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Research Article

# Buckling analysis of natural fiber reinforced composites

Celal Cakiroglu [a,*], Gebrail Bekdaş [b]

[a] Department of Civil Engineering, Turkish-German University, 34820 İstanbul, Turkey
[b] Department of Civil Engineering, İstanbul University-Cerrahpaşa, 34320 İstanbul, Turkey

## ABSTRACT

In the recent years natural fiber reinforced composites are increasingly receiving attention from the researchers and engineers due to their mechanical properties comparable to the conventional synthetic fibers and due to their ease of preparation, low cost and density, eco-friendliness and bio-degradability. Natural fibers such as kenaf or flux are being considered as a viable replacement for glass, aramid or carbon. Extensive experimental studies have been carried out to determine the mechanical behavior of different natural fiber types such as the elastic modulus, tensile strength, flexural strength and the Poisson's ratio. This paper presents a review of the various experimental studies in the field of fiber reinforced composites while summarizing the research outcome about the elastic properties of the major types of natural fiber reinforced composites. Furthermore, the performance of a kenaf reinforced composite plate is demonstrated using finite element analysis and results are compared to a glass fiber reinforced laminated composite plate.

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## 1. Introduction

Composite materials are playing an important role in the manufacturing of lightweight structural components in the recent years. The increase in the application of composites as a structural material is mainly because of their superior mechanical properties compared to the regular structural materials such as steel and aluminum. The high stiffness and light weight of composites reduce the production cost and increase the product quality. Carbon fiber reinforced polymers (CFRP), boron/epoxy composites and glass fiber reinforced polymers are some of the most widely used composite material types in the lightweight structures industry. However, despite their ability to deliver high structural performance these types of composite materials do not have optimum recyclability and biodegradability. In order to eliminate these shortcomings, the application of natural fibers reinforced composite materials has been proposed in the literature (Sanjay et al., 2013; Holbery and Houston, 2006). Some of the advantages of using natural fibers over synthetic fibers are their worldwide availability and the ease of manufacturing since natural fiber yielding plants are mostly available in nature in stringy forms. A wide variety of natural materials were reported to have the capability of serving as fiber reinforcement in composites. Some of the most frequently mentioned natural materials in the literature are hemp, jute, kenaf, sisal and banana leaf. Especially kenaf differentiates itself in this group of materials because of its abundant availability, low water usage and high absorption of carbon dioxide.

Synthetic fiber reinforced composite plates have been mainly used as shell structures in aerospace, automotive and construction industries. On the other hand, due to the advancements in the natural fiber reinforced composite technology, these novel materials are being considered as viable replacements for synthetic composites in structural applications. Since buckling is a major failure mode of shell structures the buckling load is widely used as a performance indicator for this type of structural member. Therefore, the buckling response of natural fiber reinforced composites must be assiduously investigated in order to make a large-scale deployment of these materials in the industry possible. In this study the buckling behavior of glass fiber reinforced laminated composite plates has been compared to laminates with various types of natural fiber constituents.

* *Corresponding author.* E-mail address: cakiroglu@tau.edu.tr (C. Cakiroglu)
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## 2. Mechanical Properties of Natural Fiber Reinforced Composites

Akil et al. (2011) presented an overview of the general characteristics and the application of kenaf fibers as a composite constituent (Fig. 1). In this work kenaf was put forward as an alternative to replace glass as the fiber reinforcement because of the high energy consumption associated with the glass fiber production. Nishino (2004) reported that the energy needed to produce 1kg of kenaf is 15MJ while the energy required to produce 1kg of glass fiber is 54 MJ. Moreover, it was observed that within three months of sowing the seeds kenaf plants are able to grow to a height of more than 3m and a base diameter of 3 to 5 cm under various weather conditions (Aziz et al., 2005). Because of these circumstances kenaf as a fiber material has obvious economic and ecological advantages over glass. The mechanical properties of kenaf reinforced composites were studied by various researchers. Some of the factors that affect the mechanical properties such as ultimate tensile strength or flexural modulus of the fiber reinforced composites are the type and orientation of the fibers (unilateral or randomly oriented) as well as the fiber volume fraction and the type of resin in which the fibers are embedded. Ochi (2008) investigated the mechanical properties of biodegradable composites with unidirectional fibers made of kenaf and a PLA (polylactic acid) matrix. The kenaf used in the fabrication of the biodegradable composites was cultivated in two different ambient temperatures (22°C and 30°C) and the effect of the ambient temperature on the tensile strength of the fibers was studied.

