International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Impact Testing of New Athletic Prosthetic Foot

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Accepted 11 Jan 2015, Available online 01 Feb 2015, **Vol.5, No.1 (Feb 2015)**

Abstract

No artificial limb can replace what is lost. However, aggressive rehabilitation and appropriate prosthetic provision will enhance the ability of injured individuals to pursue athletic activities once again. To design and manufacture an athletic prosthetic foot that can perform at the level of professional athletes, it must pass some tests to improve its suitability and comfort ability to use, one of these tests is the impact test. In order to test the suitability of the manufactured athletic prosthetic foot, impact foot tester were designed and manufactured for this purpose. Impact test simulates the response of the foot during running and calculating the peak force. This paper presents the results of tests designed to (a) measure the loads and loading rates. For this purpose, tests the impact plate was instrumented with a load cell, the pendulum with proximity sensor. Peaks load-time response was observed with an event duration of about 30 ms.

Keywords: *Impact Testing, Athletic Prosthetic Foot etc.*

Introduction

The aim of a prosthetic device is to imitate the function of the human body as closely as possible. Although, no artificial limb can replace what is lost. Understanding the biomechanics of the sport and physical characteristics of the remnant limb are the first steps in determining what prosthesis can provide, the needs of the amputee should be clearly understood, and the functional demands of the activity should be determined prior to generating the prescription (Fergason J. R. *et al*, 2012).

For athletics, especially the runners, the loss of lower limb(s) causes loss of mobility, even for amputee who loses the lower limb. The two most often performed amputation procedures are truncation of the femur bone above the knee (AK) and truncation of the tibia bone below the knee (BK).

The Athletic Foot

In 1982, an aerospace composite engineer, who was a member of a team working at the University of Utah, cut a carbon fiber (a well-known material in the aerospace industry for its superior strength and flexible properties) into an (L) shaped foot and attached it to a sole below and to a prosthetic socket above . When weight was applied on the heel, it was converted into energy that literally put a spring action into the step, simulating the spring action of the normal foot and allowing the wearer to run and jump.

The Flex-Foot concept was born in 1984, and the demand for the new foot soared as active amputees across America became aware of its incredible spring and energy-return features (Cheskin M. *et al*, 2004).

The Flex-Foot Cheetah, first produced by Össur in 1996, was designed in order to give amputee athletes the ability to compete at an entirely different level in running sports.

In order to produce a prosthetic foot that can perform at the level of professional athletes, the materials used need to be light weight, responsiveness and incredibly strong. Carbon fiber is the ideal material for this situation as it has high tensile strength while being very light weight.

The objective of this paper is to manufacture an athletic prosthetic foot and test it for body impact load. Designing and manufacturing an impact foot tester and using special electromechanical device to measure instantaneously the response of impact with time.

Walking versus Running

Running, like walking, is a series of pronation and supination. Running is distinguished from walking by increased velocity or distance traveled per unit time, and the presence of an air borne (takeoff) or float phase. Judges in race walking determine that participants are running illegally if they observe a period of time when both feet are off the ground.

