(REFEREED RESEARCH)

MECHANICAL EVALUATION OF A COMPOSITE OVERSHOE PROTECTOR

KOMPOZİT BİR AYAKKABI KORUYUCUNUN MEKANİK AÇIDAN DEĞERLENDİRİLMESİ

Seçkin ERDEN[1], Mustafa ERTEKİN[2]

[1] Ege University, Engineering Faculty, Department of Mechanical Engineering, 35040, İzmir, Turkey
[2] Ege University, Engineering Faculty, Department of Textile Engineering, 35040, İzmir, Turkey

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ABSTRACT

Equipments named as “safety shoes” are used against occupational accidents. These usually involve toe caps, made of steel or metal alloys, which are placed at the front part, in order to protect the toes. Within this study, a polymeric composite toe cap reinforced with technical textiles was developed. Additionally, a prototype of an “overshoe protector” having also a technical textile reinforced polymeric composite upper (vamp) part was entirely manufactured. The prototype was designed to wear over casual shoes. This way, it can be used easily during work or visits. Protective toe impact resistance test was conducted for the composite toecap. Puncture resistance test was performed for the composite upper part.

Keywords: Occupational safety, Overshoe protector, Polymeric composite, Technical textile.

ÖZET

İş kazalarına karşı, “iş güvenliği ayakkabısı” olarak adlandırılan ekipmanlar kullanılmaktadır. Bunlar genelde, ayak parmaklarını korumak amacıyla ayakkabı ya da botun ucuna yerleştirilen, çelik ya da metal alaşımlı bombeler içermektedir. Bu çalışmada, teknik tekstil takviyeli polimerik kompozit bir bombe geliştirilmiş, ilave olarak da, teknik tekstil takviyeli polimerik kompozit kılıfı olan bir “ayakkabı koruyucu” prototipi yekpare olarak imal edilmiştir. Üretilen prototip, günlük ayakkabı üzerine giyilebilecek şekilde tasarlanmıştır. Böylece, çalışırken ya da ziyaretlerde kolayca kullanılabilecektir. Kompozit bombeye, darbe direnci testi, kompozit kılıfa delinme direnci testi uygulanmıştır.

Anahtar Kelimeler: İş güvenliği, Ayakkabı koruyucu, Polimerik kompozit, Teknik tekstil.

Corresponding Author: Seçkin Erden, seckin.erden@gmail.com.

1. INTRODUCTION

The statistics of occupational accidents show that feet and legs are in the high level of risk group. According to the Bureau of Labor Statistics (BLS), of the 917,060 private industry nonfatal occupational injuries and illnesses involving days away from work during 2013, 22 percent (202,280 cases) involved injuries to the lower extremities. More than 89,000 (43 percent) of these cases involved injuries to the ankle or foot [1]. Similarly, according to the Social Security Institution (Turkey), feet injuries between 2004 and 2006, also represented a large proportion of the occupational accidents (approximately 22%) [2]. Also, a study on the distribution of injured workers by body parts revealed that 18.81% of total injuries in the chemical industry occurred in feet, which was the second after hand injuries [3].

In order to prevent this type of accidents, safety equipments known as “work boots/shoes” or “safety boots/shoes” are used as personal protective equipment (Figure 1. (a), (b)). These are usually composed of toecaps, which are placed at the forepart of the shoe or boot, and metatarsal protectors, which absorb impact at the upper part (Figure 1. (c), (d)). Toecaps are usually made of steel, aluminum, titanium-aluminum alloy, etc. Recently, some newly developed products have been also incorporated with composite toecaps. For instance, in a product composed of a shock absorbing polyurethane sole and a steel or composite midsole, a steel or composite toecap meeting the requirement of the standard ISO 20345 was used [4]. Since fiber reinforced composites have both high specific stiffness (modulus/density) and specific strength (strength/density), they have been widely used in lightweight structures [5]. It is also stated in the literature that, toecaps made of fiber reinforced composite are lighter than steel, thermally nonconductive, non-magnetic, anti-static and are not alerted by metal detectors [6]. Additionally, in some products it was indicated that composite toecaps provided more lightweightness when compared to steel toecaps [7]. Metatarsal protectors are shock absorbing products generally produced by using metallic or polymeric materials. An example to that can be given with a commercial product having a thermoplastic polyurethane (TPU) based protecting part [8]. TPU is well known for its high impact and chemical resistance [9]. Metatarsal protectors can either be placed within safety boots during their manufacturing process or later attached separately on the upper part of the boot.

