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Innovativeness in tradition: a study on the physical performance of leather scale armors during the Joseon Dynasty

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Abstract

During the Joseon Dynasty, light and convenient leather armors were developed to replace metal armors, which were heavy and difficult to manufacture. Leather armors allowed easy movement of the troops and, because arrows were the primary weapons at the time, provided them with protection. The excellent performance of leather armors can be attributed to their materials and manufacturing method. The scales of the leather armor relics are prepared by layering animal skins, attaching them with natural glue, and then coating their outer surface with lacquer. The lacquer extracted from the lacquer (Ott) tree is an excellent material with high strength, waterproofing and antiseptic properties, insect repellency, heat resistance, as well as chemical resistance. The superior performance of the leather scale was reported in old scripts; however, it has not been proven through scientific analysis and testing. Therefore, in this study, the physical and mechanical properties, impact resistance, and anti-stab performance of leather scales manufactured following the traditional method were investigated. The results confirmed the excellent protection, impact resistance, and mechanical properties of the leather specimens glued with fish glue and coated with lacquer compared to those of specimens glued with synthetic glue and uncoated specimens glued with fish glue. This study reveals the excellent properties of fish glue and lacquer, which enable them to be used in various industries.

Keywords: Leather armor, Scale armor, Lacquer, Protection, Stab resistance

Introduction

During the Joseon Dynasty, iron armors (鐵甲) provided the best protection among different types of armors. However, it was very heavy, which hindered the mobility of infantry. Light and convenient leather armors were developed to replace heavy and difficult to manufacture iron armors. According to the records of the late Joseon Dynasty, approximately 75% of the troops wore leather armors (皮甲), which is evident by its appearance in old documents and relics (Park, 2019). According to *Seungjeongwon ilgi* (承政院日記; daily record of the Royal Secretariat), arrows penetrated iron armors but not leather ones (Seungjeongwon, 1667). Because arrows were the main weapon at that time, leather armors could protect the troops without limiting their mobility. Therefore, the traditional scale armor (甲札) made of leather exhibited excellent protection.

The excellent performance of leather armors could be attributed to the material and manufacturing method of the scale. Based on the relics depicting leather armors. Looking at the materials needed to make one set of leather armor in the Joseon Dynasty, armor scales were made of cowhide and Eo-gyo (魚膠; fish glue), and coated with two types of lacquer, raw lacquer (生漆) and pure lacquer (全漆) (Eoyeongcheong, 1707, 22b-23b). In another record, a sample of the armor was made to know the materials and quantity needed to mass-produce 5,000 pieces of leather armor worn by soldiers. At this time, cowhide was layered in three layers to make armor scales, and cotton fabric, pure lacquer, and fish glue were needed (Hunlyeondogam, 1765, 24a-24b). Combining the old documents and relics, armor scales were made of three pieces of overlapping leather cut to the same size, glued together, and then coated with Korean lacquer on their outer surface. *Eo-gyo* (魚膠; fish glue), which was used as a traditional adhesive, is a paste fabricated by decocting the fish air bladder, and *A-gyo* (阿膠; glue) is a paste prepared by boiling animal skins, tendons, intestines, bones, etc. Among them, fish glue hardens at room temperature and is water soluble, i.e., it can be wiped off. Moreover, it was widely used for making arrows and armor scales because of its good adhesion and flexibility (Lee et al., 2004). Lacquer (漆) used as a coating material is the sap obtained from cuts on the lacquer tree (Ott tree), and it is a traditional natural coating agent. It has been widely used since ancient times because of its excellent properties such as high strength, gloss, waterproofing, antiseptic properties, insect repellency, heat resistance, and chemical resistance (Jang, 2016). These characteristics enabled the relics to withstand decay and maintain their form for thousands of years (Lim et al., 2019).

Leather armors and their scales were fabricated by correction through trial and error for a long time. The records show that they exhibited excellent protection abilities; however, they have never been scientifically and systematically studied. Therefore, in this study, the physical and mechanical properties of traditionally made leather armor scales were examined, and impact resistance tests were conducted to verify their defensive capability.

