

Mechanical and Energy Engineering

Impact Response for Two Designs of Athletic Prosthetic Feet

Dr. Mohsin N. Hamzah
Assistant Professor
Mechanical Engineering Department
University of Technology
20066@uotechnology.edu.iq

Dr. Ammar S. Merza
Lecturer
Mechanical Engineering Department
University of Technology
20086@uotechnology.edu.iq

Lamees Hussein Ali
BSc. In Mechanical Eng.
Mechanical Engineering Department
University of Technology
lamees.mail@gmail.com

ABSTRACT

The present work evaluated the differences in mechanical properties of two athletic prosthetic feet samples when subjected to impact while running. Two feet samples designated as design A and B were manufactured using layers of different orientations of woven glass fiber reinforced with unsaturated polyester resin as bonding epoxy. The samples' layers were fabricated with hand lay-up method. A theoretical study was carried out to calculate the mechanical properties of the composite material used in feet manufacturing, then experimental load-deflection test was applied at 0 degree position and 25 degree dorsiflexion feet position and impact test were applied for both feet designs to observe the behavior of the feet under static and impact loading and compare properties like stiffness, efficiency, rigidity, and shock absorption at different drop angles range from 25 degrees to 60 degrees which perform the foot positions while running. The load-deflection test result shows that the maximum deflection of the proposed design B was 32.2 mm at 0° and 38.45mm at 25°. While it was 41mm at 0° and 39mm at 25° for design A. Impact test result shows that design B foot gives peak load of 128.7 kg with a peak time of 0.06 sec, while design A foot gives 125.32 kg peak load with a time of 0.069 sec.

Keywords: Athletic prosthetic feet; composite materials, impact test.

استجابته الصدمه لتصميمين من الاقدام الاصطناعية الرياضيه

لميس حسين علي
بكالوريوس هندسة ميكانيكية
قسم الهندسة الميكانيكية
الجامعة التكنولوجية

د. عمار سليم حميد
مدرس
قسم الهندسة الميكانيكية
الجامعة التكنولوجية

د. محسن نوري حمزه
أستاذ مساعد
قسم الهندسة الميكانيكية
الجامعة التكنولوجية

الخلاصة

يقيم البحث الحالي الاختلافات في الخواص الميكانيكية لعينتين من الاقدام الاصطناعية عند التعرض للصدمه أثناء العدو. حيث في هذا العمل، تم تصنيع عينتين اشير اليها ب A و B باستخدام طبقات من الألياف الزجاجية المنسوجة باتجاهات مختلفه والتي تم ربطها مع بعضها باستخدام راتنج البوليستر غير المشبعة باستخدام طريقه الترتيب اليدوي لطبقات الألياف. ثم أجريت دراسة نظرية لحساب الخواص الميكانيكية للمواد المركبة المستخدمة في تصنيع الأقدام، و تم تطبيق عدة اختبارات تجريبية منها اختبار الحمل- الانحراف عند وضع القدم بزوايه 0 و 25 درجة واختبار صدمه على كلا العينتين لمراقبة سلوك القدمين تحت تأثير الحمل الثابت وحمل الصدمه ومقارنه خصائص كالصلابه والكفاءه والصلاده وقابليه امتصاص الصدمه عند زوايا سقوط مختلفه



تتراوح من 25 درجة الى 60 درجة والتي تمثل مواقع القدم اثناء دوره العدو. من نتائج اختبار الحمل-الانحراف تبين ان اقصى انحراف لعينه القدم B كان 32.2 ملم عند زاويه 0 و 38.45 ملم عند زاويه 25 في حين كان 41 ملم عند زاويه 0 و 39 ملم عند زاويه 25 لعينه القدم A. نتائج اختبار الصدمه اظهرت ان عينه القدم B تعطي حمل ذروه يعادل 128.7 كغم خلال 0.06 ثانيه في حين عينه القدم A تعطي 125.32 كغم حمل ذروه خلال 0.069 ثانيه.

الكلمات الرئيسيه: قدم اصطناعيه رياضيه; مواد مركبه, اختبار صدمه.

1. INTRODUCTION

The energy storage prosthetic foot is a new generation of prosthetic feet that appears and becomes common, especially among athletes, **Michael, 1987**. In 1977 Terry Fox, **Scrivener, 2010**, an athlete runner was diagnosed with bone cancer and that force his leg to be amputated. In 1979 he started training on marathon using a heavy prosthetic leg that is not designed for running, that prosthetic was not designed to absorb the shock created by running, so the foot was adjusted by adding a spring but it broke while Terry Fox was running to Sault Ste. After that incident, he died but inspired a lot of peoples to develop a prosthetic leg suited for running. Bruin and Iler (cited in reference **Marshall, 2008**, designed an improved prosthetic leg with a spring shaft that reduces shock and shortens the leg to lower the center of gravity while compression, then all the energy will be released while toe-off pushing the runner forward. Lower limb prosthetics have enhanced broadly since 1980, numerous sorts and states of these feet were created, for example, SACH foot, CHEETAH flex foot, and FLEX RUN foot. In 1988 the FLEX foot prosthetic was being set up to be wear in the sport. The FLEX foot can deal with change in load while running the foot store energy when compressed by the body weight. The foot then discharges the energy giving a forward movement to the runner, **Niehar, et al., 2014**. A composite material fiber fortified polymer is the primary materials for building these feet. The composite fiber generally distraught by staking fiber layers in different directions and numbers to give the wanted properties and shape the reinforcement is a polymer, ceramic, or metal. Polymers have a low strength, and rigidity than with metals. Metal has a high ability to deform under tensile load and ceramic is weak. Matrix is used to maintain the directions of the fibers and save them from the surrounding conditions. The best properties of these components are their low density, high strength and stiffness, and lightweight, **Campbell, 2010**. The moment of inertia of both Cheetah and Flex Foot is much lower than the other jointed leg types, due to better mass distribution. That's gives smoother control when moving. Cheetah flex foot can straightforwardly convert the vertical force into a linear movement, **Ossur, 2014**. The size of the elastic area also helps to execute the response of the natural leg during running gait cycle.