**Fig. 1.** Kenaf plants (Akil et al., 2011).

In addition to the effect of the ambient temperature also, the effect of the location of the fiber on the plant i.e. its distance from the root was studied by dividing the kenaf in 500 mm sections and testing each section separately. Besides the effect of the ambient temperature on the mechanical properties of kenaf also its effects on the growth of kenaf was examined. It was observed that at the end of 168 days, the height of kenaf grown in a 30°C environment was on average 1650 mm taller than kenaf grown in a 22°C environment. Moreover, the kenaf fibers taken out of the longer rods grown at 30°C were observed to have greater tensile strength and elasticity modulus compared to the fibers taken out of shorter rods. A comparison of the average tensile strength of the fibers taken from the top 500 mm and bottom 500 mm of the kenaf rods showed that the tensile strength of the top fibers is 80% of the tensile strength of the bottom fibers. Because the fiber tensile strength was found to be increasing with ambient temperature and inversely proportional to the distance from the roots, only fibers taken from the bottom portions of the kenaf rods cultivated at 30°C were used in the fabrication of kenaf fiber reinforced composite specimens that were tested in (Ochi, 2008). The kenaf/PLA composites were found to have tensile and flexural strengths of 223 MPa and 254 MPa respectively. These values are in the same order of magnitude with glass fiber reinforced composites (GFRP) (Naresh et al., 2018). In the experiments of Nishino et al. (2003) the Young's modulus of kenaf/PLA (poly-lactic acid) composites was observed to be comparable to the Young's modulus of synthetic fiber reinforced composites. The average fiber direction Young's modulus of the kenaf reinforced composites in these experiments was reported as 6300 MPa whereas the Young's modulus in the direction perpendicular to the fibers was on average 1500 MPa. Andre et al. (2016) studied the effect of kenaf fiber volume fraction on the tensile strength and the Poisson's ratio of the composites. It was observed that the highest tensile strength and Poisson's ratio occurs at a volume fraction of $V_f$=0.42. According to the research data collected by multiple researchers in the field (Andre et al., 2016; Ku et al., 2011), a volume fraction around 0.4 is a limit value after which the tensile strength of the composite material begins to decrease since the matrix is not filling the gaps between the fibers properly at these higher volume fraction values (Sawpan et al., 2013;

Dent et al., 2008). In the research carried out by Andre et al. (2016), the modulus of elasticity ($E_C$) and Poisson's ratio ($\nu_C$) of the kenaf fiber reinforced composites were predicted using the equations developed by Tsai-Pagano, Manera and Cox-Krenchel. The predicted values together with the experimental outcome can be seen in Fig. 2.

Also, the predicted values of the Poisson's ratio were compared to the experimental values as shown in Fig. 3.