Experimental

Materials

Specimens for the stab-resistance test were produced to resemble the scales of leather armors depicted in relics and reported in documentary records. Based on old documents, such as *Eoyeongcheong-gusigrye* (御營廳舊式例; old guidelines and regulations enforced by a military camp called *Eoyeongcheong*)(Eoyeongcheong, 1707, 22b-23b) and *Hungug-sarye-chwalyo* (訓局事例撮要; a book that only reported the important facts from a central military camp called *Hunlyeondogam*)(Hunlyeondogam, 1765, 24a-24b), three pieces of cowhide were glued together using fish glue to form an armor scale, and lacquer was then applied. In addition, other specimens using other types of adhesives and without lacquer coating were also prepared to compare the difference in the defense power. All samples comprised the same three layers of cowhide but with different coating and adhesive: (1) a specimen bonded using fish glue, (2) a specimen bonded using synthetic glue, and (3) a specimen bonded using fish glue and coated with lacquer.

During the Joseon Dynasty, the hides of various animals, such as cows, pigs, horses, deer, and roe deer, were used for manufacturing leather armors. Among them, cowhide was selected here because it was the most commonly used for armors and was known for its high quality. Rawhide (生地) was prepared without dyeing and finishing so that it would be close to the raw material used during that era. Fish glue was prepared according to the production method recorded in *Imwon Gyeonggi-ji* (林園經濟志; the largest practical encyclopedia of Joseon) (Seo, 1806). Fish glue is a type of animal glue made from fish parts that contain collagen, keratin, or elastin. These proteins are extracted with hot water and then dried to form gelatin or glue (Messler, 2011). The chemical composition of fish glue depends on the source and method of production, but it typically contains amino acids such as Glycine; NH_2-CH_2-COOH (R group = H), Proline; NH-$(CH_2)_3$-CH-COOH (R group = cyclic aliphatic), Hydroxyproline; HO-CH_2-$(CH_2)_2$-NH-CH-COOH (R group = cyclic aliphatic with hydroxyl), Alanine; NH_2-CH(CH_3)-COOH (R group = CH_3), Glutamic acid; NH_2-$(CH_2)_2$-C(O)-NH-(CH_2)-COOH (R group = carboxylic acid) (Lopez & Mohiuddin, 2020). The dried air bladder (200 g) was placed in water (1600 ml), soaked for 13 h, cut into small pieces, and boiled in a clay pot over medium heat for 3 h to maintain a constant temperature. Next, impurities were removed by filtering through a hemp cloth. For a comparison, an artificial rubber-based synthetic glue (OKong bond 601 T) was purchased from local hardware shop. It composed by cyclohexane (5–10%), acetone (20–30%) and neoprene (10–15%).

Raw lacquer (生漆) was used for a priming coat to remove moisture and impurities from the sap of the lacquer tree, and refined lacquer (精製漆), which is made by processing the raw lacquer, was used as a paint because it has the appropriate concentration and viscosity (Korea, 2021). The sap of the lacquer tree is a milky white liquid resin, and when it comes into contact with air, it undergoes a self-neutralization process to form urushiol, lacquer acid (漆酸), and a small amount of laccase, turning brown after reacting with the oxygen in the air. It then hardens and forms a coating film (Park, 2020). The main component of lacquer is urushiol, which has the chemical formula $C_{21}H_{32}O_2$. Urushiol can undergo oxidation and polymerization reactions with oxygen and laccase (an enzyme present in the sap) to form a cross-linked network of phenolic compounds (Lu & Miyakoshi, 2015). These reactions result in the formation of a cross-linked network of molecules that hardens and adheres to the surface of the material (Zohuri, 2012). The cross-linked network of phenolic compound acts as a barrier that prevents water, oxygen, and other substances from penetrating or reacting with the underlying material. The network also has low surface energy and friction of the material, making it less attractive for insects or fungi to attach or grow on it (Fig. 1).