On the other hand, “overshoe protectors”, which is the topic of this study, are rarely found as commercial products. Among these, the model called as “safety overshoe” is common (Figure 2). These products generally include a steel toecap and cover the forepart of the shoe. Besides, there are products resembling babette shoe shapes, which surround the shoe and have a sole itself [10,11]. Also, there are safety overshoes having toecaps made of aluminum-titanium alloys, which are said to be 50% lighter than the ones having steel toecaps [12]. Moreover, some other commercial safety overshoes are present which are aimed to protect against atmospheric conditions such as water, wind, heat, and slippage due to wet surfaces [13].

The damage tolerance of composite materials should be considered carefully to apply them to the toecap, because the low-velocity impact on the toecap may reduce the residual strength of the composite material of the toecap, even when the damage due to the low velocity impact is not detectable [5]. In the literature, there are several studies investigating the low velocity impact properties of hybrid fabric reinforced epoxy composites (ASTM D7136), which have test conditions similar to the standards [14-17] related to foot protectors. By using C-scan technique, it was shown that the damaged area was the smallest in case of aramid/carbon hybrid fabric epoxy composite. Other reinforcements investigated in this work were carbon, carbon/glass, and aramid/glass, which were also impregnated with epoxy resin [18]. It should be noted that aramid fibers are well-known for their high impact and abrasion resistance and they can withstand high temperatures [19]. In another study involving carbon and glass fabric reinforced epoxy composite, it was found that the composite’s impact resistance increased when S2-glass fabric was used at the bottom layer. Additionally, it was concluded that the in-plane properties can be optimized in case the inner layers would be unidirectional (UD) carbon fabric [20]. It was also reported that impact tests of aramid and glass fabric reinforced epoxy composites resulted in higher ductility for hybrid layered structures against the uniform fabric structures [21]. When the impact resistance of aramid/glass and aramid/carbon hybrid epoxy composites were compared, it was observed that the aramid/glass structure having aramid layers on top had slightly higher energy absorption capacity [22]. Another study advised the use of low modulus yarn on the top layer in order to improve the low velocity impact performance of hybrid polymeric composites. Furthermore, laying the glass woven fabric on the top layer of carbon/epoxy composites led to delaying of penetration of the impactor and prevent delamination. Although this layup caused slight increase in weight of the composite, it increased the impact resistance 3-5 folds [23]. Additionally, it was found in glass and carbon hybrid epoxy composites that mid layers increased the propagation and strength value for compression after impact test. This was due to the shifting of the critical load value to higher impact resistance. It was also observed that glass fabric was superior to carbon fabric [24].

a b c d

Figure 1. (a) Work shoe, (b) work boot, (c) toecap and (d) metatarsal protector.

Figure 2. Safety overshoes

In this study, in order to replace the traditional metal toecaps, a polymeric composite toecap reinforced by technical textiles was developed. Not only a toecap, but a composite overshoe protector having a polymeric composite cover reinforced by aramid fabric was manufactured as one-piece which makes this study innovative in this field. The prototype was designed to be easily put on casual footwear. Thus, the labourers will be able to work while wearing their own daily shoes. Similarly, white-collar personnel and visitors will not require additional safety equipment. The first stage of this work involves the production of epoxy composite toecaps with five different reinforcement fabric configurations by using a hot press. Reinforcement fabrics used were E-glass, carbon, and aramid fabrics. In the second stage, the produced toecaps were integrated with a polymeric composite cover consisting of aramid fabric and TPU matrix. As a result, an overshoe protector prototype was developed and its mechanical properties were evaluated.

