Journal of the mechanical behavior of biomedical materials 68 (2017) 303–307

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: www.elsevier.com/locate/jmbbm

Investigation of the elastic modulus, tensile and flexural strength of five skull simulant materials for impact testing of a forensic skin/skull/brain model

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A R T I C L E I N F O

Keywords:
Skull simulant
Epoxy resin
3D printing filament
Cranial bone

A B S T R A C T

Conducting in vitro research for forensic, impact and injury simulation modelling generally involves the use of a skull simulant with mechanical properties similar to those found in the human skull. For this study epoxy resin, fibre filled epoxy resin, 3D-printing filaments (PETG, PLA) and self-cure acrylic denture base resin were used to fabricate the specimens (n=20 per material group), according to ISO 527-2 IBB and ISO20795-1. Tensile and flexural testing in a universal testing machine was used to measure their tensile/flexural elastic modulus and strength. The results showed that the epoxy resin and fibre filled epoxy resin had similar tensile elastic moduli (no statistical significant difference) with lower values observed for the other materials. The fibre filled epoxy resin had a considerably higher flexural elastic modulus and strength, possibly attributed to the presence of fibres. Of the simulants tested, epoxy resin had an elastic modulus and flexural strength close to that of mean human skull values reported in the literature, and thus can be considered as a suitable skull simulant for a skin/skull/brain model for lower impact forces that do not exceed the fracture stress. For higher impact forces a 3D printing filament (PLA) may be a more suitable skull simulant material, due to its closer match to fracture stresses found in human skull bone. Influencing factors were also anisotropy, heterogeneity and viscoelasticity of human skull bone and simulant specimens.

1. Introduction

In vitro research into forensic, impact and injury simulation modelling requires a simulant material with mechanical properties similar to that of the range of properties found in the human skull. In order to develop a skull simulant it is essential to consider the properties of the skull's bone anatomy. It consists of various bones (22) that are all mainly connected together via sutures with their main function being to protect the brain (Fehrenbach et al., 2007). In general the skull is made up of a porous energy-absorbing layer (diplöe) that is located in between denser, stronger and stiffer layers (tabula external and internal) (Gurdjan et al., 1950; Roberts et al., 2013). The skull bones are all immovable with the exception of the mandible and its temporomandibular joint (Fehrenbach et al., 2007).

Thali et al. (2002) were the first to develop a spherical skin/skull/brain model, which used polyurethane to mimic the human skull bone. A glass/epoxy resin mixture was used by Merkle et al. (2010) and Roberts et al. (2013) used layered epoxy resin and urethane foams as a skull simulant. Das et al. (2015) investigated various simulant materials for the human head, while using polycarbonate panels and medium dense fibreboard to mimic the skull. Their study concluded that neither material were suitable simulants, as the polycarbonate is too ductile and even though the medium dense fibreboard behaved in a brittle manner similar to human bone it differed in its fracture pattern around the impact site.

Compression, tension, flexure, torsion and shear tests (McElhaney et al., 1970; Wood, 1971, Hubbard, 1971; Delille et al., 2007; Motherway et al., 2009) have been conducted using human adult cranial bone to determine the mechanical response when subjected to traumatic loads. McElhaney et al. (1970) and Delille et al. (2003) found that the method of preservation (*e.g.* frozen, embalmed) resulted in a deterioration of the mechanical properties. In addition, age, sex, geometry and cutting quality (resulting in edge defects) of the specimens resulted in a large range of reported values. Hence these authors did not recommend cadavers as a source of skull bone material for testing. Compression, tension, shear and torsion tests (McElhaney et al., 1970) on embalmed calvarium of frontal, parietal and occipital bone resulted in elastic modulus values ranging from 2.41–5.58 GPa ($3.50–8.10\times10^5$ Ib/in.^{2}) for compression, from 1.24–5.38 GPa ($1.8–7.8\times10^5$ Ib/in.^{2}) for tension and 1.38 GPa (2.0×10^5 Ib/in.^{2}) for torsion,

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http://dx.doi.org/10.1016/j.jmbbm.2017.02.023
Received 2 October 2016; Received in revised form 20 January 2017; Accepted 18 February 2017
Available online 20 February 2017
1751-6161/

depending on the tangential loading direction. The authors concluded the skull bone to be anisotropic, meaning it had different properties depending on the direction tangent to the skull surface. Wood (1971) subjected specimens from frontal, parietal calvaria bones to tension and reported a rate-dependent increase of the elastic modulus, ranging from 10.34–22.06 GPa (1.50–3.20×10^6 Ib/in.^{2}), which was also transversely anisotropic, as previously indicated by McElhaney et al. (1970). Hubbard (1971) conducted a flexure study utilizing the 'sandwich' structure (layered skull bone – diploe in between the Tabula layers) and reported the elastic modulus to be 9.5 GPa and the cranial bone to have a visco-elastic nature. A three-point bending test was used by Delille et al. (2007) to identify the mechanical properties of the human skull to develop a physical head model. They reported the mean elastic modulus to be 5.21 GPa (frontal bone – 3.79 GPa, left parietal bone – 4.40 GPa, right parietal bone – 5.01 GPa). In a more recent study by Motherway et al. (2009) cranial bone specimens from fresh-frozen cadavers (81 ± 11 years) were subjected to a three-point bending test (dynamic speed). They found that the frontal bone specimens required the highest forces upon failure and prior to failure absorbed the most energy, compared to the parietal bones. In addition, they reported the elastic modulus of the cranial bone to be 7.46 ± 5.39 GPa to 15.54 ± 10.29 GPa, depending on the loading speed (0.5–2.5 m/s).