Manufacturing process

The raw cowhide was peeled off to a thickness of 1.5 mm and cut to a size of 100×100 mm^2. The fish glue was then evenly applied to the inner surface of both leather specimens using a brush, and they were then attached so that the faces with the glue are connected. Next, they were pressed together by rollers by horizontal and vertical movements. After waiting for both sides to dry, fish glue was applied again and another sheet was added, so that 3 sheets are overlapped. The 3-piece specimens were pressed for approximately 8 h under a weight of 18 kg to prevent gap formation. Lacquer was applied four times

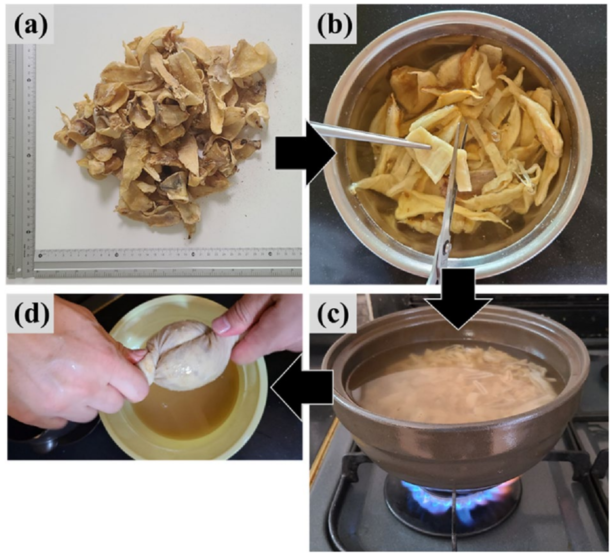


Fig. 1 Manufacturing process of fish glue: (**a**) dried air bladder (200 g); (**b**) fish air bladder is soaked in water (1600 ml) for 13 h and is then cut into small pieces (width = 5–10 mm); (**c**) bladder is placed in a pot containing boiling water over medium heat for 3 h to maintain the temperature; (**d**) impurities are removed via filtering using a hemp cloth

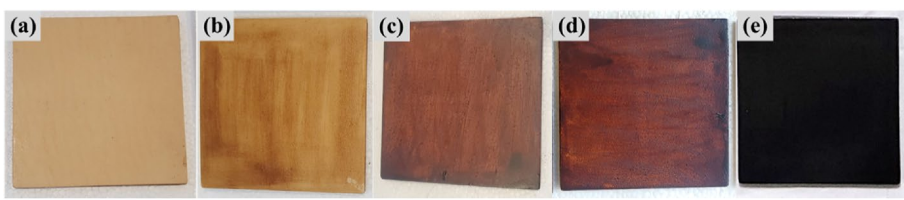


Fig. 2 Manufacturing process of leather armor scale specimen: (**a**) raw cowhide; (**b**) raw lacquer (生漆); (**c**) 1st refined lacquer (精製漆) (*Chochil*; 初漆); (**d**) 2nd refined lacquer (*Jungchil*; 中漆); and (**e**) 3rd refined lacquer (*Sangchil*; 上漆)

to each specimen: 1 layer of raw lacquer and 3 layers of refined lacquer [*Chochil* (1st refined lacquering), *Jungchil* (2nd refined lacquering), and *Sangchil* (3rd refined lacquering)]. After painting and drying each coat, the surface was polished with sandpaper to ensure that the next coat was applied adequately. Each coat was carefully applied to the outer surface, inner surface, and side edges, and it was then dried. Lacquer only dries under certain conditions (humidity = 60–80% and temperature = 18–30 °C) (Park & Lim, 2017). Thus, the drying environment was maintained at a humidity of 75–80% and a temperature of 24 °C, and the specimens were sufficiently dried for more than 12 h. As shown in Fig. 2, the color of the specimens became increasingly darker after several coatings.

Characterization

The physical, thermal, morphological, and mechanical properties of the prepared leather specimens were investigated. In the physical characteristics, the density, hardness, and water contact angle were measured. The thermal characteristics were measured using differential scanning colorimetry (DSC, DSC 200 F3 Maia, Netzsch, Germany)/ thermogravimetric analysis (TGA, TGA Q50, TA Instruments, USA). The surface and cross-sectional morphological characteristics were examined, and the mechanical characteristics were determined through tensile-strength, bending-strength, drop impact, and stab-resistance tests. The surface hardness of the leather plate and lacquer coat was measured using a digital Shore C durometer (100HC, T&D system). The water contact angle was measured using a contact angle analyzer (TDCAT 11EC, resolution $= \pm 0.1°$). The photos of the specimens were obtained using a DSLR camera (EOS 800D, Canon, Japan).