2. MATERIAL AND METHOD

2.1. Materials

E-glass, carbon, and aramid fabrics (Dost Kimya, İstanbul) were used as reinforcement material and epoxy resin was used as the matrix material in the manufacture of the composite toecaps. Their properties are given in Table 1 and Table 2, respectively. Polivaks SV-6 (Poliya) was used as mold release agent. TPU films (0.40 mm thickness) used in the production of overshoe protector upper part were supplied from Arya Polimer.

2.2. Composite Toecap Mold

The aluminum mold (Figure 3) used in the production of composite toecaps was comprised of two parts, which were machined by a CNC. To achieve this, firstly steel toecaps were used as models to obtain the computer model using a 3D scanner (Steinbichler Comet L3D 2M) [26].

2.3. Production of the Composite Toecap

Hybrid fabric reinforced composite toecaps were manufactured by laying E-glass (G), carbon (C) and aramid (A) fabrics in five different configurations (Table 3). The subscript “s” denotes that the configuration has a symmetrical structure. For instance, second specimen B2 indicated as $[A/C/G]_s$ was manufactured using six layers of fabrics as [A/C/G/G/C/A]. Additionally, the subscript “3” used for the specimen B5 $[A/G/C_3/G/UD\ C/G]_s$ indicates that the carbon fabric is used in three layers. As can be seen in Table 3, the composite toecaps were produced as three, six, twelve, and sixteen layered structures.

Table 1. Properties of the reinforcement fabrics used

Reinforcement fabric	Fabric construction	Weight [g/m^2]	Warp Density [pick/cm]	Weft Density [pick/cm]	Warp Yarn Count	Weft Yarn Count	Thickness [mm]
E-glass	Plain	320	5	5	320 tex	320 tex	0.30
Aramid	Plain	181	20	20	420 tex	420 tex	0.23
Carbon	Plain	220	5.5	5.5	3K	3K	0.25
Carbon	Unidirectional (UD)	399	4.2	2.8	12K	200	0.45

Table 2. Properties of the epoxy resin used [25]

Trade name	Density [g/cm^3]	Viscosity [mPa s] (25 ºC)	Process parameters	Tensile strength [MPa] (8 hr, 80 ºC)	Flexural strength [MPa] (8 hr, 80 ºC)
Huntsman Araldite LY1564	1.1 – 1.2	1200 – 1400	Gel time: 33 - 43 min, 80 ºC Pot life: 560 - 620 min, 100 g	70 - 74	118 - 130
Huntsman Aradur 3486	0.94 –0.95	10 – 20	-		

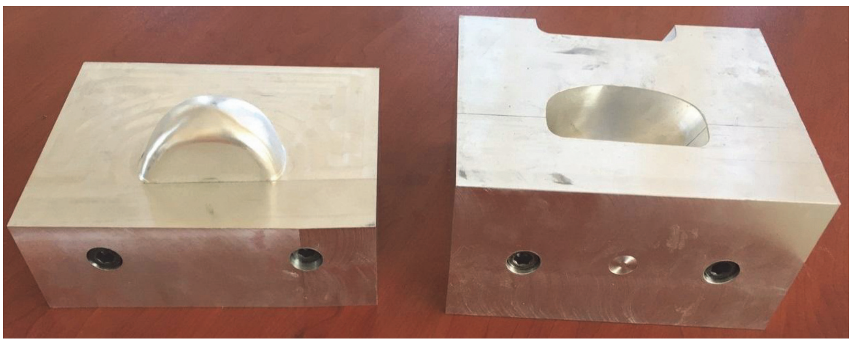


Figure 3. Aluminum mold manufactured by CNC machining.

Table 3. Composite toecap configurations

No.	Composite toecap components	Layer count
B1	A/C/G	3
B2	$[A/C/G]_s$	6
B3	A/G/C/G/UD C/G	6
B4	$[A/G/C/G/UD\ C/G]_s$	12
B5	$[A/G/C_3/G/UD\ C/G]_s$	16

A thin layer of release agent was applied to the internal faces of the mold, three times at intervals of fifteen minutes before the laying of fabrics. Reinforcing carbon, aramid and E-glass fabrics were cut to size of 25 x 25 cm and weighed precisely. Then, epoxy resin system having two times the weight of the fabrics was prepared. The resin mixture of epoxy/hardener had a weight ratio of 100:34 [25]. After the drying of mold release, reinforcing fabrics were impregnated with epoxy resin by using a brush, which were then placed within the mold. The mold was heated up to 120ºC for 2 hours to cure the composite toecaps, which were removed from the mold after being cooled at room temperature (Figure 4) [22, 27].