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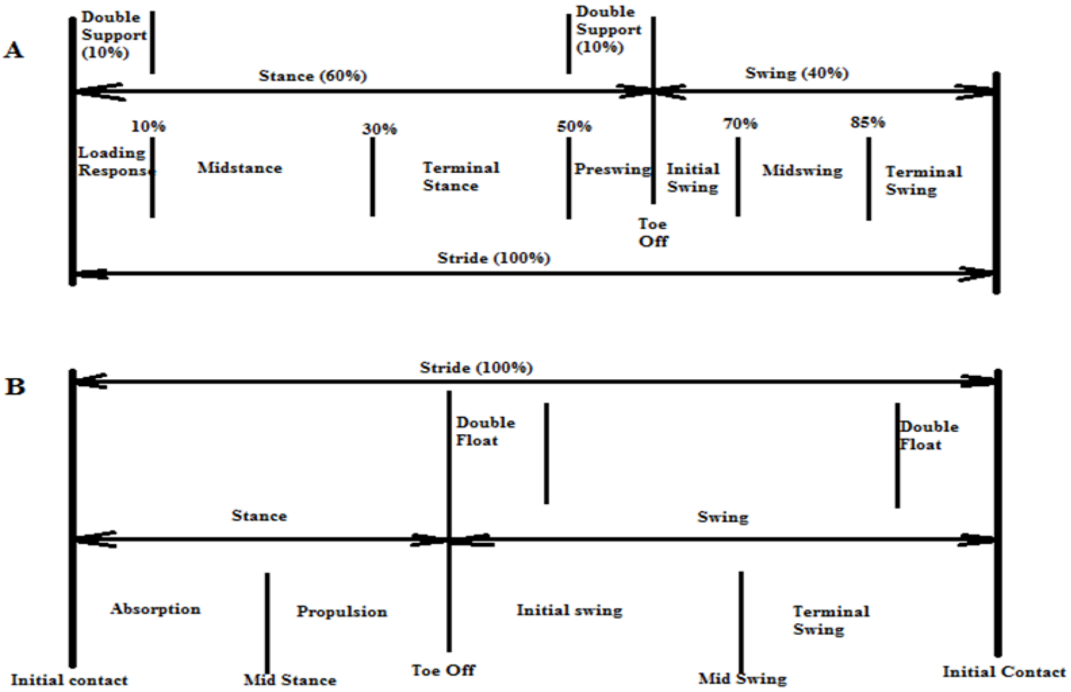


Figure 1: Gait cycle with phases and individual components (*A*) Walking. (*B*) Running.

During a running gait cycle, there are two periods of float when neither foot is in contact with the ground, Figure 1 (Dugan S. A.. *et al*, 2005). This results in decreased time in stance phase and increased time in swing phase. As velocity continues to increase, further reduction in stance phase occurs, whereas swing phase duration increases. Unlike walking, the forward momentum, which is needed for running, is produced by the swinging leg and arms, rather than the stance leg (Mann R. A. *et al*, 1982).

Runners also require more from their joints and muscles than walkers. A greater joint excursion has been noted with hip flexion, knee flexion and ankle dorsiflexion with running (Ounpuu S. *et al*, 1994).

The differences between running and walking (Zabjek K. F. *et al*, 1997) are:

1. Increased velocity.
2. Increased ground reaction force.
3. Float phase.
4. No double stance phase.
5. Decreased stance phase and increased swing phase.
6. Overlap of swing phase rather than stance phase.
7. Requires more range of motion of all lower limb joints.
8. Requires greater eccentric muscle contraction.
9. Initial contact varies, depending on speed.
10. Decreased center of gravity with increased speed.

The Development of Prosthetic Foot

For the last 20 years of the 20th century, the major development of the flexible foot was seen. Two pieces of carbon fiber, light weight, flexible and strong material more commonly used in aeronautics at the time, were utilized to build a foot that more easily enabled sports participation (Figure 2).

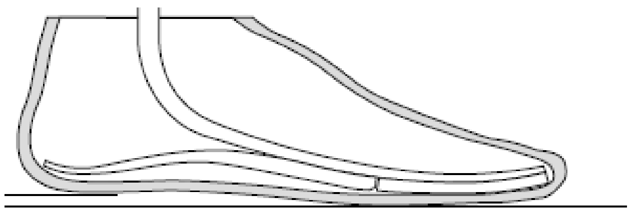


Figure 2: Flex foot

Each time body weight moves over this flexible foot, it compresses, and energy is stored. As body weight shifts off the foot, the carbon fiber returns to its original shape, returning energy as it decompresses. This foot named the flex foot (Össur, Reykjavik, Island) , effectively provides a puss-off, something not seen in other prosthetic feet at the time (Nolan L *et al*, 2008). The flex foot was first seen in elite sport at the (1988) Para-Olympic games (Pailler D *et al*, 2004). For years later, the prosthetic heel, for some athletes, was absent (Pailler D *et al*, 2004) creating the first sprint prosthesis. Today in elite running and jumping events, the carbon fiber prosthesis is seen almost exclusively.

