

Effect Of Porosity On Buckling Behavior Of Shallow FG Naturel Fiber Reinforced Composite Arches Under Hydro-Thermo Mechanical Loads

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Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Mechanical Engineering

Eastern Mediterranean University
September 2022
Gazimağusa, North Cyprus

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ABSTRACT

This project dedicates the finding of a study that investigated the extent to which there may be differential effects for different types of moisture field, temperature field, and porosity on in-plane nonlinear buckling response of functionally graded arch reinforced with natural nanocomposite which uniform radial hydro-thermo-mechanical loads are applied to it. The natural fiber reinforcement layers with various gradients of concentration in each layer are distributed through the arch. Analytical solution of nonlinear buckling load are achieved by deriving the virtual work axiom, and merged with a developed model of Halpin-Tsai for the sake of appraising the modulus of natural fiber reinforced composite (NFRC), and also, conducted the porous distribution for exploring the effectiveness composite properties. Furthermore, both the limit point and bifurcation buckling load are studied, simultaneously. The aim of this study was to investigate the influence of the temperature and moisture change, different distribution patterns and geometry of bamboo, and also various porosity distribution patterns on the route of nonlinear equilibrium and buckling response of FGM-nanocomposite shallow arch. The obtained result indicated that even though higher temperature and moisture fields lead to rising up the buckling load, it's worth mentioning that, moisture is able to perfume substantially prominent in thriving the buckling load magnitude. In contrast, moisture and temperature field are able to reduce the value of the minimum dimensionless special geometry parameter of the arch. It's also found that symmetric porous distribution pattern plays a significant role compared with unsymmetric porous distribution pattern, however, FGM shallow curve without considering porosity experienced a superior magnitude of buckling loading. Consequently, results show the geometry of Bamboo does not have a remarkable

impact on the buckling response of shallow arch. Last but not least, the distribution pattern including a higher amount of Bamboo fiber close to outer layers performed better than other distribution patterns for the sake of developing the buckling efficiency.

Keywords: FGM, Shallow Arches, Porosity, Natural Fiber Composite, Buckling, Post-Buckling.

ÖZ

Makale, farklı nem alanı, sıcaklık alanı ve gözeneklilik için farklı etkilerin ne derece olabileceğini araştıran bir çalışmanın bulgusunu sunmaktadır. düzgün radyal hidro-thermo-mekanik yük. Her katmanda çeşitli konsantrasyon gradyanlarına sahip doğal elyaf takviye katmanları, kemer boyunca dağıtılır. Doğrusal olmayan burkulma yükünün analitik çözümü, sanal çalışma ilkesi türetilerek elde edilir ve doğal elyaf takviyeli kompozitin modülünü tahmin etmek için değiştirilmiş bir Halpin-Tsai modeli ile birleştirilir ve ayrıca, etkililik kompozit özelliklerini araştırmak için gözenekli dağıtım yapılır. Ayrıca, sınır noktası ve çatallanma burkulma yükü incelenmiştir. Bu çalışmanın amacı, sıcaklık ve nem değişiminin, farklı dağılım desenleri ve bambu geometrisinin ve ayrıca çeşitli gözeneklilik dağılım desenlerinin FGM-nanokompozit sıg kemerin doğrusal olmayan denge yolu ve burkulma davranışı üzerindeki etkisini araştırmaktır. Elde edilen sonuç, daha yüksek sıcaklık ve nem alanlarının burkulma yükünün artmasına neden olmasına rağmen, nemin burkulma yükünün değerini arttırmada önemli ölçüde belirgin bir şekilde parfüm verebildiğini belirtmekte fayda var. Buna karşılık, nem ve sıcaklık alanı, kemerin minimum boyutsuz özel geometri parametresinin değerini azaltabilir. Simetrik gözenekli dağılım modelinin, simetrik olmayan gözenekli dağılım modeline kıyasla önemli bir rol oynadığı, ancak gözenekliliği dikkate almadan FGM sıg eğrisinin daha yüksek bir burkulma yükü değeri yaşadığı bulundu. Sonuç olarak, sonuçlar Bambu geometrisinin sıg kemerin burkulma davranışı üzerinde önemli bir etkisi olmadığını göstermektedir. Son olarak, dış katmanlara yakın daha yüksek miktarda Bambu elyafı içeren dağıtım modeli, kabarma performansını iyileştirmek için diğer dağıtım modellerinden daha iyi performans gösterdi.

Anahtar Kelimeler: FGM, Sığ Kemerler, Gözeneklilik, Doğal Elyaf Kompozit, Burkulma ve Burkulma Sonrası.

DEDICATION

TO MY FAMILY

ACKNOWLEDGMENT

I am honored to impart my acknowledgment towards my advisor Assistant Professor Dr. Babak Safaei who guided, supported and inspired this thesis to be possible. I have nothing but praise for his valuable attempt to challenge my knowledge and technique to obtain this rewarding work.

I honestly appreciate my dear father and brothers for selflessly offering moral support and emotional backing under all circumstances.

PREFACE

For my whole life I was always seeking for challenges. Whenever I found something particularly difficult to others, I wanted to grasp the chance to challenge myself by. Hence, I decided to dedicated my life to scientific research. I always used to look for a solution for real world problems by my knowledge in applied science specially mathematic. So, my inclination to challenge myself by real world problems drove me forwards opting Mechanical Engineering in both undergraduate and graduate programs. Performing successful defense at EMU, encouraged me to put my heart on continuing PhD degree in Mechanical engineering.

Furthermore, as a matter of fact, I have been firmly enthusiastic in both programming and computer simulation in order to make a difference in industrial world. I take a view that after emerging technology whole of the knowledges around the world revolve around computer knowledge and software. Consequently, it is inevitable reason that I have been dedicating my time and study to deal with programming and simulation. Last but not least, it is worth mentioning that regarding to mentioned computer importance, in order to solve this thesis equations MATLAB programing has been utilized, when it is the crystal clear prove.

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Chapter 1

INTRODUCTION

Tailoring the material properties has been dedicated in order to hand out the engineers to create the well-organized designs. In addition, protecting the natural resources has become significant challenge for modern industries. So that, various innovative design ,e.g. light weight composite material, has become first and foremost need of industries. Stem from the incredible mechanic and physical properties of NFC materials in comparison with their price, has caught plentiful attention in recent years [1][2][3]. These merits, together with the interface with nanoscale effect, gained prominence in industry and aerospace industries stem from their mechanical and thermal properties, and also their ability in absorbing moisture. Hence in recent years, nanocomposite reinforced with natural fiber composite has become the emerging and magnificent investigation area in advanced composite material.

1.1 Natural Fiber Composites

Substantial amount of petroleum exhaustion is one of the inevitable concern of global environmentalist and scientists. Hence, in recent years biodegradable alternative natural fiber material has been caught considerable attention. Recently the considerable amount of investigations are in the academic and industrial level devoted to study on thriving of novel superseded materials to the available common materials, such as, metals, carbons, glasses, alloys, fiber composites, and synthetic materials)[4]. Therefore, research in the field of utilizing this material (e.g. animal silk, hemp, bamboo, banana, pineapple, and wood), has caught the significant attention in the

science and engineering disciplines. Combining these natural fibers with recyclable and environmentally polymers is able to spark off generation of new classes of materials [5]. Not only are Fiber Composites (NFC) are kind of valuable renewable resources, but also, offer noticeable noticeably. Industrial ecology, eco-efficiency, and green chemistry have been showing a considerable tendency to develop and substitute these materials for the next materials generation, products, and processes. In addition construction industry, aerospace and marine industry, circuit boards, automobile and robotic applications have experienced considerable growth in utilizing NFC over the past decade. Furthermore, some investigations are derived to find the most appropriate applications in the mechanical, aerospace , automobile, biotechnology industries, and other engineering fields.[6].

Nevertheless, with suitable development, NFC has noticeable potential in order to leave significant influence on new markets and area. Furthermore, interestingly, the agricultural wastes are capable of being utilized for preparing fiber polymer reinforcement composites. NFC have become more preferable in comparison with the available artificial fiber composites because of their noticeable benefit, e.g. limitless storage in nature, low weight and high strength and stiffness in terms of weight ratio, and above all, approximately low cost. Moreover, their eco-friendly perspective for instance, biodegradability, renewability, recyclability and sustainability play key roles by their own right [7].

Currently, automotive and building industries have witnessed the substantial amount of Natural Fiber Reinforced Polymer (NFRP) composites usage. However, still there is a room for improvement of these materials to developed structural applications specially in aerospace and maritime structures application. According to various

published research activities NFCs is able to adapt successfully for various applications. However, studying on their properties and the characteristics of the materials has to be carried out in-depth to ensure repeatable and reliable results can be obtained before utilizing for especial application. These comprise the interaction of fiber/matrix, mechanical and physical performance, manufacturing procedure, and scattering properties of the outcome composites. Several issues such as the ability of humidity absorbency and vary the microstructure of these fibers are able to leave a substantial influence on the composites' properties. on the contrary, their biodegradability potential of NFCs may also create influence on generation of fully recyclable composites. Indeed, NF is a bridgeable resource, which is able to be produced within a concise period. Consequently, the reserve is able to be unbounded in comparison with conventional carbon and glass fibers in order to produce optimized composites. To be precise, the shortage of the NF is able to be tackled by governing the morphological variation by different treatment methods such as physical or chemical [8]. Due to noticeable advantages of NFCs and their properties substituting the natural fiber composite with glass, carbon or aramid fiber-reinforced polymer (FRP) composites has been caught significant attention. An increasing amount of researchers have conducted the mechanical behavior of bamboo/ polymeric composite. Although many studies have investigated with bamboo/ epoxy resin. Interestingly, this matrix has performed better than polymeric. Consequently, bamboo/ Epoxy composites has been utilizing in the past decade. Nevertheless, there is no study on behavior of bamboo with epoxy and for shallow arches. As a result, epoxy matrix has been found efficient in increasing the value of tensile strength and fracture toughness of NFRCs. A classification and comparison of is shown in Figure 1.1.

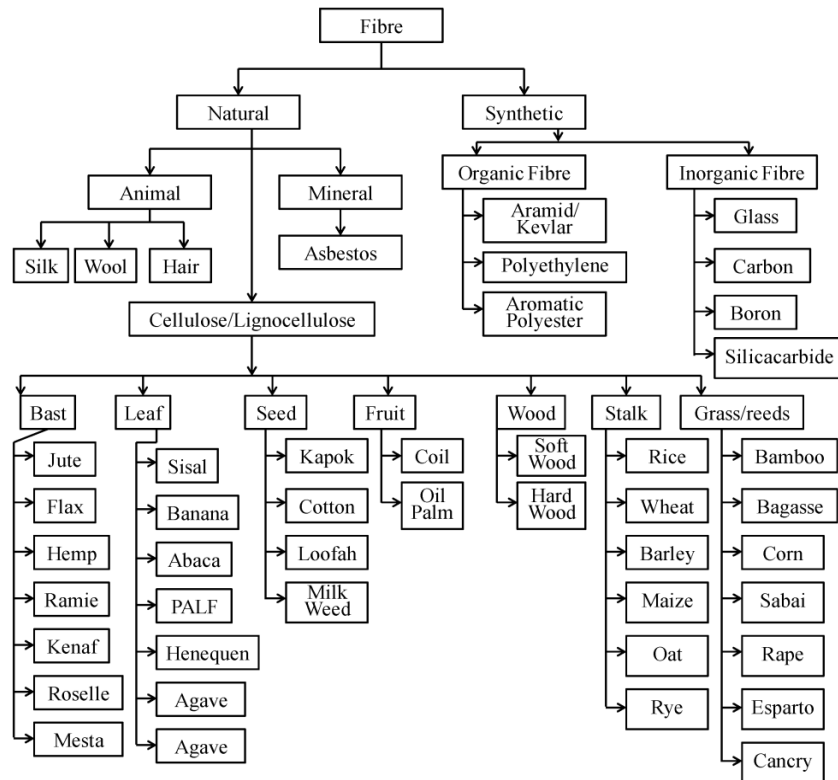


Figure 1.1: Natural fibers variation [9]

1.2 FGM

In recent years, researchers have shown increased interest in functionally graded materials (FGM), these materials are newfound classes of non-homogeneous microscopic composites that are generally made up of materials that use a metallurgical process. These materials are new found classes of non-homogeneous microscopic composites that are generally are made up of two materials that using metallurgical process, which are usually metal and ceramic. Due to low thermal conductivity of ceramic these materials have dramatic thermal resistance and also, steel presents material fracture in the face of high stresses stem from extreme temperature fluctuation in a short period of time [10]. These materials have substantial advantage, one of the most significant advantage can instance the volumetric fraction of each component as well as mechanical and physical properties vary thorough a thickness of beam as continuous function, which these function can be linear, cubic,

power an exponential [11]. FGMs are able to designed in such a way that they have ceramic thermal resistance on one side and mechanical behavior of material on other side [12]. These materials were first introduced in the mid-1980s by scientists for use in nuclear reactors and space applications as materials with satisfying properties also accumulation of tension and cracking are able to vary successfully within these materials without sudden variation in their properties [13]. These materials have a substantial advantage, one of the most significant advantages can instance the volumetric fraction of each component, in addition to, mechanical and physical properties vary through the thickness of the structure as a continuous function, which these function can be linear, cubic, power an exponential [10]. The stress caused by Hygro-thermal loads that come from the variation of temperature and moisture can have a significant effect on the engineering industry. FGMs are able to have gradual properties changing under hygro-thermal elastic loads through the required direction. In the light of mechanical and physical properties and remarkable benefits, FGMs in practical applications especially in aerospace automotive, biochemistry, and biomechanics industries lead to receiving much attention in the study of this subject. Accordingly, due to these substantial properties of some FGM configuration such as bars , shafts, curves, plates, and shells are used for advanced function in nonlocal or micro-size. Figure 1.2 illustrates the different type of FGM distribution.

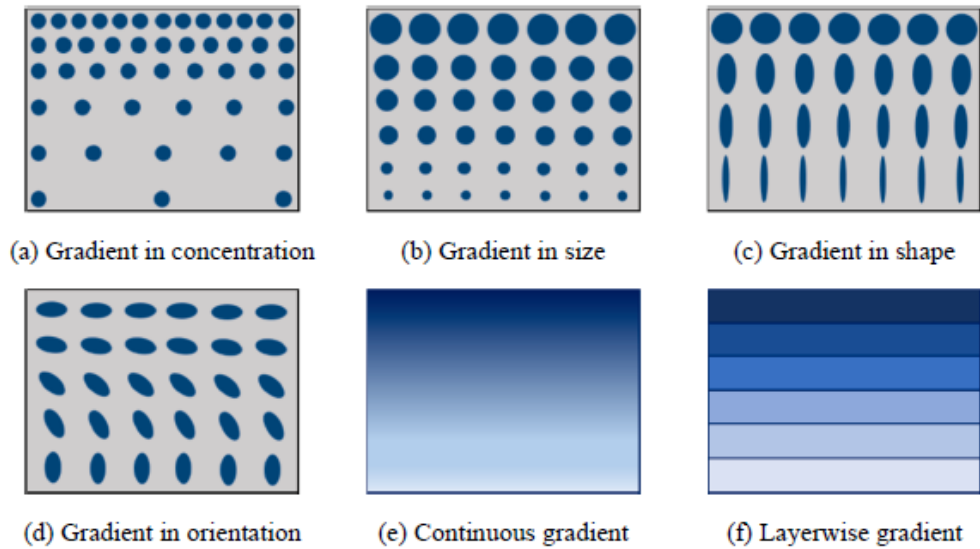


Figure 1.2: various types of distribution pattern of FGM [14]

1.3 Porosity

There are different sort of porous material with different strength and weakness exist (e. g. zeolites, metal organic frame works, porous polymers, and etc.). The main common exclusivity of the porous material is the most of the include substantial internal surface area and having good amount of adsorption capabilities. The isolated building blocks or the structure of this material rarely significant for adequate adsorption porosity prediction. In addition, by introducing the porous composite material, it is found that due to their lightweight, electrical properties, impact and thermal resistance they can enhance the properties of composite substantially [15] [16] [17]. Furthermore, since structure stiffness is low in porous material conducting an investigation of the material behavior in view of the variable situation and boundary load and condition and the reinforced natural fiber inclusion are guaranteed. Figure 4.3 shows the various types of porous distribution pattern.

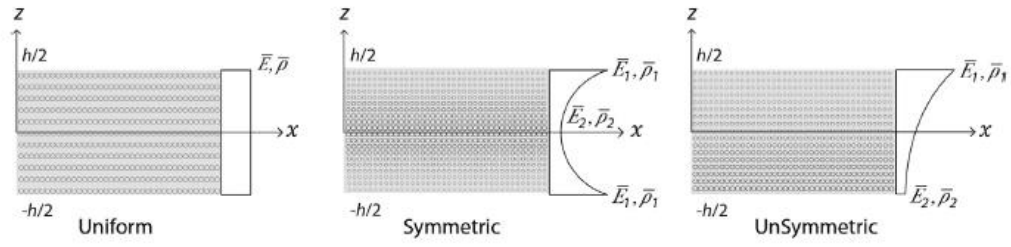
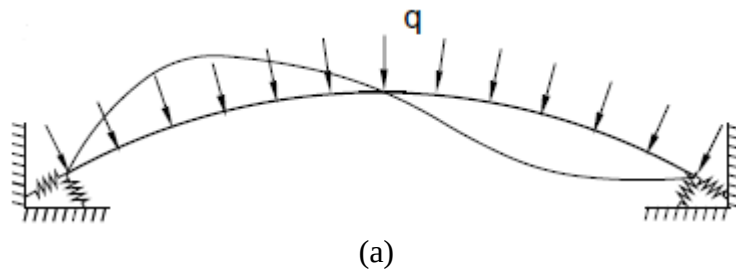


Figure 1.3: Different distribution pattern of porosity [18]

1.4 Buckling and Stability

Early history of buckling and post buckling dates back hundred years ago by Koitor [19] conducted. Considerable amount of investigation on his area. To be more specific, during recent decade buckling and post buckling have been paid attention. In addition many publication on the general buckling and post buckling theory in the language of finite dimensional system emerged by other researcher [20][21]. Investigation on potential challenge in handling the buckling and post-buckling precision of composite structure have caught considerable eyes for researchers. It is inevitable fact that in real life all configuration under the different type of loads. Hence, various loads and applications call for substantial strength and stiffness magnitude. Buckling deal with the both stiffness and the slenderness ratio of the configuration. Through not a permeant deformation, buckling behavior is significantly critical phenomenon in certain applications [22]. Figure 4.4 shows the buckling behavior of shallow curves.



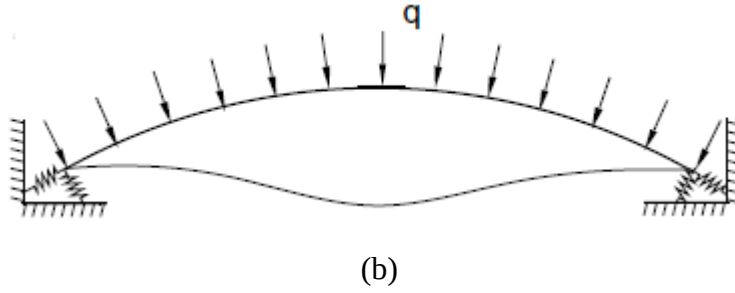


Figure 1.4: Buckling behavior of shallow beam when. (a) Bifurcation buckling and (b) snap-through buckling [23]

1.5 Definition of the Problem

One of the most useful and useable structure in aerospace, mechanical and civil engineering is curves structure. Designing the stable structure considering the various circumstance and boundary condition in order to barricade the irreparable damage plays the key role. The in-plane and out-plane buckling behavior of circular shallow arches consist of homogenous material have experienced noticeable dedication studied to itself [24–27]. Furthermore, stem from incredible properties of composite material buckling behavior of circular shallow arches composite has attracted attention. there are grounds for supposing that, one of the most and common application of arch structure is in intelligent devices, such as robotic devices. So that, by the aid of taking advantage from curve structures multiple instabilities, smart apparatus are able to be created by manipulating robotic devices. Consequently, by the aim of reducing the creating crack and delamination in FGM-NFC material under the effect of hygro-thermo- mechanical loads, application of proposed material for intelligent devices is able to be predicted.

1.6 Contribution Research

The work contributed through investigating on the buckling behavior of the various distribution pattern of FGM shallow arch's composite combined with Epoxy and Bamboo as a natural fiber reinforcement by considering the different distribution

porosity under the various moisture and temperature field and radial mechanical loads.

1.7 Research Objective

Buckling and post buckling are some of the most momentous failure and damage modes for composite material and configuration. Under normal real circumstance different loads apply to general structure. Accurate prediction of deformation and buckling behavior is crucial in order to achieve safe and reliable configuration in design. It is also worth mentioning that, based on substantial application of curve structure utilizing have experienced considerable increase. Therefore, curve structures call for significant challenging attempt to predict nonlinear in- plane buckling behavior of them. Consequently, the challenge within this existing investigation on study of load deformation response and estimate buckling behavior of homogenous arches to FM porous arches reinforced Bamboo natural nanocomposite for the first time. The configuration of the problem is subjected to uniform radial hydro- thermo- mechanical loads along the arch axis.