Based on popular feet models available in markets, two athletic prosthetic feet were designed and designated as design A and design B, the measurements for both feet designs are calculated using KINOVEA software, by applying a side-view picture of the foot to the program and specifies the known dimension as in our case only the length of the foot as shown in **Fig.1**. The software then will give all the rest of the desired profile dimensions. The width and thickness of both feet were concluded by suggesting different values and applying then on the foot model then analyzing the stresses and deflections of each suggested one to obtain the best width and thickness for the foot. Afterwards, the final feet dimensions resulted then draw using SOLID WORK 2014 software as shown in **Fig. 2** and **Fig. 3**. The current research objective is, firstly, manufacturing of two proposed designs of flexible leaf spring prosthetic feet by using woven fiberglass. Secondly, to evaluate the differences in mechanical properties of two athletic prosthetic feet samples when subjected to impact while running.



2. MANUFACTURING OF ATHLETIC PROSTHETIC FEET SAMPLES

Design A and B athletic prosthetic feet were manufactured in order to study their behavior while running by subjecting them to experimental static and impact tests and compare the obtained results.

2.1 Preparing Mold

Two steel plates are cut in dimensions of 71cm × 15cm, and curved to resemble the profile of the design B foot; one presents the top cover mold and the other plate will be base fixed on a steel column. For Design A prosthetic foot each plate are cut in dimensions of 61cm × 15cm and curved to match the shape of the foot. The steel plates are shielded with a thick sheet of rubber to give a smooth surface to the mold. The second film of a clear plastic sheet is added to protect the foot from adhesion with the mold, as shown in **Fig.4**.

2.2 Preparing Composite

The material used for molding both feet designs is a woven glass fiber reinforced with unsaturated polyester resin. -45°, 45°, and 0°, 90° woven fiberglass layers are cut into multiple lengths in order to give the required thickness reduction for the foot **Fig.5**. Several resins to harden mixing ratios were tested in order to obtain a value that gives enough time to finish laying up the fibers before starting to solidify. The resin is mixed with the hardener in a ratio of 1 liter: 1.5 milliliters. This gives an approximate time of 2 hours to start solidifying within outside temperature of 44-degree centigrade.

2.3 Molding

Fibers layers were added in the sequence of 0°, 90° fibers orientation layer followed by -45°, 45° fibers orientation layer. The first layer is added and the resin is laid over it by using a painting brush until the layer is fully saturated, a second layer is then placed and the resin is added over it by means of a brush. After the second layer, a steel teathed roller was used to roll over the added fibers layers before applying any additional resin to remove any trapped air bubbles and ensure equal distribution of the resin along the fibers layers, This process was repeated till all the fabric layers were placed and the required foot thickness was obtained. The assembly afterward transferred into the mold and pressed using special clamps to get rid of excess resin. The mold was then left for 4 days in the outside conditions of 44°C temperature to dry. **Fig.6** shows the final step of molding including clamps arrangement.

After completely dried, both feet samples are cut to 7 cm width and drilled in order to fix it on test devices.

3. FEET SAMPLES PROPERTIES:

The elastic properties of the composite are calculated using the rule of mixture equations. It is a quick way to estimate the material properties, i.e., the module in 1 and 2 directions of a composite. It assumes that the modulus of the composite is a combination of the modulus of the fiber and the matrix that are related by the volume fraction of the constituent materials. To apply the equation, the properties of the glass fiber and the resin were obtained using the datasheets given by the



manufacturing company, and the fiber volume fraction (\mathcal{V}_f) was obtained from the densities and weights of fiber used in foot sample as listed in **Table 1** and **2** respectively.