There is much doubt about the reliability of measurements taken from gait tests alone due to the subject altering their gait style when being analyzed in the laboratory setting and accommodating different prosthetic components. For this reason, some investigator have performed a static mechanical test to avoid the variability introduced by a subject.

Daniel and Polizzi (Rihs D. *et al*, 1988) utilized the impact tests. The purpose of these tests is to decrease the shock exerted on the residual stamp of the amputee at heel strike. The material in the prosthesis needs to absorb and transfer this force into forward movement. Therefore, this study has focused on the characteristics of shock time over which the force is applied.

Glenn *et al.* (Glenn K. Kulte. *et al*, 2004) studied the heel region properties of prosthetic feet and shoes. A pendulum was constructed to measure the response of heel to impact and mechanically simulate the conditions immediately following the initial heel ground contact during walking. A pendulum mass of (6 kg) was used to duplicate the effective mass of stance limb at instant of heel ground reaction contact. The velocity immediately prior to impact, by using two fiber optic photoelectric sensors and the energy dissipation capacity of various prosthetic feet, was calculated using the force deformation diagram.

Experimental Work

To design and manufacture the athletic prosthetic limb Figure 3, some experimental tests are recommended (Movaghghar A. *et al*, 2012), one of these tests is the impact test. The three most important and widely studied mechanical properties are (Chai H *et al*, 1981):

1. Stiffness and Young's modulus.
2. Range of motion.
3. Shock absorption.

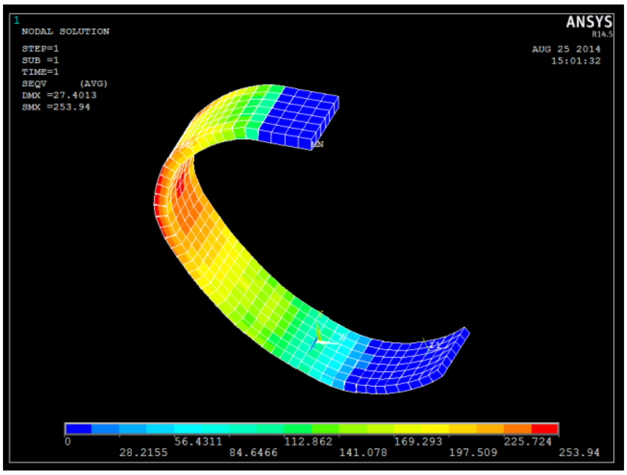


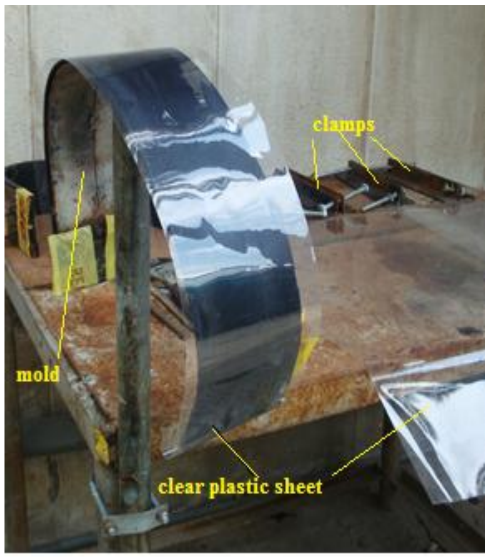
Figure 3: Design and stress distribution on the new athletic foot

Design and Manufacturing the New Athletic Prosthetic Foot

In order to investigate the influence of the matrix material of the foot, i.e., the epoxy type, on the dynamic behavior of the components, and to contribute for a better understanding of the dynamic behaviors of the fiber reinforced composite materials, specifically for the case of athletic prosthetic foot, three types of resin were used to build three samples using glass fiber as reinforcement. Firstly, the templates (mold die) were made from 3mm thick steel plate according to the desired profile, Figure 4. The layup process was employed to manufacture the samples.