The significant target of this thesis is to estimate an approximation of the nonlinear in-plane buckling behavior. In order to satisfy this objective:

1. The analytical parameter solutions to evaluate the nonlinear buckling performance are derived by the aim of virtual work principle and modified Halpin- Tsai model for estimating of the modulus of Bamboo layers.
2. The influence of Bamboo nanofiber distribution pattern, volume fraction, geometry of Bamboo nanofiber, different porous distribution pattern, temperature and moisture loads under the range of geometry parameter on nonlinear equilibrium path and buckling behavior was conducted comprehensively.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Functionally graded materials (FGMs) are innovative sort of materials that have been created to resist significant temperature gradients among other things [28].. Figure 2.1 displays the present material hierarchy [29].

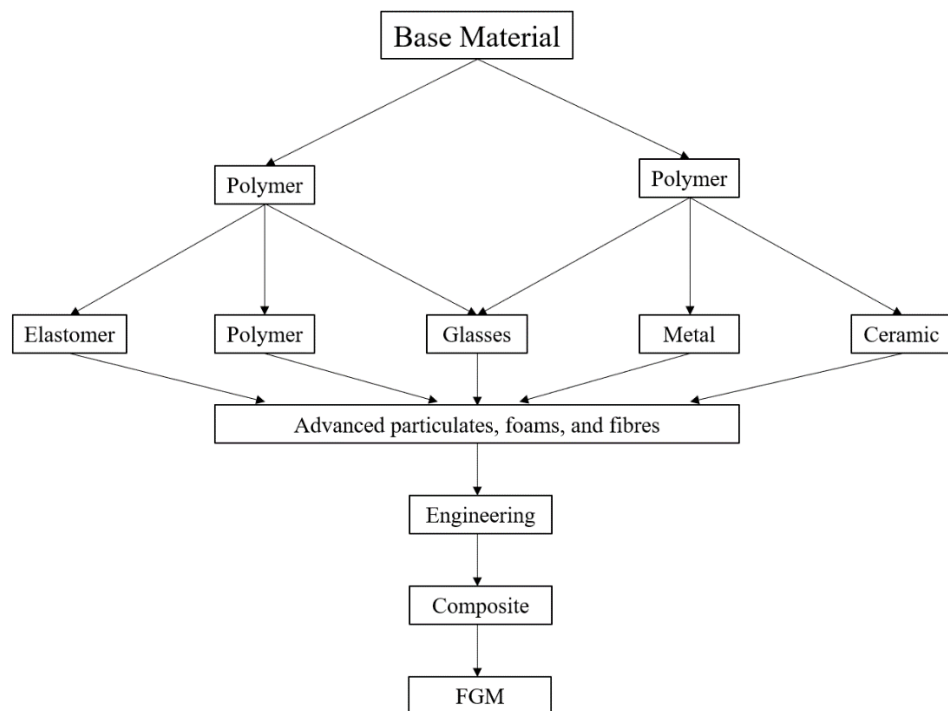


Figure 2.1: Demonstration of contemporary material flowchart [29]

FGM arches include the structural and geometrical connection elements for bending and stretching. The FGM shallow arch experiences severe distortion due to thermal loads before collapsing in the plane of its curvature. The critical buckling temperature

of the functionally graded shallow arches is significantly impacted by the presence of such deformations [28]. A unique functionally graded porous (FGP) material was recently created with success. Graphene platelets (GPLs) may be used to strengthen this FGP material and increase its load carrying capability for rings with low thickness [30], curves [31], bars [32] or discs and plates [33]. The FGP-GPLs material's exceptional strength-to-weight ratio has led to widespread adoption of its arch-shaped components in both airplanes and submarines [34]. FGMs constantly alter the material's mechanical, chemical, and physical characteristics over time in the desired spatial direction. Examples include density, Young's modulus, shear modulus, Poisson's ratio, ν , and CET [35–38] (Figure 2.2).

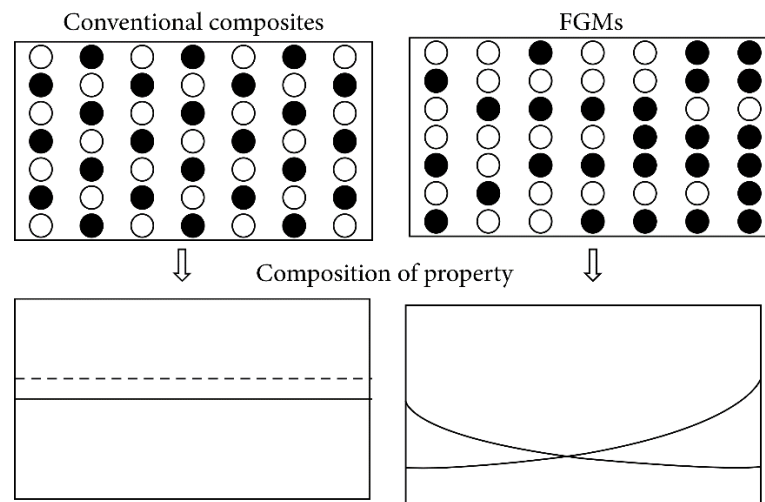


Figure 2.2: Conventional Composite and Functionally graded material properties variety [39]

The usage of eco- friendly materials has experienced the significant attention as a result of growing public interest and environmental consciousness, new environmental restrictions, and unsustainable petroleum use. Natural fibers in comparison to synthetic fiber are thought to have superiority in being ecologically friendly materials [40]. NFRCs allocate more benefits, for instance, economical, , lightweight, good amount

of strength and stiffness, and above all recyclability [41], and may have a substantial functions in the aerospace, automobile and marine sectors [42, 43], such as thermal conservation and moisture absorber application in aerospace industry [44].

Natural fibers (NFs) are ones that aren't synthetic or man-made, to put it simply. Both plants and animals can serve as their sources [45]. The production of composite materials using NFs like flax, sisal, and pineapple, both renewable and nonrenewable resources, has attracted a lot of consideration recently. The plants which generate cellulose fibers are able to be split off into a variety of different types, including bast fibers (jute, flax, ramie, hemp, and kenaf), seed fibers (cotton, coir, and kapok), leaf fibers (sisal, pineapple, and abaca), grass and reed fibers (rice, corn, and wheat), and core fibers (hemp, kenaf, and jute) as well as all other kinds (wood and roots) [46].

2.2 Natural Fiber Composite

Although employing NFR in polymers consists of several benefits, there are a number of disadvantages when using these fibers to make composite materials. (Table2.1).

Table 2.1: Superiority and non-superiority of NFs selection for composite material.[6]

	Pros	Cons
Physical-mechanical	Lighter weight equates to low density. Greater consideration strength and stiffness than glass Outstanding properties of thermal and acoustic insulating	odor production as a result of the degrading process Compared to glass fiber composites, impact strength has worse strength properties. Fibers soak up moisture, which results in edema.

Processing	abrasion-free screws and other metallic components No skin irritation, no tool wear, and no toxic processing	To improve the apparent density, some fibers must be pelletized. Maximum processing temperatures are constrained, particularly when it comes to glass fiber.
Environmental	Because it is a renewable resource, there will always be a supply. For glass fibers, production energy is just a third as great. The amount of plants' CO₂ absorption when they are growing includes an equal amount to the amount released when they decay.	When plants develop, they absorb the same amount of CO₂ as they emit when they decompose. Relative price changes that are significant because of crop outcomes or agricultural politics Low durability as a result of weathering, fungus attack, etc.

The inconsistent fiber characteristics caused by harvesting circumstances, processing conditions, and the material's sensitivity to heat, moisture, and UV radiation are what cause the variety in natural fiber properties. Additionally, each stage of the production process has a number of variables that might the quality efficacy of the fiber is cab be seen in Table 2.2 [47]. The plant species, crop yield, circumstance, settle, and climate during the growth stage of plant all have an impact on the fiber quality.

Table 2.2: Effective factors for quality of fiber at various procedure of natural fiber generation [47]

Stage	Effective factors on quality of fibers
Plant growth	plants type
	yield cultivation
	yield locality

	Fiber spot in plant
	Local climate
Yielding crops stage	Fiber ripeness, which effects:
	-Cell wall thickness
	-Coarseness of fibers
	-Adherence between fibers
	and surrounding structure
Fiber extraction stage	Decortication procedure
	Sort of soaking process
product stage	Transportation circumstance
	Storage circumstance
	Fiber's generation

Baillie et al.[48] demonstrated the relationship between the chemical compound of NFs and their qualities (strength, thermal deterioration, biological degradation, and moisture absorption). (Figure 2.3). Although the underlying chemical structure of cellulose and all of the natural fibers are equal, the polymerization degree varies. The different fiber characteristics of natural fiber are influenced by the different cell shapes of each form of cellulose.

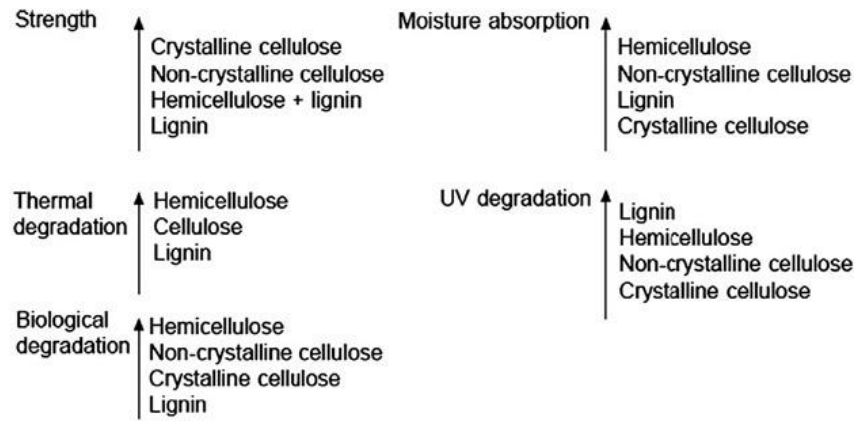
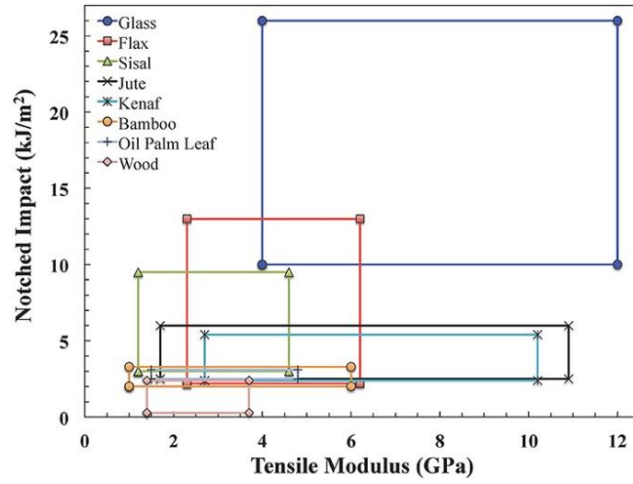


Figure 2.3: Cellulose fiber properties and their relevance to chemical constituents [48].

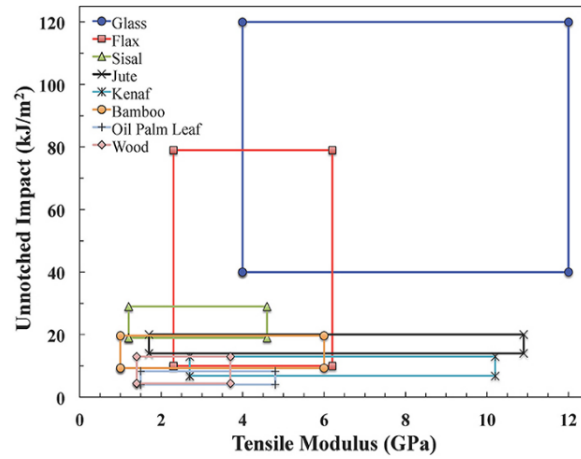
2.2.1 Performance of NFC

Faruk et al. [6] conducted the investigation that the most frequently examination of the NFs reinforced plastic consist of the mechanical and physical properties (e.g. tensile, flexural, and impact capabilities). One of the unfavorable weaknesses of these materials spots in terms of mechanical performance is impact strength. In addition to these tensile, flexural, and impact capabilities, natural fiber composites' everlasting efficiency, such as dynamic/static mechanical and tensile/compressive properties are examined.

one of the highlighted utilization of NFs is when a single mechanical performance parameter's performance must be either sufficient or high, especially in engineering composite applications, so natural fiber is successful. The impact-modulus balance is frequently one of the many delicate balances that must be achieved when choosing materials. An survey of the areas of impact vs. tensile modulus addressed by Thomason and Fernández is illustrated in Figures 2.4 a, and b [49].



(a)



(b)

Figure 2.4: a) Notched impact vs tensile b) unnotched impact vs tensile [49]

John et al. [50] discovered that the mechanical qualities of the glass-micro balloon/cyanate ester syntactic foam with carbon-cyanate ester skin improve with resin content after investigating the tensile and compressive properties. An analytical method has created by Aiello and Omres in order to assess the buckling stress of a sandwich comprised of Poly Vinyl Chloride (PVC) foam and fiber laminated shell made from glass, carbon, and boron fiber laminate skin [51]. A minor amount of shell ratio thickness to whole thickness of the sandwich improved the global buckling behavior of sandwich panels, according to the theoretical model. Gonclaves et al. [52] utilized the coupled stress FEM to computationally study the buckling and free

vibration of a PVC foam core sandwich with steel face sheets. With the aid of the traditional Timoshenko beam model, the results were more accurately anticipated by the microstructure-dependent beam element. Fleck and Sridhar [53] performed practical research on sandwich columns built of PVC foams of various thicknesses and woven glass fiber epoxy skins. They noticed that, relevant to the shape of the sandwich columns, the columns experience several forms of buckling phenomena (Euler macro buckling, shear micro buckling, and face micro buckling). Grogneec and Soaud [54] on the numerical behavior of sandwich beams with symmetric homogeneous and isotropic core/skin layers buckling under compressive load. The numerical consequence and the available analytic answers are in good agreement.

Waddar et al. [55] study the experimentally and mathematically research by examining the free vibration frequencies response and buckling performance of a sandwich beam combination of the sisal fabric reinforced epoxy laminate's elastic and the core is the the fly ash cenosphere subjected to compressive load. The equality of the both analytical and experimental results validate the accuracy of this method. Due to the fact that the modified cores have a stiffer core because of good component adhesion, in comparison to neat samples, the potential weight savings of unmodified and modified cenosphere/epoxy composite foams are 15.81 and 14.61 percent, respectively. The sandwich beams exhibit skin delamination and wrinkle-free global buckling mode shape. Value of the buckling load and vibration are seen to be rising as filler loading rises. Additionally, when the axial compressive force increases, the natural frequencies drop. Due to a rise in the geometric stiffness of the beam, the first natural frequency indicates the minimal value at the critical buckling load and then climbs exponentially beyond that. Using CADEC, the skin's characteristics are

discovered, and they are determined perfectly acquiescence with the experimental results. For the sake of the numerical study, additional characteristics from the CADEC and Bardella-Genna models are employed. Comparing the experimental results with mathematically anticipated values reveals a fair degree of agreement.

Rajesh and Jeyaraj reported experimental analyses are done to determine the effects of the compressive load on the buckling and dynamic behavior of the NF/polymer composite beam. The critical buckling load, free vibration frequencies, and modal loss factors were extracted and evaluated. It has been discovered that some layers of fabric ply of beam enhance its buckling strength. Additionally, the weaving pattern of the fabric has also been found to have an impact on the buckling behavior, for instance, basket-type woven textiles have superiority compared to the value of the buckling load over plain and herringbone composites. [56].

2.3 NFRCs

The use of the NFRCs is gaining increased attention in industry and in the academic research community as a means of reducing environmental effects and, as a result, meeting the demand for textiles for various application areas [57, 58] T The development and use of NFRCs will eventually improve the sustainability and environmentalist of material production. In Figure 2.5, the NFPC life cycle is shown.



Figure 2.5: The life cycle of biodegradable, NFRCs [59]

For instance, Banmboo, oil palm, flax, kenaf, and Jute allocated the good amount of strength to theirselves which can be utilized in natural fiber polymer composites (NFPC) [60]. Thermoplastics and thermosets are the two main categories for polymers. dimensional molecular nature of their structure. Furthermore, one of the most are strongly conjoin polymers are thermosets that cure by the use of heat alone, heat plus pressure, light irradiation, or any combination of these. Thermoset polymers benefit from good features such as being considerable flexible for customizing favorable final qualities, tremendous strength, and modulus because to this structure [45, 46, 57].

Polyethylene [61], polypropylene [62], and poly vinyl chloride (PVC); are thermoplastics that are often used to make biofibers; phenolic, polyester, and epoxy resins are typically employed as thermosetting matrices [60]. The features and performance of NFPCs are able to be affected by a variables variation. The characteristics of the composite are also influenced by the natural fiber's hydrophilicity [63] and fiber loading [64]. In most cases, significant fiber loading is required to

achieve acceptable NFPC characteristics [65]. Generally speaking, observe how the tensile characteristics of composites improve as fiber content increases [66]. Another crucial element that significantly affects the composite characteristics is the parametric procedure that was employed. Relevant methods for procedure and parameters ought to be carefully considered to obtain the foremost qualities for generating the composite material. [60]. The chemical combination of NFs has a significant impact on the composite specification. Table 2.3 displays the chemical mixture of a few well-liked natural fibers [46].

Table 2.3: Chemical compounds of several standard NFs [46].

Fiber	Cellulose (wt%)	Hemicellulose (wt%)	Ligning (wt%)	Waxes (wt%)
Bagasse	55.2	16.8	25.3	—
Bamboo	26–43	30	21–31	—
Flax	71	18.6–20.6	2.2	1.5
Kenaf	72	20.3	9	—
Jute	61–71	14–20	12–13	0.5
Hemp	68	15	10	0.8
Ramie	68.6–76.2	13–16	0.6–0.7	0.3
Abaca	56–63	20–25	7–9	3
Sisal	65	12	9.9	2
Coir	32–43	0.15–0.25	40–45	
Oil palm	65	—	29	—
Pineapple	81	—	12.7	—
Curaua	73.6	9.9	7.5	—
Wheat straw	38–45	15–31	12–20	—
Rice husk	35–45	19–25	20	—
Rice straw	41–57	33	8–19	8–38

2.4 FGM

Stem from its exceptional mechanical, electrical, and thermal characteristics, graphene [67], a carbon atoms' 2D sheet, has received a lot of interest recently [68–71]. Interestingly, Tensile strength may approach 130 GPa , and also, and Young's modulus is able to be reached by 1 TPa , respectively, where they allocate significant value in

comparison with the frequently utilized materials (e.g. steel, concrete, or fiber reinforced polymers) to their selves [72]. Numerous studies have shown that graphene and its derivatives have a considerable reinforcing influence on the mechanical characteristics of polymer composites.

Rafiee et al. [73] were tested and difference among them. The characterization of epoxy nanocomposites is added by various amounts of single-walled carbon nanotubes (SWCNTs), multi-walled carbon nanotubes (MWCNTs), and graphene platelets (GPLs). They discovered that GPL nanofillers outperform carbon nanotubes significantly and that the nanocomposites' mechanical properties are all substantially higher than pure epoxy. Yang et al. [72] examines the buckling and post-buckling behaviors of FGM nanocomposite beams with multilayer reinforced a negligible amount of GPLs with elastic supports.

Used the commercial software ANSYS to do FE analysis by meshing the Functionally graded-GPLRC arch with the element of SHELL181 element. The SHELL181 element has four nodes and three DOFs in rotation and three in translation. with the aim of modeling the section with several layers that have different properties depending on how thick they are, like the FGM used in this study, this element took the lead. [74]. As shown in Figure 2, the finite element model meshes the given arch into 100 SHELL181 components over its entire length, with 10 layers of varying material qualities divided across one section's thickness.