The unidirectional elastic constants of the composite material used in both feet, that includes the elastic modulus in x-axis direction (E_1), in y-axis direction (E_2) and in z-axis (E_3), the shear modulus in x-y plane (G_{12}), x-z plane (G_{13}), y-z plane (G_{23}), and the Poisson's ratios in x-y plane (ν_{12}), x-z plane (ν_{13}), y-z plane (ν_{23}), are calculated by applying equations below, **Aly, et al., 2010**.

$$\begin{aligned}
 E_1^{udf} &= E_f \mathcal{V}_f + E_m (1 - \mathcal{V}_f) \\
 E_2^{udf} &= E_m \left[\frac{E_f + E_m + (E_f - E_m) \mathcal{V}_f}{E_f + E_m - (E_f - E_m) \mathcal{V}_f} \right] \\
 \nu_{12}^{udf} &= \nu_f \mathcal{V}_f + \nu_m (1 - \mathcal{V}_f) \\
 \nu_{23}^{udf} &= \nu_f \mathcal{V}_f + \nu_m (1 - \mathcal{V}_f) \left[\frac{1 + \nu_m - \frac{\nu_{12} E_m}{E_{11}}}{1 - \nu_m^2 + \frac{\nu_m \nu_{12} E_m}{E_{11}}} \right] \\
 G_{12}^{udf} &= G_m \left[\frac{G_f + G_m + (G_f - G_m) \mathcal{V}_f}{G_f + G_m - (G_f - G_m) \mathcal{V}_f} \right] \\
 G_{23}^{udf} &= \frac{E_{22}}{2(1 + \nu_{23})}
 \end{aligned} \tag{1}$$

where E_f and E_m are the elastic moduli of the fiber and resin, respectively, ν_f and ν_m are the Poisson's ratio of fiber and resin, G_f and G_m are the shear modulus of fiber and resin, respectively, and \mathcal{V}_f is the fiber volume fraction

A composite with a woven of 0, 90 and 45,-45 fibers orientation were used in manufacturing design A and B feet samples. The woven fibers elastic constants can then be calculated by using the following equations:

$$\begin{aligned}
 \left(\frac{2 E_1 (E_1 + (1 - \nu_{12}^2) E_2) - \nu_{12}^2 E_2^2}{E_1 E_1 (E_1 + 2E_2) + (1 + 2\nu_{12}^2) E_2^2} \right)^{udf} &= \left(\frac{1}{E_1} \right)^{wf} \\
 \left(\frac{4 \nu_{12} E_2 (E_1 - \nu_{12}^2 E_2)}{E_1 E_1 (E_1 + 2E_2) + (1 + 2\nu_{12}^2) E_2^2} \right)^{udf} &= \left(\frac{\nu_{12}}{E_1} \right)^{wf} \\
 \left(\frac{1 + \nu_{23}}{E_2} + \frac{1}{2G_{12}} \right)^{udf} &= \left(\frac{1}{G_{13}} \right)^{wf}
 \end{aligned} \tag{2}$$



$$\left(\frac{1}{E_1} \frac{E_1(v_{12} + v_{23} + v_{12}v_{23}) + v_{12}^2 E_2}{E_1 + (1 + 2v_{12})E_2} \right)^{udf} = \left(\frac{v_{13}}{E_1} \right)^{wf}$$

$$\left(\frac{(1 - v_{23}^2)E_1^2 + (1 + 2v_{12} + 2v_{12}v_{23})E_1E_2 - v_{12}^2 E_2^2}{E_1E_2(E_1 + (1 + 2v_{12})E_2)} \right)^{udf} = \left(\frac{1}{E_3} \right)^{wf}$$

$$\left(\frac{1}{G_{12}} \right)^{udf} = \left(\frac{1}{G_{12}} \right)^{wf}$$

Subscripts 1, 2, and 3 present lamina references axes. And *wf* and *udf* denote woven fiber, and unidirectional fiber respectively.

4. EXPERIMENTAL TESTS

A load deflection test was performed to measure the deflection of the foot for 0 degree and 25-degree foot positions by applying a vertical load that equals to three times body weight, increases from zero to 1600 N maximum on both feet. The load was applied on the location of the socket connection to the foot to present the load that the body will force through the period of mid stand (the foot is perpendicular to the ground with maximum weight applied on it) to push off. After mid stance and just before the toe off the period start, the foot developed an angle with the ground. To measure the dorsiflexion angle, the foot was fixed on a triangular shape wood piece fixed on the device frame; a force was applied on the prosthetic foot sample, this force present the ground reaction force while running. By using Dartfish 9 software analyzer, the angle was measured at each desired load value, **Fig. 7** and **8**.

The impact tests were then performed to study the behavior and response of the foot when the first impact the ground while running, the experiments were executed using an impact foot tester device that is set to examine the impact characteristics of athletic prosthetic foot **Merza, 2015**. The device consists of a steel frame, a pendulum arm, a 6 kg mass that is attached to the pendulum end to increase the stance effective mass **Toh, et al., 1990**, and a thick steel plate attached to a load cell, that works as a ground for the foot to hit. Design A foot was fixed to the pendulum mass while raised and dropped each time with a different drop angle range from 25 to 60 degrees that simulate the positions of the foot while running. On each drop, the foot hits the plate with a force that measured by the 1000 kg capacity load cell attached to the plate and transforms it to a DAQ system device, which reads the signals with time and displays it in a chart. The same test procedure was applied to the design B foot sample with some modifications on the way the foot attaches to the pendulum mass, **Figs. 9** and **10**.

5. RESULTS AND DISCUSSION

The elastic properties of the composite materials used in both feet sample were calculated by using the rule of mixture equations (1) and (2) are listed in **Table 3**. It can be noticed that there is a



difference in the elastic properties of composite between design A and design B foot in spite of using the same material in manufacturing and that due to the difference in the amount of fiber used (fiber volume fraction) in manufacturing both feet. The elastic modulus of the composite was compared with results from a tensile test performed by **Jweeg, et al.** and it's found to be close at the same woven glass fiber volume fractions with a percentage error of 5%.