In the thermal tests, samples (15 mg) were placed in an aluminum pan at a constant heating rate of 10 °C/min within 30–750 °C under nitrogen–air atmosphere at a flow rate of 50 ml/min. The thermal decomposition temperature (T_d) of the specimen was estimated using a TGA thermogram within -50 to 250 °C obtained at a heating rate of 10 °C/min under nitrogen–air atmosphere. The surface and interface of the specimen were observed using an optical microscope (VHX-900F, Keyence Corporation, Japan) and a scanning electron microscope (SEM, Nova NanoSEM 450, FEI) at 10 kV.

Tensile and 3-point bending tests were performed using universal material testing machines (Instron 4464) following ASTM standards D2209 and D790 (ASTM, 2008, 2010) on at least three specimens. The tensile tests were conducted at a crosshead speed of 300 mm/min using $25 \times 5\text{-mm}^2$ specimens. The 3-point bending tests were conducted at a crosshead speed of 1.92 mm/min using $100 \times 15\text{-mm}^2$ specimens. The low-velocity drop-weight impact tests were conducted according to the ASTM D7136 standard using a drop-weight impact tester (Instron Dynatup 9350) (ASTM, 2015). A hemispherical impactor tip with a diameter of 20 mm was used. The test was conducted starting at an impact energy of 5 J and increasing it by 2.5 J at each step until each specimen was punctured.

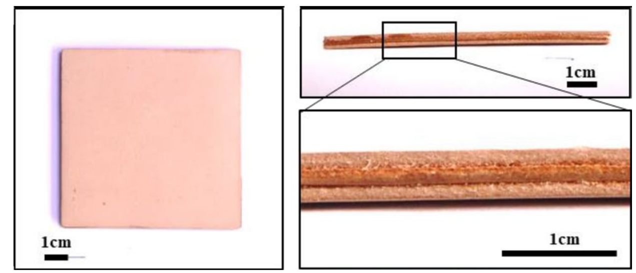
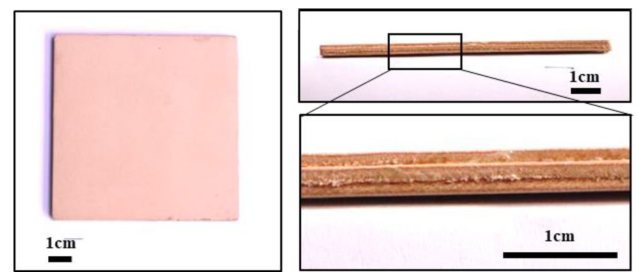
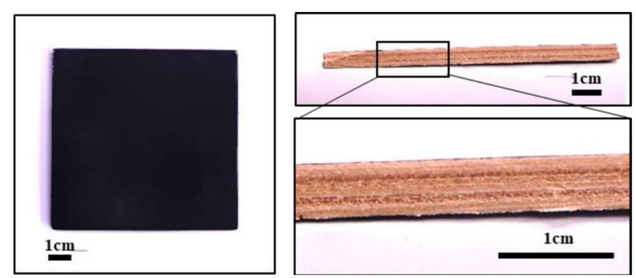
The stab-resistance test was performed using a drop tower impact test machine (CEAST 9350, Instron, USA) based on the US National Institute of Justice (NIJ) standard 0115.00. Using BS4659 BO1 Tool Steel (West Yorkshire Steel Co Ltd, UK) based on NIJ standards for stab resistance testing, a knife blade P1 impactor with 1 cutting edge was manufactured. The total length of the blade, blade length, and the blade thickness were 100, 33, and 2 mm, respectively. The specimen was placed on a support material consisting of four 6-mm layers of neoprene sponge, a single layer of 30 mm closed-cell polyethylene foam, and two 6-mm rubber layers. The total drop mass and impact velocity used in the stab resistance test were 2.437 kg and 2.09 m/s, respectively. The impact velocity, force, displacement, and energy during the stab resistance test were measured using the CEAST data acquisition system (DAS 64 K, Instron, USA), and the penetration depth was calculated from the time-displacement results.

