Orientational Variation and Failure criteria of Cortical bone under Shear conditions using FEM with its applications in Animals and Aquatic Species

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Abstract
Bone in the daily activities come in to contact with different type of loads and sometimes become a reason of fracture or failure when it exceeds the value of failure limit. Among these load types, the stresses generated due to shear loading are typically minor in contrast to tensile and compressive stresses, but they can become significant in bones with long lengths. Therefore, it becomes necessary to define the failure criteria during shear so that a necessary measure can be taken to avoid the failure or fracture of a bone. In the current study, two type of specimens with orientations Longitudinal and Transverse to the axis of femur animal bone has been considered to measure the shear properties of a cortical bone using Iosipescu test FEM model. The shear modulus of longitudinal specimen found to be more in comparison to transverse orientated specimen. Also, it has been found that when the value of external applied load stress becomes 0.18 and 0.21 times the ultimate compressive stress for longitudinal and transverse orientated specimens, a shear failure appears at the specimen. The longitudinal orientated specimen found to be stronger during compressive loading and transverse orientated specimen found stronger during shear loading. Overall, the cortical bone shows weaker behaviour during shear in comparison to compressive loading. The results of this study can be applied for the bones in aquatic species like fishes, crocodiles etc. as in water, these species shall wear shear and compressive load on their bones during swimming.

Introduction
Bone is a complex natural material with a hierarchical structure, and its characteristics vary from microstructure to macrostructure level, as well as related to composition. In daily activities, bone is exposed to various loading situations such as compressive, tension, torsion, bending, shear, and so on. Shear stresses are typically minor in contrast to tensile and compressive stresses, but they can become significant in bones with long lengths. Furthermore, cortical bone is thought to be weaker in shear compared to compression and tension, making shear qualities of cortical bone crucial. Furthermore, the composition and alignment of the bone are such that it is subjected to compressive loads most of the time, but under some unavoidable conditions, bone is subjected to shear as well as tensile forces. Investigations into the mechanical characteristics of bone might benefit not just clinical scientists but also engineers working on bio-inspired materials. Most significantly, for the design and development of prosthetic bone implants and FE models, critical features and behaviour of bone, such as shear behaviour at different anatomic regions, must be evaluated. Many researchers have worked in determining the behaviour of cortical bone under shear conditions i.e., measuring the shear modulus and young's modulus of cortical bone [1] and correlating with different type of species using different methods that include three-point bending [2] [3], shear lap procedure [4], fracture mechanics approach [5] [6] and indentation method [7]. The damage in bone is caused by shear failure of the organic matrix [8]. The porosity of a bone also effects the longitudinal shear modulus, transverse shear modulus of a bone [9] and the crack is caused in

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a bone due to high level of shear and compression [7]. Under indentation, the bone experiences high levels of compression and shear, causing cracks to form and grow [10]. Shear is an important strain regime in the squamosal suture as per Strain ratios [11] and also, there found a correlation of fracture pattern and microstructure on the shear behaviour of a bone [12]. Mechanical behaviour of a cortical femur bone has been studied and compared for demineralized and deproteinized while applying pure shear and equi-biaxial tension loading [13]. The shear bonding strength of cortical bone varies with the wet conditions [14] and there found a variation in the failure of cortical bone while applying shear stress for different orientations of sample microstructure [15]. Digital image correlation has been used to measure the non-linear shear behavior of bovine cortical bone by coupling with the Arcan test [16] [17] and find out experimentally the mechanical properties while applying tensile, compressive and shear loading on two different orientations i.e., longitudinal and transverse [18]. Different FEM models have been developed to measure the mechanical properties of a cortical bone [19] [20], [21] for different type of specimens.