The deflection behavior of both feet samples under loading and unloading for both 0 degrees and the 25-degree position was obtained, **Ali, et al., 2017**, in this test and the results demonstrate that the maximum deflection of the design B athletic prosthetic foot was 32.2 mm at 0° and 38.45mm at 25°. While it was 41mm at 0° and 39mm at 25° for design A athletic prosthetic foot. The difference in stiffness for each foot at 0 and 25-degree position is required to attain a smooth transition from the heel strike to the toe off phases of the running gait as well as the development of an angle that mimics the ankle dorsiflexion angle.

The efficiency to store and release energy for each foot was calculated depending on the loading and the unloading curves of the load-deflection test results, as shown in **Table 4**.

At each drop's angle, the foot load response with time was recorded, the peaks load and the maximum first peak, at each drop angle, for both feet samples were showed graphically in **Figs. 11 through 15**.

Figs. 11 to 13 showed that the behavior of the foot when hits the plat rebound seven times until its settled (which gives seven load peaks) for the design A foot, while six rebound times until settling was recorded for design B foot.

Fig.14 shows that for design A foot sample, at 60-degree drop angle the first peak started from zero at 0.84 sec and increased highly to reach a 125 kg load at 0.867 sec and that means it takes time period equal to 0.027 sec to reach the maximum load. In this period, the foot hit the force plate giving a signal to the load cell to start recording load then deflect giving an extra push toward the plat until reaching the maximum peak load. The foot then started to return to its natural shape leaving the plate and reducing the load until it reaches zero kg at 0.909 sec with a time period equal to 0.042 sec. That gives a total time approximate to 0.069 sec for the peak to start and finish, while for design B foot, at the first peak the load increases from zero to 128kg maximum within 0.032 sec and then the load decreases to zero within 0.028 sec. That gives 0.06 sec time for the peak to finish. The difference in peak shape between design A and B foot is because of the higher peak loading rate for the design B foot while impact due to low cushioning effect which gives a sharper more pointer peak compare to design A foot.

From the data given by the figures, it is possible to determine the peak impact time and peak load value for each foot design, as listed in **Table 5**.

Table 5 indicates that design B foot first peak is higher in value and is taken less time to start and finish than for design A foot.



There are dissimilarities in the overall impact behavior between both feet as shown in **Fig.15**, where the number of peaks produced at the 60-degree impact is 7 peaks for design A and 6 peaks for design B foot, also the peaks values are higher which indicate the variation in stiffness between the two feet.

5. CONCLUSIONS

In the current paper, two athletic prosthetic feet designs have been made using unsaturated polyester resin reinforced with fiberglass by means of hand laying method. Studies of the mechanical behavior of the manufactured feet were performed experimentally using load-deflection test and impact test, and results for both feet were compared as follows:

Under the same load value, the foot sample designated as design B has a higher stiffness than of the corresponding one of design A, taken into account that both feet are within the standard maximum deflection range for athletic prosthetic feet. The dorsiflexion angle of the design B foot is more than that of the corresponding one in design A, which may give a bend up to an acceptable limit gaining a better application for the gait cycle profile according to published work, **Resan, et al., 2011**.

Although the absorbing of the shock when the foot hits the ground while running depends mostly on the existing of a high-density foam or rubber at the foot rear end, the spring characteristic of the fiber forming the foot as well as foot shape has an effect on the shock absorbing **Rihs and Polizzei, 2001**. And that shows on results were the first peak applied time for the design A is longer than the design B, as well as the small difference between the first and second peak load, indicate that design A has a higher ability to observe the shock.

Design B foot has a higher first peak load compare to design A foot which means that design B foot is stiffer since stiffness for a prosthetic athletic foot is defined as the amount of flexibility while impact. The height of the impact peak depends on the stiffness, as the stiffness increase the impact peak load increase, **Fey and Neptune, 2011**. The body support will decrease as the foot stiffness decrease, and that will exert an extra work on the leg muscles to support the body. The decrease in foot stiffness led to low body force activity which has generally been known stiffness will provide a big support to the body while decrease stiffness will provide extra forward motion.

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NOMENCLATURE

E	Modulus of elasticity	N/m ²
G	Shear modulus	N/m ²
ν	Poisson's ratio	m/m
ν_f	Fiber volume fraction	
f	Fiber	
m	Matrix	
1	X axis	
2	Y axis	
3	Z axis	
wf	Woven fiber	
udf	Unidirectional fiber	

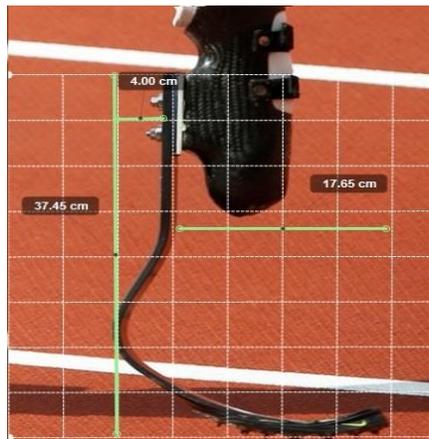


Figure 1. KINOVEA software foot dimensions analyses, Willer, 2014.