Results and Discussion

Physical properties of the leather scale panels

The physical properties and pictures of the specimens are summarized in Table 1. Specimen (a) consists of 3 pieces of leather attached using fish glue, and Specimen (c) is similar but is coated with Lacquer on its the top and bottom surfaces. In specimen (b) synthetic glue was used instead of fish glue with no additional coating. The changes in

Table 1 Physical properties and pictures of the prepared specimens

Type	Density (g/cm^3)	Thickness (mm)	Picture (top surface/cross-section)
Fish glue	0.74 ± 0.10	4.72 ± 0.27	
Synthetic glue	0.74 ± 0.05	4.01 ± 0.29	
Fish glue–lacquer coat	0.82 ± 0.04	4.94 ± 0.14	

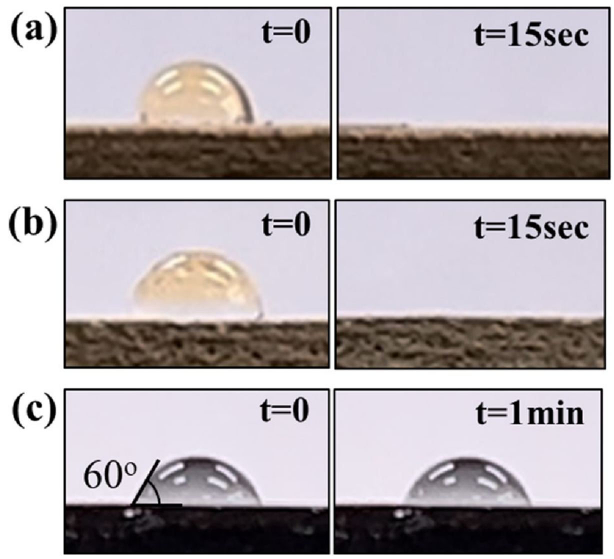


Fig. 3 Water absorption/repellency test: (**a**) fish-glue specimen, (**b**) synthetic-glue uncoated specimen, and (**c**) fish-glue lacquer-coated specimen

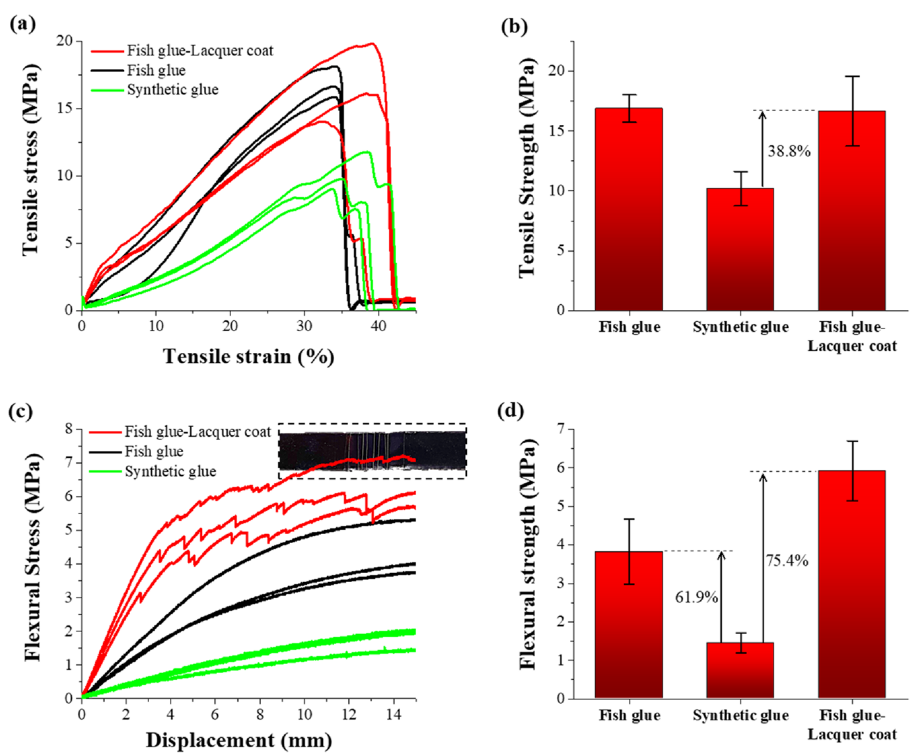


Fig. 4 Mechanical properties of the specimens: (**a**) tensile stress–strain curve, (**b**) tensile strength, the inset shows a fish glue–lacquer coated specimen after three-point bending test, (**c**) flexural stress–displacement curve, and (**d**) flexural strength