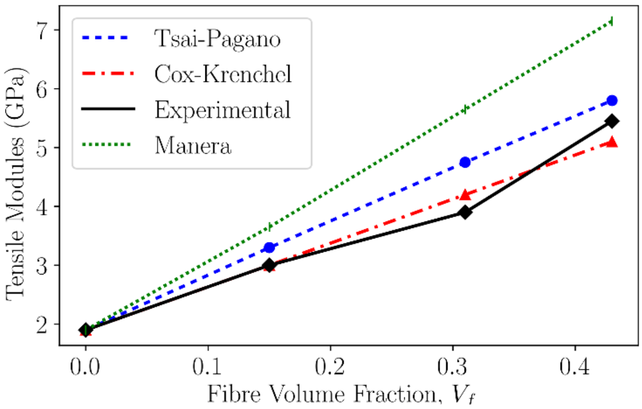


**Fig. 2.** Experimental and predicted tensile modulus for kenaf reinforced composite (Andre et al., 2016).

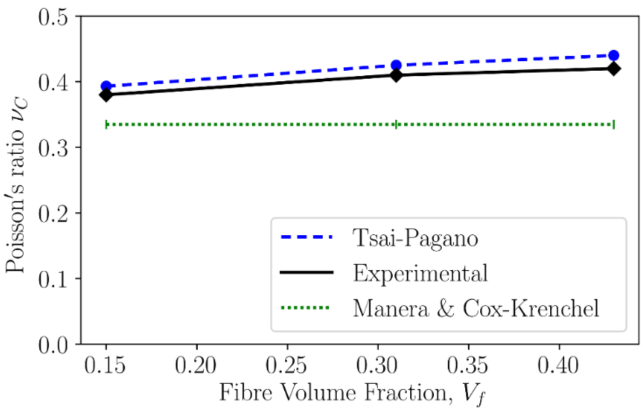


**Fig. 3.** Experimental and predicted Poisson's ratio for kenaf reinforced composite (Andre et al., 2016).

Another environmentally friendly fiber material that can be used in composites is flax. Oksman et al. (2003) studied the mechanical properties of flax/PLA composites (Fig. 4). In this study it was shown that as a matrix material for composites with flax fibers, PLA performs 50% better than polypropylene (PP). The elasticity modulus and tensile strength reported in the experiments of Oksman et al. (2003) were 8300 MPa and 53MPa respectively. Andersons and Spa (2016) carried out tensile experiments with composites which consist of flax fiber mats embedded in polypropylene matrix in order to determine the mechanical properties. The experiments were carried out with rectangular specimens (250 mm long and 25 mm wide) cut out of plates with 3 mm thickness manufactured for these experiments. An average elasticity modulus of 8700 MPa was measured in these experiments. Pozzi and Sepe (2012) also carried out tensile tests with flax fiber reinforced polymers in order to determine the elasticity modulus, tensile strength and Poisson's ratio. In these experiments a tensile modulus of 7882 MPa and a tensile strength of 103 MPa were measured. The Poisson's ratio was observed to vary with the flax fiber orientation angle in a range from 0.24 to 0.51.

**Fig. 4.** Flax fibers (Oksman et al., 2003).

Another natural fiber material that was examined in the literature is hemp. Sawpan et al. (2013) carried out tensile tests with hemp fiber reinforced UPE (unsaturated polyester) composites which is a type of natural composite that possesses low density and good stiffness. The result of these tensile tests can be seen in Fig. 5.

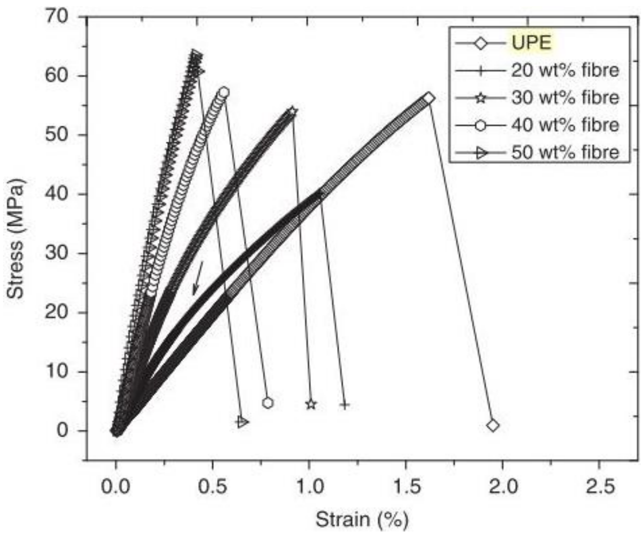


**Fig. 5.** Stress-strain response of hemp reinforced UPE (unsaturated polyester) compo-sites at various fiber volume fractions (Dent et al., 2008).

Fig. 5 shows the stress-strain response of hemp reinforced composites at four different levels of fiber volume fraction and the stress strain behavior of a matrix only specimen. It can be concluded from Fig. 5 that the composites with 20% fiber volume fraction have less tensile strength than the matrix only specimen, while the tensile strength tends to increase with the fiber content. The decrease in the tensile strength due to the addition of the fibers into the matrix is a subject that was investigated in the literature. (Piggott, 1994) introduced an equation that predicts the minimum fiber volume fraction ($V_{f,min}$) that leads to increased tensile properties as follows:

$$V_{f,min} = \frac{(\sigma_m - \sigma_m^*)}{(K_1 K_2 \sigma_f - \sigma_m^*)} \tag{1}$$

In this equation, $\sigma_m$ is the tensile strength of the matrix, $\sigma_m^*$ is the strength of the matrix at the failure strain of the fiber and $\sigma_f$ is the strength of the fiber. The values recommended in the literature for the fiber orientation coefficient $K_1$ and the stress transfer factor $K_2$ are 0.2 and 0.96 respectively (Bos et al., 2006; Kalaprasad et al., 1997).

Lu et al. (2012) tested hemp fiber reinforced composites with high-density poly-ethylene matrix at fiber volume fractions between 20% and 40%. In these experiments a maximum tensile strength of 60 MPa was observed while the best mechanical properties were obtained from the composites with 40% fiber volume fraction. Moreover, the stiffness and fiber volume fraction were observed to be proportional to each other. A maximum elastic modulus of 2574 MPa was exhibited by composites with 40% fiber volume fraction. An overview of the mechanical properties of kenaf, flax and hemp fibers reported in the literature is listed in Table 1.