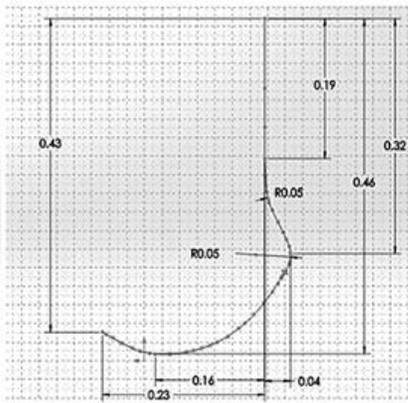


Figure 2. Dimensions of the Design B foot in m.

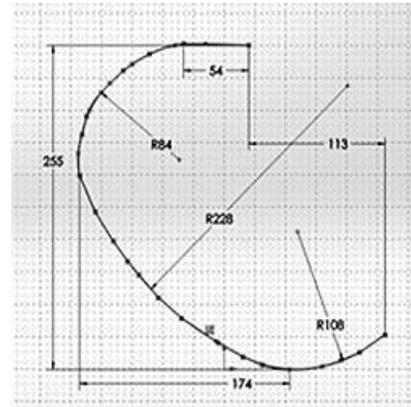


Figure 3. Dimensions of the Design A foot in mm.



Figure 4-A. Design A foot mold.



Figure 4-B. Design B foot mold.



Figure 5. Woven glass fiber layers.



Figure 6. Clamps distribution of the mold.

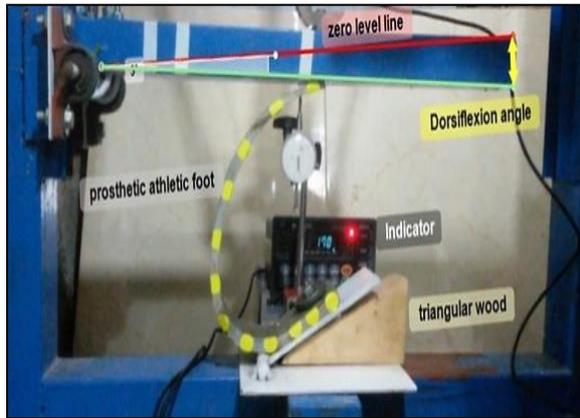


Figure 7. Measuring dorsiflexion angle for design a foot sample.



Figure 8. Measuring dorsiflexion angle for design B foot sample.

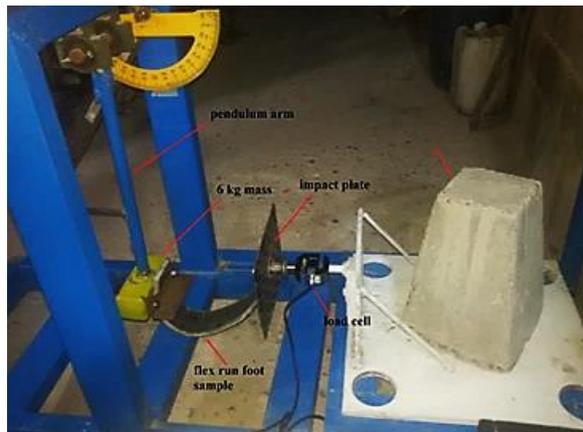


Figure 9. Design a foot impact test.



Figure 10. Design B foot impact test.

Table 1. Material properties giving by manufacturing company, **JPS Composite Materials Corporation.**

Material	Properties	Value
Glass Fibers	Elastic modulus (GPa)	74
	Shear Modulus (GPa)	30
	Density (kg/m ³)	2600
	Poisson's ratio	0.25



Unsaturated Polyester Resin	Elasticity Modulus (GPa)	4.0
	Shear modulus (GPa)	1.4
	Density (kg/m ³)	1200
	Poisson's Ratio	0.4

Table 2. the weight and volume fractions of fiber and resin used in manufacturing feet samples.

Foot Sample	Fiber Weight (gm.)	Resin Weight (gm.)	Fiber volume Fraction
DESIGN B	954	186	70%
DESIGN A	523	165	68%

Table 3. Elastic properties of woven fiber composite lamina.

Properties	Design B	Design A
Elastic modulus $E_1=E_2$ (MPa)	35969.7	35426.5
Elastic modulus E_3 (MPa)	18382.599	17444.59
Shear modulus in plane 1–2 G_{12} (MPa)	6325.834	5956
Shear modulus in plane 1–3 G_{13} (MPa)	6360.0	5977
Shear modulus in plane 2–3 G_{23} (MPa)	6360.0	5977
Poisson's ratio in plane 1–2 ν_{12}	0.1497	0.144577
Poisson's ratio in plane 1–3 ν_{13}	0.364	0.37
Poisson's ratio in plane 2–3 ν_{23}	0.364	0.37