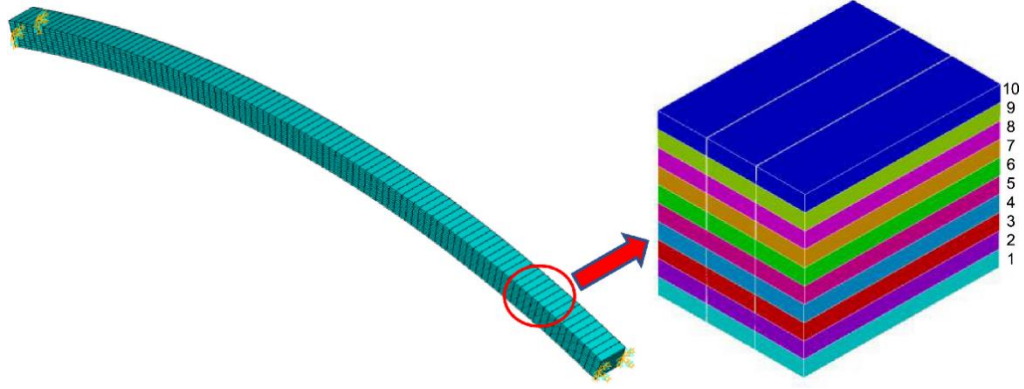


Figure 2.6: FEM model of a FGM arch reinforced GPLRC [72]

According to the aspect ratio a/b and width-to-thickness ratio b/t . Figure 2.7 illustrates the emphasis influence of graphene plates form and geometry on the behavior of buckling loadings. While the width of graphene plates refuses to vary, aspect ratio suggests a greater graphene plate's face area, and a width-to-thickness ratio's value indicates less single-layer sheets of graphene in the graphene plates. When both the aspect and width-to-thickness ratios grow, the critical buckling load also rises, GPLs are able to reinforce structures more effectively

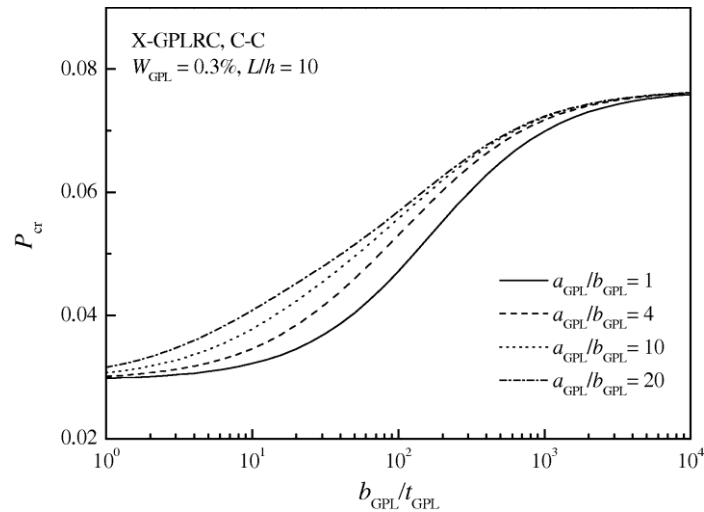


Figure 2.7: Graphene plates geometry and dimensions' influence on the critical buckling behavior of FGM including multilayer X-GPMRC beams [72]

By the aim of obtaining the required structural representation of the composite, it is

possible to construct FGMs include a contiguous gradient in both the mechanical and physical properties that allows for specialized features [14, 75]. Advanced engineering materials recognized as FGMs are created for a particular applications or purpose. To do this, detailed graded compositions, microstructures, and characteristics are provided [76–81]. The mixing ratio and characteristics of FGMs, which comprise two or more unique material constituents, change continuously along one or more directions [82–85]. Functionally graded shallow arch depicted in Figure 2.8 [28].

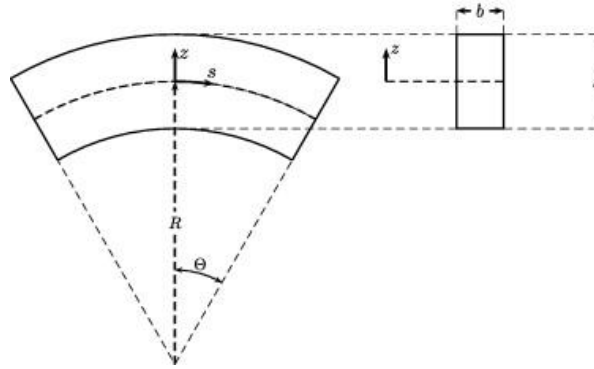


Figure 2.8: Schematic demonstration of FGM shallow arch configuration

2.5 Stability

Liu et al. [34] carried on the investigating the stability and nonlinear static behavior of FGP reinforced arches. Wu et al. [86–89] investigated the dynamic imbalance buckling, and post-buckling behaviors of FG polymer composite beams subjected to the thermal loading [86–88] and plates [89] reinforced with GPLs [34]. Bateni and Eslami [90, 91] was performed the investigation on in-plane durability of FG curves, under the distributed radial load and central focused force, respectively.

In-plane disequilibrium of FG shallow arches with negligible GPLs reinforcement concentration is examined by Yang et al. [77] subjected to single point load. The volume fraction of GPL is fluctuated layer by layer throughout the direction of the

thickness. The modified Halpin-Tsai theory is derived to determine the GPLRC's effective Young's modulus. The nonlinear buckling behavior of the fixed FG arch-reinforced GPLs is established using the virtual work concept and is then analytically solved. The FG-GPLRC arch's geometrical characteristics, distribution pattern, weight percentage, and size are studied parametrically to see how they affect the arch's nonlinear equilibrium path.

In order to validate the results the analytic findings compared to the FE results by the aim of ANSYS 14.5 [92]. When creating the layered composite arch in the ANSYS formulation, the section commands may be used to characterize the geometry, material, and direction of each ply. Figure 2.9 (a) shows the quality and density of meshing in FE model, whereas Figure 2.9 (b) shows the model geometry.

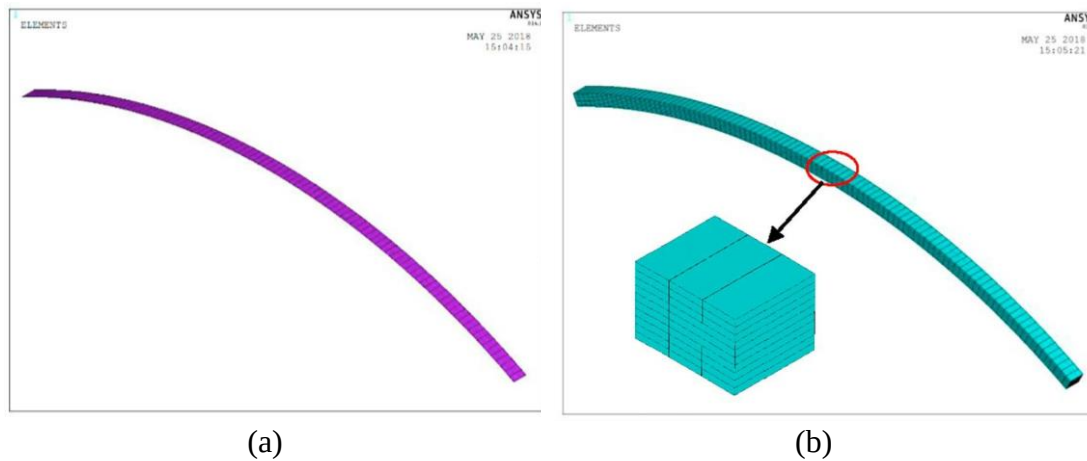


Figure 2.9: Finite element models for functionally graded arches reinforced GPLR (a) meshing model, (b) model of geometry [77]

Wang and Wang studied; a theoretical model is put forth for forecasting how bidirectional natural fiber reinforced composites would behave mechanically when subjected to hydrothermal loading [44]. They study on Figure 2. 10.

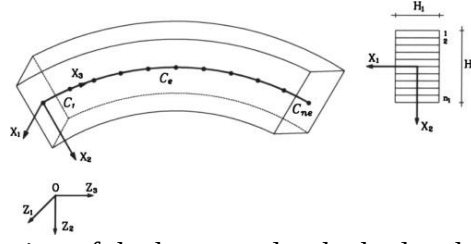


Figure 2.10: Demonstration of the beam under the hydro-thermal-mechanical loads [44]

Fraternali et al. [93] FEM has been taken into place in order to conduct the investigation of the composite beam arch's buckling and post-buckling performance is included various types of elastic responses in order to the estimation of the nonlinear geometric response. The studies for the curved example have focused on the both in/out-plane buckling of arches made up of laminated composite with mechanical and physical properties (Young modulus in the fiber-direction) under tension and compression pressure. They have found that the bi-modularity ratio of the material has a notable impact on the post-buckling performance of the beam in all of the problems we have studied. When the material stiffness shows better results in tension compared to compression, the response is stable; however, when the opposite is true, the response is unstable (or just barely unstable). Attributable to the strong deformation stem from shear stress of some configurations, it has also been noticed that the influence of the warping has a considerable impact on the both in/ out buckling behavior of the composite curved beams. [93]. Li explores the nonlinear stability mechanism of the FGP arch graphene nanocomposite reinforcement. To best increase bending stiffness, symmetric pores and nanocomposites are scattered on the middle of the arch's surface, it is not equally along the cross-profile though. [94].

2.6 Arc-Buckling

The arch is a commonly used important structural feature in the domains of aeronautical, civil, and marine engineering [26, 95, 96]. Figure 2.11 illustrates the

stringent limitations placed on the entire structure's weight and strength. Research on developed curve configuration with a focus on great strength base on weight is therefore important [34].

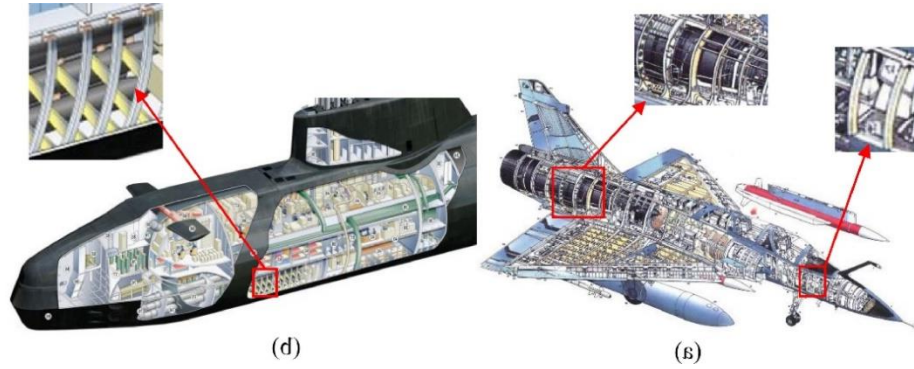


Figure 2.11: Curves configuration's application in (a) aircraft industry and (b) submarine industry [34]

Yang et al. [97] examines mathematically and experimentally the nonlinear dynamic buckling behavior of shallow curves relying on a fixed elastic support, and also, under a center impact load stem from a collapse. where interesting, investigating the arch's crown, analytical and experimental research has been carried on. the juxtaposition of the result achieved experimentally and with the FEM succeed to demonstrate that the analytical techniques are able to brig about precise dsicove of dynamic buckling behavior of arches subjected to impact loads.

A vertically falling object causes a central in-plane impact on the considered arch depicted in Figure 2.12 shows the displacements in radial and axial directions, the length and radius of the arch, the included angle of the arch, the mass of the object, and the height of the object, which is the distance from the item's center to the top of the arch crown.

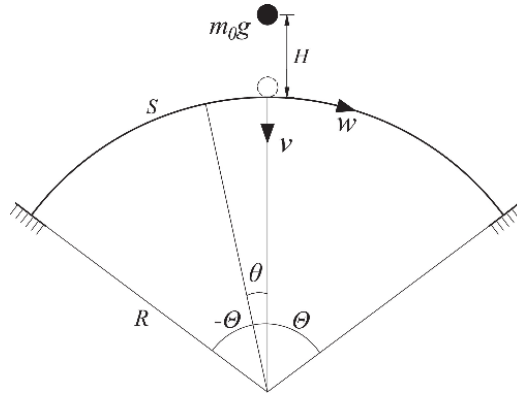


Figure 2.12: Fixed arch and impact load (falling object) [97]

The axial load and bending moment brought on by the FGM arch's temperature field increase in direct proportion to temperature rise, according to thermo-elastic calculations by Asgari et al.[28]. In the case that the rising temperature field the parameter reaches a critical value, the arch is assumed to deviate from its principle equilibrium course and its in-plane buckling. The buckling of homogeneous arches has been studied by several academics. furthermore, its worth mentioning that, driving the energy-based strategy leads to bringing about the equation's solution. [98] or the static equilibrium approach [99]. In that study, thermal and nonlinear buckling behavior of FGM circular shallow arches stem from thermo- elastic load is examined and which is shown in Figure 2.13. The arches experience a constant temperature increase. Properties' sensitivity to temperature is considered. Kinematic presumptions are according to the Donnell's shallow shell theory and the classical theory of arches. The whole set of boundary conditions and the nonlinear equilibrium equations are achieved, simultaneously, by governing the virtual displacements principle. The analysis of a functionally graded pinned curve with immovable ends is provided.

Direct analytical methods are used to determine the peripheral scattered stress and strain as well as radial and axial displacements. The stability equations are achieved

by applying the adjacent equilibrium criteria. This study takes non-linear pre-buckling deformations into consideration. The bifurcation temperatures of the arch are determined using closed-form solutions that are provided. Results that are illustrative show how displacement field, stress, strain, and bending moment are distributed along the span. The fluctuation of the critical buckling temperature is then explored [28] according to the power law index, geometric parameter, and opening angle.

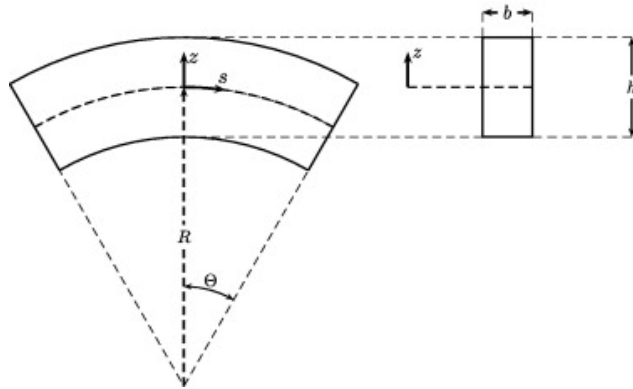


Figure 2.13: Schematic demonstration of FGM shallow arch [28]

The nonlinear dynamic buckling behaviors come to be the primary determinants of the curve-carrying valence as a result of taking the compression and bending stress characteristics of the arches into account. The open literature has several studies on the dynamic durability and buckling behavior of isotropic curve configuration [26, 97, 100–105]. According to Pi and Bradford, this paper's four primary objectives exploring the dynamic buckling behavior of a pinned shallow arch accompanied by a uniform cross profile subjected to a impact radial loading with an unbounded period (Figure 2.14); using the idea of energy conservation, provide a standard for the dynamic buckling of an arch. [104].

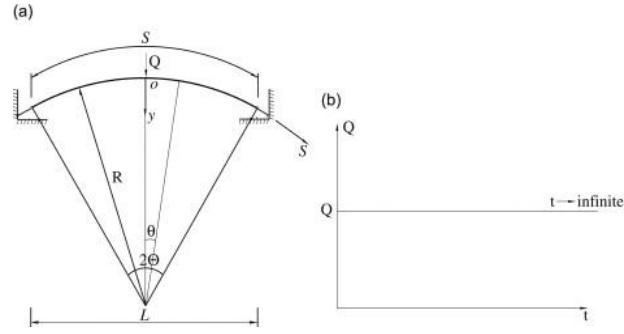


Figure 2.14: shallow arch : (a) pinned-supports curve and (b) snap load with unlimited continuity [104]

Zhang et al. [106] describe theoretical, computational, and experimental investigations of the nonlinear in-plane buckling response of orthotropic composite curves relying on fixed support subjected to radial point loading. Analytical solutions that account for the bending-stretching coupling effect are given for both the critical buckling load and the nonlinear equilibrium approach. The finite element model then validates these solutions. Figure 2.15 depicts the mechanical structure of a rotational arch subjected to the concentrated load.

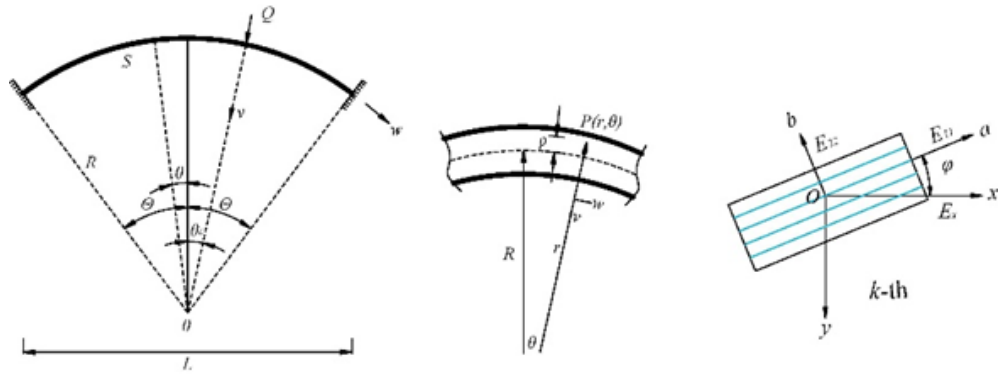


Figure 2.15: The arbitrary composite curve under the concentrated radial load is shown schematically [106].

In order to examine the buckling behavior (both snap-through and bifurcation) of Functionally graded arches with pin-ended, Eroglu [107] employed a variational iteration approach. To explore the nonlinear performance of isotropic curves

reinforced by orthotropic fiberglass layer subjected to -point radial loads in their plane, Xu [108] published a CUF-based finite element model. The numerical forecasts and the outcomes of the laser-based experiment were well-aligned, according to comparisons.

2.6 Porosity

Advanced composites, such as composite materials especially metal foams with porosity have experienced substantial popularity in the mechanical and electrical fields, especially in automotive and aerospace sectors, owing to their lightweight, impact resistance, and heat resistance [16, 18, 109, 110]. According to Zhao et al. [111], subjected to the combination of a static and dynamic uniform radial loads, a FGP arch uniformly dispersed GPLs influence is dynamically unstable. innovative functionally graded porous materials have been suggested and produced by considering the graded scattering of the pore in them during the production procedure, combining the benefits of FGMs and porous materials. A porous beam's elastic buckling was studied by Magnucki and Stasiewicz [112].

2.6.1 Porous ARCH

Yang et al. [100] investigated on a buckling behavior of the rotational constrained FG-GPLs porous arch under a uniform step loading, where the porosity coefficient changes through the direction of the thickness of the arch and the GPLs nanocomposite are equally spread. In Figure 2.16, a rotationally constrained functionally graded - porous arch reinforced the direction of the thickness with is displayed subjected to the uniform step loading.

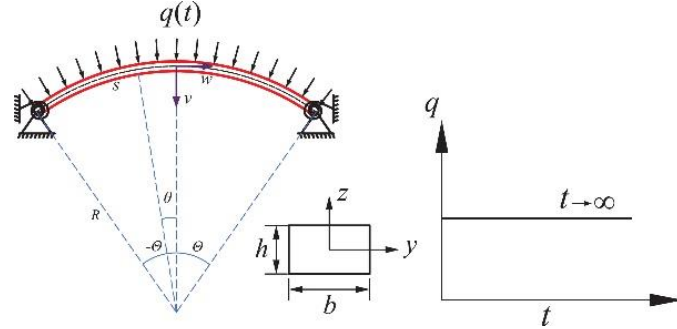


Figure 2.16: schematic of the FG-GPLRC porous curve which is subjected to the uniform step load [100]

Liu et al. [113] investigate the lateral-torsional buckling of spherical FGP arches included an I-profile reinforced GPLs. The effects of the scattering pattern and coefficient of porosity, volume fraction of the GPLs, location of the load, and geometry of the arch are carefully evaluated on the buckling behavior of the curve. The findings reveal that while a larger GPL weight percentage can significantly improve the arch's buckling resistance, increasing porosity coefficient leads to occur lesser buckling stresses. on the other hand, comparing the uniform and symmetric porosity distribution, arch with symmetric porosity distribution showed better lateral-torsional buckling stresses.

Figure 2.17 depicts the arch deformation structure by considering L , S , R , and 2Θ as the arch's span, length, radius, and included angle, respectively. ϕ is the angular coordinate, c angular position of the load $Q_{\phi\theta}$ the twist angle of arch, ϕ_z the in-plane rotation angle of the section, ϕ_y the lateral rotation angle of the section, ϕ_{sz} the in-plane shear angle, ϕ_{sy} the lateral shear angle, u the lateral displacement of the effective centroid axis, v the radial displacement of the effective centroid axis, w the axial displacement of the effective centroid axis. It is presumed that the arch is pinned in the in-plane direction and fixed in the out-of-plane direction.

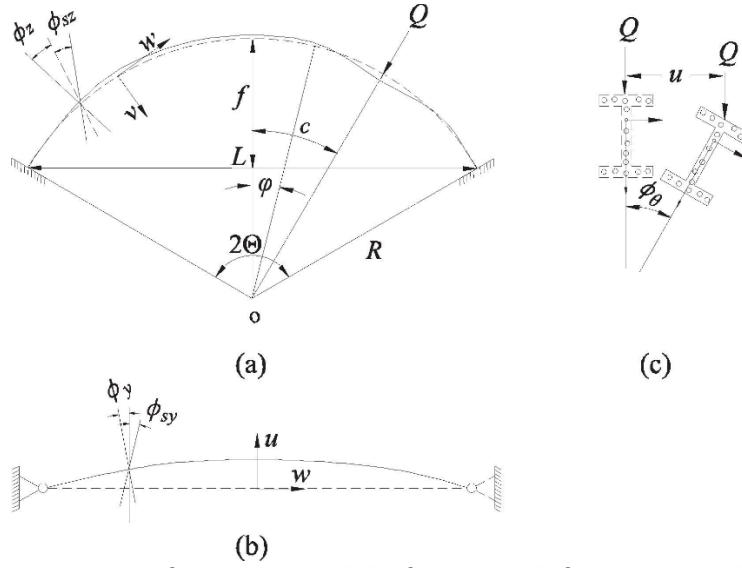


Figure 2.17: ((a) Configuration model of arch (b) deformed curved structure lateral-torsional; (c) deformed Section. [113]

Figure 2.18 (a) depicts the cross profile porosity distribution pattern of curve structure: when the distribution patterns include Uniform; symmetric, and Unsymmetric. [34, 94, 114] . it is worth mentioning that, material characteristics of the arch presumed to change along the radial direction of the arch section.