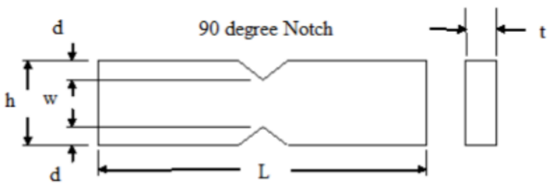
It has been observed from the existing literature that researchers have studied shear behaviour for different applications and domains experimentally. In the experimental study, it is difficult to fabricate a small size specimen of bone as per anatomical location and orientation of lamellae. Moreover, it is difficult to perform different type of tests on different testing equipment's. The results obtained from experimental study may results in variation due to type of species, location, environmental conditions, strain rates, preservation solution etc. Therefore, to reduce the variation in the results the FEM study can be performed for different type of specimens to predict different mechanical properties of a bone. The present study focuses on applying the Iosipescu test to study the variation in shear behaviour of bovine cortical bone and predicting the failure criteria while considering specimens from different orientations i.e., longitudinal and transverse using FEM model.

Materials and Methods

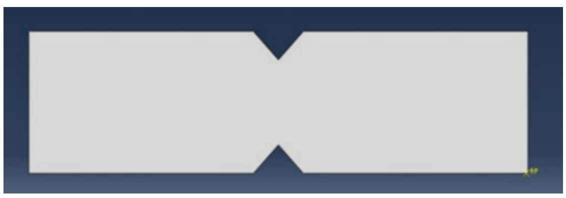
In the present study, the Iosipescu shear test has been used to identify the variation in shear properties of cortical bone for two different orientations i.e., longitudinal and transverse using the FEM approach. Iosipescu shear test is relatively simple and it's easy to prepare specimens for it. This method is useful in the case of a variety of composite materials, therefore applied for material which is biological composite in the present study.

CAD model of Specimen used for Iosipescu Shear Test:

The V-notch Iosipescu shear test uses a flat specimen that is easier to prepare while achieving a pure and uniform shear stress state between the V-notches. The shear test specimens were obtained with thickness = 1 mm, width = 5 mm and length = 20 mm [18]. A 90° notch was cut on each edge of the specimen at the mid-length to a depth = 2 mm as shown in Figure 1(a). The specimens were obtained for conducting Iosipescu shear test in 1-2 plane. The CAD model of the specimen created in ABAQUS has been shown in Figure 1(b). The complete assembled model of Iosipescu test is shown in Figure 1(c).



(a)



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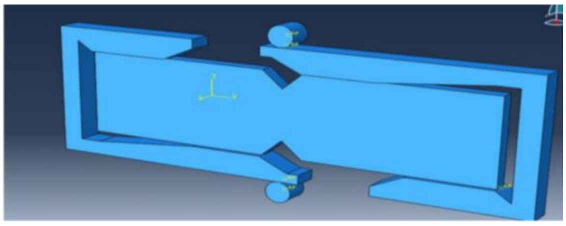


(c)

Figure 1: (a) Dimensions of Specimen; (b) CAD model of specimen; and (c) Assembly model of Iosipescu Shear test in Abaqus

Material properties and Meshing

The present study has been conducted on the specimen modelled using properties obtained from two different orientations i.e., Longitudinal and Transverse of the bone diaphysis of a bovine femoral bone. The details about the type of specimen along with its material properties has been mentioned in Table 1.

Table 1: Material Properties of specimens [18]

Specimen No.	Longitudinal: Compressive Elastic Modulus (MPa)	Transverse: Compressive Elastic Modulus (MPa)	Poisson Ratio
1	8279.55	3042.77	0.37
2	9292.33	2539.66	0.37
3	4429.66	1580.11	0.37
4	4554.22	1423.66	0.37
5	3187.66	1336.77	0.37
6	3347.77	1213	0.37