The surface of the mold was thoroughly cleaned to be ready for use by removing dust and dirt residues. After the mold surface has been cleaned, a releasing agent was applied uniformly by coating the mold surface with a silicon free wax using a smooth cloth. Then, a clear plastic sheet was applied over the wax surface that had good surface finish.

(a)



(b)

Figure 4: (a) Mold and Die for Manufacturing the Athletic Foot (b) Preparing the Mold

The matrix material was prepared by adding a hardener to the resin according to the ratio described by the manufacturer. The mixture was left for some time, so that bubbles formed during stirring totally disappeared.

The glass fiber (E-glass woven of 600 g/m^2) or carbon fiber (woven 400 g/m^2) was used as reinforcement. The fabrics were made of fibers oriented along two perpendicular directions. One is called the warp and the other is called the fill (or weft) direction. The fibers are woven together, which means the fill yarns pass over and under the warp yarns, following a fixed pattern , Figure 5 shows a plain weave, where each fill goes over a warp yarn then under a warp yarn and so on (Akkerman R. *et al*, 2006).

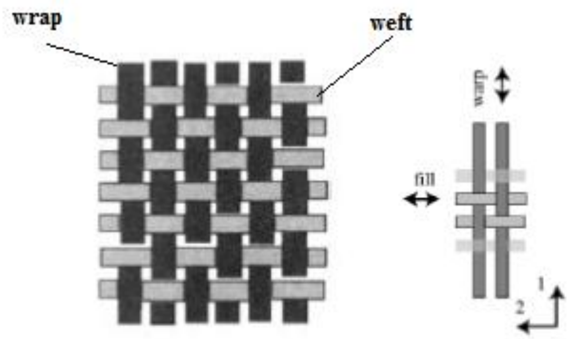


Figure 5: Schematic representation of woven fabric architecture

Preparation of the laminated sample

The fibers were cut to the desired size, so that they can be deposited on the template layer by layer during fabrication, Figure 6.

Figure 6: Fibers cut to desired size.

The first layer of mat was laid, and the resin was spread uniformly over the mat by means of brush. The second layer of mat was laid and resin was spread uniformly over the mat by means of brush. After the second layer, to enhance wetting and impregnation, a teethed steel roller was used to roll over the fabric before applying the resin. This process was repeated till all the fabric layers are placed, and the required dimensions were obtained. External pressure was applied while casting or curing to squeeze out the uncured matrix material under high pressure. The duration of the process may take up to 30 mins. Then, the whole thing is swung into an autoclave that melts and fuses the resin and sheets into a solid. The mold was allowed to cure for several days (4-5 days) at room temperature. After the curing process, the test samples were cut to the desired dimension by using a diamond impregnated wheel. All the test samples were finished by abrading the edge on fine carborundum paper. The laminated plate was cut at different off-axis angles 0°, 45°. Since each fabric layer corresponds to two different fiber orientations (fiber at 0° and 90°), two different layers can be used to stimulate each ply as ([0/90], [-45/45]).

Designing and Manufacturing the Impact Foot Tester

The construction of the impact foot tester was designed and manufactured in the present work, Figure 7. The impact tester consists of a frame, a pendulum arm of 0.6 m length, which can be justified, a journal bearing pivot at the top fixing the pendulum arm, 6 kg mass was used to duplicate the effective mass of the stance (Toh S. L. *et al*, 1990), and a fixture to fix the athletic prosthetic foot to the mass. The load cell and sensors were connected to data acquisition system type NI-6009 through an amplifier and then a computer to receive the data and store it as an excel file.