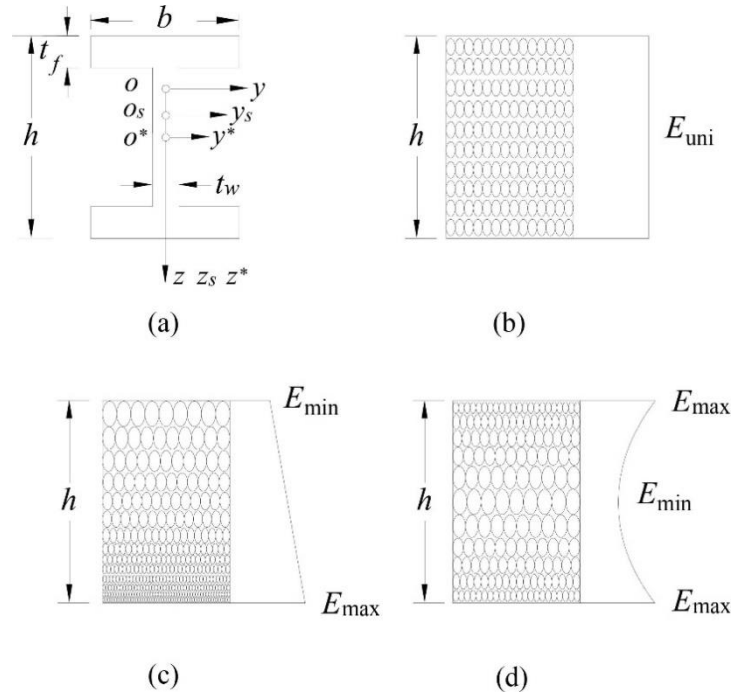


Figure 2.18: The cross profile porous distribution pattern of curve structure: (a)

Coordinates system; (b) Uniform; (c) symmetric; (d) Unsymmetric

In Figure 2.19 the buckling performance of the aluminum solid arch with various porous distribution(e.g. uniform, symmetric, and unsymmetric) illustrated. Furthermore, as can be seen there are results regards to buckling behavior of porous arch by utilizing the GPLs as reinforcement. It is noticeable that the porous arch without graphene plates additive allocated the lowest magnitude of the buckling to itself. So that, it is inevitable fact that GPLs are able to create significant effect on thriving the buckling behavior of the aluminum solid curves.

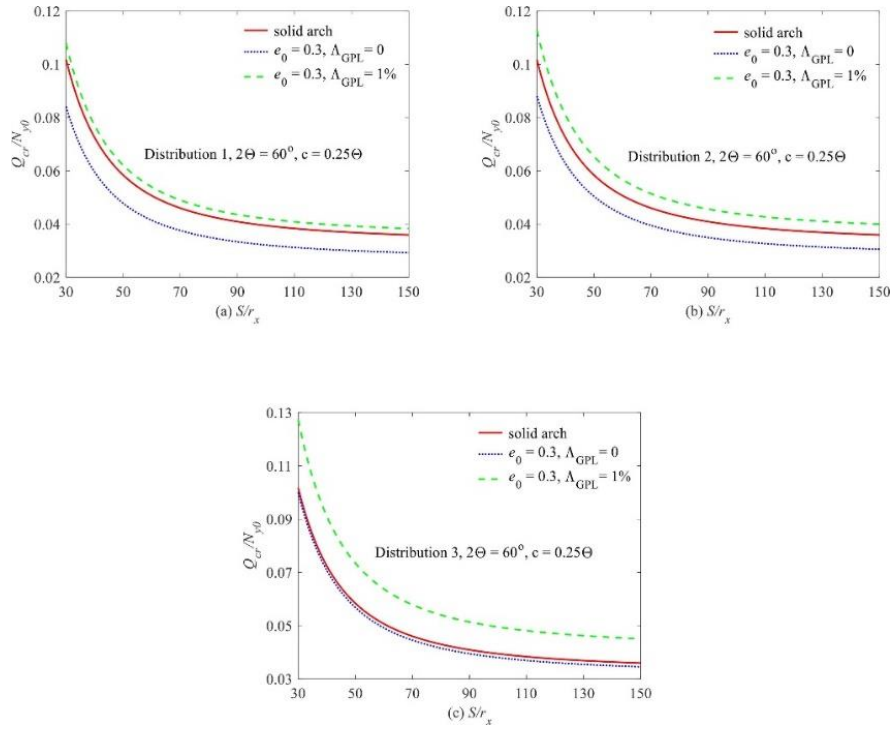


Figure 2.19: differentiation of an arch's buckling behavior with and without porosity when various distribution patterns of porosity are considered [113]

2.7 Thermal Load

In high temperature working situations, FG-GPLs can reduce material cracking and delamination and enhance the structure's strength, which is encouraging for safer and

more robust smart devices [115]. Functionally graded arches have the material and configuration couple properties of the bending-stretching. Thermal stresses cause the FGM shallow arch to distort significantly before it buckles in the plane of its curvature [28].

In order to estimate the linear thermal buckling behavior and vibration of the functionally graded beams a modified the third order shear deformation theory developed from the theory of elasticity is utilized, according to Wattanasakulpong et al [116].s investigation. It is explored how different material compositions, slenderness ratios, and boundary conditions affect the significant variations in thermal buckling and frequency outcomes. According to the material depended and in depended on thermal load properties provided as well for both thermal buckling and vibration analysis, the solutions The temperature-dependent solution is seen to play a significant function for consideration according to the thermo-elastic vibration examination. As temperature rises, At the critical temperature primer frequency falls and shows a tendency to be zero, where it trends to its lowest point. However, as the value of the temperature experiences the increase in the post-buckling area, the primary frequency rises as well. The fact that a rise in temperature is followed with a rise in the power law index value, which causes a decrease in frequency, is another interesting observation during the pre-buckling period. Nevertheless, the tendency is reversible after passing the pre-buckling duration. Wang et al. [117] studied on mechanical behavior of the FGM micro beam under the temperature and moisture effect by considering moisture between 0 to 10 percent. Noteworthy, it is inevitable fact temperature resistance of epoxy matrix is until 100 °C based on the Korolev et al. [118] and Borah et al. [119] investigations, however bamboo is able to resistant till

220 °C according to the Md Shah et al. [120]. Furthermore, even though epoxy can resist moisture till 80% based on ISO 3219 for moisture load, based on ISO 22157 for Bamboo fiber, normally this fiber studied for moisture less than 12%.

2.8 Buckling- FGM- Thermal Load

Using the differential quadrature approach, Kiani and Mirzaei [121–125] examined the buckling and post-buckling response of functionally graded structures reinforced graphene plates under the thermal field. Zhicheng et al. [115] examine the FG graphene plates reinforcement composite arches' nonlinear in-plane buckling in response to thermomechanical stress. They concluded from their findings that the functionally graded GPLs curves' limit point buckling or bifurcation buckling subjected to the thermo- mechanical loadings. The buckling behavior of these type of arches also rise when the thermal load rises because when the temperature exceeds the maximum temperature, reaching to the maximum limit point or bifurcation buckling is impossible, possibility for obtaining the max limit point buckling or bifurcation buckling load is only at a certain maximum temperature. The FG-GPLRC arch cannot buckle at the limit point or at the bifurcation when the temperature exceeds the maximum temperature.

Li et al. [126] describe the FGP arch structure's analysis procedure in an enhanced thermal field. Graphene platelets provide as reinforcement for the FGP arch (GPLs). Figure 2.20 shows the cross section of the arch [96].

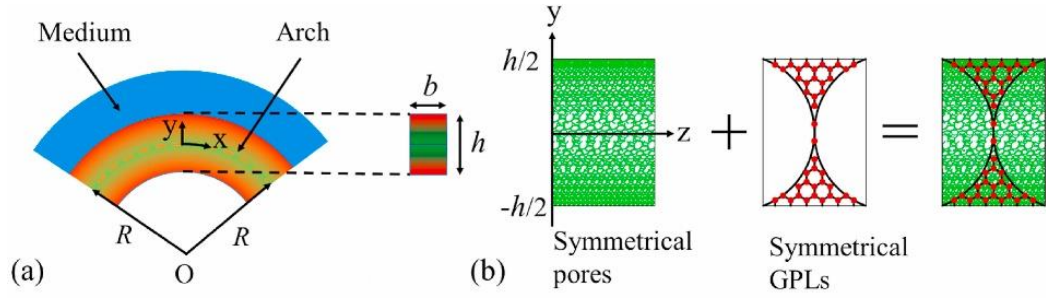


Figure 2.20: (a) A functionally graded porous arch reinforced -GPLs, surrounded with medium and (b) the GPLs and the pores distribution pattern along the cross-section of the arch [126]

The non-linear behavior of FG curved beams stem from thermal load was studied by Dehrouyeh [127]. The in-plane examination of the fixed arches with pin-ended that are exposed to a thermal load is presented in a systematic manner by Pi and Bradford utilizing the classical buckling theory [98]. It is discovered that only extremely shallow arches may actually experience thermoelastic bifurcation buckling. Using Shariat and Eslami's examination of the thermal functionally graded plate's buckling leads to bringing about several geometrical mistakes, so that, the equilibrium, durability, geometrical, and compatibility equations of an imperfect FGM were developed [128]. A number of different types of FGM sandwich plates were tested for thermal buckling by Zenkour and Sobhy [129]. Lanhe present that buckling behavior of a simply supported approximated thick rectangular FGM plate relying on simply support subjected to thermal load. [130]. Tang et al. [131] investigated performance of the heated FGM arches buckling arches subjected to a mechanical and thermal loads. the compressive stresses increase by warming the FGM arch because of expansion, and an upward displacement is introduced that is symbolized by the crown displacement, as seen in Figure 2.22 (a). The spread of material non uniformity along the thickness direction also contributes to the development of a thermal bending moment. When the pressure field is used after the heating process, the arch deforms asymmetrically as seen in Figure 2.21 (b). consequently, the FGM arch displays various stability

performances as opposed to the traditional arch with homogeneity.

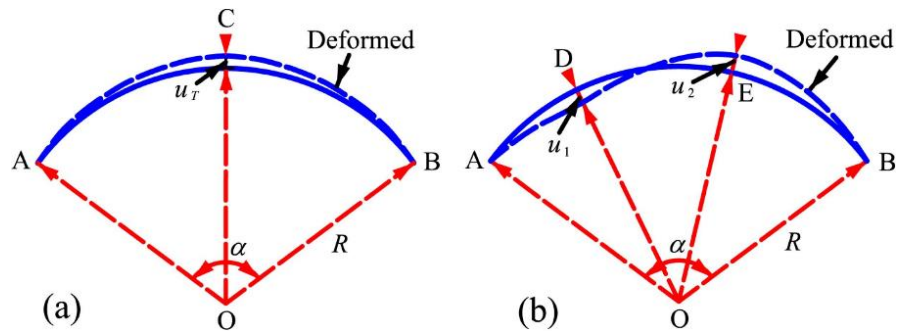


Figure 2.21: Functionally Graded arch's deformation subjected to a) Thermo load and b) thermo-mechanical loads

Chapter 3

METHODOLOGY

The flowchart of the methodology illustrated in Figure 3.1.

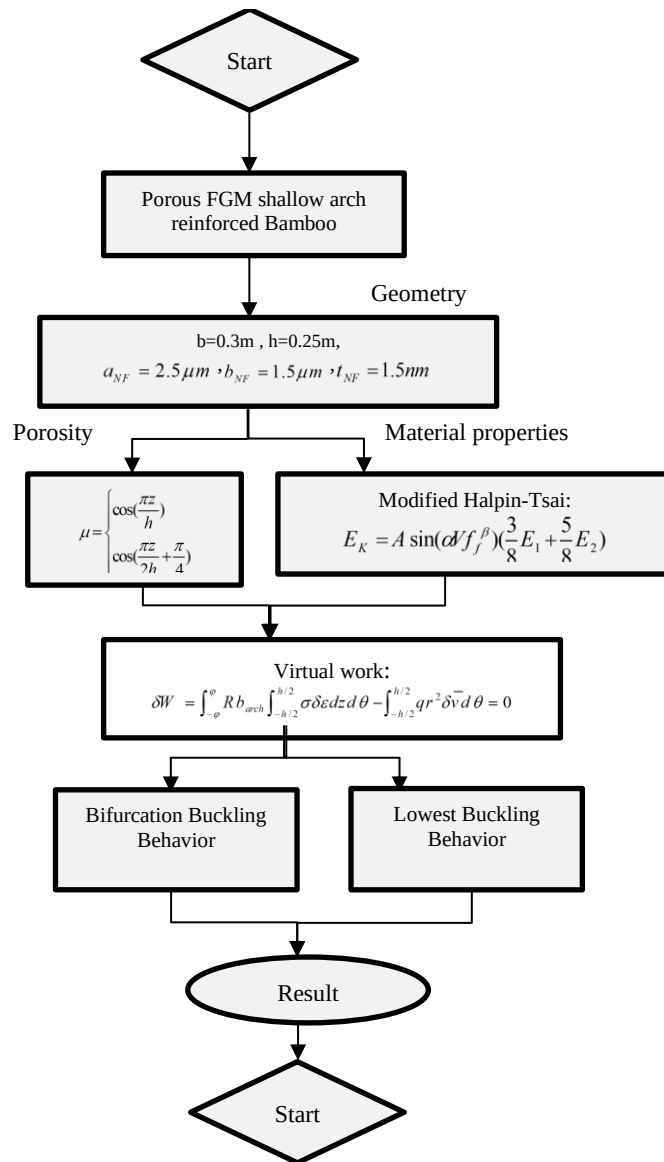


Figure 3. 1: Methodology flowchart

3.1 Formulation And Effective Material Properties

Figure 3.2 demonstrated the in-plane structural behavior of FGP shallow curves reinforced NFC surrounded with external hydro-thermo mechanical loads. The material considered here is natural fiber porous composite curved shallow with gradient concentration change of natural fiber porosity is spread off through the shallow in various pattern (Figure 3.3).

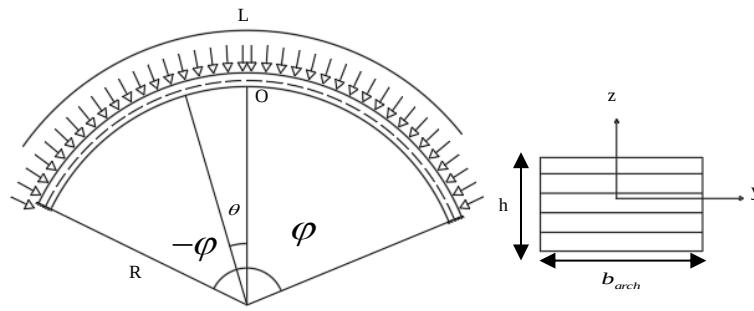


Figure 3.2: Configuration of arch and cross section

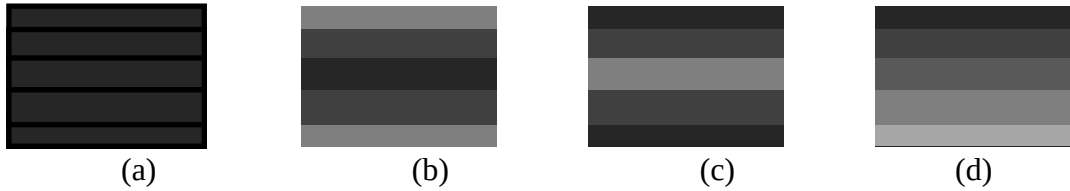


Figure. 3.3: Distribution pattern of arch: a) Uniform, b) Sym₁-NFC, c) Sym₂-NFC, and d) Unsym-NFC

The FG-NFC properties are achieved by deriving geometric parameter and considering effect of changeable material porosity pattern. The evaluation of effective material properties are recapitulated here. The modified properties of the NFC are achieved according to the Osaka [132] model, reached from Halpin- Tsai model. Where, effectiveness young modulus of natural fiber reinforced composite proposed as:

$$E_K = A \sin(\alpha \mathcal{V} f_f^\beta) \left(\frac{3}{8} E_1 + \frac{5}{8} E_2 \right) \quad (1)$$

Where E_1 and E_2 are fiber and transvers direction modulus, defined as:

$$E_1 = E_m \left(\frac{1 + \zeta_L \eta_L V_f}{1 - \eta_L V_f} \right) \quad (2)$$

$$E_2 = E_m \left(\frac{1 + \zeta_T \eta_T V_f}{1 - \eta_T V_f} \right) \quad (3)$$

Where E_f and E_m are fiber and matrix modulus, respectively. η_L , η_T , ζ_L and ζ_T are the reinforcement efficiency in the length and transvers direction, respectively.

$$\eta_L = \frac{E_f - E_m}{E_f - \zeta_L E_m} \quad (4)$$

$$\eta_T = \frac{E_f - E_m}{E_f - \zeta_T E_m}$$

where:

$$\zeta_T = 2(b/t) \quad (5)$$

$$\zeta_L = 2(a/b)$$

where a , b , t , a/b , and b/t are the average length, width, thickness, thickness aspect ratio and width to thickness ratio of Bamboo, respectively.

Moreover, density of k^{th} layer defined as:

$$\rho_k = \rho_f V_f + \rho_m V_m \quad (6)$$

where volume fraction of matrix given as:

$$V_m = 1 - V_f \quad (7)$$

3.2 NFC Distribution

The volume fraction V_f of k^{th} ply in Eq 1 is assuming to be various dispersion pattern Uni-NFC is uniform in each ply. Sym₁-NFC and Sym₂-NFC are changed in thickness direction where inner layers richer than outer, and outer layers are filled more

than inner layer in them, respectively. Unsym-NFC is verified in the thickness and amount of NFC is increased up to down. By the same taken, shown in Fig. 2, Vf_f distribution is written as:

$$Vf_f^k = \begin{cases} Uni : Vf_f \\ Sym_1 : \frac{2Vf_f (12K - N_L - 1)}{N_L} \\ Sym_2 : 2Vf_f \left(1 - \frac{|12k - N_L - 1|}{N_L}\right) \\ Unsym : \frac{Vf_f (2k - 1)}{N_L} \end{cases} \quad (8)$$

3.3 Porosity Distribution

The material behavior of functionally graded close-cell porous(FGP) structure is presumed to be changeable through the thickness as a function of z coordination [18].

The effective young modulus and mass density of NF-FGP material followed by:

$$\rho(z) = \rho_k [1 - C_m \mu(z)] \quad (9)$$

$$E(z) = E_k [1 - C_p \mu(z)] \quad (10)$$

Where C_m , C_p and $\mu(z)$ are coefficients of porosity relevant to density and stiffness

function and scattering pattern of porosity, respectively. C_m and C_p are given as:

$$C_p = \frac{E_1 - E_2}{E_1} \quad (11)$$

$$C_m = \frac{1.121[1 - (E(z)/E_k)^{\frac{1}{2.3}}]}{\mu(z)} \quad (12)$$

Porosity dispersion pattern is presumed to be uniform, symmetric and unsymmetric variation [133]:

$$\mu = \begin{cases} \cos(\frac{\pi z}{h}) \\ \cos(\frac{\pi z}{2h} + \frac{\pi}{4}) \end{cases} \quad (13)$$

Where μ_1 and μ_2 are symmetric and unsymmetric, respectively.