the density of specimens (a) (0.746 g/cm^3) and (b) (0.748 g/cm^3) are negligible. However, the lacquer coat of specimen (c) increases its density by approximately 10% (0.825 g/cm^3) compared to the other specimens. The lacquer coat exhibits a dark brown color and its thickness, which is observed in the magnified image in Table 1, is 83.2 ± 7.2 μm. The thickness of the specimens were relatively different (4.01–4.94 mm) because of the different processing conditions of the raw leather. However, the thickness was normalized in the following analyses. The waterproofing ability of the lacquer coating was also tested. As seen in Fig. 3a, b, a water drop was gently placed on the leather surface and was completely absorbed by the uncoated leather within 15 s. However, a water drop is not adsorbed by the lacquer-coated surface (Fig. 3c). Lacquer coating is a known good water repellent (Lee et al., 2015, 2021), which can protect natural leather. Otherwise, natural leather is easy to decay under the effect of moisture and microorganisms.

Mechanical properties of the leather scale panels

The mechanical characteristics of the leather panels were investigated by tensile, bending, drop-weight, and stab-resistance tests. In Fig. 4, the tensile strength and flexural strength of the three leather specimens were tested. Figure 4a shows the tensile stress–strain curves. The tensile tests were repeated three times for each case. The stiffness of the leather specimen could not be measured. However, it fails at a strain of approximately 35–42%. The average tensile strengths of the fish glue and fish glue/lacquer-coated specimens were similar, but they were 38.8% stronger than that of the synthetic-glue specimen (Fig. 4b). Thus, the lacquer coating does not affect the tensile strength, but the fish glue provides the leather with a higher tensile strength than the synthetic glue. The three-point bending test results indicate that the bending stress behaves differently in the three cases. As seen in Fig. 4c, fish glue (black line) provides the leather with a better flexural strength than synthetic glue (green line), and the lacquer coat (red line) further strengthens the flexural strength of the fish-glue specimen. The bending stress curves of the fish-glue–lacquer-coated specimen are not as smooth as those of the uncoated specimens (fish-glue and synthetic-glue specimens). Several kinks are found in the bending curves of the lacquer-coated specimen, which is possibly due to the cracks in the hard

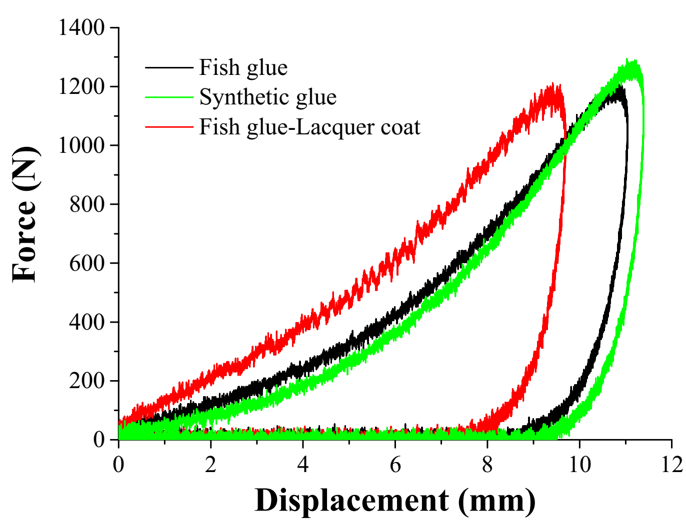
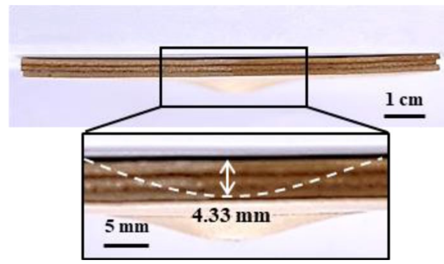
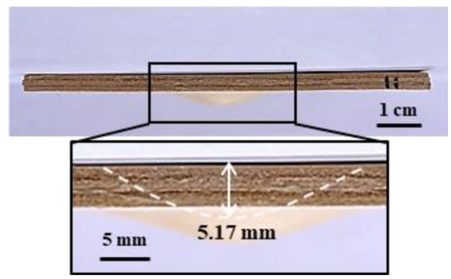
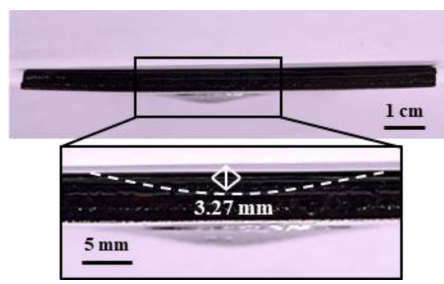