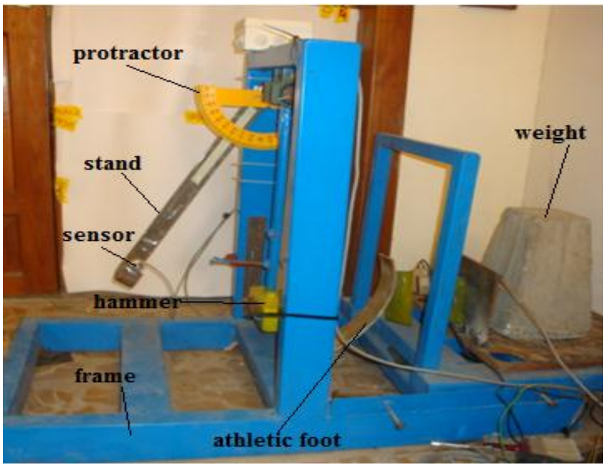


Figure 7: Impact Foot Tester

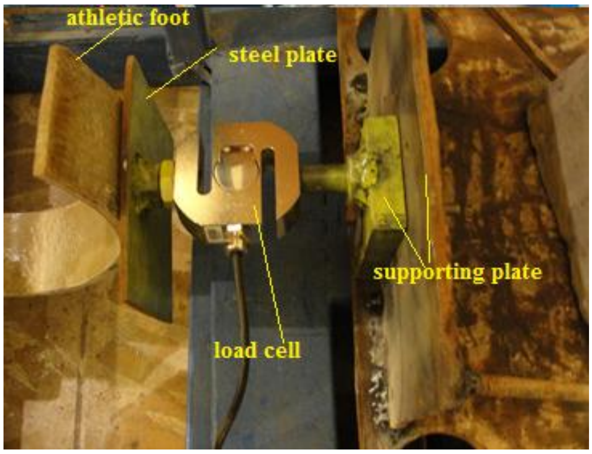


Figure 8: Strike Plate Fixed with Load Cell on Frame

Pendulum motion was measured using two sensors type ABB-SIN-M18N-N2-NO / 1SAF 118122 R3000.

The pendulum and the attached prosthetic foot were lifted to desired heights and released down. The foot impacts a steel strike plate to which a (1000 kg) load cell was attached, Figure 8.

Certain details of the experimental equipment can have a significant influence on the behavior of the test, such as restraining the impact tester against translation. However, in preliminary tests, it was found that the impact event would cause the frame to move across the lab. Therefore, it was propped against the wall to restrain the frame from forward translation during the tests.

Impact test

Four athletic prosthetic feet were studied. Three samples used different epoxy material to manufacture with glass fiber, the other one used AXSON epoxy with carbon fiber.

The foot was fixed rigidly to the pendulum hammer, Figure 9.

Ranges of impact tests were conducted for each sample to characterize the response of the foot. Figure 10 shows the response of a sample with time for a certain height of the pendulum.

Figure 11 shows the variation of maximum impact load (the first peak) with angle of drop for the sample manufactured from carbon fiber with AXSON epoxy.