3.4 NF-FGM Shallow Arch Formulation

The considered circular shallow configuration here considered is established on a curved includes central angle of 2φ and arch length L , and radius of curvature R having perfectly bounder NF layer, without any slip, of some thickness h , and width b_{arch} as depicted in Figure 3.2 Shallow curve structure exposed to combination of radial temperature and hydro load, and they are uniform through the thickness of the profile.

$$\begin{aligned} \Delta T &= T - T_0 \\ \Delta C &= C - C_0 \end{aligned} \quad (14)$$

3.5 Differential Nonlinear Equilibrium Equations

The formulation of the in-plane nonlinear equilibrium of simply support shallow circular arch under the uniform radial load and hygro-thermal loading, speared around the axis of the curve is able to be achieved from the virtual work principle as:

$$\delta W = \int_{-\varphi}^{\varphi} R b_{arch} \int_{-h/2}^{h/2} \sigma \delta \epsilon dz d\theta - \int_{-\varphi}^{\varphi} q r^2 \delta \bar{v} d\theta = 0 \quad (15)$$

Correspondingly, v , w , $\bar{v}$ and $\bar{w}$ are the radial, axial displacement and the dimensionless radial and axial displacement, respectively. The structure deformation behavior is elastic and following Euler Bernoulli assumption and Donnell's shallow shell theory to represent the normal strain of rotation position along through z direction in the cross section as:

$$\varepsilon = \varepsilon_m + \varepsilon_b \quad (16)$$

Where ε_m and ε_b are the mid- axis membrane strain and bending strain stem from curvature, respectively, defined by:

$$\varepsilon_m = \frac{dw}{d\theta} \quad (17)$$

$$\varepsilon_b = -\frac{z}{r} \frac{d^2v}{d\theta^2} \quad (18)$$

By the same taken peripheral normal stress of the each ply under hygro-thermo-mechanical load, followed by:

$$\sigma_k = E_k (\varepsilon - \alpha_k \Delta T - \beta_k \Delta C) \quad (19)$$

Where α_k and β_k are the effective linear coefficient of thermal expansion(CTE) and coefficient of moisture expansion (CME) respectively., where is able to be achieved as:

$$\alpha_k = \alpha_m (1 - V_f^k) + \alpha_f V_f^k \quad (20)$$

$$\beta_k = \beta_m (1 - V_f^k) + \beta_f V_f^k \quad (21)$$

Since A_{11} , B_{11} and D_{11} are the stiffness components as:

$$\begin{aligned} A_{11} &= b_{arch} \int_{-h/2}^{h/2} E dz \\ B_{11} &= b_{arch} \int_{-h/2}^{h/2} E z dz \\ D_{11} &= b_{arch} \int_{-h/2}^{h/2} E z^2 dz \end{aligned} \quad (22)$$

And N^T , N^C , M^T and M^C are the temperature and moisture impelled axial load and bending moment, respectively, defined as:

$$N^T = b_{arch} \int_{-h/2}^{h/2} E \alpha \Delta T dz \quad (23)$$

$$N^C = b_{arch} \int_{-h/2}^{h/2} E \beta \Delta C dz \quad (24)$$

$$M^T = b_{arch} \int_{-h/2}^{h/2} E \alpha \Delta T z dz \quad (25)$$

$$M^C = b_{arch} \int_{-h/2}^{h/2} E \beta \Delta C z dz \quad (26)$$

Correspondingly by substituting Eq. 16 and Eq.19 into Eq. 15 leads to virtual work as:

$$\delta W = \int_{-\varphi}^{\varphi} [-NR (\frac{\delta d\bar{w}}{d\theta} - \delta\bar{v} + \frac{d\bar{v}}{d\theta} \delta \frac{d\bar{v}}{d\theta}) - M \delta \frac{d^2\bar{v}}{d\theta^2} - qr^2 \delta\bar{v}] d\theta = 0 \quad (27)$$

Where,

$$\bar{v} = \frac{v}{r} \quad (28)$$

$$\bar{w} = \frac{w}{r} \quad (29)$$

And,

$$N = A_{11} [\frac{d\bar{w}}{d\theta} - \bar{v} + \frac{1}{2} (\frac{d\bar{v}}{d\theta})^2] + \frac{B_{11}}{r} (\frac{d^2\bar{v}}{d\theta^2}) + N^T + N^C \quad (30)$$

$$M = B_{11} [\frac{d\bar{w}}{d\theta} - \bar{v} + \frac{1}{2} (\frac{d\bar{v}}{d\theta})^2] + \frac{D_{11}}{r} (\frac{d^2\bar{v}}{d\theta^2}) - M^T - M^C \quad (31)$$

Differential equation of equilibrium for the axial and radial deformation in Eq. 27, followed by Eq. 32 and Eq. 33, as:

$$\frac{d(NR)}{d\theta} = 0 \quad (32)$$

$$NR + \frac{d}{d\theta} (\frac{d\bar{v}}{d\theta}) - \frac{d^2 M}{d\theta^2} - qR^2 = 0 \quad (33)$$

Solving equation 33 under boundary condition $\bar{v} = \bar{w} = \frac{d\bar{v}}{d\theta} = 0$ at $\theta = \pm\varphi$ leads to:

$$M = -(D_{11} - \frac{B_{11}^2}{A_{11}}) \frac{d^2 \bar{v}}{R d \theta^2} - \frac{B_{11}}{A_{11}} (N - N^T - N^C) - M^T - M^C \quad (34)$$

Substituting the Eq. 33 and Eq.35 into Eq. 34 leads to the equilibrium equation of the functionally graded NFC circular shallow arch in radial direction as:

$$\frac{\bar{v}^{iv}}{\chi^2} + \frac{d^2 \bar{v}}{d \theta^2} = F \quad (35)$$

where F is a dimension loads and χ is an axial compressive force followed by:

$$\chi = \frac{NR^2}{\kappa} \quad (36)$$

K is the effective bending stiffness defined as:

$$\kappa = D_{11} - \frac{B_{11}^2}{A_{11}} \quad (37)$$

where boundary condition at $\theta = \pm\varphi$ assumed as:

$$\bar{v} = \bar{w} = \frac{d\bar{v}}{d\theta} = 0 \quad (38)$$

Solving the Eq.35 according to the boundary condition achieved the radial displacement of the fixed FG-NFC shallow arch as:

$$\bar{v} = \frac{F}{\chi^2} \left(\frac{\chi^2 \theta^2 - \Psi^2}{2} + \Psi \left[\frac{\cos \chi \theta}{\sin \Psi} - \cot \Psi \right] \right) \quad (39)$$

where,

$$F = \frac{qR}{N} - 1 \quad (40)$$

Then nonlinear equilibrium equation obtained by substituting Eq. 39 into Eq. 30 and deriving the integration over arch entire length, given as:

$$\gamma_{11}F^2 + \gamma_{12}F + \gamma_{13} = 0 \quad (41)$$

where,

$$\begin{aligned} \gamma_{11} &= \left(\frac{0.5}{\tan(\Psi)}\right)^2 + \left(\frac{0.75}{\tan(\Psi)}\right) - \left(\frac{1}{\Psi}\right)^2 + 0.42 \\ \gamma_{12} &= \frac{1}{\Psi \tan(\Psi)} - \left(\frac{1}{\Psi}\right)^2 + 0.42 \\ \gamma_{13} &= \frac{\Psi \kappa h^3}{A_{11} r^2 \varphi^4} - \frac{(N^T + N^C)r}{A_{11} h} \end{aligned} \quad (42)$$

where dimensionless geometrical parametric defined as:

$$\lambda = \frac{L}{h} \cdot \frac{\varphi}{2} = \frac{R \varphi^2}{h} \quad (43)$$

And,

$$R = \sqrt{\frac{\kappa h}{A_{11}}} \quad (44)$$

3.6 Buckling Analysis

3.6.1 Limit Point

The local highest and less point on the nonlinear equilibrium shallow arch curve are unknown as a limit points when the load is gone up negligible more than limit point, there is no adjusted balance configuration and the only feasible balance condition is limited distance apart. The limit points are able to obtained as:

$$\frac{dF}{d\Psi} = \frac{\partial f(F, \Psi)}{\partial \Psi} \cdot \frac{\partial F}{\partial f(F, \Psi)} \quad (45)$$

where F is a dimensionless load, which represented as an implicit function of Ψ .

where

$$f(F, \Psi) = 0 \quad (46)$$

Which results to the equation equilibrium for buckling loadings as:

$$\gamma_{21}F^2 + \gamma_{22}F + \gamma_{23} = 0 \quad (47)$$

where,

$$\begin{aligned} \gamma_{21} &= \Psi \cdot \frac{\partial \gamma_{11}}{\partial \Psi} - 4\gamma_{11} \\ \gamma_{22} &= \Psi \cdot \frac{\partial \gamma_{12}}{\partial \Psi} - 4\gamma_{11} - 2\gamma_{12} \\ \gamma_{23} &= \Psi \cdot \frac{\partial \gamma_{13}}{\partial \Psi} - 2\gamma_{12} \end{aligned} \quad (48)$$

Solving the Eq.41 and Eq.47 is parallel leads to producing the axial force parameter and the limit point imbalanced load. Consequently, substituting F and Ψ into the Eq.40 is able to yield the dimensionless radial displacement.

3.7 Bifurcation Buckling Equilibrium

Along with limit point buckling, uniform radial-hydro-thermal load also is able to spark off bifurcation mode buckling for shallow curve. As a matter of fact, bifurcation buckling mode is adjoining deformation. When the loading goes along its critical phase, the curve transmits from the balanced configuration without buckling to an extremely small balanced configuration with buckling. Furthermore, both the external load and internal stress yields are constant simultaneously, so that the axial compressive load in the both buckled shape and pre-buckled shape are equal [115].

It is assumed that, a primary equilibrium state definition as $\{\bar{v}, \bar{w}, N, M, q\}$ while bifurcation mode in equilibrium configuration describe as $\{\bar{v} + \bar{v}_b, \bar{w} + \bar{w}_b, N, M, q\}$. Hence, linear homogeneous differential equation for bifurcation equilibrium of the circular shallow arches can be obtained by:

$$\frac{d^2 \bar{v}_b}{d\theta^2} + \frac{\bar{v}_b}{\chi^2} = 0 \quad (49)$$

where,

$$\overline{v}_b = K_1 + K_2\theta + K_3 \sin \chi\theta + K_4 \cos \chi\theta \quad (50)$$

where K_1 , K_2 , K_3 and K_4 are the undetermined coefficient.

The boundary conditions for bifurcation buckling at $\theta = \pm\varphi$ defined as:

$$\overline{v}_b = \overline{w}_b = \frac{d\overline{v}_b}{d\theta} = 0 \quad (51)$$

The requirement of nontrivial solution for $K_1 - K_4$ leads to disappearing of the determinant of the coefficient as:

$$K_2 + K_3\chi \cos \Psi - K_4\chi \sin \Psi = 0 \quad (52)$$

$$K_2 + K_3\chi \cos \Psi + K_4\chi \sin \Psi = 0 \quad (53)$$

$$K_1 - K_2\varphi - K_3 \sin \Psi + K_4 \cos \Psi = 0 \quad (54)$$

$$K_1 + K_2\varphi + K_3 \sin \Psi + K_4 \cos \Psi = 0 \quad (55)$$

Hence, sparks off the characteristic equation to be achieved as:

$$\cos^2 \Psi + \Psi \sin \Psi \cos \Psi - 1 = 0 \quad (56)$$

Solving Eq. 56 leads to give Ψ_b , then substituting Ψ_b to Eq.??? determinates the corresponding axial FG-NFC shallow curve at bifurcation buckling as:

$$N_b = \frac{4(\Psi_b \pi)^2 \kappa}{L^2} \quad (57)$$

By the same taken, substituting Ψ_b into Eq.48 leads to the nonlinear equilibrium equation of the corresponding unsymmetric bifurcation buckling as:

$$\gamma_{31}F^2 + \gamma_{32}F + \gamma_{33} = 0 \quad (58)$$

where

$$\gamma_{33} = \frac{(\psi\pi)^2 \kappa h^3}{A_{11}r^2\varphi^4} - \frac{(N^T + N^C)}{4A_{11}\varphi^2} \quad (59)$$

Solving Eq.58 is able to achieve the bifurcation load yield, where a real solution

requires the existent of $B_3^2 - 4A_3C_3 \geq 0$. Hence, the critical parameter is determined as the limiting shallowness for possible bifurcation buckling of the FG-NFC shallow curve as:

$$\lambda_b = \sqrt{302.86\left(\frac{\kappa h}{A_{11}}\right) - 15\left(\frac{r^2 \varphi^4 (N^T + N^C)}{A_{11} h^2}\right)} \quad (60)$$

3.7.1 Lowest Bifurcation Buckling

Since, according to the Eq.56 each parameter is equal to zero, when the second term Eq.56 is equal to zero, primary solution of Ψ reaches to Ψ_s . Hence, substituting Ψ_s to nonlinear equilibrium equation leads to the lowest buckling load to be equal to the axial compressive, defined as:

$$qR = \frac{4\pi^2 \kappa}{L^2} \quad (61)$$

furthermore, the real solution for the lowest buckling load calls for satisfying the $\lim_{\Psi \rightarrow \Psi_s} (B_1^2 - 4A_1C_1) - 4 > 0$. So that, the critical geometric parameter λ_s is obtained as

minimum geometric parameter for possible bifurcation buckling of the arch as:

$$\lambda_L = \pi \sqrt{\pi^2 \left(\frac{\kappa h}{A_{11}}\right) - \left(\frac{r^2 \varphi^4 (N^T + N^C)}{A_{11} h^2}\right)} \quad (62)$$

Chapter 4

RESULT AND DISCUSSION

4.1 Numerical Result And Discussion

Here, the nonlinear buckling and disequilibrium of FGM porous shallow arch reinforced Bamboo under influence of radial hydro-thermo-mechanical load and fixed support is carried out. The geometry taken into account here consist of cross profile by width $b=0.3m$ and height $h=0.25m$ with 10 layers including the combination of epoxy and natural fiber, bamboo is taken into account here, with $a_{NF} = 2.5\mu m$, $b_{NF} = 1.5\mu m$ and $t_{NF} = 1.5nm$.

The properties of epoxy and Bamboo are taken as [115, 134, 135]:

- Material of fiber (Bamboo): Young's modulus, $E_f = 20Gpa$; density, $\rho_f = 0.8Kg / m^3$; TEC, $\alpha_f = 22.08*10^{-6} / K$; MEC, $\beta_f = 990*10^{-6}$.
- Material of matrix (Epoxy): Young's modulus, $E_m = 3Gpa$; density, $\rho_m = 1200Kg / m^3$; TEC, $\alpha_m = 60*10^{-6} / K$; MEC, $\beta_m = 1.03$.

4.2 Validation Of The Model

Before discussing the obtained numerical result the proposed buckling behavior of FGM shallow curve reinforced graphene platelets(GPL) nanocomposite validated. For this purpose, the dimensionless load of shallow arch having various layers including GPL and epoxy through the arch are calculated by taking only temperature and

mechanical load into account based upon the Donnell's shallow shell theory and in comparison with those previously achieved by Yang et al. [115], as listed in Table 4.1. The table tabulated the accuracy and instability of established model, is able to be confirmed.

Table 4.1: Dimensionless buckling load of FGM shallow curve reinforced GPLRC $Vf_f = 0.3\%$

	$\Delta T = 0$				$\Delta T = 100$			
	Limitpoint		Bifurcation		Limitpoint		Bifurcation	
	Present	Ref	Present	Ref	Present	Ref	Present	Ref
Uni	1.9973	1.9976	1.8189	1.8191	2.4435	2.4440	1.9639	1.9641
Sym ₁	1.6364	1.6367	1.4191	1.4189	2.0464	2.0462	1.5230	1.5227
Sym ₂	2.3152	2.3157	2.1263	2.126	2.5960	2.5963	2.3845	2.3848
Unsym	1.8804	1.8805	1.6860	1.6862	2.3139	2.3141	1.8160	1.8165

Assessment of the present model, here, comprehensive investigation is carried at assuming parameter for FG NFC shallow arches by $s/h=30$ (length to thickness ratio), dimensionless geometric parameter e.g. $\lambda=8$, and beam angle 2φ . Moreover, distribution of natural fiber(Bamboo) and porous dispersion in the thickness direction C_m and $C_p = 0.5$ of Bamboo reinforced porous shallow curve composite.

Table 4.2 tabulated the amount of the lowest amounts of special geometric parameter for both bifurcation and lowest buckling, λ_b and λ_L , respectively, under temperature change $\Delta T = 20, \Delta C = 0$, and symmetric porosity distribution. By the same taken, Table 4.3 listed the special geometric parameter under moisture change $\Delta T = 0$, $\Delta C = 3$, and symmetric porosity distribution. As can be seen, the critical geometric parameter under moisture failed to bring on significant difference, this phenomenon will be shown in Figure 4.3

Figure 4.1(a-d) illustrates the nonlinear buckling load diagram when dimensionless geometrical parameter of arch is $\lambda = 5.5$ and $\lambda = 8$, when Fig 4.1(a-b) are for temperature change and Figure 4.1(c-d) are for temperature change. Comparing the diagram it is noticeable that the magnitude of the buckling load is under moisture effect with $\lambda = 5.5$ performed better than $\lambda = 8$, with buckling loadings approximately higher than 1.5 and 1.1, respectively, while nonlinear buckling load under temperature field showed tendency to decrease by increasing λ from 5.5 to 8, with magnitude of slightly higher than 0.11 and less than 0.15, respectively.

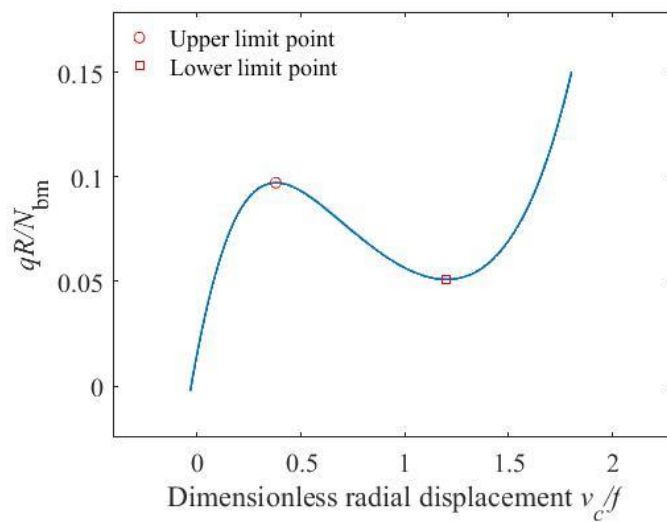
Table 4.2: Special geometry parameters of arch under the effect of temperature field

	Uni	Sym ₁	Sym ₂	Unsym
	2.6369	1.8548	3.1135	1.9934
λ_L	5.0831	3.8618	5.3615	4.0704

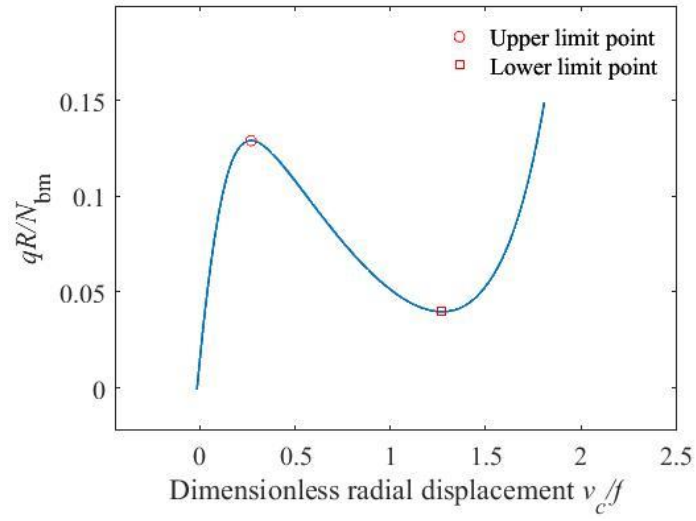
λ_b

Table 4.3: Special geometry parameters of arch under the effect of moisture field

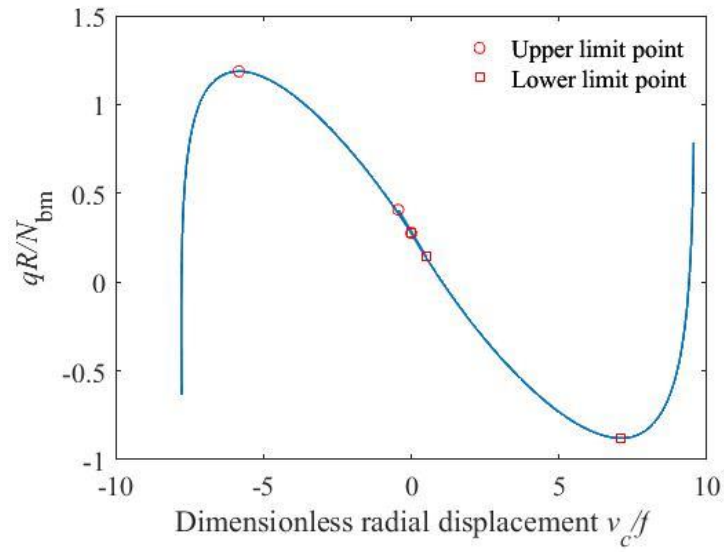
	Uni	Sym ₁	Sym ₂	Unsym
λ_L	58.5387j	58.547j	58.4065j	0.3754
λ_b	47.5852j	47.551j	47.5094j	58.5520j



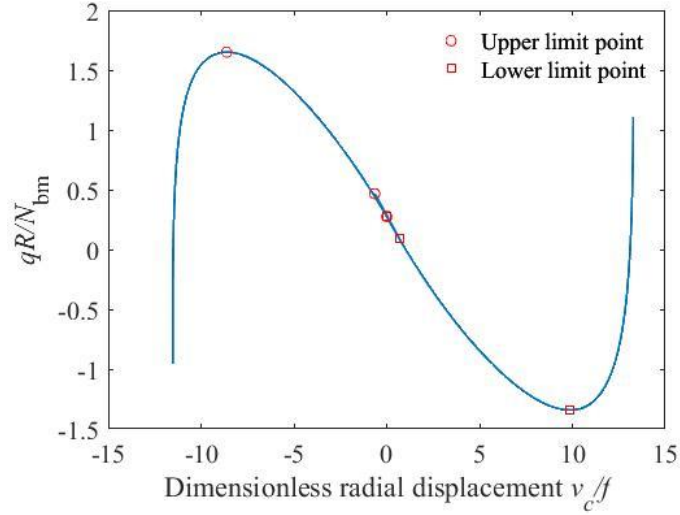
(a): $\Delta T = 20, \Delta C = 0, \text{ and } \lambda = 5.5$



(b): $\Delta T = 20, \Delta C = 0$, and $\lambda = 8$



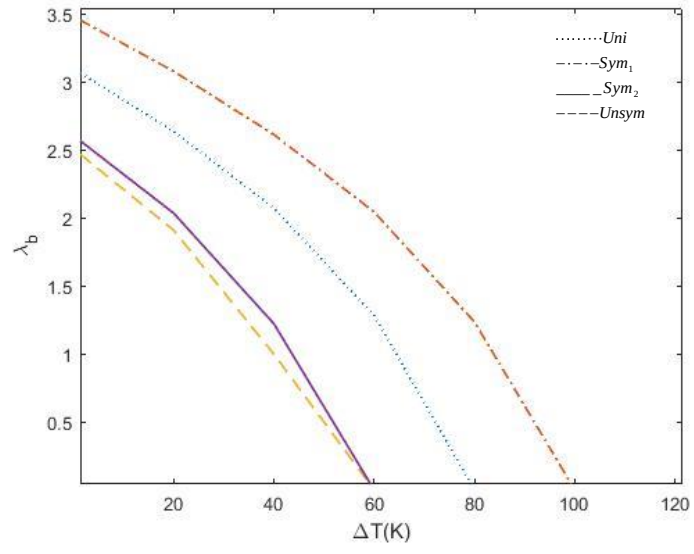
(c): $\Delta T = 0, \Delta C = 3$, and $\lambda = 5.5$