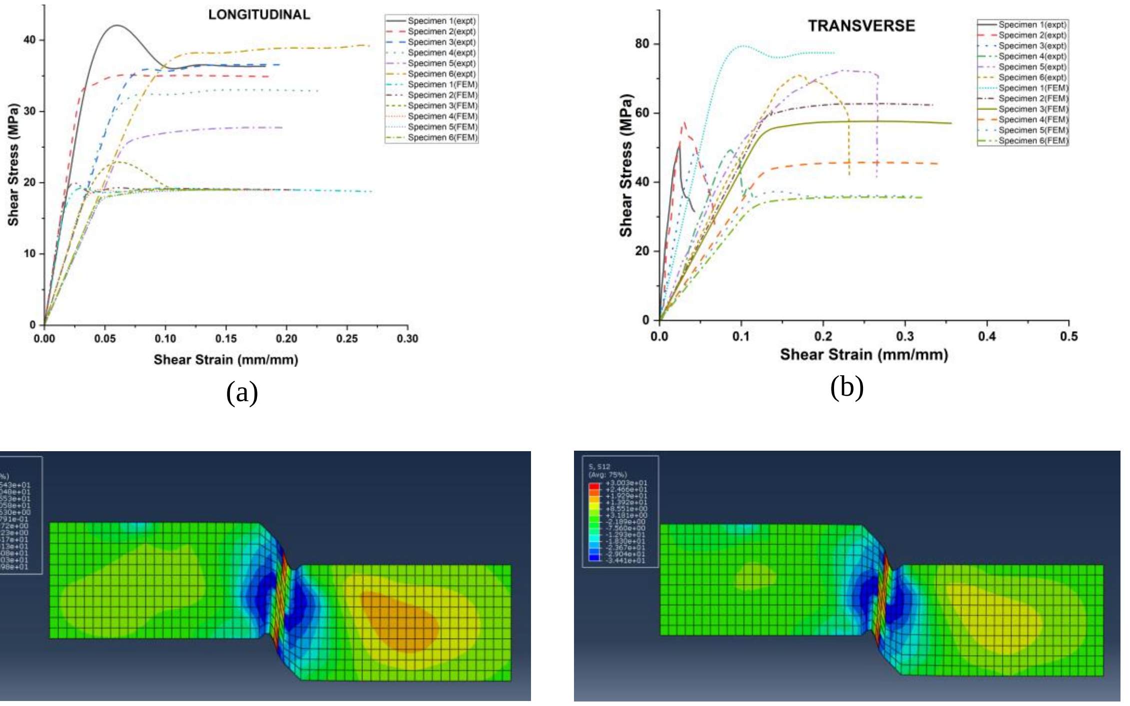
The fixture of Iosipescu test has been modelled as analytically rigid and the specimen has meshed using 8-noded quadratic quadrilateral elements. The model is subjected to a quasi-static loading applied by a cylindrical bead which is rigid in nature. The left portion of the test specimen holder is fixed using the boundary condition option Encaster (rigidly constrained) whereas the right test specimen holder is left to move freely in the x-y plane. The specimen and the test specimen holder have been assigned a close surface interaction of Slave and Master using the contact algorithm in ABAQUS. The quasi-static loading is applied using amplitude option and small incremental steps are used at the reference node at the interaction of cylindrical bead and specimen holder.

Results and Discussion

The shear stress-strain plots for two types of specimens with orientation of longitudinal and transverse measured using experimental study [18] and FEM model is shown in Figure 2(a) and Figure 2(b). The FEM simulation contours for shear stress in the plane 1-2 i.e., S12 is shown in Figure 2(c) and Figure 2(d) for longitudinal and transverse specimen respectively. The shear modulus, shear failure stress and shear failure strain are measured from shear stress-strain plots for each type of specimen and further, these parameters are compared that are shown in Table 2. The ratio of shear failure stress and ultimate compressive stress is also been measured for each specimen and shown in Table 2. The shear modulus and shear failure stress obtained in the current study has been compared statistically with the experimental obtained values that are shown using Box and Whisker plots as shown in Figure 3.

