strain diagrams are plotted as shown in Fig. 6, together with a linearization for each sample behavior. Each specimen test has been repeated three times and achieved according to the standard ASTM-D638. The results shown in Tables 2 and each value represents the average tensile and the average modulus of elasticity for three samples for each test. The results are approximately agree with those published in the previous literatures, with a wide stress-strain diagram area with an indication of high strain energy absorption and then high toughness and impact strength [31-34]. The using of Orhocrylic resin 80:20 with hardener 1.5-3% is better than using the araldite and ployster resins.

Fig. 4. Specimen preparation

Fig. 5. Tensile Sample According to ASTM-D638 Standard.
a. sample S1a

\[ y = 153.35x + 3.4296 \]

b. sample S1b

\[ y = 178.31x - 2.8625 \]

c. sample S1c

\[ y = 162.74x + 2.8199 \]

d. sample S2a

\[ y = 224.52x + 3.8333 \]

e. sample S2b

\[ y = 237.64x + 3.6574 \]

f. sample S2c

\[ y = 253.92x + 5.1434 \]

g. sample S3a

\[ y = 224.66x + 5.4348 \]

h. sample S3b

\[ y = 237.7x + 6.0444 \]
2. The three points bending test (Fig. 7) for the specimens shown in Table 1 from which the modulus of elasticity and the tensile strength are obtained. Three samples were tested to determine the average values of modulus of elasticity and tensile strength as shown in Tables 2 and 3. The test was achieved according to the standard ASM-D790, [35-40].

This flexural test mentioned is carried out to calculate modulus of elasticity and tensile strength, with the help of the following equations, the modulus elasticity and the tensile strength are calculated as follows:

\[ E = \frac{L^3m}{4bh^3} \]  \hspace{1cm} (11)

\[ \sigma_f = \frac{3FL}{2bh^2} \]  \hspace{1cm} (12)

\[ \delta = \frac{6\delta_{ch}}{L^2} \]  \hspace{1cm} (13)

For the beam under bending shown in Fig. 7 , the load - deflection for the sample S2c in which the layers are arranged ( 4 perlon+ 4 carbon fibers + 4 perlon) with Ortocrylic resin . It is expected that the break occurs at strain not more than 5% of the outer surface of the laminate without failure. In Fig. 7(b) a decline is observed due to the interfacial de-ponding which results in higher strains with respect to the applied loading. Then, the deflection occurs until the specimen rupture. Having obtained the plot of the load- deflection, equations (11) and (12) are used to calculate the modulus of elasticity and tensile strength. Each result shown in Tables 2 and 3, represents the average of three samples.
a. Three Point Bending Test.

b. Load Deflection

c. ASTM-D790 Standard

d. Bending Composite Sample

Fig. 7. Three Point Bending Sample According to ASTM- D790 Standard

Table 2: Results of Tensile strength and modulus of elasticity from tensile test.

| Experiment No. | Laminate sequence | Average tensile strength MPa (Tensile Test) | Average tensile strength MPa (Bending Test) | Discrepancy (%) |
|---------------|-------------------|---------------------------------------------|---------------------------------------------|-----------------|
| 1             | S1a               | 71.5                                        | 65.8                                        | 7.97            |
| 2             | S1b               | 72.8                                        | 68.2                                        | 6.32            |
| 3             | S1c               | 76.3                                        | 70.4                                        | 7.73            |
| 4             | S2a               | 96.6                                        | 90.7                                        | 6.11            |
| 5             | S2b               | 78.3                                        | 72.8                                        | 7.02            |
| 6             | S2c               | 98.8                                        | 93.4                                        | 5.47            |
| 7             | S3a               | 120.8                                       | 113.4                                       | 6.13            |
| 8             | S3b               | 122.2                                       | 115.7                                       | 5.32            |
| 9             | S3c               | 124.7                                       | 116.8                                       | 6.34            |
| 10            | S4                | 118.3                                       | 111.2                                       | 6.00            |
| 11            | S5                | 95.3                                        | 88.4                                        | 7.24            |
| 12            | S6                | 102.3                                       | 95.6                                        | 6.55            |

Table 3: Results of tensile strength and modulus of elasticity for the three points bending test.

| Experiment No. | Laminate sequence | Average modulus of elasticity GPa (Tensile Test) | Average modulus of elasticity GPa (Bending Test) | Discrepancy (%) |
|---------------|-------------------|-----------------------------------------------|-----------------------------------------------|-----------------|
| 1             | S1a               | 15.3                                         | 14.3                                         | 6.54            |
| 2             | S1b               | 17.8                                         | 16.7                                         | 6.18            |
| 3             | S1c               | 18.3                                         | 17.3                                         | 5.46            |
| 4             | S2a               | 22.5                                         | 20.8                                         | 7.56            |
| 5             | S2b               | 23.8                                         | 22.4                                         | 5.88            |
| 6             | S2c               | 25.4                                         | 23.7                                         | 6.69            |
| 7             | S3a               | 22.5                                         | 21.1                                         | 6.22            |
| 8             | S3b               | 23.8                                         | 22.6                                         | 5.04            |
| 9             | S3c               | 25.6                                         | 23.8                                         | 7.03            |
| 10            | S4                | 31.5                                         | 29.7                                         | 5.71            |
| 11            | S5                | 24.6                                         | 23.1                                         | 6.10            |
| 12            | S6                | 26.3                                         | 24.7                                         | 6.08            |
3. The Charpy test is employed to obtain the impact strength of material. Similarly, each value represents the average impact strength of three samples. The test was achieved according to the international standard ED-23.