The wide range of reported values (Table 1) for the mechanical properties of the skull presents a challenge when trying to find an appropriate skull simulant. Therefore, this study aims to investigate five potential skull simulant materials in terms of their elastic moduli and flexural/tensile strength compared to the published range of human skull values (Table 1), to identify a suitable material for a forensic skin/skull/brain model impact testing.

2. Materials and method

2.1. Test specimens

Epoxy resin (Masterflow 622, Degussa, Hanau, Germany); fibre filled epoxy resin (Sawbones, Vashon, Washington, USA); polyethylene terephthalate glycol modified (PETG) (Mindkits, Auckland, New Zealand); polylactic acid (PLA) 3-D printing filament (Mindkits, Auckland, New Zealand) and self-cure acrylic denture base resin (Castapress, Vertex-Dental, Soesterberg, Netherlands) were used. 100 specimens (n=20 per group) were fabricated according to ISO 527-2 1BB (International Standard Organization, 1996) (Fig. 1a) for tensile testing, and 100 specimens (n=20 per group) according to ISO 20795-1 (International Standard Organization, 2013) for flexural testing (Fig. 1b). The PETG and PLA specimens were 3-D printed (Ultimaker 2, Ultimaker B.V., Geldermalsen, Netherlands). The self-cure acrylic denture base resin (1 ml monomer:1.7 g polymer) and epoxy resin (5:1 Part A:B) specimens were fabricated from a silicone mould formed from the 3D printed specimens. The fibre-filled epoxy resin specimens were cut from supplied sheets (130×180×4 mm) using a scroll saw (Frejoth, MS-18, Taichung, Taiwan). All faces and edges were sequentially polished with metallographic grinding paper with a grit size of 30µm (P500), 18 µm (P1000) and 15 µm (P1200). Tensile testing until failure was carried out in a universal testing machine (Instron 3369; Instron, Norwood, MA, USA), using a 1 kN (± 2 N) load cell at a crosshead speed of 1 mm/min with an extensometer (W-6280 series, Instron, Norwood, MA, USA) used to record the strain. The maximum force (N), tensile stress (MPa) and strain (mm/mm) were recorded and the elastic modulus (MPa) calculated (tangent of the slope of the stress-strain curve). Flexural testing until failure was carried out in the same universal testing machine using a 1 kN load cell at a crosshead speed of 5 mm/min. The cross head was used to record the flexural strain. The maximum force (N), flexural stress (MPa) and strain (mm/mm) were recorded and the elastic modulus (MPa) calculated (stress/strain of the slope of the stress-strain curve).

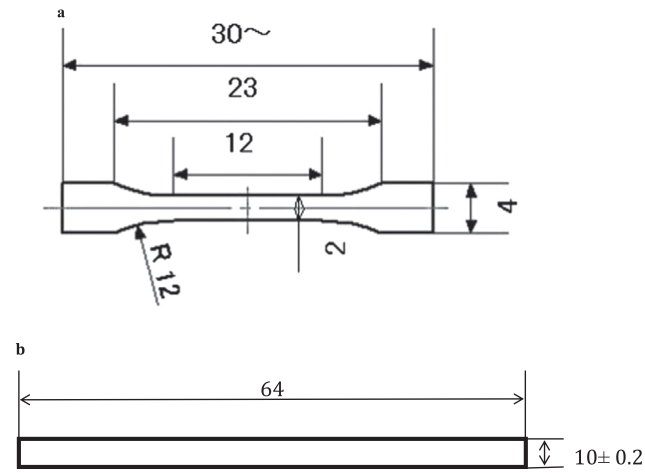

Fig. 1. a Test specimen according to ISO 527-2 1BB in mm. **b** test specimen according to ISO 20795-1 – 64×10 ± 0.2×3.3 ± 0.2 mm.

2.2. Statistical analysis

The statistical analysis (one-way analysis of variance (ANOVA) and a Kruskal-Wallis test) was conducted using SPSS (IBM, 2016, Version

Table 1
Elastic modulus, tensile and flexural strength of published skull bone properties.

	Elastic modulus (GPa)	Tensile strength (MPa)	Flexural strength (MPa)	Loading type	Sample information
Hubbard (1971); Wood (1971)	11.73 ± 0.95		82.00 ± 25.50	flexure	Parietal bones (embalmed); temporal, frontal, parietal bones, age: 25–95 years
Robbins and Wood (1969); McElhaney et al. (1970); Wood (1971)		67.73 ± 17.80			Entire embalmed skull cap; parietal, occipital bones, age: 56–73 years; Temporal, frontal, parietal bones, age: 25–95 years
Delille et al. (2007)	5.21			Flexure	Frontal, parietal, temporal, occipital bones
McElhaney et al. (1970)	2.41–5.58 1.23–5.38 1.38			Compression Tension Torsion	Parietal, occipital bones, age: 56–73 years
Motherway et al. (2009)	7.46 ± 5.39 to 15.54 ± 10.29			Flexure	Parietal, frontal bones (frozen), age: 81 ± 11 years
Values of published studies used for comparison.	8.51 (mean)	67.73 ± 17.80	82.00 ± 25.50		