Figure 4. Produced composite toecap prototype.

2.4. Production of the Composite Upper (Vamp) Part and Overshoe Protector

The vamp was prepared by impregnating aramid (A) fabric with TPU films. Two types of layer configuration was determined for the A/TPU composite upper part of the overshoe protector (Table 4).

Table 4. Composite vamp configurations

No.	Components of the vamp	Layer count
V1	TPU/A/TPU/A/TPU	5
V2	TPU/A/TPU/A/TPU/A/TPU	7

Aramid fabrics and TPU films used in the layers of the composite vamp structure were cut to fit the dimensions of the toecap mold. These vamp layers and the composite toecap produced in the first stage were hot pressed together at 180ºC for a short period of 5 minutes in order to give the final form of the overshoe protector. Thus, the composite toecap was enclosed within the composite vamp. As the final process, an industrial sewing machine was used for assembly and elastic band attachment (Figure 5).

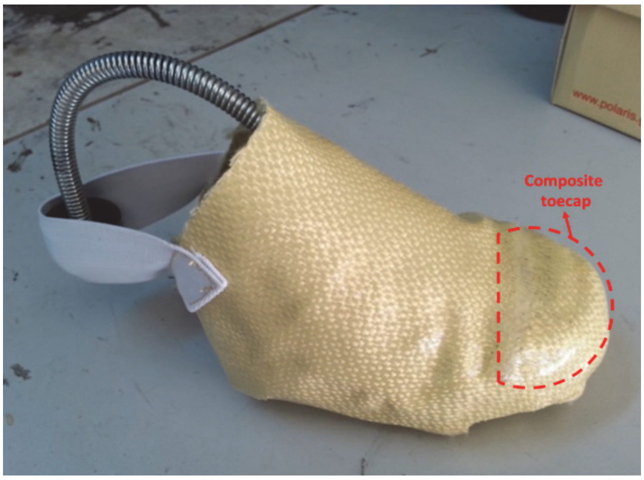


Figure 5. Composite toecap integrated overshoe protector prototype.

2.5. Impact Resistance Testing of Composite Toecaps

Pegasil Zipor EL-99 Steel Toe Caps Impact Tester was used for “Protective Toe Impact Resistance” testing of the composite toecaps according to ASTM F2412 and ASTM F2413 standards (Figure 6). The impactor consists of a steel weight having a mass of 22.7 ± 0.23 kg. The nose of the impactor is a steel cylinder having a diameter of 25.4 ± 0.8 mm and length of 50.8 mm. The impact side of the cylinder has a smooth spherical surface with a radius of 25.4 ± 0.127 mm. The longitudinal centerline of the cylinder is parallel and coincident with 3.175 mm to the symmetry of its vertical axis. The impactor is dropped from a height that results in an energy of 101.75 J. Prior to impact testing, modeling clay, kept at room temperature and formed approximately as a vertical cylinder having a diameter of 25 mm, was placed under the protective toecap to back rear edge of the cap positioned inside the specimens directly under the point of impact. After impact, the height of the modeling clay cylinder is measured. For the toecap to meet the requirement in the standard, minimum clay height must be at least 21.0 mm [28].

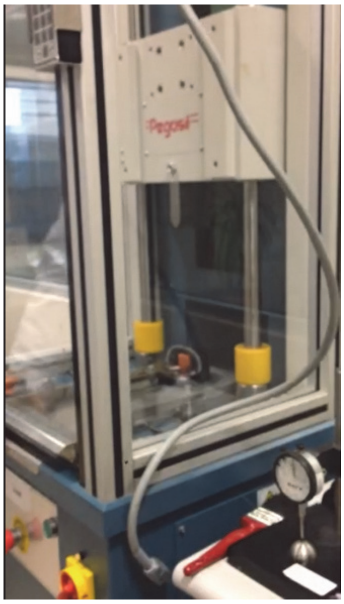


Figure 6. Protective toe impact tester.

