Nature Inspired Design in Fiber Orientation Trends for Reinforcement of Composites

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Abstract. In this paper, review of the literature in the practice and method of nature-inspired design has been reported. Engineering design enhancement that has been achieved by natural phenomena mimicking and adapting it to develop new products is the designers' initiative as cost-effective design methods. The use of spider web geometry practice and trends as a technique for orienting fiber to reinforce composite has been reviewed rigorously and reported in this paper. An Orb web possesses many unique features to be mimicked for engineering structures. Spider web develops a self-stressing nature, which offers its excellent inelasticity and provides webs a mechanism for competent and economical means for harmonizing the local and global induced stresses in the structure. These make a spider web a model of engineering material with exceptional properties of combining a unique strength and toughness, because the mechanical properties of the fiber-reinforced composites are intensely swayed by the fiber orientation. Spider web-oriented types of fiber orientation are not yet widely used for the engineered composite product except for some cable-stayed bridges load suspensions. Lastly, a significant research gap between engineering design cognition and natural phenomena are identified for forthcoming researchers and concluding remark on natural emulating design practice has been lightened.

Keywords: Fiber orientation · Nature-inspired design · Polymer composite · Spider-web · Biomechanics

1 Introduction

Nature-inspired developments are clustered into three groups of inspirations as (1) graphic, (2) notion and (3) computational type [1]. A graphic inspiration agrees with the shape of several creatures or their structures, and to mimic similar roles and methods. A notion of inspiration arises when a designer or an engineer uses a philosophy established in nature, and a computational level stimulated by mechanisms or organisms occurring in nature. Biomaterials are the construction materials used by nature to build all living matters. The structures of most of these biomaterials have evolved to maximize the performance of the function provided. Humanmade biomaterials or processes are made through emulating natural phenomena. The silks that form spiders' webs excellent

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examples of these natural biomaterials that contribute to early human fishing net production. Spider silk is the model for engineering materials for its exceptional properties combining a unique strength and toughness.

Apart from the notable material properties, spider webs are natural models of a particular class of pre-stressed structures that are termed as tensegrity (tensional integrity) structures [2]. Such structures are characterized by unique geometry and mechanics that are used for very efficient structures because of their geometries with optimal distribution of structural mass and play significant parameters for the present as well as the toughness of a tensegrity creation of it. A self-stressing nature, which offers its inelasticity, provides spider webs the mechanism for competent and economical means for harmonizing the induced stresses. A sympathetic for the interaction of material properties and structural geometry may lean to light on our ability to design the next generation of ultra-lightweight, large area space structures. Orb-weaving spiders construct orb webs by depositing protein-based silk materials through their spinnerets for catching prey, sensing vibration, and protecting offspring. They are primarily a collection of structural radial filaments and gluey spiral threads with circular geometry, as illustrated in Fig. 1 [3].

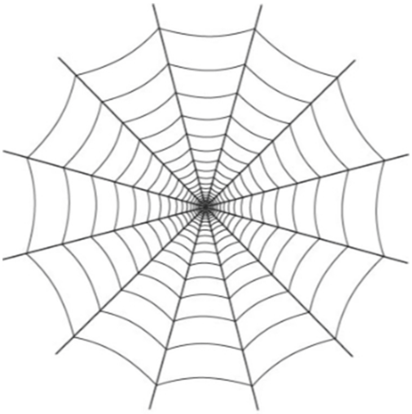

Fig. 1. Schematic diagram of a spider's web.

The objective of this article is to investigate the practice and method of nature-inspired design and identifying a significant research gap between engineering design cognition and natural phenomena. Spider web geometry for fiber orientation to reinforce the composite was a focus area of this review work. Although there are many varieties of the web making spiders, orb webs make spired is chosen among the exiting varieties. Orb web possesses many unique features mimicked for engineering structures, and many scholars suggested its adaptation techniques.