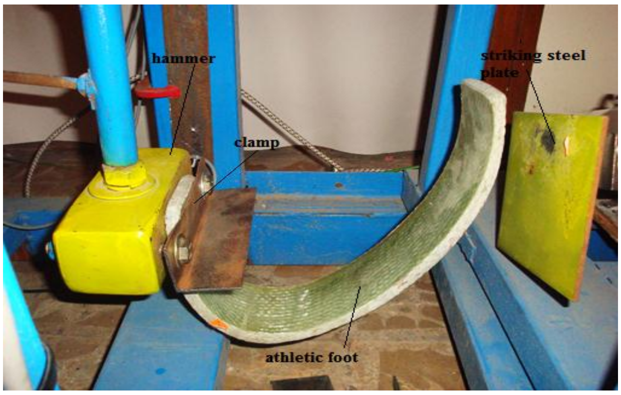


Figure 9: The foot fixed on a pendulum mass

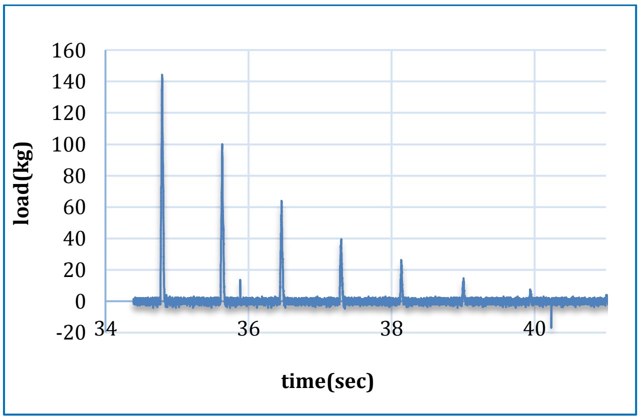


Figure 10: Response of a Foot with Time for a Certain Height (H) of the Pendulum

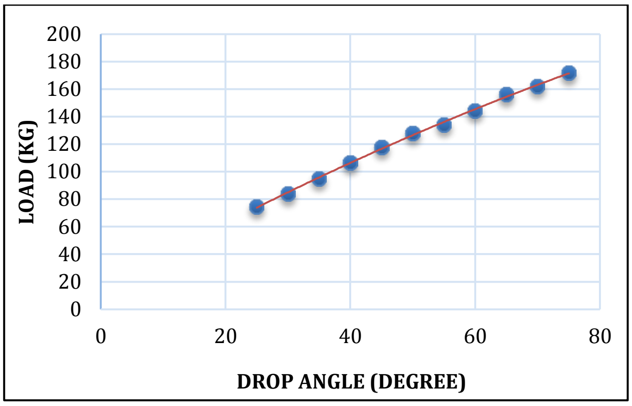


Figure 11: Variation of Maximum Load with Drop Angle for carbon fiber with Axson sample

Mechanical properties of the composite materials

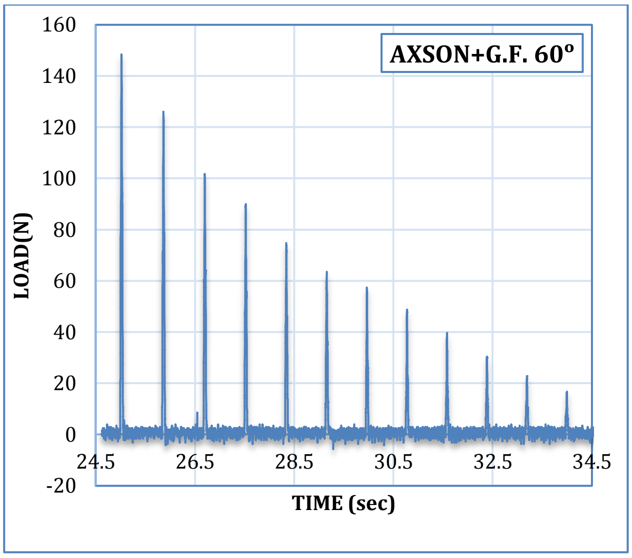
The mechanical properties of the composite materials used are shown in Table 1.

Table1: Mechanical properties for glass and carbon fiber samples

	Carbon fiber + AXSON	Glass fiber + AXSON
E_1 (GPa)	91.772	39.95
E_2 (GPa)	91.772	39.95
E_3 (GPa)	20.432	20
υ_{12}	0.0505	0.14
υ_{13}	0.2796	0.31
υ_{23}	0.2796	0.31
G_{12} (GPa)	7.5	7.655
G_{13} (GPa)	7.494	7.5
G_{23} (GPa)	7.494	7.5

Results of impact tests

Figures 12 and 13 show graphically the impact load versus time of the four samples of athletic prosthetic feet used the impact tester.