Longitudinal Orientation Specimen

It has been observed from Figure 2(a) that the shear stress-strain curve obtained from the FEM model for different specimens found a good relation with the experimental obtained results [18]. The FEM contour profile for longitudinal specimen is shown in Figure 2(c) obtained using average value of material properties mentioned in Table 1. The shear modulus and shear failure stress obtained from FEM model and experimental study found to be statistically with non-significant difference at $p<0.05$ as shown in Figure 3(a) and Figure 3(b). The average shear modulus obtained from experimental study is 684.02 MPa and using FEM model the value found to be 666 MPa as shown in Table 2. The value of shear modulus varies from 384.35 MPa to 1106.5 MPa and the value of shear failure stress varies from 27.74 to 39.14 MPa. The average value of shear failure stress obtained using experimental study is 35.38 and using FEM model, the value is 34.66 as shown in Figure 3(b). The ratio of elastic modulus (experimental) and shear modulus (FEM) is evaluated for each of the specimen and found an average ratio of 7.74. Also, the ratio of shear failure stress (FEM) and ultimate compressive stress(experimental) of each specimen has been mentioned in Table 2; the average value of ratio found to be 0.18. The external load applied while performing Iosipescu test using FEM is obtained for each specimen and found an average as 4104.53 N that represents the maximum load at which shear failure occurs. The average value of shear failure strain found to be 0.15 mm/mm.



(a) (b)

(c) (d)

Figure 2: (a) Shear stress-strain plot for longitudinal specimen; (b) Shear stress-strain plot for transverse specimen; (c) Shear stress (S12) for longitudinal specimen; and (d) Shear stress (S12) for transverse specimen

Transverse Orientation Specimen

The shear stress-strain curve for different specimens obtained using FEM model are compared with the experimental that are shown in Figure 2(b). The FEM contour profile obtained after considering the average value of elastic modulus and Poisson's ratio is shown in Figure 2(d). The shear modulus found a non-significant difference at $p<0.05$ while comparing the experimental and FEM model results using paired t-test as shown in Figure 3(a). The shear failure stress found non-significant difference at $p<0.05$ for FEM model and experimental obtained results as shown in Figure 3(b). The shear modulus for each specimen is calculated using shear stress-strain curve and found an average of 779.85 MPa for FEM model; 893.16 MPa for experimental results.

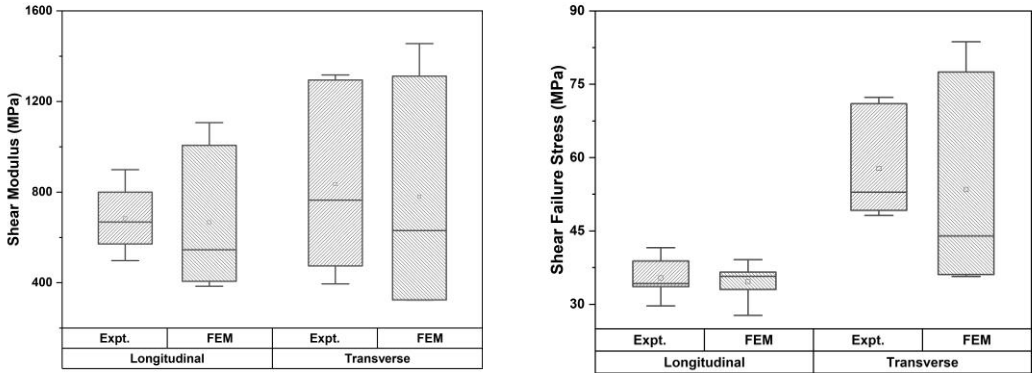


Figure 3: Box-Whisker Plots: (a) Shear Modulus; and (b) Shear Failure Stress

The shear failure stress is also calculated for each specimen as shown in Table 2 and found an average for FEM model and experimental as 53.48 MPa and 57.76 MPa. The value of shear failure varies from 35.68 MPa to 83.70 MPa and the value of shear modulus varies from 323.11 MPa to 1456 MPa. The ratio of elastic modulus (experimental) and shear modulus (FEM) for each specimen is measured and found an average of 2.84. The ultimate compressive stress (experimental) for each specimen is obtained from existing literature and the average value found to be 248.49 MPa. The ratio of shear failure stress and ultimate compressive stress is also calculated for each specimen and found an average ratio to be 0.21. The maximum compressive external load that can be applied for shear failure is also been measured for each specimen and found an average of 3032.67 N. The value of share failure shear also varies for each specimen and the average value is 0.25.