2 Methods

As a method of research, beyond physical observation and examination of the environment and locally available spider web, the researchers have reviewed the latest published articles. Those reviewed research materials used for:

1. evaluating trends of using nature-inspired design methods,
2. pointing out the most used types of fiber orientation for reinforcing the composite structure.
3. assessing the effect of fiber orientation on mechanical strength.
4. evaluating the application of nature-inspired design for product development and innovations.
5. reviewing tools used for modeling and simulation of a spider web.

To conduct the review work for this article, the following keywords were used while searching the databases: ‘fiber orientation’, ‘spider web geometry’, ‘modeling of spider web’, ‘mechanics of spider web’, ‘effect of fiber orientation on mechanical strength’, ‘nature inspired-design’, ‘application of nature-inspired design’ and standard and published articles, conference papers and handbooks from indexed publishers were used.

3 State-of-the-Art on Polymer Composite

3.1 Fiber Orientation for Polymer Composites

Figure 2 illustrates the alignment of a single fiber measured by a unit vector **p** directed by the angles (θ, ϕ). Such geometrical representation can be used to describe the motion of cylindrical fibers with a large aspect ratio $(R_p = l/d > 10)$, where l is the length, and d is the diameter of fiber. At higher fiber concentrations, fiber to fiber connections result in variation of fiber orientation whose status is determined upon the volume fraction (ϕ_f) of fibers in the composite and for the dilute state. For instance, in the case when $\phi_f \ll (d/l^2)$, the interactions between fibers are rare. For the semi-dilute states, i.e. when $(d/l^2) \ll \phi_f \ll (d/l^2)$, contacts between fibers are quite common. Nevertheless, fiber to fiber interactions are purely hydrodynamic, and the change in orientation due to mechanical contact between fibers has no significant effects on fiber interaction [4].

The appropriate fiber orientation is primarily determined by the loading condition which can be either uniaxial, biaxial, shear, or impact state of loading on the structures. Countless scholars carried out experiments to explore the impact of fiber orientation on fiber structure of random mat, unidirectional 0/90, and woven fabric. State [5] investigated that the mechanical behavior of plain knitted and twill weaved fiber and revealed that a twill woven fiber ensures excellent mechanical properties as compared to the woven mat. Woven mat fiber affords a proper equilibrium in mechanical properties, and it is the favorite form of standard fiber mat for an engineered composite product by hand methods.

Nevertheless, the impact of hybrid fiber orientation for ultimate tensile strength (UTS) of unidirectional and biaxial strength of fiber reinforcements is not studied yet [6].

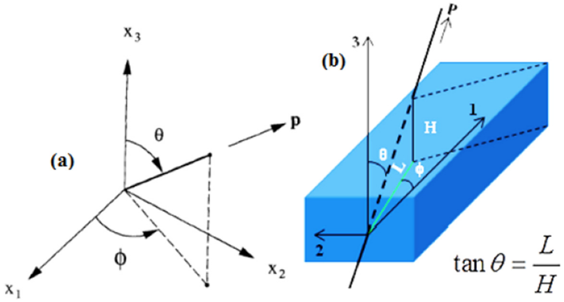

Fig. 2. (a) Geometry of fiber orientation, (b) extracting the (L, ϕ) values for each fiber on the 1–2 plane, and calculating the out-of-plane angle, θ, from its state height, H.

Hybrid fiber orientation promotes a composite with high strength for different loading conditions and headway for composite structure reliability. Fiber orientation with 0º, 90º, +45º, and or −45º is a standard method for designing fiber orientation and it is a common practice to produce composite structures. Figure 3 (adapted from [7]) shows practical fiber orientations 0/90, +45/−45 and/or orientation types that are frequently used by engineers.

The deviation of fiber orientation is defined by a curve relating the cumulative fraction of fibers to their alignment angle. A numerical study has shown that a single parameter exponential equation can best define the experimental cumulative curves of fiber alignment [8]:

$$X = 1 - e^{-\lambda\alpha} \tag{1}$$

where X is the cumulative fraction of fibers aligned between (−α) to (+α), α is the angle from alignment axis, and λ is a single experimental factor.