2.6. Puncture Resistance Testing of Composite Vamps

Zwick/Roell Z010 instrument was used to conduct the “Puncture Resistant Footwear” tests of the aramid/TPU composite vamp structure according to ASTM F2412 and ASTM F2413 standards. The puncture resistance is defined in the standard as the force (N) required for the steel pin to penetrate through the specimen. The tests were performed by using the apparatus prepared according to the standards (Figure 7) for the V1 and V2 structures, each by repeating three times.

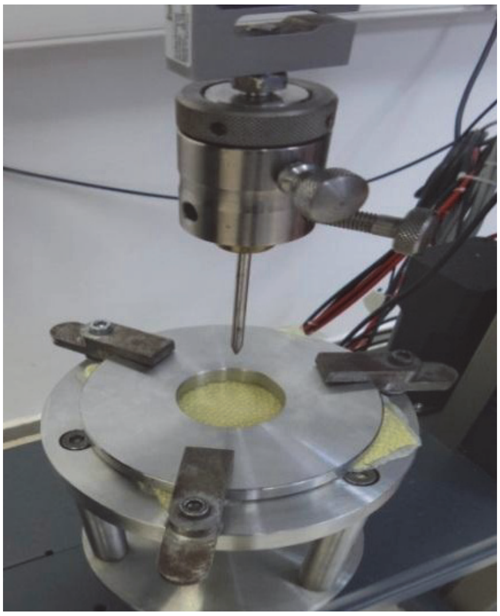


Figure 7. Puncture resistance test.

3. RESULTS AND DISCUSSION

3.1. Weights of the Produced Toecaps

To evaluate the lightweightness of the composite toecaps, the manufactured samples were weighed and compared with the other toecaps. The weight measurement results are given in Table 5. It was found that B5 composite toecap was 56.4% lighter than the traditional steel toecap. Alloy toecaps made from lightweight materials such as titanium, aluminum or a combination of other light materials are 30-50% lighter than steel But these are more expensive and can be sensed by metal detectors. Besides steel and alloy toecaps should not be used in environments with electrical hazards since they conduct electricity [29, 30].

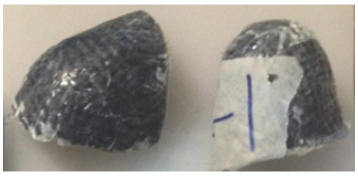
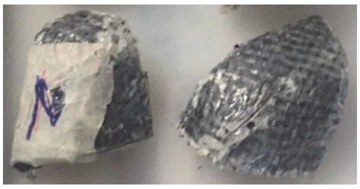
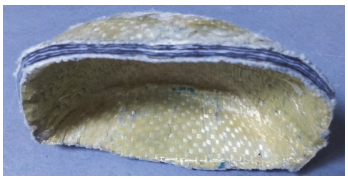
Table 5. Weight measurements of the toecaps

No	Weight (gr)
Steel toecap	98.2
Alloy toecaps [29]	≈49.1-68.7
Composite toecaps [30]	≈68.7
B1	13.5
B2	23.7
B3	24.6
B4	39.5
B5	42.8