Table 2: Comparison of Shear Properties

Type of Orientation	Specimen No.	Shear Modulus (MPa)	Ratio of Elastic Modulus/Shear Modulus	Ultimate Compressive Stress (MPa)	Shear Failure Stress (MPa)	Ratio of Shear Failure Stress/ Ultimate Compressive	Maximum Compressive External Load (N)	Shear Failure Strain (mm/mm)
Longitudinal	1	1006.3	10.34	191.45	36.42	0.19	4307.8	0.12
	2	1106.5	10.33	183.57	35.03	0.19	4167.79	0.10
	3	537.91	6.79	194.09	36.58	0.18	4311.48	0.17
	4	553.17	6.65	174.83	33.03	0.18	3891.96	0.13
	5	384.35	5.58	147.48	27.74	0.18	3273.26	0.17
	6	406.14	6.72	211.95	39.14	0.18	4674.91	0.26
	Average	**666**	**7.74**	**183.89**	**34.66**	**0.18**	**4104.53**	**0.15**
Transverse	1	1456	2.08	151.62	77.50	0.51	3362.41	0.18
	2	1312	1.93	242.67	83.70	0.34	5117.95	0.27
	3	816	1.93	309.77	42.23	0.13	2577.33	0.28
	4	444.89	3.20	300.06	45.70	0.15	2785.33	0.27
	5	323.11	4.13	181.31	36.09	0.19	2182.03	0.26

	6	324.1	3.74	305.52	35.68	0.11	2170.94	0.24
	Average	**779.35**	**2.84**	**248.49**	**53.48**	**0.21**	**3032.67**	**0.25**

The results obtained from FEM and experimental study [18] have been compared statistically and found non-significant difference at $p<0.05$. There found a difference while comparing the average value of shear failure strain for longitudinal and transverse specimens. Moreover, the difference in values also appears while comparing the FEM results with the individual specimen that is due to the heterogeneity and anisotropic nature of cortical bone. Also, in FEM model the porosity of a cortical bone has been neglected that can also be one of the reasons of divergence in results.

The average ratio of shear failure stress and ultimate compressive stress found to be more for transverse orientated specimens. The average value of elastic modulus for longitudinal specimens found 2.97 times the transverse orientated specimens and the average value of shear modulus for transverse specimens is 1.16 times the longitudinal orientated specimens. It means the longitudinal specimens are more stiffer during compressive loading and transverse specimens are more stiffer during shear loading but transverse orientated specimens show more value of ultimate compressive stress. The average value of shear failure stress for transverse specimens found to be 1.54 times the longitudinal specimens. The value of shear failure strain is more for transverse specimen in comparison to longitudinal specimens. It is evident from this study that the results obtained from FEM model is closer to experimental results available in the existing literature.

Conclusion

In the current study, six specimens each of two different orientations i.e., Longitudinal and Transverse to the axis of femur bovine bone has been considered to measure the shear properties of a cortical bone using Iosipescu test FEM model. The material properties that include elastic modulus and poison ratio for these six specimens have been considered as per available literature. The average shear modulus found to be 666 MPa and 779.35 MPa; shear failure stress as 34.66 MPa and 53.48 MPa; shear failure strain as 0.15 mm/mm and 0.25 mm/mm for longitudinal and transverse orientated specimen. it has been found that when the value of external applied load stress becomes 0.18 and 0.21 times the ultimate compressive stress for longitudinal and transverse orientated specimens, the shear failure start showing at the V-notch location of a specimen. There found a variation in the results of different shear parameters of a cortical bone that is due to the porosity, anisotropic and heterogenous behaviour of a cortical bone that has not been considered in the current study. The longitudinal orientated specimen found to be more stiffer during compressive loading and transverse orientated specimen found stiffer during shear loading. Overall, the cortical bone shows weaker behaviour during shear in comparison to compressive loading. The results obtained using FEM model has been compared with the experimental obtained results and found a good relation with difference of 5-6 % that is due to anisotropic and heterogenous properties of a bone.

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