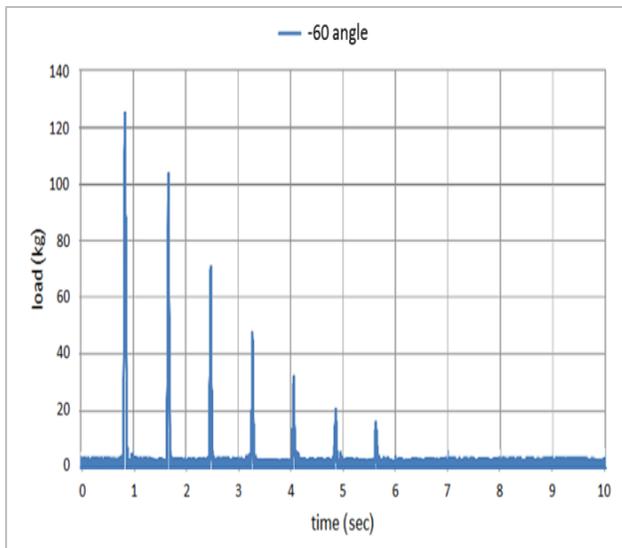


Table 4. Efficiency of design A and design B samples.

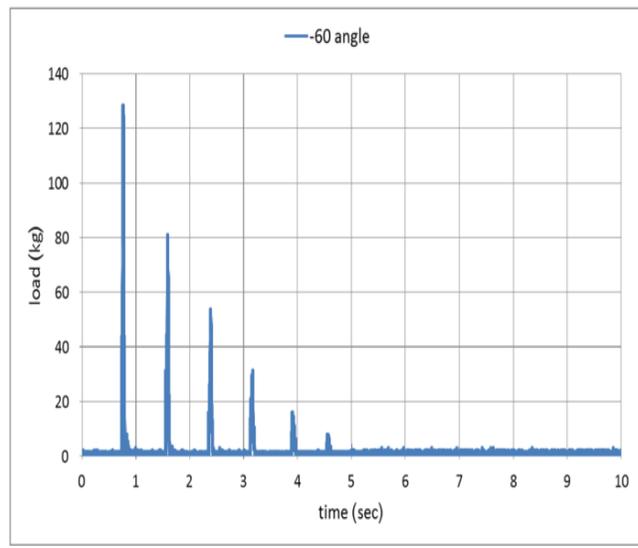
Foot	Angle	Efficiency (%)
Design A	0°	78.88
	25°	84.50
Design B	0°	89.77
	25°	71.96

Table 5. Impact foot result at 60 degree drop angle.

	Peak Load (kg)			Firs Peak Time (sec)		
	First	Second	Difference	Start	Finish	Difference
Design A	125.3	103.4	21.85	0.840	0.909	0.069
Design B	128.7	80.31	48.44	0.729	0.789	0.060



(a)



(b)

Figure 11. Response with time at -60° angle height for (a) Design A foot (b) Design B foot.