**Table 1.** Ranges of the mechanical properties of kenaf, flax and hemp fiber composites.

| Fiber | Tensile strength [MPa] | Young's modulus [GPa] |
|---|---|---|
| Kenaf | 60 – 223 | 1.5 – 6.3 |
| Flax | 53 – 103 | 8.3 – 8.7 |
| Hemp | 60 – 65 | 2.6 – 16.3 |

### *2.1. Mechanics of laminated composite plates*

Laminated composite plates are widely used in the industry due to the advantages they offer in terms of structural performance and cost reduction. These structures consist of a certain number of layers where each layer is made of a certain type of composite material. Some of the commonly used composite materials are carbon fiber composites, boron/epoxy composites and glass fiber composites whereas natural fiber reinforced composites such as kenaf reinforced composites are a newer addition to the list of composite materials. The performance of these structures is largely determined by the fiber orientations and thicknesses of each layer.

Fig. 6 illustrates a section out of a laminated composite plate where $\theta_1$ and $t_1$ denote the fiber orientation angle and the thickness of the first layer respectively. The long and short sides of the rectangular plate are denoted with $a$ and $b$, and $N_x$ denotes the compressive line load in the $x$-direction. The stacking sequence optimization of laminates is an extensively studied area of research (De Almeida, 2016; Cakiroglu et al., 2020) that deals with finding the optimum sequence of fiber orientation angles and ply thicknesses that deliver the best possible structural performance or the lowest cost. In these studies, mostly the buckling load is used as a measure of structural performance. The buckling load of a laminate can be computed using the eigenvalue buckling analysis procedure implemented in the finite element analysis program Abaqus.

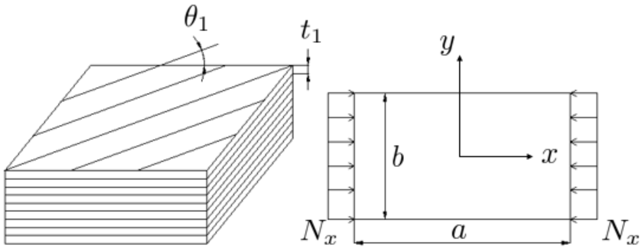


**Fig. 6.** Laminated composite plate under uniaxial compression.

Fig. 7 illustrates the model of a rectangular laminate with the aspect ratio $a/b$=2, under uniaxial compression. The finite element mesh consists of reduced integration elements and the colour map shows the displacements ($U$) in the first buckling mode. On each side of the plate the constrained degrees of freedom are shown with letters such that each letter indicates a constrained degree of freedom in the corresponding direction. The compressive force is applied on the plate using a unit force which increases during the eigenvalue buckling analysis incrementally and multi-point constraints (MPC). The MPC are applied in such a way that all the nodes on the right-hand side of the plate go through the same amount of displacement as the upper right corner node where the concentrated unit force is applied.

### *2.2. Performance comparison between fiberglass and kenaf reinforced laminated composite plates*

In order to compare the performances of kenaf reinforced laminates with fiberglass composite laminates eigenvalue buckling analysis has been carried out using Abaqus. In this analysis optimized stacking sequences have been adopted from the study of Cakiroglu et al. (2020) and are listed in Table 2 for each value of the plate aspect ratio ($a/b$) where the angles have the unit of degrees and the layer thicknesses have the unit of millimeters. The same stacking sequences have been applied to both kenaf and glass reinforced composites for each aspect ratio.

Table 2 shows the elasticity moduli of kenaf and glass reinforced composites where E1 denotes the elasticity modulus in the fiber direction and E2 denotes the elasticity modulus in the direction perpendicular to the fibers. The stacking sequences for the fiber angles and the ply thicknesses listed in Table 2 are the optimum stacking sequences for 9 layered fiberglass laminates of different aspect ratios obtained through harmony search optimization. It can be seen that the GFRP plate performed on average 4.37 times better than the kenaf reinforced plate in terms of buckling load. The comparison of the two materials in terms of buckling load is also visualized in Fig. 8.