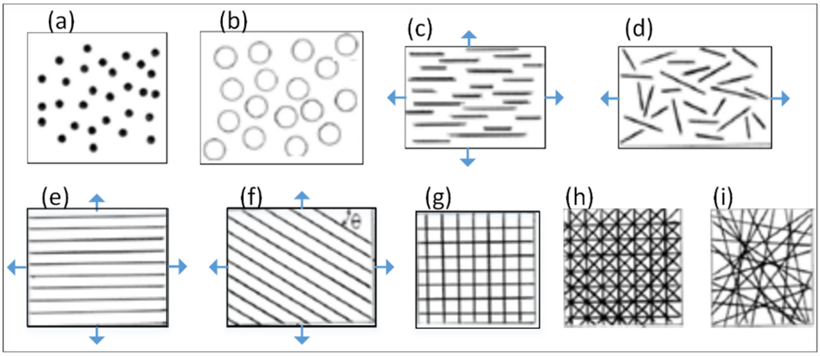

Fig. 3. Practiced fiber orientations: (a) and (b) homogeneous particle distribution in a matrix. (c) and (d) aligned (anisotropic) and random (quasi-isotropic) discontinuous fibers. (e) and (f) aligned (unidirectional) continuous fibers: θ = 0°, θ = 90°; 0° < θ < 90°. (g) bidirectional or cross-ply continuous fibers. (h) Multidirectional fibers and (i) Continuous random.

Since the raising spreading curves trail a common mathematical law, the continuous calculated curves can be plotted describing the dependence of mechanical properties on the fiber alignment. Research work by [9] revealed that composites having deficient levels of fiber orientation, tensile modulus, and ultimate strength of the reinforced sheets are predicted precisely. However, their stress-strain characteristics deviate from theoretical curves by as much as 20–30%.

3.2 Effect of Fiber Orientation on Mechanical Strength of Polymer Composite

The mechanical properties of the fiber-reinforced composites are intensely swayed by fiber orientation. In early theories, researchers used the strength of misaligned or planar random fiber for predicting the composite's strength based on the assumption that strength is an additive property [10]. These imply that the strength of random fiber orientation is equivalent to the average strength, with respect to alignment or orientation, of a set of unidirectional composites of the same composition. Pipes et al. [11] tested the strength of these concepts for glass-epoxy composites. They determined that strength is not an additive property, and the modest integration technique is insufficient for visualizing the strength of multi-directional composites. Unevenly aligned fibers, whose axes do not match with the loading direction, drive fewer to the strength of the composite than correctly aligned fibers. Since fibers are the principal stress-bearing structures in composites, the kind of fiber, state of fiber, and the used orientation affected properties the structures. The mechanical and physical performance of short fibers are hugely affected by the flaw induced during processing of fiber alignment for structural construction of composites.

A module of research conducted on woven and random mat fibers revealed that a woven fiber yields greater flexural strength than other forms. In contrast, a comparatively random mat indicates meager characters for all loading situations of woven and unidirectional fibers. Likewise, auxiliary factors like knitting and winding types, wrap and weft as well textile values can affect the mechanical properties of woven fiber reinforcement of composite structures. Computing the useful properties of a fiber-reinforced polymer composite as a uniform continuum comprises averaging the characteristics of the two phases. If the fiber scattering is anisotropic, the averaging system is subjected according to the fiber orientation and distribution. Such averages are termed orientation averages. The fiber orientation p is given in an ordinary sense by its probability distribution $\psi(\mathrm{p})$ so that the macroscopic statistical averaged stress tensor (the stress tensor used in engineering computations) is written in the form of:

$$\sum = \int T(p)\psi(p)\partial p \tag{2}$$

For most engineering uses, the exact design for fiber orientation at each point of $\psi(\mathrm{p})$ is neither necessary nor possible. This orientational information is correctly approximated with the use of the second-order and fourth-order orientation tensors [12] as:

$$\underline{\underline{a}} = \int \underline{p} * \underline{p}\, \psi\left(\underline{p}\right)\partial p; \quad \underline{\underline{\underline{\underline{a_4}}}} = \int \underline{p} * \underline{p} * \underline{p} * \underline{p}\psi \tag{3}$$

The strengthening of a 2-phase composite can be approximately expressed by [7]

$$\sigma_c = V_\alpha \sigma_\alpha + V_\beta \sigma_\beta \tag{4}$$

where V_α, V_β and σ_α, σ_β, are the equivalent volume fractions ($V_\alpha + V_\beta = 1$) and yield strengths (flow stress) of the two phases α and β respectively. Such modeling approach assumes that one phase (the dispersoid or phase dispersed in a matrix) is much harder or stronger than the other (the matrix phase) [13].