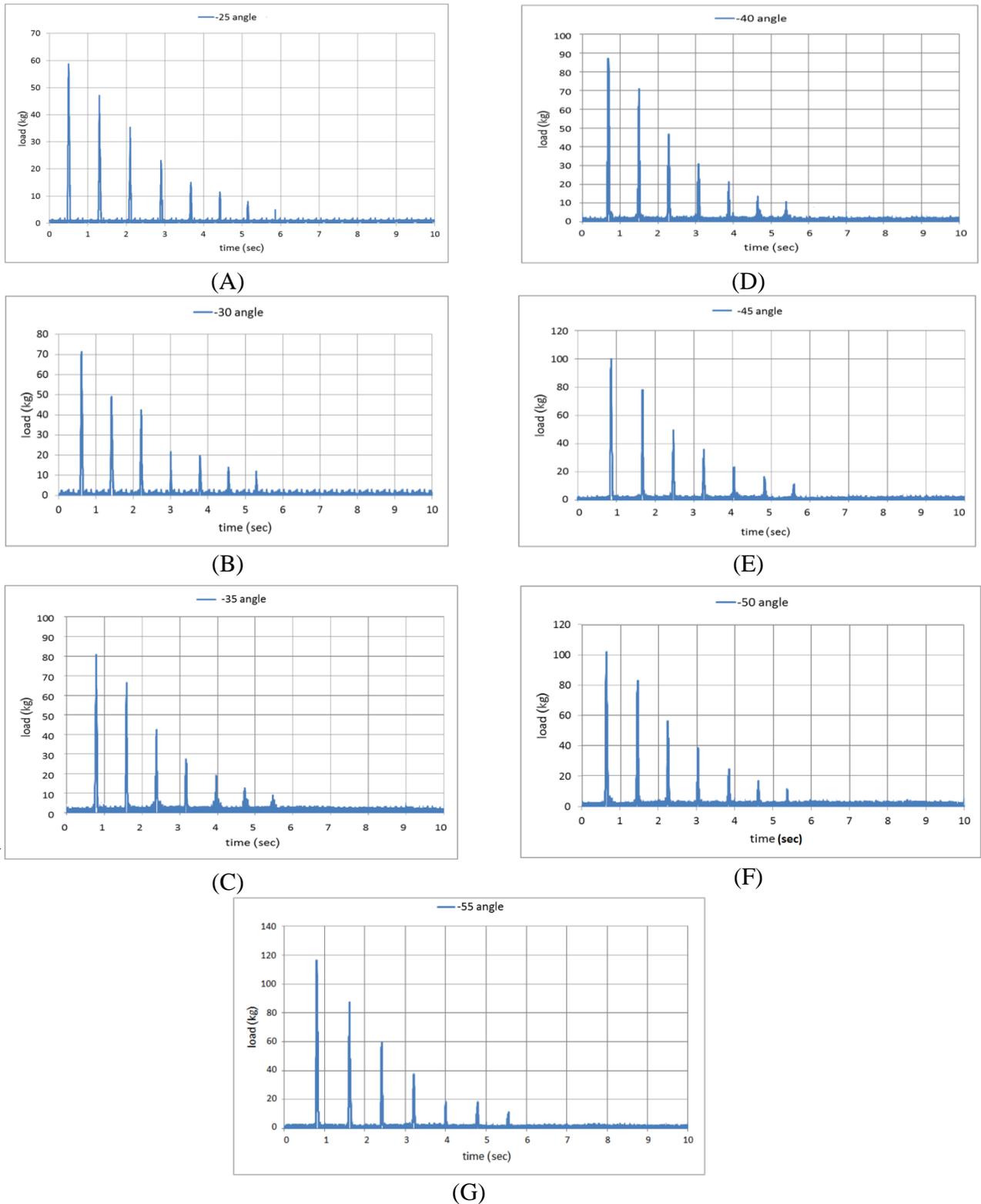


Figure 12. Impact load response with time for design A foot at: A)25°, B)30°, C)35°, D)40°, E)45°, F)50°, G)55°.

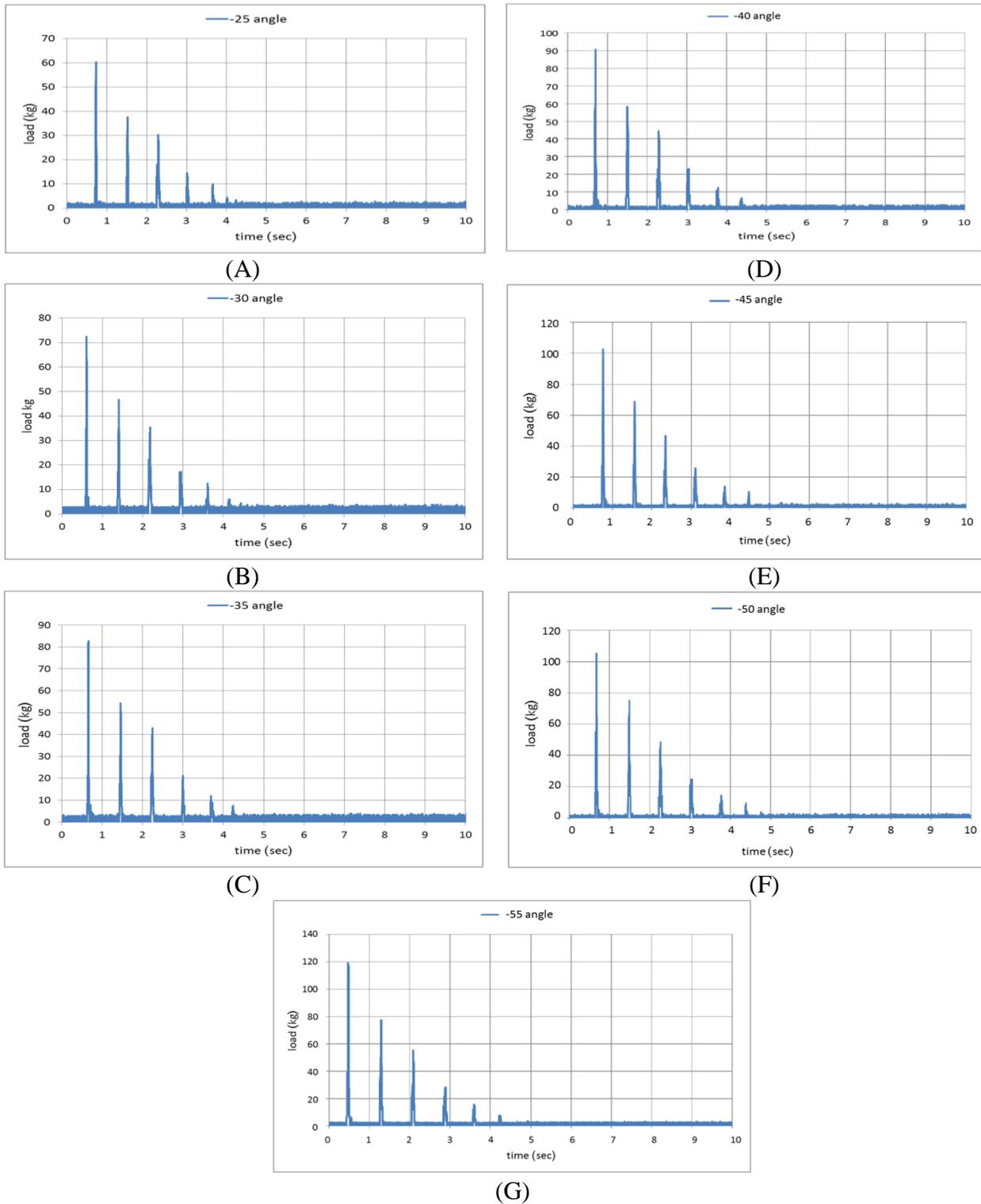
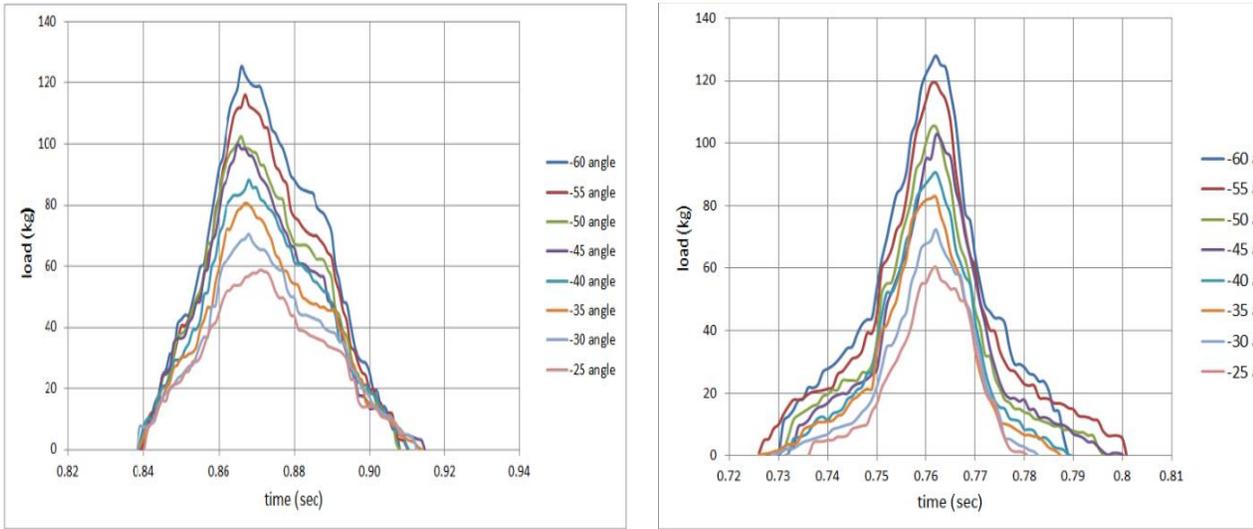