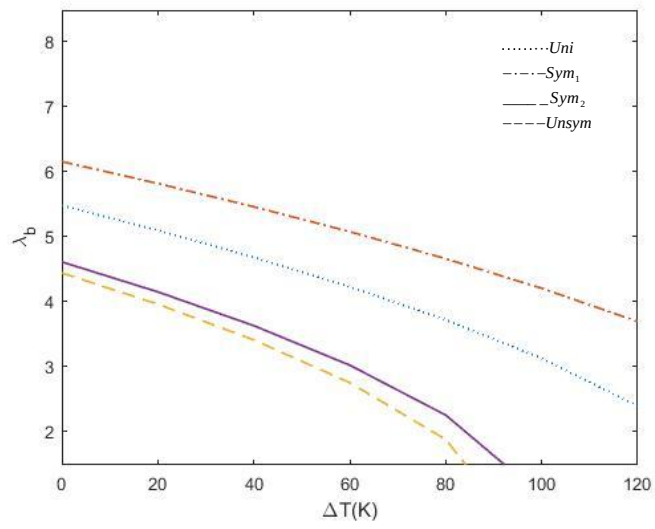
(d): $\Delta T = 0, \Delta C = 3$, and $\lambda = 8$

Figure 4.1: Effect of special dimensionless geometry parameter on the nonlinear buckling behavior of arch: ($s/h = 30$, $Vf_f = 0.6\%$, and sym₁-NFC distribution)

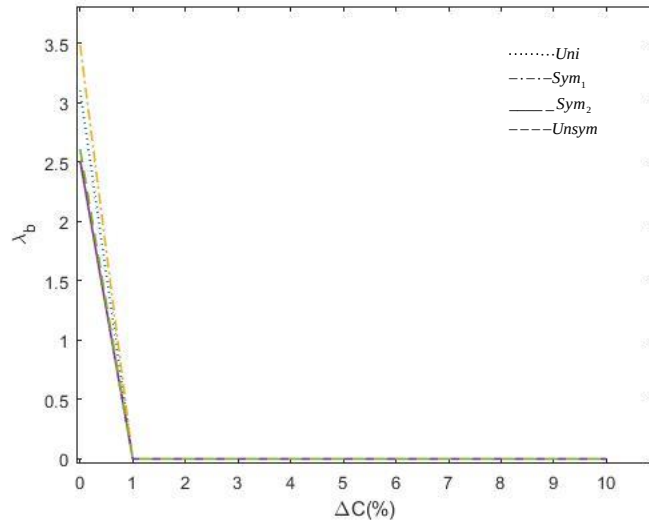
Figure 4.2(a-d) depict the behavior of bifurcation and lowest geometric parameter of arch, λ_b and λ_l , respectively, under the influence of temperature and moisture change. Apparently, both λ_b and λ_l have seen significant falling down by rising up temperature. Furthermore, as its demonstrated in Figure 4.2(a-b), Sym₂-NFC and Sym₁ NFC distribution have allocated the highest and lowest magnitude to their selves, respectively. Moreover, both λ_b and λ_l have decreased by increasing moisture change, but interestingly, only from $\Delta C = 0$ to 1, after 1 λ_b and λ_l are experienced the equal amount. Last but not least, Sym₂-NFC distribution takes the lead in magnitude of special dimensionless geometric parameter.



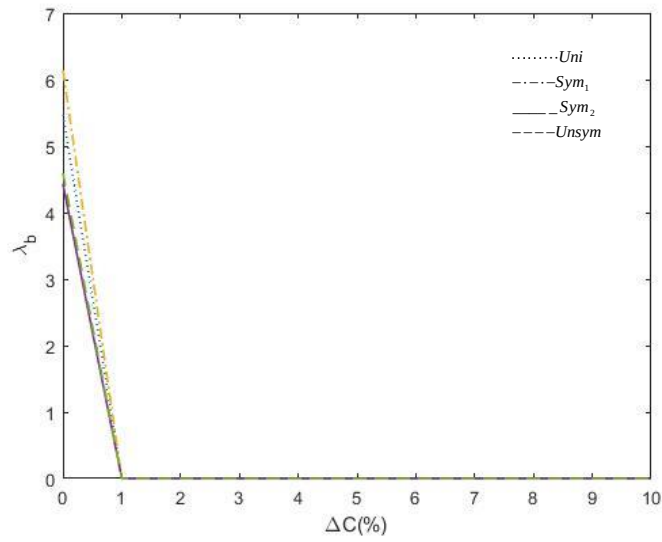
(a): Temperature effect on λ_b



(b): Temperature effect on λ_L



(c): Moisture effect on λ_b

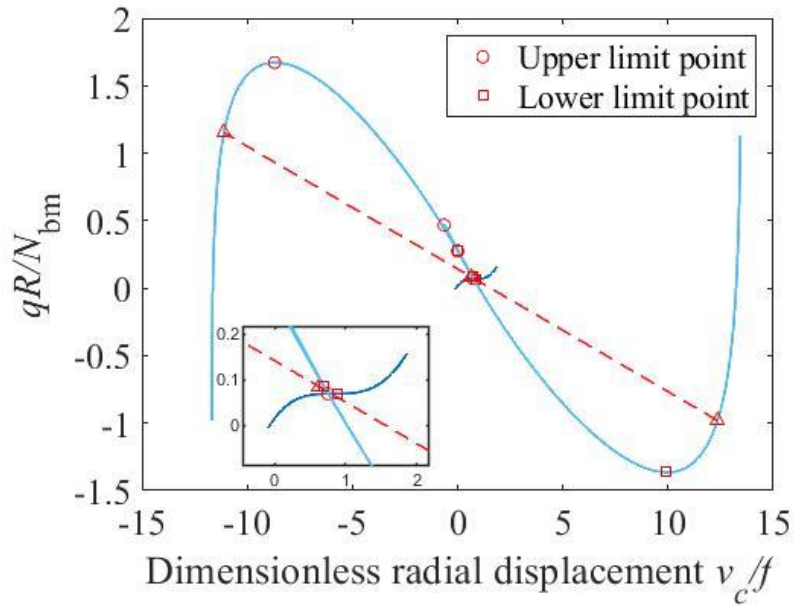


(d): Moisture effect on λ_t

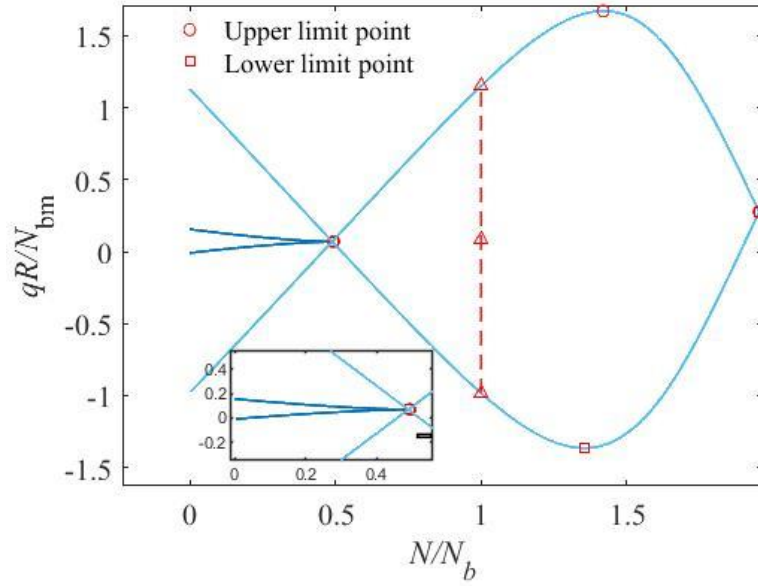
Figure 4.2: The temperature and moisture influence on the bifurcation and lowest geometric parameter of arch, λ_b and λ_t : ($s/h = 30$, $\lambda = 5$, $Vf_f = 0.6\%$, $a/b = 4$, and $b/t = 10^3$)

Considering the information of Table 4.1 lowest dimensionless geometric parameter λ for uniform distribution is $\lambda_t = 3.1135$. Hence, typical lowest buckling behavior of FGM porous shallow arch reinforced Bamboo with uniform fiber distribution for both load displacement and load external force are illustrated in Figure 4.3. It is noticeable

that the both highest and lowest limit point loads have experienced the same value. Furthermore, noteworthy that the magnitude of the λ less than lowest $\lambda (\lambda_L)$ leads to occur no buckling for shallow curve. On the other side, as can be see, the lowest critical geometry parameter it refused to create the considerable effect on buckling load when there is only moisture, so that, the difference is substantially significant. To be more specific and based on Table 4.3 critical geometric parameter when only moisture exists was reduced significantly, approximately close to zero. Hence, here, critical special dimensionless geometry parameter when only temperature field is available plays significant role.



(a) (Load displacement curve)

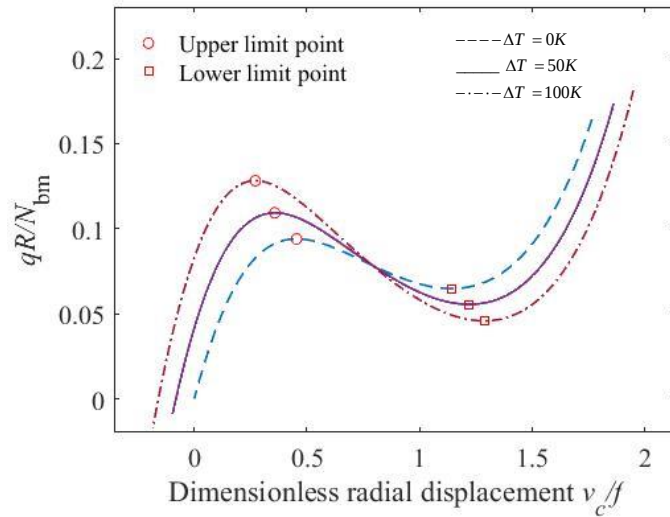


(b) (Load-axial force curve)

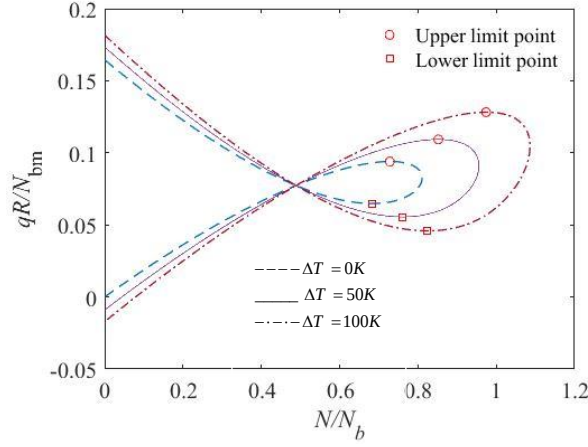
Figure 4.3: Lowest buckling behavior of arch: ($s/h = 30$, $\lambda = 3.1135$, $Vf_f = 0.6\%$, and sym₁-NFC distribution)

Buckling load and effect of hydro-thermo-mechanical load by considering symmetric porosity distribution arch with $s/h=30$, temperature change and moisture change and volume fraction of fiber $Vf_{bamboo} = 0.6\%$ illustrated in Figure 4.4(a-d). It is noticeable that Figure 4.4(a-b) are load displacement and load axial force curve, respectively for $\Delta T = 0, 50, 100$ and $\Delta C = 0$, while Figure 4.4(c-d) are belong to the same information unless there is no temperature and uniform moisture change is $\Delta C = 1, 3, 10$. It is apparent form the information of Figure 4.4(a-b) that by increasing the temperature from 0 to 50 or 100 both the buckling load axial and load displacement have experienced considerable increase. So that, crystallly clear the impact of temperature on nonlinear behavior of FGM porous shallow arch reinforced Bamboo fiber is inevitable. Moreover, in Figure 4.4(c-d) the influence of the uniform humidity variation on the nonlinear behavior of arch is shown. Hence, it is noticeable that impact of moisture rise on nonlinear response of nominated arch is substantially significant.

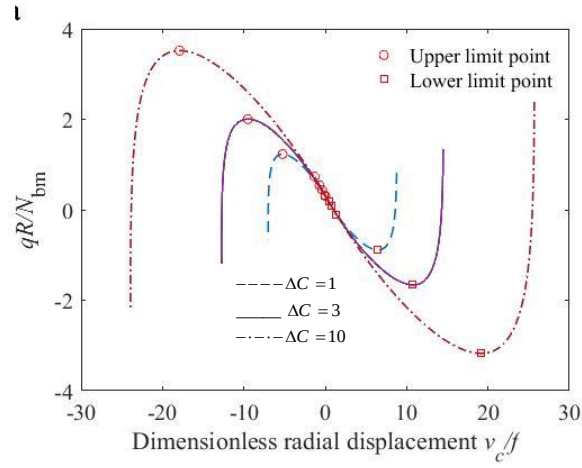
What is more, noteworthy that there is significant different between the effect of temperature and moisture on nonlinear equilibrium path of FGM-NFC porous shallow arch. Therefore, it is inevitable that effect of temperature pales compare to moisture effect. Comparing the unique upper and lower limit point on curves ,from Figure 4.4 (a) and (c), were represented lowest and upper buckling of curve, it is found that dimensionless lowest and upper limit point under radial thermal load for $\Delta T = 0, 50, 100$ are approximately 0.8, 0.11, and 0.13, respectively, while under moisture effect, $\Delta C = 1, 3, 10$, are almost 1.5, 2, and slightly less than 4, respectively, where interestingly, difference is quite significant. To be more precise, Figure 4.5 shows the effect of both moisture and temperature field, simultaneously, in order to illustrate their significant difference. Consequently, inevitably the moisture impact takes more prominent part in comparison with the temperature effect on increasing the buckling load.



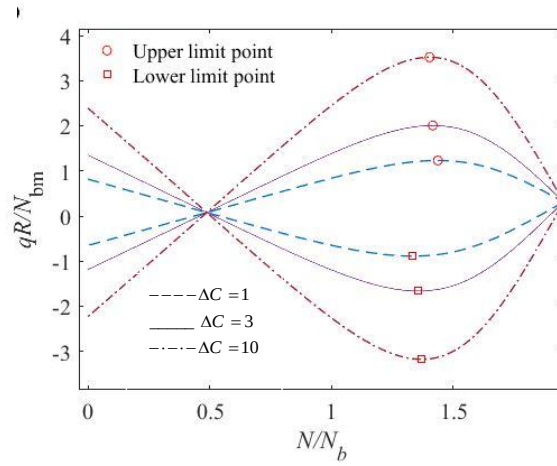
(a): Effect of ΔT (Load displacement arch)



(b): Effect of ΔT (Load-axial force arch)



(c): Effect of ΔC (Load displacement arch)



(b): Effect of ΔT (Load-axial force arch)

Figure 4.4: The temperature and moisture impact on the nonlinear performance:(
 $s / h = 30$, $\lambda = 5$, $Vf_f = 0.6\%$, and sym₁-NFC distribution)

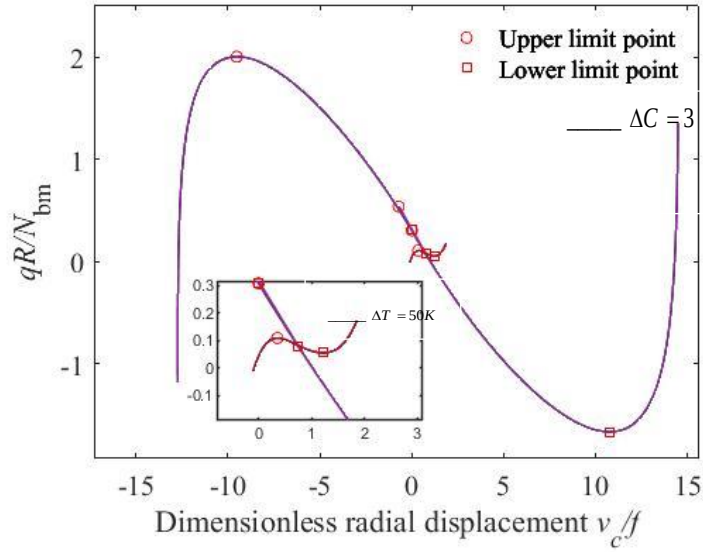
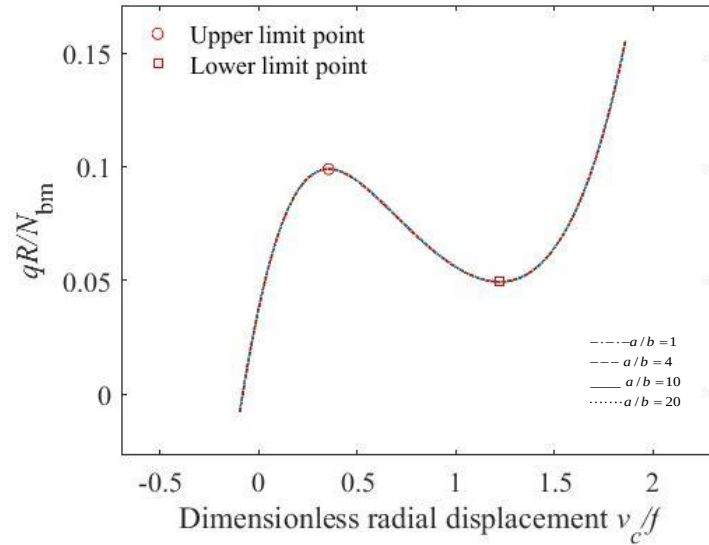


Figure 4.5: Comparison between the temperature and moisture effect on the nonlinear performance of arch: ($s/h = 30$, $\lambda = 5$, $V_f = 0.6\%$, and sym₁-NFC distribution)

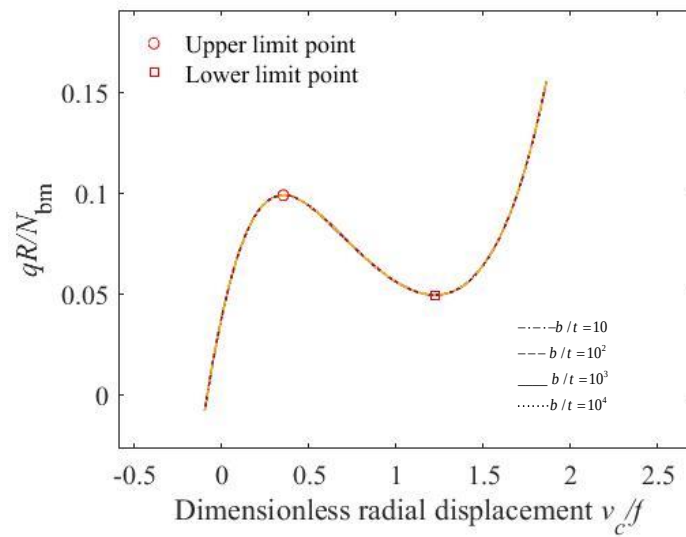
Figure 4.6(a-d) demonstrates the effect of Bamboo geometry on dimensionless external load qR/N_E based on dimensionless radial displacement V_C/f of arch. It is apparent in Figure 4.6(a-c) depict the route of nonlinear equilibrium of FGP shallow arch reinforced Bamboo with width to thickness ratio of Bamboo $b/t = 10^3$ and various range of aspect ratio $a/b = 1, 4, 10$ and 20 , while Fig 8(b-d) show the nonlinear equilibrium path and thickness ratio is various and is equal to $b/t = 10, 10^2, 10^3, 10^4$ and aspect ratio of Bamboo is $a/b = 4$.

What is more, noteworthy that in Fig 8(a-b) temperature effect has been included, while Figure 4.6(c-d) deal with effect of moisture field. It is apparent from the information of the figure that, even though it is inevitable fact that buckling load including moisture effect takes a lead in comparison with temperature effect,

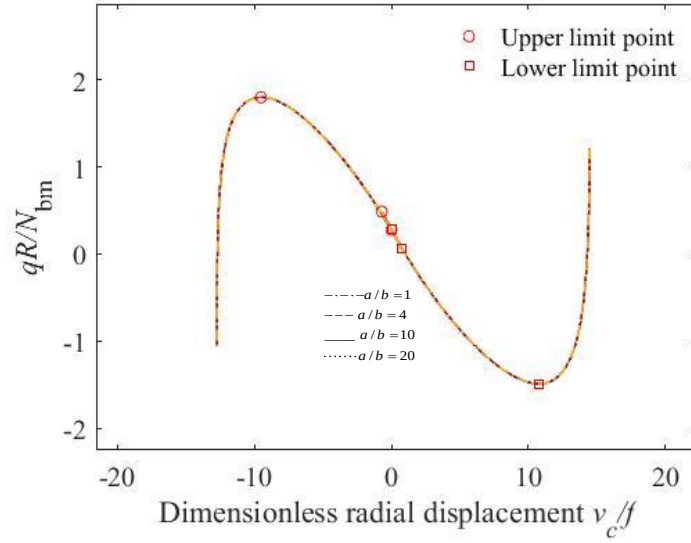
interestingly, buckling load does not have experienced significant variation by changing both aspect ratio and width to thickness ratio. As a matter of fact, as can be seen, Bamboo geometry failed to have notable influence on buckling response of the arch.