3.2. Impact Resistance Testing of Composite Toecaps

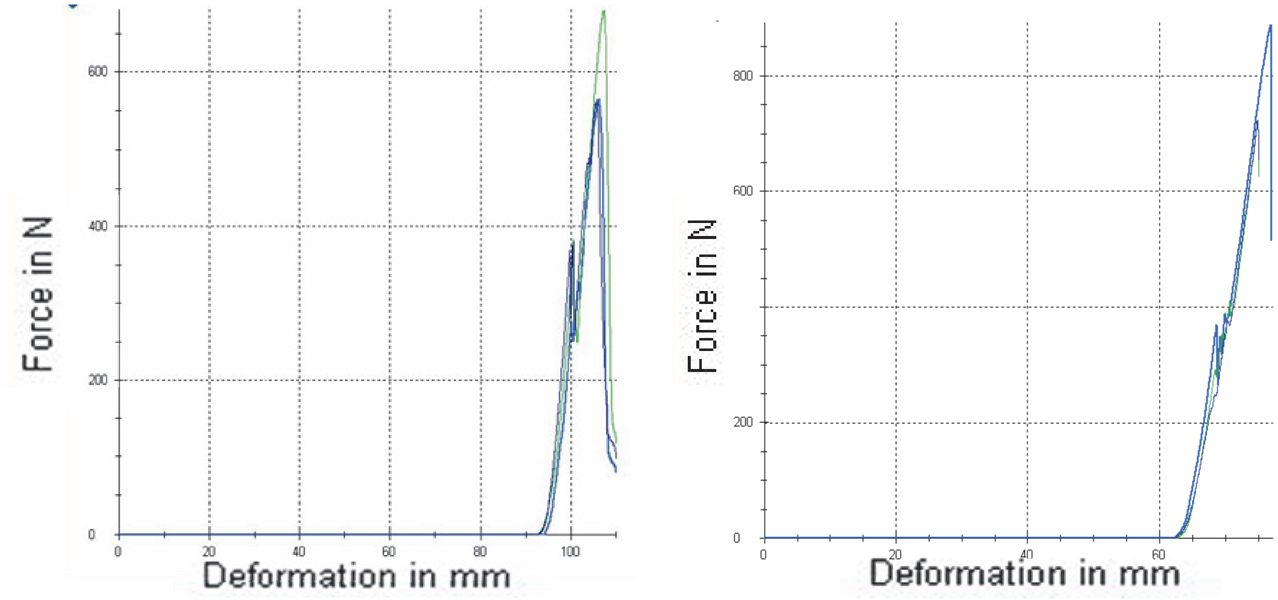
Images of the toecap specimens after the impact testing are given in Table 6. According to this, specimens except B5 all failed after impact loading and did not meet the requirements stated in the standards. The toecap B5 succeeded with a clay height of 22.1 mm. This result is in accordance with another study, which resulted in 21.33 mm clay height by using different fabric structures and resin material [28].

Table 6. Results of toecap impact tests

No	Toecap specimens after impact testing	Result
B1		Broken-Failed
B2		Broken-Failed
B3		Broken-Failed
B4		Broken-Failed
B5		22.1 mm - Passed

3.3. Puncture Resistance Testing of Composite Vamps

Typical graphs of puncture test results of V1 and V2 specimens were given as examples in Figure 8. Additionally, test results are given in Table 7. It was observed that, increase in layer count of the TPU impregnated vamps due to the increment in mass per square meter values led to increase in puncture resistance. This conclusion is in agreement with the literature stating that TPU coating of the fabrics improve their puncture resistance significantly [31].



a b

Figure 8. Puncture resistance test for V1 (a) and V2 (b) specimens.

Table 7. Composite vamp puncture test results

	V1	V2
Puncture resistance [N]	633,8±57,2	815,3±82,5

4. CONCLUSION

This study is composed of two parts. In the first part, epoxy composite toecaps with five different reinforcement fabric configurations were produced. And in the latter part, the produced toecap was integrated with a polymeric composite cover consisting of aramid fabric and TPU matrix. As a result, an overshoe protector prototype was developed. In summary, composite toecap impact resistance tests of composite toecaps were performed and one of the specimens which had the highest layer count and areal weight met the standard requirements. Also it was found that this composite toecap was significantly lighter than the traditional steel toecap. According to the puncture test results of the aramid vamps impregnated with TPU films, adding one more layer of TPU film and aramid fabric increased the puncture resistance value which is in accordance with the literature. In further research, it might be possible to increase the layer counts, change the construction of the fabric and design of the vamp, in order to improve the puncture resistance. Furthermore, the use of polymeric composite toecaps instead of the traditional metal ones will allow to take the advantages of polymers against metals such as corrosion resistance, being chemically inert, nonconductivity and high specific strength. Additionally composite toecaps are good for extreme high or low temperatures because they won't heat up or cool down like a metal toecap would.

ACKNOWLEDGEMENT

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