Figure 13. Impact load response with time for design B foot at: A)25°, B)30°, C)35°, D)40°, E)45°, F)50°, G)55°.



(a) (b)
Figure 14. Maximum first peak load at each drop angle for; (a) Design A foot sample, (b) Design B foot sample.

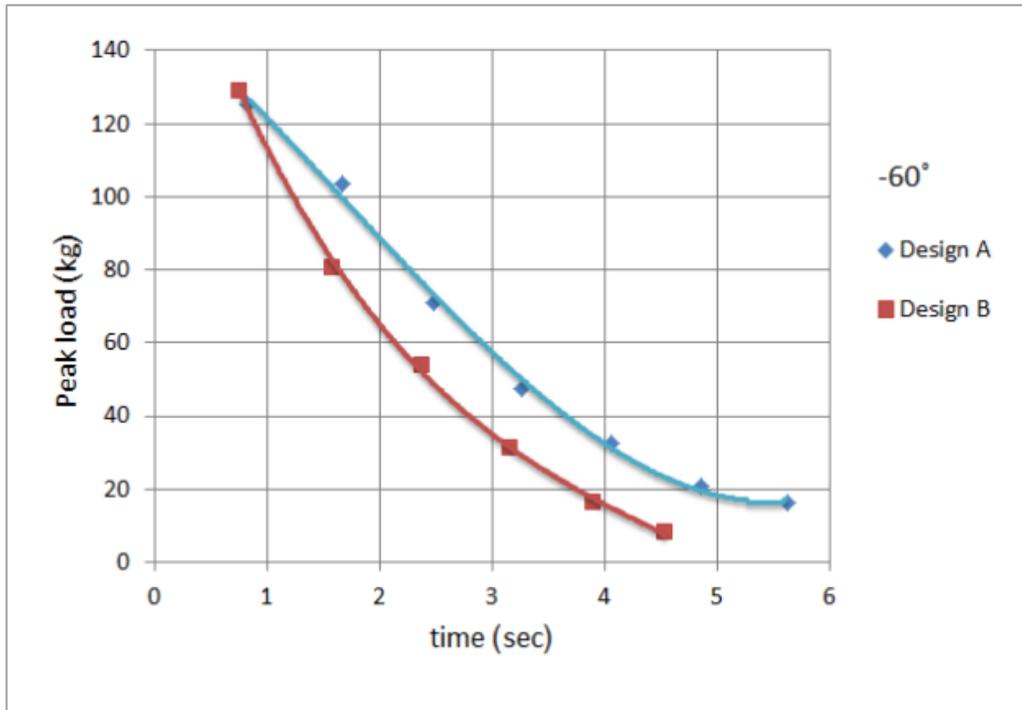


Figure 15. The decreasing of impact load peaks with time at -60° angle for both feet.