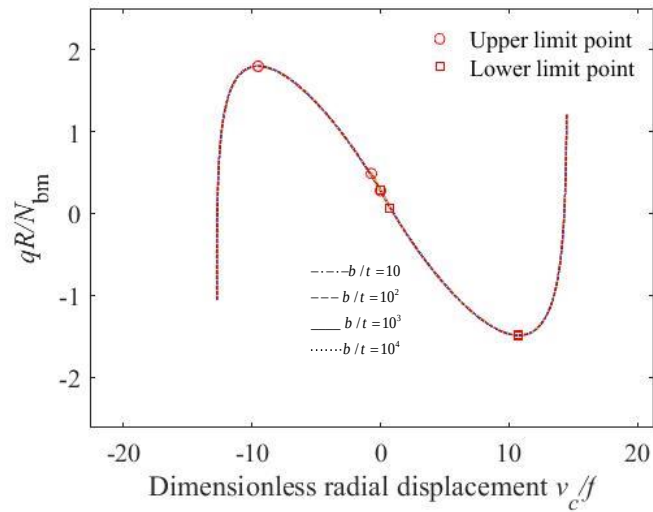
(a): $\Delta T = 50, \Delta C = 0$ and $b/t = 10^3$



(b): $\Delta T = 50, \Delta C = 0$ and $a/b = 4$



(c): $\Delta T = 0, \Delta C = 3$, and $b/t = 10^3$



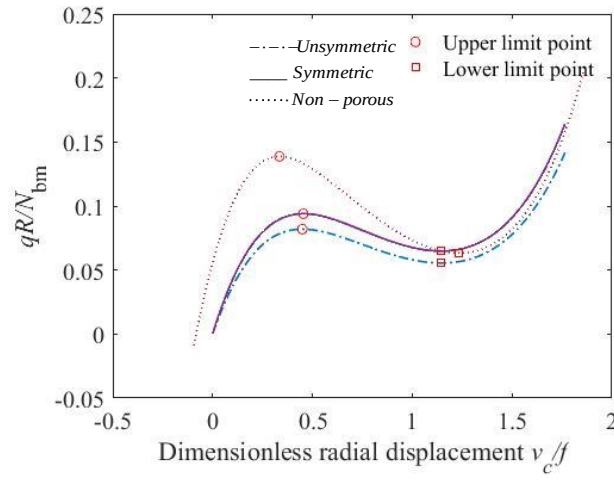
(d): $\Delta T = 0, \Delta C = 3$, and $a/b = 4$

Figure 4.6: Influence of geometry of bamboo on the nonlinear buckling behavior of arch: ($s/h = 30$, $\lambda = 5$, $Vf_f = 0.6\%$, and sym₁-NFC distribution)

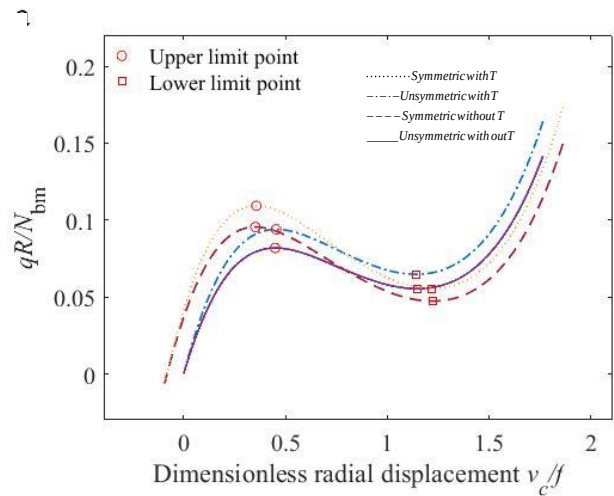
4.3 Effect Of Porosity

Figure 4.7(a-c) display the effect of various porosity distribution of nonlinear equilibrium path of FGM-Bamboo porous shallow arches. It can be found that from Figure 4.7(a) that, even though symmetric porous distribution is higher than unsymmetric porous distribution under only mechanical load, $\Delta T = 0$ and $\Delta C = 0$, still

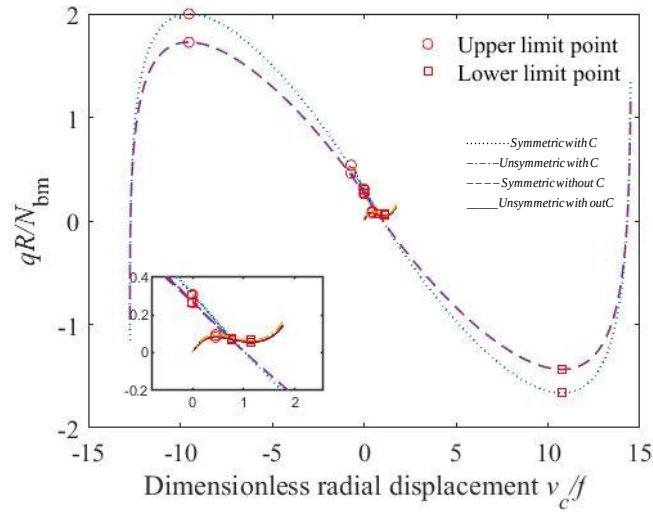
it's worth mentioning that upper limit point of buckling load without any porous distribution is slightly higher than with porosity. By the same taken according to Figure 4.7(b) upper and lower limit point of nonlinear equilibrium path delt with temperature change $\Delta T = 50$ are higher than when $\Delta T = 0$, and also, for both situation symmetric porosity situation is higher than unsymmetric porous distribution significantly. Last but not least, as its noticeable buckling load when $\Delta C = 3$ is significantly higher than when $\Delta C = 0$. Furthermore, crystally clear, moisture has incredibly prominent impact on buckling of FGM-Bamboo porous shallow arches in comparison with temperature.



(a): $\Delta T = 0, \Delta C = 0$



(b): $\Delta T = 50, \Delta C = 0$



(c): $\Delta T = 0, \Delta C = 3$

Figure 4.7: Influence of different porous distribution pattern on buckling behavior of arch: ($s/h = 30$, $\lambda = 5$, $V_f^f = 0.6\%$, and sym₁-NFC distribution)

Table 4.4(a-b) tabulated the dimensionless limit point and bifurcation buckling load of functionally graded porous shallow arch reinforced Bamboo fiber for different volume fraction of bamboo, various moisture and temperature field, different pattern distribution, and different porosity pattern distribution. As can be seen, Sym₂ -NFC distribution allocated the most value of buckling load to itself. Furthermore, as can be seen from both tables temperature failed to create a significant change in the value of the buckling loadings for all distribution, in some point for two first circumstance (when $\Delta T = 0, \Delta C = 0$ and $\Delta T = 100, \Delta C = 0$) there is no substantial difference. While, moisture has produced significant change between the value of buckling load, and also, value of limit point and bifurcation, that its moisture superiority. It is also noteworthy that comparing Table 4a and Table 4b, by increasing the volume fraction of bamboo from 0.1% to 0.6% value of buckling load has seen considerable increase. Above all, its noticeable that again moisture effect takes lead compare to temperature effect noticeably. Last but not least, comparing porosity distribution symmetric porous distribution pattern created the higher value comparison

with unsymmetric porous distribution pattern.

Table 4.4 : Dimensionless buckling load of functionally graded porous shallow curve reinforced Bamboo nano fiber $Vf_f = 0.1\%$

	Limitpoint		Bifurcation		Limitpoint		Bifurcation		Limitpoint		Bifurcation	
	Symet ric	Unsyme tric	Symet ric	Unsyme tric	Symet ric	Unsyme tric	Symet ric	Unsyme tric	Symet ric	Unsyme tric	Symet ric	Unsyme tric
Uni	0.021 9	0.0194	0.019 9 + 0.005 9i	0.0173 + 0.0044i	0.031 3	0.0279	0.030 4	0.0267	0.422 7	0.3671	0.291 2	0.2529
Sym 1	0.014 7	0.0133	0.014 7	0.0133	0.022 6	0.0206	0.018 7	0.0167	0.236 2	0.2088	0.162 7	0.1438
Sym 2	0.026 5	0.0231	0.026 7 + 0.012 9i	0.0230 + 0.0107i	0.036 2	0.0317	0.036 1	0.0317	0.564 8	0.4876	0.389 1	0.3359
Unsy m	0.017 4	0.0156	0.017 3	0.0155	0.026 4	0.0236	0.022 6	0.0201	0.288 9	0.2569	0.199 0	0.1769

$$Vf_f = 0.6\%$$

Table 4.5 Dimensionless buckling load of functionally graded porous shallow curve reinforced Bamboo nano fiber

	$\Delta T = 0, \Delta C = 0$				$\Delta T = 100, \Delta C = 0$				$\Delta T = 0, \Delta C = 3$			
	Limitpoint		Bifurcation		Limitpoint		Bifurcation		Limitpoint		Bifurcation	
	Symet ric	Unsyme tric	Symet ric	Unsyme tric	Symet ric	Unsyme tric	Symet ric	Unsyme tric	Symet ric	Unsyme tric	Symet ric	Unsyme tric
Uni	0.077 0	0.0680	0.070 0 + 0.020 6i	0.0608 + 0.0155i	0.109 9	0.0978	0.106 6	0.0938	1.481 9	1.2869	1.020 8	0.8865
Sym 1	0.051 5	0.0465	0.051 5	0.0463	0.079 1	0.0721	0.065 3	0.0581	0.820 5	0.7256	0.565 1	0.4997
Sym 2	0.094 0	0.0819	0.094 9 + 0.046 3i	0.0819 + 0.0386i	0.128 2	0.1123	0.127 8	0.1122	2.004 5	1.7303	1.380 9	1.1921
Unsy m	0.061 3	0.0548	0.061 0	0.0545	0.092 9	0.0832	0.079 3	0.0707	1.010 1	0.8986	0.695 7	0.6189

Chapter 5

CONCLUSION

In the performed investigation, the in-plane nonlinear buckling response and durability of FGM porous shallow arch reinforced nano natural composite shallow curve under uniform radial hydro-Thermo- mechanical load is studied. The combination of a virtual work theory and developed model of Halpin-Tsai formulation generated analytical solution in order to achieve the nonlinear equilibrium buckling behavior, bifurcation and limit point buckling loadings of shallow arch. A comprehensive investigation is carried on to give prominence to the influence of Bamboo fiber pattern distribution, porosity pattern distribution, temperature, moisture, and geometry on buckling behavior, bifurcation buckling load, and nonlinear equilibrium path have been obtained precisely. It has been found rising up temperature is able to increase the value of the arch's buckling loading of the arch. It is also found that increasing moisture field brought about substantial increase of the buckling load. To be more precise, increasing of buckling load stem temperature effect significantly pales in comparison with moisture effect, so that, upper limit point rooted from moisture for $\Delta C = 1, 3, 10$ was between 1.5 and 4 when stem form temperature change, $\Delta T = 0, 50, 100$, was between 0.1 and 0.15. Furthermore, its seen that, different pattern distribution of Bamboo are able to spark off various result for buckling behavior of curve when Sym₂ -NFC, more fiber close the surface of layers, distribution takes a lead compared to other pattern. It is also worth mentioning that, unsymmetric porous distribution pattern pales in comparison with symmetric porous distribution dealing with buckling load behavior.

Interestingly, Bamboo geometry failed to have significant effect on nonlinear equilibrium path and buckling load, while increasing volume fraction of bamboo increased the buckling load of FGM-composite arch. What is more, influence of temperature and moisture fields on bifurcation and lowest dimensionless special geometry of arch found that by increasing both moisture and temperature fields λ_b and λ_L , experienced significant decrease, for moisture after certain amount stayed unchanged though. The theoretical solution derived in this investigating, left comprehensive information regards to influence of various pattern on the buckling behavior and path of the nonlinear equilibrium of functionally graded porous shallow arch reinforced Bamboo nanofiber, in order to prevent any dire consequence or irreparable damage, and creating safer and more durable configuration.

The investigation of the present study required to properly select the parameters to generate the successful result. It is also worth mentioning that, the dimension of shallow arch fiber, and slenderness, also, value of the temperature and moisture loads should be considered carefully. The present study utilized temperature field equal to 0, 20, 50, and 100 and moisture field 0, 3, and 10 based on maximum temperature and moisture resistance of the Epoxy and Bamboo to create reliable result.

Based on the previous studied and ISO3219 and ISO 22157 standards for epoxy and Bamboo, respectively, study on this work when is surrounded with more temperate and moisture is limited. Furthermore, considering the result quite sufficed to show that decreasing the slenderness parameter less than 3.1135 is able to bring about the failure and fracture so slenderness should be considered more than this specially under the effect of temperature field.

Future work

Moreover, it is worth mentioning that in future not only effect of different natural fiber, in order to find the most appropriate material will be studied, also, the dynamic and vibration behavior of FGM shallow arches reinforced natural fiber will be investigated. What is more, interestingly, effect of piezoelectric layer in order to harvesting the energy one of the rewarding job which is going to bear in mind to study for future investigation.

REFERENCES

- [1] Mulenga, T. K., Ude, A. U., & Vivekanandhan, C. (2021). Techniques for modelling and optimizing the mechanical properties of natural fiber composites: A Review. *Fibers 2021*, Vol. 9, Page 6, 9(1), 6.
- [2] Sharan Gupta, U., Dharkar, A., Dhamarikar, M., Choudhary, A., Wasnik, D., Chouhan, P., & Namdeo, R. (2021). Study on the effects of fiber orientation on the mechanical properties of natural fiber reinforced epoxy composite by finite element method. *Materials Today: Proceedings*, 45, 7885–7893.
- [3] Veerasimman, A., Shanmugam, V., Rajendran, S., Johnson, D. J., Subbiah, A., Koilpichai, J., & Marimuthu, U. (2021). Thermal properties of natural fiber sisal based hybrid composites- a brief review. <https://doi.org/10.1080/15440478.2020.1870619>.
- [4] Khan, T., Sultan, M. T. B. H., & Ariffin, A. H. (2018). The challenges of natural fiber in manufacturing, material selection, and technology application: A review: <https://doi.org/10.1177/0731684418756762>, 37(11), 770–779.
- [5] Ku, H., Wang, H., Pattarachaiyakoo, N., & Trada, M. (2011). A review on the tensile properties of natural fiber reinforced polymer composites. *Composites Part B: Engineering*, 42(4), 856–873.
- [6] Faruk, O., Bledzki, A. K., Fink, H. P., & Sain, M. (2014). Progress report on natural fiber reinforced composites. *Macromolecular Materials and*

Engineering, 299(1), 9–26.

- [7] Rohan, T., Tushar, B., & T, M. G. (2018). Review of natural fiber composites. *IOP Conference Series: Materials Science and Engineering*, 314(1), 012020.
- [8] Pickering, K. L., Efendy, M. G. A., & Le, T. M. (2016). A review of recent developments in natural fibre composites and their mechanical performance. *Composites Part A: Applied Science and Manufacturing*, 83, 98–112.
- [9] Kozłowski, R., fibers, M. W.-P.-N., and, plastics, & 2004, undefined. (2004). Uses of natural fiber reinforced plastics. *Springer*, 249–274.
- [10] Moghimi Zand, M., & Ahmadian, M. T. (2010). Dynamic pull-in instability of electrostatically actuated beams incorporating Casimir and van der Waals forces. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 224(9), 2037–2047.
- [11] Javaheri, R., & Eslami, M. R. (2002). Thermal buckling of functionally graded plates based on higher order theory. *Journal of Thermal Stresses*, 25(7), 603–625.
- [12] Eltaher, M. A., Emam, S. A., & Mahmoud, F. F. (2012). Free vibration analysis of functionally graded size-dependent nanobeams. *Applied Mathematics and Computation*, 218(14), 7406–7420.
- [13] Tang, Y., & Ding, Q. (2019). Nonlinear vibration analysis of a bi-directional

functionally graded beam under hygro-thermal loads. *Composite Structures*, 225.

- [14] Zhao, S., Zhao, Z., Yang, Z., Ke, L. L., Kitipornchai, S., & Yang, J. (2020). Functionally graded graphene reinforced composite structures: A review. *Engineering Structures*, 210, 110339.
- [15] Mittal, G., Dhand, V., Rhee, K. Y., Park, S. J., & Lee, W. R. (2015). A review on carbon nanotubes and graphene as fillers in reinforced polymer nanocomposites. *Journal of Industrial and Engineering Chemistry*, 21, 11–25.
- [16] Lefebvre, L. P., Banhart, J., & Dunand, D. C. (2008). Porous metals and metallic foams: current status and recent developments. *Advanced Engineering Materials*, 10(9), 775–787.
- [17] Pollien, A., Conde, Y., Pambaguian, L., & Mortensen, A. (2005). Graded open-cell aluminium foam core sandwich beams. *Materials Science and Engineering: A*, 404(1–2), 9–18.
- [18] Anirudh, B., Ganapathi, M., Anant, C., & Polit, O. (2019). A comprehensive analysis of porous graphene-reinforced curved beams by finite element approach using higher-order structural theory: Bending, vibration and buckling. *Composite Structures*, 222, 110899.
- [19] Koiter, W. T. (1976). Current Trends in the Theory of Buckling. *Buckling of Structures*, 1–16.

- [20] Thompson, J. M. T. (1969). A general theory for the equilibrium and stability of discrete conservative systems. *Zeitschrift für angewandte Mathematik und Physik ZAMP* 1969 20:6, 20(6), 797–846.
- [21] A general theory of equilibrium paths through critical points. II. (1968). *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 306(1485), 225–238.
- [22] Budiansky, B. (1974). Theory of buckling and post-buckling behavior of elastic structures. *Advances in Applied Mechanics*, 14(C), 1–65.
- [23] Pi, Y. L., Bradford, M. A., & Tin-Loi, F. (2007). Nonlinear analysis and buckling of elastically supported circular shallow arches. *International Journal of Solids and Structures*, 44(7–8), 2401–2425.
- [24] Liu, A. R., Huang, Y. H., Fu, J. Y., Yu, Q. C., & Rao, R. (2015). Experimental research on stable ultimate bearing capacity of leaning-type arch rib systems. *Journal of Constructional Steel Research*, 114, 281–292.
- [25] Bradford, M. A., Uy, B., & Pi, Y.-L. (2002). In-Plane elastic stability of arches under a central concentrated load. *Journal of Engineering Mechanics*, 128(7), 710–719.
- [26] Liu, A., Yang, Z., Bradford, M. A., & Pi, Y.-L. (2018). Nonlinear dynamic buckling of fixed shallow arches under an arbitrary step radial point load. *Journal of Engineering Mechanics*, 144(4), 04018012.

- [27] Huang, Y. F., Chiueh, P. Te, Kuan, W. H., & Lo, S. L. (2018). Product distribution and heating performance of lignocellulosic biomass pyrolysis using microwave heating. *Energy Procedia*, 152, 910–915.
- [28] Asgari, H., Bateni, M., Kiani, Y., & Eslami, M. R. (2014). Non-linear thermo-elastic and buckling analysis of FGM shallow arches. *Composite Structures*, 109(1), 75–85.
- [29] Jha, D. K., Kant, T., & Singh, R. K. (2013, February 1). A critical review of recent research on functionally graded plates. *Composite Structures*. Elsevier.
- [30] Li, Z., & Zheng, J. (2019). Analytical consideration and numerical verification of the confined functionally graded porous ring with graphene platelet reinforcement. *International Journal of Mechanical Sciences*, 161–162, 105079.
- [31] Huang, Y., Yang, Z., Liu, A., & Fu, J. (2018). Nonlinear buckling analysis of functionally graded graphene reinforced composite shallow arches with elastic rotational constraints under uniform radial load. *Materials* 2018, Vol. 11, Page 910, 11(6), 910.
- [32] Wang, Y., Feng, C., Santiuste, C., Zhao, Z., & Yang, J. (2019). Buckling and postbuckling of dielectric composite beam reinforced with Graphene Platelets (GPLs). *Aerospace Science and Technology*, 91, 208–218.
- [33] Wang, Y. Q., & Zhang, Z. Y. (2019). Bending and buckling of three-dimensional graphene foam plates. *Results in Physics*, 13, 102136.

- [34] Liu, Z., Yang, C., Gao, W., Wu, D., & Li, G. (2019). Nonlinear behaviour and stability of functionally graded porous arches with graphene platelets reinforcements. *International Journal of Engineering Science*, 137, 37–56.
- [35] Fukui, Y., Takashima, K., & Ponton, C. B. (2004). Measurement of Young's modulus and internal friction of an in situ Al-Al₃Ni functionally gradient material. *Journal of Materials Science* 1994 29:9, 29(9), 2281–2288.
- [36] Abbas, M. R., B., U. M., Noor, A. M., Ahmad, N., & Rajoo, S. (2016). Microstructural evaluation of a slurry based Ni/YSZ thermal barrier coating for automotive turbocharger turbine application. *Materials & Design*, 109, 47–56.
- [37] Dhineshkumar, S. R., Duraiselvam, M., Natarajan, S., Panwar, S. S., Jena, T., & Khan, M. A. (2016). Enhancement of strain tolerance of functionally graded LaTi₂Al₉O₁₉ thermal barrier coating through ultra-short pulse based laser texturing. *Surface and Coatings Technology*, 304, 263–271.
- [38] Naga, S. M., Awaad, M., El-Maghraby, H. F., Hassan, A. M., Elhoriny, M., Killinger, A., & Gadow, R. (2016). Effect of La₂Zr₂O₇ coat on the hot corrosion of multi-layer thermal barrier coatings. *Materials & Design*, 102, 1–7.
- [39] Gupta, A., & Talha, M. (2015). Recent development in modeling and analysis of functionally graded materials and structures. *Progress in Aerospace Sciences*, 79, 1–14.
- [40] May-Pat, A., Valadez-González, A., & Herrera-Franco, P. J. (2013). Effect of

fiber surface treatments on the essential work of fracture of HDPE-continuous henequen fiber-reinforced composites. *Polymer Testing*, 32(6), 1114–1122.