The impact energy (Joule) are plotted against $bh_{\text{Comp}}$ (mm$^3$) in Fig. 8 for all the samples presented in Table 1. It seems that the impact energy values are increased due to using the fibers in laminates in with the using the resin only. Many literatures presented sockets using the polypropylene for amputees in developing countries since it is cheap, but the mechanical properties can’t meet the durability and the acceptable percentage of weight/strength. The results indicate that using the present work samples may be used in rehabilitation centers for artificial limbs for amputees. The sample Sc3 has shown the high values of toughness and fracture toughness as shown in Figs. 9, 10, 11, 12, and 13 compared to using the other types of fibers. This is because that the Kevlar fibers have the applicability in responding to the impact loading and instead of that the fracture occurs across its section, the Kevlar fibers will absorb the energy in two directions which results in increasing the toughness and the fracture toughness of the sample. This may give an indication of ductile behavior of Kevlar in opposite to the other types of fibers if the other laminates are the same. The other samples of mixing the fibers, as shown in Fig. 8.d. The contribution of the Kevlar fibers are clear in responding to the impact loading compared to the other types of fibers. It is noticed that the toughness of the model with layers (4 perlon + 4 kevlar fibers + 4 perlon ) with Ortocrylic resin has shown a maximum toughness energy as in Fig. 8.c with a value equal to 147.9 KJ/ m$^2$ and the maximum impact energy for this model is equal to 13.5 Joule.

The results of the maximum toughness was obtained by using Eq. (8) via a linearization equation which was obtained by curve fitting technique for each case and presented in Fig. 9 together with the straight line equation. The slope of each line represents the toughness of the lamination for each case. The results are shown on histograms in Figs. 10 and 11. This factor is so important in the choice of the lamination to be used in the manufacturing of the sockets, because the patient may face impact loading in his motion during daily life. Therefore, the sockets manufacturers ask for the toughness of the laminate before taking action in manufacturing in the rehabilitation centers for the people of special needs. Also, the fracture toughness are calculated by using Irwins [19] formula Eq. (10) and presented in Figs. 12 and 13. It is seen that the fracture toughness of the sample (4 perlon + 4 Kevlar + 4 perlon) has the highest value (65.70 MN/m$^3$/2) which can be recommended to be used in rehabilitation centers of people of special needs.

![Diagram](image_url)

a. Laminate (4 perlon + 4 glass fiber + 4 perlon) + resin ( arladite, Polyester, Orthocrylic)
b. Laminate (4 perlon + 4 carbon fiber + 4 perlon) + resin (Arladite, Polyester, Orthocrylic)

c. Laminate (4 perlon + 4 kevlar fiber + 4 perlon) + resin (Arladite, Polyester, Orthocrylic)

d. Different types of laminations using Orthocrylic resin

Fig. 8: Impact Energy (Joule) versus (b.h. Comp.) (mm³) for Different Composite Samples
a. Laminate (4 perlon + 4 glass fiber + 4 perlon) + resin (Arladite, Polyester, Orthocrylic)

b. Laminate (4 perlon + 4 carbon + 4 perlon) + resin (Arladite, Polyester, Orthocrylic)

c. Laminate (4 perlon + 4 kevlar fiber + 4 perlon) + resin (Arladite, Polyester, Orthocrylic)
d. Different types of laminations using Orthocryl resin

Fig. 9: Fitting of the experimental results between the impact energy and (b.h. Comp.).

Fig. 10: Toughness comparison for different composite.

Fig. 11. Toughness for different composite materials using Orthocryl resin.
5. Conclusions
From the suitability of the materials used in manufacturing the prostheses sockets point of view, the following conclusions are drawn:
1. The energy consumed to fracture the composite laminate is decreased with increasing the crack depth.
2. The laminate of 12 layers, (4 perlon + 4 kevlar + 4 perlon) using Orthocrylic resin has shown a maximum toughness energy compared to using glass or carbon fibers.
3. The using of Orthocrylic with all the samples has shown a good toughness and high fracture toughness compared to other resins.
4. The using of Kevlar fibers with other fibers modifies its toughness and fracture toughness characteristics. This proves that the Kevlar fibers has better absorbing energy compared to other fibers used in laminates of prostheses sockets.
5. The level of tensile stress is considerably acceptable for manufacturing the sockets of the prostheses since the contact pressure between the socket and the stump is of a low value which may reach 250 KPa.
6. In the case of increasing the crack length, it is noticed that the strain energy is decreased due to the decrease of the stiffness.

7. Finally, the recommendation for the rehabilitation centers to manufacture the sockets with Kevlar fibers to absorb energy and may work as dampers.

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