Fig. 5 Force–displacement curve of the drop-weight test

Table 2 Peak force and maximum displacement obtained by the drop-weight test

Type	Peak force (N)	Max displacement (mm)	Picture
Fish glue	1214.04	10.80	
Synthetic glue	1295.00	11.02	
Fish glue–lacquer coat	1212.08	9.41	

coating on the surface. This is evident by the broken lines observed across the leather (inset image marked by a black dashed line in Fig. 4c). As shown in Fig. 4d, the flexural strength of the leather specimens treated with synthetic glue, fish glue, and fish glue/lacquer are 1.45, 3.82, and 5.92 MPa, respectively. Thus, fish glue enhances the flexural strength compared to synthetic glue. The flexure strength is further increased by lacquer coating. The flexure strength of the fish-glue–lacquer-coated specimen is 75.4% higher than that of the synthetic-glue specimen.

The impact resistance test was performed by dropping weight on each leather specimen. Figure 5 shows the drop-weight test results, which indicated that the curve of the fish-glue–lacquer-coated specimen (red color) is smaller than the fish-glue (black color) or synthetic-glue (green color) ones. This suggests that either the impact force or the maximum displacement of the fish-glue–lacquer coated panel is less than those of the fish-glue and synthetic-glue ones. This means that the impact energy is well consumed in the first case, reducing the damage to the panel. The peak force and maximum displacement in the fish-glue–lacquer-coated specimen are 6.4% and 13.1%, respectively, lower than the synthetic-glue specimen due to the effects of fish glue and lacquer coating (Table 2). The depth of the impact mark is denoted by a white-dashed line in the inset

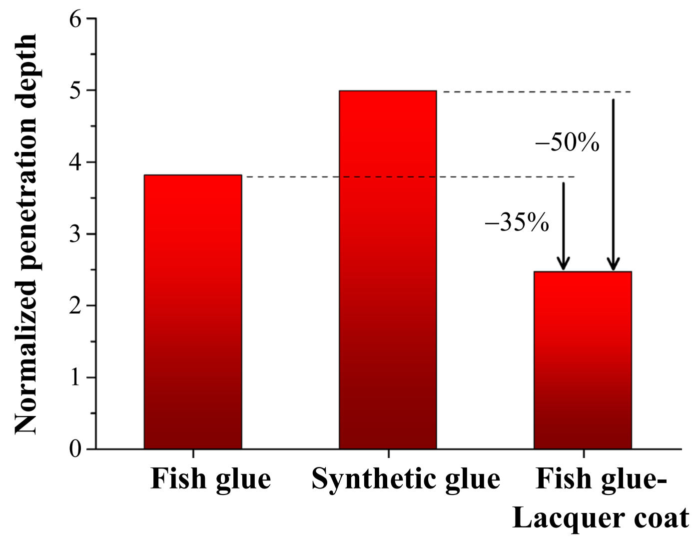


Fig. 6 Normalized penetration depth of the stab resistance test

Table 3 Thickness, penetration depth, and normalized penetration depth obtained during the stab resistance test

Type	Thickness, *t* (mm)	Penetration depth, *d* (mm)	Normalized penetration depth, *D* (=*d*/*t*)
Fish glue	4.57	17.43	3.81
Synthetic glue	3.84	19.16	4.99
Fish glue–lacquer coat	4.91	12.09	2.46

picture. As shown in the image, the lacquer-coated specimen exhibited the lowest damage ($d = 3.27$ mm), which is 24% and 36% lower than those of the fish-glue ($d = 4.33$ mm) and synthetic-glue ($d = 5.17$ mm) specimens, respectively. This might be attributed to the hardening of the leather surface by the lacquer coating. The enhancement of the stab-resistance and hardness by the lacquer coating is further investigated in the following section.