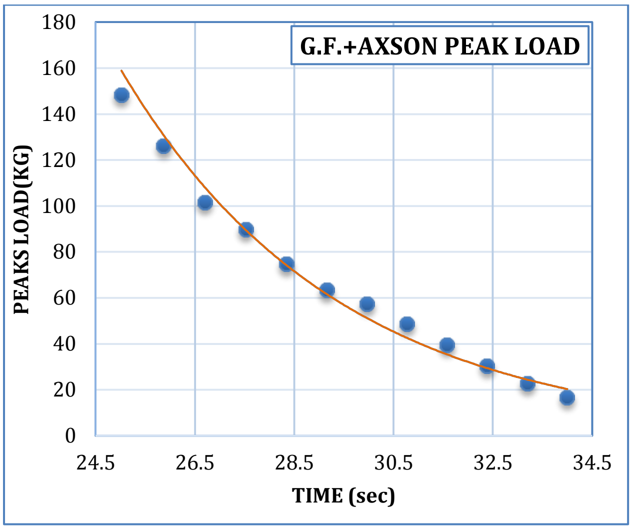


Figure 12: Impact load versus time and peak load characteristics for the resin and fiber shown

It is possible to determine the impact time of each prostheses and the shock absorption characteristics. These figures show the impact response and the characteristics of peaks during the time. All experiments have the same drop position (60°).

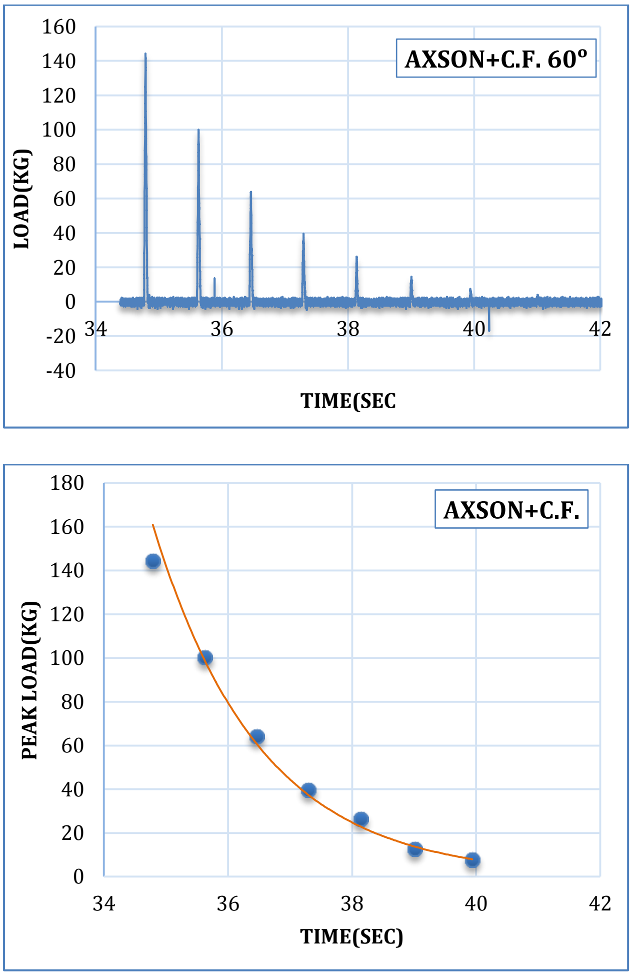


Figure 13: Impact load versus time and peak load characteristics for the resin and fiber shown

Figure 14 shows the impact load-time curve for four samples of the athletic prosthetic foot for a range of impact drop position from 25° to 60°. The curves reveal a non-smooth response through the event. The first response happened between (0-20) ms, then the peaks response occurred at about 30 ms and the third occurred between (36-45) ms of the total event ending at about (55-65) ms. This response indicates the behavior of athletic prosthetic foot during the total event time.