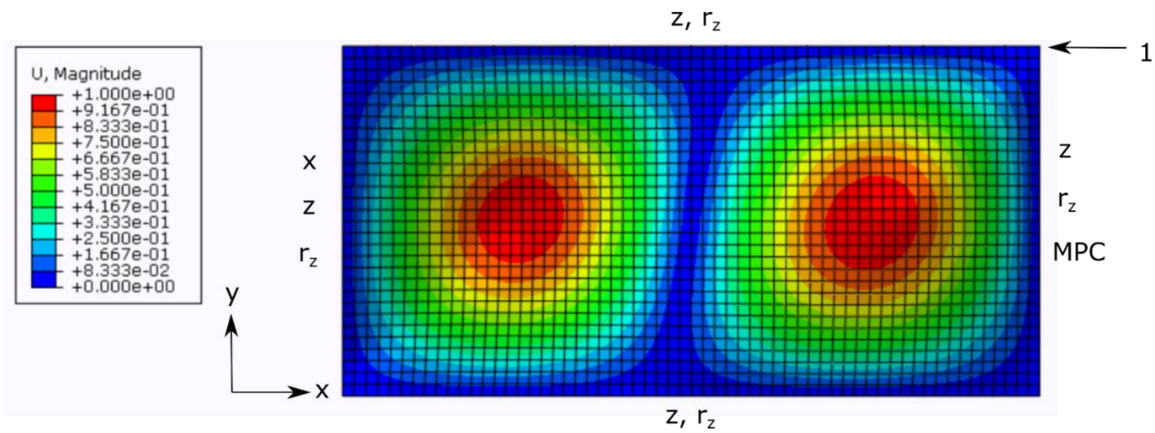


**Fig. 7.** Boundary conditions in the eigenvalue buckling analysis.

**Table 2.** Young's modulus and buckling load values for kenaf and glass reinforced composites.

| Fiber | Kenaf | Glass | Fiber orientation angle sequence | Ply thickness sequence |
|---|---|---|---|---|
| *E*1 [MPa] | 6300 | 33000 | | |
| *E*2 [MPa] | 1500 | 3100 | | |
| Buckling load [N] for *a*/*b*=1 | 969 | 4201 | [-53, 34, 49, 20, 61, -76, -29, 38, -45] | [0.32, 0.1, 0.22, 0.1, 0.11, 0.78, 0.1, 0.42, 0.1] |
| Buckling load [N] for *a*/*b* =2 | 964 | 4237 | [41, 50, -50, -16, -83, 40, 62, -51, -34] | [0.1, 0.17, 0.43, 0.1, 0.45, 0.63, 0.1, 0.16, 0.1] |
| Buckling load [N] for *a*/*b* =3 | 962 | 4210 | [49, -47,68, 45, -66, 60, 52, -36, -42] | [0.2, 0.26, 0.38, 0.26, 0.1, 0.3, 0.42, 0.1, 0.22] |

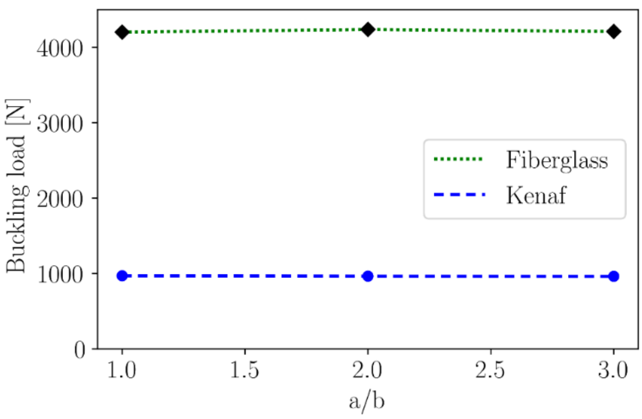


**Fig. 8.** Variation of the buckling load with the aspect ratio.

## 3. Conclusions

The low cost, abundant availability and eco-friendliness of natural fiber reinforced composites lead to an increased interest in this field in the recent years. Especially the high $CO_2$ consumption by the natural fiber producing plants and their easy bio-degradability makes natural fibers an attractive material that can be used in structural applications. On the other hand, a large-scale industrial adoption of these natural composite materials requires a meticulous investigation into the mechanical properties of these materials. One of the most significant challenges in manufacturing with natural composites reliably is that the mechanical properties of natural fibers can exhibit randomness and wide variability. This wide variability is also evident from the large differences in the values of mechanical properties reported in the literature (Yukseloglu and Yoney, 2016). Further causes of variability in the mechanical properties of natural composites are the material selected for the matrix of the composite and the fiber volume fraction.

Although using natural composites in lightweight structures has many advantages, the wide variability in the documented mechanical properties of these natural materials makes numerical modelling and simulation of structures made of natural composites a challenging task. A major limitation of the current study is the scarcity of documented experimental research data about the material properties of natural fiber reinforced composites. Further research in this field can be carried out by investigating the buckling behavior of natural fiber reinforced composites under different loading conditions such as multi-directional compression and shear loading. Also, the effect of introducing cut-outs into the plate geometry can be investigated.

## Publication Note

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