The stab resistance test is performed to verify that the anti-stab capability of the leather panel matches that stated in the historical scripts. The stab-resistance performance of traditional armor materials is found to be outstanding. At an impact energy of 5 J, the knife blade penetrated through the leather panels, and the penetration depth (d) was then normalized based on the thickness (t) of each specimen so that the results are not dependent on the thickness. Figures 6 and Table 3 show the stab-resistance test results. The fish-glue–lacquer-coated specimen exhibits an excellent anti-stab performance. The normalized penetration depth, D, in case of the fish-glue–lacquer-coated specimen was 50% and 35% lower than those in cases of the synthetic-glue and fish-glue ones, respectively. Lacquer is a hard coating material with a hardness equivalent to a pencil hardness of B–9H (≈0.1–0.6 GPa) (Lee et al., 2021; Yu et al., 2021). The hardness of the uncoated and coated panel was measured by a Shore C durometer. The uncoated specimens (fish-glue and synthetic-glue specimens) exhibit a hardness of 89.8 ± 0.67 and 90.2 ± 1.20 HC, respectively, whereas the lacquer-coated one exhibit a hardness of 91.8 ± 1.25 HC, which is 1.7–2.2% higher than that of the uncoated ones.

Anti-stab material is that normally uses reinforced materials such as aramid or carbon fibers and their composites to protect from blades penetrate. Further, the effect of anti-stab coating which is relatively thin thickness depends on the strength and bonding of the materials. Some of the anti-stab coating materials are silica (SiO_2) coating (Javaid et al., 2022) and polymer coatings (Gürgen & Yıldız, 2020). These materials work by increasing the absorbing the impact energy and resisting the penetration of the knife blade. Up to date, one could not find any experimental results that show the lacquer coating as anti-stab coating. Catechol lipid based natural lacquer, also referred to as urushiol, has been used as an adhesive and coating material for craft since ancient times. Its outstanding physical properties including high durability, high strength, waterproof and preservation abilities can be proven by historical lacquerwares recently discovered that have maintained their appearances with glossiness, scratch-free surface, and preserved shape without corruption even after more than a thousand year. Fundamentally, the natural lacquer sap is a water-in-oil emulsion consisting of 60–70% catechol lipid, 20–30% water, 4–10% plant gum (polysaccharides), 3–5% glycoprotein, and 1.5–2% enzyme laccase (Lu et al., 2013). The oxidative polymerization of catechol lipid monomer catalyzed by copper ion in laccase enzyme forms a densely crosslinked network structure, resulting in a highly durable lacquer film on the various substances. In previous literatures, it was reported that the hardness of the fully crosslinked natural lacquer has 1.26 times higher hardness measured by a nanoindenter that that of the epoxy which is a representative crosslinked (Lee et al., 2020). The hardness of 5 ~ 6 μm-thick, urushiol-based natural lacquer thin film confirmed by pencil hardness tester was classified as the hardest level of 9H (Lee et al., 2021).

Conclusions

Leather scales used in ancient armors were replicated as closely as possible according to historical scripts. Other test specimens were also prepared to compare the effects of the adhesive type and lacquer coatings on the scale performance. The three used specimens are: (1) one bonded using a fish glue, (2) one bonded using a synthetic glue, and (3) one that is lacquer-coated and fish-glued. The mechanical characteristics of the leather scale panels were investigated by tensile, bending, drop-weight, and stab-resistance tests. The impact resistance test was performed on each leather specimen through a drop-weight test. The impact energy is well consumed in case of the fish-glued and lacquer-coated specimen, reducing the damage to the panel. This study has academic importance for several reasons. First, it contributes to the historical and cultural understanding of the Joseon Dynasty and its military technology. Leather armor was widely used by soldiers in this period, but it has not been well studied or preserved compared to metal armor. Second, it reveals the scientific and engineering principles behind the leather armor's design and performance. Leather armor was made of natural materials that had high strength, durability, and resistance to various factors such as water, insects, heat, and chemicals. Third, it provides insights for developing new applications of leather and its alternatives in various industries. Thus, these materials can be utilized to enhance the mechanical properties of materials in various industries.

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Authors' contributions
GP developed the research idea. HL and YO performed mechanical analysis and collected the data. GP and ML were major contributor in writing the manuscript, and JL substantively revised it. All authors read and approved the final manuscript.

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Availability of data and materials
The data used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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