- [41] Joshi, S. V., Drzal, L. T., Mohanty, A. K., & Arora, S. (2004). Are natural fiber composites environmentally superior to glass fiber reinforced composites? *Composites Part A: Applied Science and Manufacturing*, 35(3), 371–376.
- [42] Cheung, H. yan, Ho, M. po, Lau, K. tak, Cardona, F., & Hui, D. (2009). Natural fibre-reinforced composites for bioengineering and environmental engineering applications. *Composites Part B: Engineering*, 40(7), 655–663.
- [43] Pandey, J. K., Ahn, S. H., Lee, C. S., Mohanty, A. K., & Misra, M. (2010). Recent advances in the application of natural fiber based composites. *Macromolecular Materials and Engineering*, 295(11), 975–989.
- [44] Wang, K. F., & Wang, B. L. (2018). A mechanical degradation model for bidirectional natural fiber reinforced composites under hydrothermal ageing and applying in buckling and vibration analysis. *Composite Structures*, 206, 594–600.
- [45] Ticoalu, A., Aravinthan, T., region, F. C.-P. of the southern, & 2010, undefined. (2010). A review of current development in natural fiber composites for structural and infrastructure applications. *core.ac.uk*, 113–117. Retrieved from <https://core.ac.uk/download/pdf/11041291.pdf>
- [46] Faruk, O., Bledzki, A. K., Fink, H. P., & Sain, M. (2012). Biocomposites

reinforced with natural fibers: 2000–2010. *Progress in Polymer Science*, 37(11), 1552–1596.

[47] Dittenber, D. B., & Gangarao, H. V. S. (2012). Critical review of recent publications on use of natural composites in infrastructure. *Composites Part A: Applied Science and Manufacturing*, 43(8), 1419–1429.

[48] Baillie, C., & Jayasinghe, R. (2004). *Green composites: polymer composites and the environment*.

[49] Thomason, J. L., & Rudeiros-Fernández, J. L. (2018). A review of the impact performance of natural fiber thermoplastic composites. *Frontiers in Materials*, 5, 60.

[50] John, B., Nair, C. P. R., Mathew, D., & Ninan, K. N. (2008). Foam sandwich composites with cyanate ester based syntactic foam as core and carbon-cyanate ester as skin: Processing and properties. *Journal of Applied Polymer Science*, 110(3), 1366–1374.

[51] Aiello, M. A., & Ombres, L. (2016). Buckling load design of sandwich panels made with hybrid laminated faces and transversely flexible core: <http://dx.doi.org/10.1177/1099636207070854>, 9(5), 467–485.

[52] Reinaldo Goncalves, B., Karttunen, A., Romanoff, J., & Reddy, J. N. (2017). Buckling and free vibration of shear-flexible sandwich beams using a couple-stress-based finite element. *Composite Structures*, 165, 233–241.

- [53] Fleck, N. A., & Sridhar, I. (2002). End compression of sandwich columns. *Composites Part A: Applied Science and Manufacturing*, 33(3), 353–359.
- [54] Le Grogne, P., & Sad Saoud, K. (2015). Elastoplastic buckling and post-buckling analysis of sandwich columns. *International Journal of Non-Linear Mechanics*, 72, 67–79.
- [55] Waddar, S., Pitchaimani, J., Doddamani, M., & Barbero, E. (2019). Buckling and vibration behaviour of syntactic foam core sandwich beam with natural fiber composite facings under axial compressive loads. *Composites Part B: Engineering*, 175, 107133.
- [56] Rajesh, M., & Pitchaimani, J. (2017). Experimental investigation on buckling and free vibration behavior of woven natural fiber fabric composite under axial compression. *Composite Structures*, 163, 302–311.
- [57] Mohammed, L., Ansari, M. N. M., Pua, G., Jawaid, M., & Islam, M. S. (2015). A Review on Natural Fiber Reinforced Polymer Composite and Its Applications. *International Journal of Polymer Science*, 2015.
- [58] Ramamoorthy, S. K., Skrifvars, M., & Persson, A. (2015). A Review of Natural Fibers Used in Biocomposites: Plant, Animal and Regenerated Cellulose Fibers. <http://dx.doi.org/10.1080/15583724.2014.971124>, 55(1), 107–162.
- [59] Khan, M. Z. R., Srivastava, S. K., & Gupta, M. K. (2018). Tensile and flexural properties of natural fiber reinforced polymer composites: A review:

<https://doi.org/10.1177/0731684418799528>, 37(24), 1435–1455.

- [60] Ku, H., Wang, H., & N. P.-C. P. B., & 2011, undefined. (n.d.). A review on the tensile properties of natural fiber reinforced polymer composites. *Elsevier*.
- [61] Arrakhiz, F. Z., El Achaby, M., Malha, M., Bensalah, M. O., Fassi-Fehri, O., Bouhfid, R., & Qaiss, A. (2013). Mechanical and thermal properties of natural fibers reinforced polymer composites: Doum/low density polyethylene. *Materials & Design*, 43, 200–205.
- [62] Di Bella, G., Fiore, V., Galtieri, G., Borsellino, C., & Valenza, A. (2014). Effects of natural fibres reinforcement in lime plasters (kenaf and sisal vs. Polypropylene). *Construction and Building Materials*, 58, 159–165.
- [63] Shalwan, A., & Yousif, B. F. (2013). In State of Art: Mechanical and tribological behaviour of polymeric composites based on natural fibres. *Materials & Design*, 48, 14–24.
- [64] Norul Izani, M. A., Paridah, M. T., Anwar, U. M. K., Mohd Nor, M. Y., & H'Ng, P. S. (2013). Effects of fiber treatment on morphology, tensile and thermogravimetric analysis of oil palm empty fruit bunches fibers. *Composites Part B: Engineering*, 45(1), 1251–1257.
- [65] Tawakkal, I. S. M. A., Cran, M. J., & Bigger, S. W. (2014). Effect of kenaf fibre loading and thymol concentration on the mechanical and thermal properties of PLA/kenaf/thymol composites. *Industrial Crops and Products*, 61, 74–83.

- [66] Shinoj, S., Visvanathan, R., Panigrahi, S., & Kochubabu, M. (2011). Oil palm fiber (OPF) and its composites: A review. *Industrial Crops and Products*, 33(1), 7–22.
- [67] Novoselov, K. S., Geim, A. K., Morozov, S. V., Jiang, D., Zhang, Y., Dubonos, S. V., ... Firsov, A. A. (2004). Electric field in atomically thin carbon films. *Science*, 306(5696), 666–669.
- [68] Lee, C., Wei, X., Kysar, J. W., & Hone, J. (2008). Measurement of the elastic properties and intrinsic strength of monolayer graphene. *Science*, 321(5887), 385–388.
- [69] Balandin, A. A., Ghosh, S., Bao, W., Calizo, I., Teweldebrhan, D., Miao, F., & Lau, C. N. (2008). Superior thermal conductivity of single-layer graphene. *Nano Letters*, 8(3), 902–907.
- [70] Du, X., Skachko, I., Barker, A., & Andrei, E. Y. (2008). Approaching ballistic transport in suspended graphene. *Nature Nanotechnology* 2008 3:8, 3(8), 491–495.
- [71] Yang, B., Kitipornchai, S., Yang, Y. F., & Yang, J. (2017). 3D thermo-mechanical bending solution of functionally graded graphene reinforced circular and annular plates. *Applied Mathematical Modelling*, 49, 69–86.
- [72] Yang, J., Wu, H., & Kitipornchai, S. (2017). Buckling and postbuckling of functionally graded multilayer graphene platelet-reinforced composite beams.

Composite Structures, 161, 111–118.

- [73] Rafiee, M. A., Rafiee, J., Wang, Z., Song, H., Yu, Z. Z., & Koratkar, N. (2009). Enhanced mechanical properties of nanocomposites at low graphene content. *ACS Nano*, 3(12), 3884–3890.
- [74] Barbero, E. J. (2013). Finite element analysis of composite materials using abaqusTM. *Finite Element Analysis of Composite Materials using Abaqus*, 1–407.
- [75] Naebe, M., & Shirvanimoghaddam, K. (2016). Functionally graded materials: A review of fabrication and properties. *Applied Materials Today*, 5, 223–245.
- [76] Kawasaki, A., & Watanabe, R. (1997). Concept and P/M fabrication of functionally gradient materials. *Ceramics International*, 23(1), 73–83.
- [77] Yang, Z., Yang, J., Liu, A., & Fu, J. (2018). Nonlinear in-plane instability of functionally graded multilayer graphene reinforced composite shallow arches. *Composite Structures*, 204, 301–312.
- [78] Reddy, J. N. (2000). Analysis of functionally graded plates. *International journal for numerical methods in engineering Int. J. Numer. Meth. Engng*, 47, 663–684.
- [79] Reddy, J. N., & Chin, C. D. (2007). Thermomechanical analysis of functionally graded cylinders and plates. <http://dx.doi.org/10.1080/01495739808956165>, 21(6), 593–626.

- [80] Yang, J., & Shen, H. S. (2001). Dynamic response of initially stressed functionally graded rectangular thin plates. *Composite Structures*, 54(4), 497–508.
- [81] Yang, J., & Shen, H. S. (2002). Vibration characteristics and transient response of shear-deformable functionally graded plates in thermal environments. *Journal of Sound and Vibration*, 255(3), 579–602.
- [82] Wang, Q., Wu, D., Tin-Loi, F., & Gao, W. (2019). Machine learning aided stochastic structural free vibration analysis for functionally graded bar-type structures. *Thin-Walled Structures*, 144, 106315.
- [83] Wu, D., Wang, Q., Liu, A., Yu, Y., Zhang, Z., & Gao, W. (2019). Robust free vibration analysis of functionally graded structures with interval uncertainties. *Composites Part B: Engineering*, 159, 132–145.
- [84] Li, Q., Wang, Q., Wu, D., Chen, X., Yu, Y., & Gao, W. (2019). Geometrically nonlinear dynamic analysis of organic solar cell resting on Winkler-Pasternak elastic foundation under thermal environment. *Composites Part B: Engineering*, 163, 121–129.
- [85] Udupa, G., Rao, S. S., & Gangadharan, K. V. (2014). Functionally graded composite materials: An Overview. *Procedia Materials Science*, 5, 1291–1299.
- [86] Wu, H. L., Kitipornchai, S., & Yang, J. (2016). Thermal buckling and postbuckling analysis of functionally graded carbon nanotube-reinforced

composite beams. *Applied Mechanics and Materials*, 846, 182–187.

- [87] Wu, H., Kitipornchai, S., & Yang, J. (2017). Imperfection sensitivity of thermal post-buckling behaviour of functionally graded carbon nanotube-reinforced composite beams. *Applied Mathematical Modelling*, 42, 735–752.
- [88] Wu, H., Yang, J., & Kitipornchai, S. (2017). Dynamic instability of functionally graded multilayer graphene nanocomposite beams in thermal environment. *Composite Structures*, 162, 244–254.
- [89] Wu, H., Kitipornchai, S., & Yang, J. (2017). Thermal buckling and postbuckling of functionally graded graphene nanocomposite plates. *Materials & Design*, 132, 430–441.
- [90] Bateni, M., & Eslami, M. R. (2015). Non-linear in-plane stability analysis of FG circular shallow arches under uniform radial pressure. *Thin-Walled Structures*, 94, 302–313.
- [91] Bateni, M., & Eslami, M. R. (2014). Non-linear in-plane stability analysis of FGM circular shallow arches under central concentrated force. *International Journal of Non-Linear Mechanics*, 60, 58–69.
- [92] +ANSYS 14.5 Computer software. Canonsburg : ANSYS; 2012. - Google Akademik. (n.d.).
- [93] Fraternali, F., Spadea, S., & Ascione, L. (2013). Buckling behavior of curved

composite beams with different elastic response in tension and compression. *Composite Structures*, 100, 280–289.

- [94] Li, Z. (2020). Exploration of the encased nanocomposites functionally graded porous arches: Nonlinear analysis and stability behavior. *Applied Mathematical Modelling*, 82, 1–16.
- [95] Liu, A. R., Huang, Y. H., Fu, J. Y., Yu, Q. C., & Rao, R. (2015). Experimental research on stable ultimate bearing capacity of leaning-type arch rib systems. *Journal of Constructional Steel Research*, 114, 281–292.
- [96] Liu, A., Lu, H., Fu, J., & Pi, Y.-L. (2017). Lateral-torsional buckling of circular steel arches under arbitrary radial concentrated load. *Journal of Structural Engineering*, 143(9), 04017129.
- [97] Yang, Z., Liu, A., Pi, Y. L., Fu, J., & Gao, Z. (2020). Nonlinear dynamic buckling of fixed shallow arches under impact loading: An analytical and experimental study. *Journal of Sound and Vibration*, 487, 115622.
- [98] Wicks, P. J. (1991). General Equations for Buckling of Thin, Shallow Arches of Any Shape. *Journal of Engineering Mechanics*, 117(2), 225–240.
- [99] Timoshenko, S., & Gere, J. (2009). Theory of elastic stability.
- [100] Yang, Z., Wu, D., Yang, J., Lai, S. K., Lv, J., Liu, A., & Fu, J. (2021). Dynamic buckling of rotationally restrained FG porous arches reinforced with graphene

nanoplatelets under a uniform step load. *Thin-Walled Structures*, 166, 108103.

- [101]Liu, A., Yang, Z., Lu, H., Fu, J., & Pi, Y. L. (2017). Experimental and analytical investigation on the in-plane dynamic instability of arches owing to parametric resonance: <https://doi.org/10.1177/1077546317726210>, 24(19), 4419–4432.
- [102]Liu, A., Lu, H., Fu, J., Pi, Y. L., Huang, Y., Li, J., & Ma, Y. (2017). Analytical and experimental studies on out-of-plane dynamic instability of shallow circular arch based on parametric resonance. *Nonlinear Dynamics*, 87(1), 677–694.
- [103]Wu, D., Liu, A., Huang, Y., Huang, Y., Pi, Y., & Gao, W. (2019). Time dependent uncertain free vibration analysis of composite CFST structure with spatially dependent creep effects. *Applied Mathematical Modelling*, 75, 589–606.
- [104]Pi, Y. L., & Bradford, M. A. (2008). Dynamic buckling of shallow pin-ended arches under a sudden central concentrated load. *Journal of Sound and Vibration*, 317(3–5), 898–917.
- [105]Pi, Y. L., & Bradford, M. A. (2013). Nonlinear dynamic buckling of pinned-fixed shallow arches under a sudden central concentrated load. *Nonlinear Dynamics*, 73(3), 1289–1306.
- [106]Zhang, Z., Liu, A., Yang, J., Pi, Y. lin, Huang, Y., & Fu, J. (2020). A theoretical and experimental study on in-plane buckling of orthotropic composite arches

under an arbitrary radial point load. *Composite Structures*, 237, 111933.

- [107] Eroglu, U. (2016). Large deflection analysis of planar curved beams made of Functionally Graded Materials using Variational Iterational Method. *Composite Structures*, 136, 204–216.
- [108] Xu, X., Augello, R., & Yang, H. (2019). The generation and validation of a CUF-based FEA model with laser-based experiments. <https://doi.org/10.1080/15376494.2019.1697473>, 28(16), 1648–1655.
- [109] Banhart, J. (2001). Manufacture, characterisation and application of cellular metals and metal foams. *Progress in Materials Science*, 46(6), 559–632.
- [110] Qin, J., Chen, Q., Yang, C., & Huang, Y. (2016). Research process on property and application of metal porous materials. *Journal of Alloys and Compounds*, 654, 39–44.
- [111] Zhao, S., Yang, Z., Kitipornchai, S., & Yang, J. (2020). Dynamic instability of functionally graded porous arches reinforced by graphene platelets. *Thin-Walled Structures*, 147, 106491.
- [112] Elastic buckling of a porous beam | Magnucki | Journal of Theoretical and Applied Mechanics. (n.d.).
- [113] Liu, L., Liu, A., Yang, J., & Fu, J. (2022). Lateral-torsional buckling of functionally graded porous arches with graphene platelets reinforcements under

an arbitrary radial concentrated load. *Composite Structures*, 281, 114973.

- [114] Wang, Y. Q., Zhao, H. L., Ye, C., & Zu, J. W. (2018). A porous microbeam model for bending and vibration analysis based on the sinusoidal beam theory and modified strain gradient theory. <https://doi.org/10.1142/S175882511850059X>, 10(5).
- [115] Yang, Z., Huang, Y., Liu, A., Fu, J., & Wu, D. (2019). Nonlinear in-plane buckling of fixed shallow functionally graded graphene reinforced composite arches subjected to mechanical and thermal loading. *Applied Mathematical Modelling*, 70, 315–327.
- [116] Wattanasakulpong, N., Gangadhara Prusty, B., & Kelly, D. W. (2011). Thermal buckling and elastic vibration of third-order shear deformable functionally graded beams. *International Journal of Mechanical Sciences*, 53(9), 734–743.
- [117] Wang, Y., Ren, H., Fu, T., & Shi, C. (2020). Hygrothermal mechanical behaviors of axially functionally graded microbeams using a refined first order shear deformation theory. *Acta Astronautica*, 166, 306–316.
- [118] Korolev, A., Mishnev, M., Zherebtsov, D., Vatin, N. I., & Karelina, M. (2021). Polymers under Load and Heating Deformability: Modelling and Predicting. *Polymers 2021*, Vol. 13, Page 428, 13(3), 428.
- [119] Borah, N., & Karak, N. (2022). Tannic acid based bio-based epoxy thermosets:

Evaluation of thermal, mechanical, and biodegradable behaviors. *Journal of Applied Polymer Science*, 139(11), 51792.

- [120]Md Shah, A. U., H Sultan, M. T., Cardona, F., Jawaid, M., Abu Talib, A. R., & Yidris, N. (2017). Thermal analysis of bamboo fibre and its composites. *ojs.cnr.ncsu.edu*, 12(2), 2394–2406. Retrieved from <http://ojs.cnr.ncsu.edu/index.php/BioRes/article/view/10807>
- [121]Mirzaei, M., & Kiani, Y. (2017). Isogeometric thermal buckling analysis of temperature dependent FG graphene reinforced laminated plates using NURBS formulation. *Composite Structures*, 180, 606–616.
- [122]Kiani, Y. (2018). NURBS-based isogeometric thermal postbuckling analysis of temperature dependent graphene reinforced composite laminated plates. *Thin-Walled Structures*, 125, 211–219.
- [123]Kiani, Y., & Mirzaei, M. (2018). Enhancement of non-linear thermal stability of temperature dependent laminated beams with graphene reinforcements. *Composite Structures*, 186, 114–122.
- [124]Kiani, Y. (2019). Buckling of functionally graded graphene reinforced conical shells under external pressure in thermal environment. *Composites Part B: Engineering*, 156, 128–137.
- [125]Kiani, Y., & Mirzaei, M. (2019). Thermal postbuckling of fg-gplrc laminated plates non-linear rapid heating of fgm beams on elastic foundation view project

application of shape memory alloys in advanced composite structures view project. *Steel and Composite Structures*, 32(6), 821–832.

[126] Li, Z., Chen, Y., Zheng, J., & Sun, Q. (2020). Thermal-elastic buckling of the arch-shaped structures with FGP aluminum reinforced by composite graphene platelets. *Thin-Walled Structures*, 157, 107142.

[127] Dehrouyeh-Semnani, A. M. (2018). On the thermally induced non-linear response of functionally graded beams. *International Journal of Engineering Science*, 125, 53–74.

[128] Samsam Shariat, B. A., & Eslami, M. R. (2006). Thermal buckling of imperfect functionally graded plates. *International Journal of Solids and Structures*, 43(14–15), 4082–4096.

[129] Zenkour, A. M., & Sobhy, M. (2010). Thermal buckling of various types of FGM sandwich plates. *Composite Structures*, 93(1), 93–102.

[130] Lanhe, W. (2004). Thermal buckling of a simply supported moderately thick rectangular FGM plate. *Composite Structures*, 64(2), 211–218.

[131] Tang, Y., Tang, F., Zheng, J., & Li, Z. (2021). In-plane asymmetric buckling of an FGM circular arch subjected to thermal and pressure fields. *Engineering Structures*, 239, 112268.

[132] Osoka, E., Invent, O. O.-I. J. E. S., & 2018, undefined. (2018). A modified

Halpin-Tsai model for estimating the modulus of natural fiber reinforced composites. *researchgate.net*, 63–70.

- [133]Deepak, B. P., Ganguli, R., & Gopalakrishnan, S. (2012). Dynamics of rotating composite beams: A comparative study between CNT reinforced polymer composite beams and laminated composite beams using spectral finite elements. *International Journal of Mechanical Sciences*, 64(1), 110–126.
- [134]Li, N., Long, J., Su, L., Wang, L., University, S. Z.-J. of C. S., & 2012, undefined. (2012). Experimental and theoretical study on thermal and moisture characteristics of new-type bamboo structure wall. *Springer*, 19(3), 600–608.
- [135]Cairns, D. S., & Adams, D. F. (2016). Moisture and thermal expansion properties of unidirectional composite materials and the epoxy matrix: <http://dx.doi.org/10.1177/073168448300200403>, 2(4), 239–255.