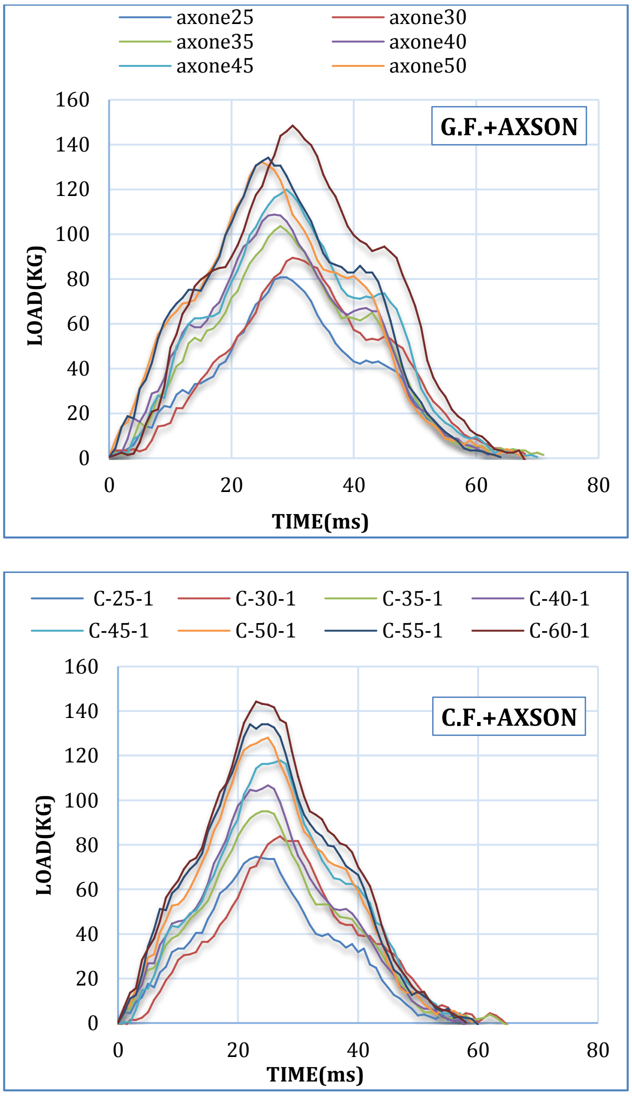


Figure 14: Impact load-time curve for four samples of the athletic prosthetic foot

Discussion of impact results

Figures 12 to 13 show the peaks from the first impact to the last one for each sample of foot and the drop of the peaks; these results can be compared with the behavior of different prosthetic feet in reference (Braddom R. L*et al*, 1996).

Figure 14 illustrates the behavior of the foot during the impact. The first part 0-20 ms indicates that the foot hits the load cell and begins to record the load, which increases until the time reached 20 ms, then the foot will begin to deflect and the load increased on the load cell to a maximum record. Hence, the deflection is decreased when the time reached about 30 ms (crossing the peak load) until the foot has the original shape (the region between 35-45 ms), and the load will be decreased in the same time, then the foot begins to rebound from the load cell until it completely leaves it in the end of event.

The difference in the stiffness between the composite material foot and the load cell is the major reason for this behavior. Comparing the graphs *a* and *b* in Figure 14, the two feet were manufactured by the same epoxy but one with glass fiber and the other carbon fiber, therefore, the foot has a higher stiffness, more smoothly response from the other.

Conclusions

The experimental work consists of manufacturing prosthetic athletic foot. The foot was manufactured using carbon fibers and epoxy that gives good mechanical response. The impact tester was designed and manufactured to perform the test.

For the same dropped level, the impact response of the samples with glass fiber and carbon fiber have the same peak load for different drop angle but.

In addition, it is clear that the responses of the sample manufactured with carbon fiber were more smoothness than the sample manufactured with the glass fiber.

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