Fibers oriented in the longitudinal direction have an excellent mechanical property than those oriented in transverse direction, and fibers oriented longitudinally (i.e., perpendicular to the fracture surface) are less exposed for new fracture conditions. Rupture and withdrawal of fibers occurres mostly while the fibers are aligned in the longitudinal direction, although for crossways oriented fibers, the crack growths in the path of fiber orientation. 0°/90° oriented fibers are used as blockades to inhibit the spreading of stress all over the matrix. Such a condition causes a higher concentration of localized stress and results in equally meager and non-linear mechanical properties on the structures [14].

4 Nature Inspired Design Process and Fiber Orientation

4.1 Nature Inspired Design Process

Nature-Inspired design is a design strategy that is established on nature theories for practically acquiring design wisdom from nature and to honor it as a model of design sustainability. The design process through the imitation of natural phenomena yields robust design. Contemporary design practices emphasis on eco-efficiency as a critical method in the arena of viable for product design advancement. This method predominantly aims at enhancing engineering products and services for the required design. Nature driven design needs interpretation of how nature performs. Though several scholars have discovered different design philosophies through natural inspiration, yet a consideration for nature as a source of sustainable engineering design does not mature well, to implement it to the practical value for sustainable production of design adaptation from nature.

For novel design through the nature-inspired system, the design spiral [15] is used as sustainable means of knowledge acquiring method to abide by nature principle for practical adaptation on product development. This design spiral involves

- Distilling the design function by identifying what the design is intended to do,
- Translating the design to biological systems and identifying how nature can do the intended function,
- Discovering natural models and creating taxonomy of natural strategies,
- Emulating nature's strategies, and
- Evaluating the design against life's principles.

This design spiral method is implemented through the principles of scoping, design generation and engineering work and evaluation [15]. While scoping involves (re)defining the design problem, the design idea generation retrieves inspirations and engineering solutions from nature. Then guidelines and sustainability criteria are developed for product engineering.

Nature-inspired design spiral dictates many features for designing and developing of justifiable products. Viewed from the product development process, the design spiral is goal-driven [15], i.e. it is directed for a workable end results that are inspired by natural methods. In addition, every approach in the spiral integrates philosophies intended at the command of closed-loop physical systems. As the design procedure is focused on cultivating invention systems for the physical world, it emphasizes eco-friendly sustainability and addresses economic viability.

Bio imitation can be a practical tool to resolve the technical and common engineering design challenges at different levels. Biology has motivated designers since primitive man created spears from the teeth of animals and copied the operative sneak-and-pounce hunting method of huge hunters. However, the growth of a practical basis for decoding natural schemes into engineering design is a modern method for the enhancement of humanmade structures. The arrangements of systems, methods, and procedures in nature have extensively helped inventors, scientists, architects, and engineers for the discovery of enhanced and advanced solutions for their respected fields [1]. The airplane structures, different construction machinery, robotic arm, and many other products are engineered products through mimicking nature. Many researchers have been attracted to conduct different studies on spider web modeling and its mechanics. However, there is a very limited document about mechanical properties of spider webs and practical implementation of such geometry.

From the biosphere of natural fiber, spider silk questioned for its unique properties of high strength and notable rapture elongation. Spider nets are one of the superior types of pre-stressed systems termed as tensegrity (tensional integrity) structures [16]. Due to the optimal spreading of structural mass, the spider web owns a unique combination of geometry that resulted in highly efficient systems mimicked for engineering structures. Spider's web geometry plays the primary role in describing the existence as well as the stiffness of a tensegrity structure. Such tensegrity arrangements are categorized as space structures. Today's human netting tools that are used for fishing are imitated from the spider web and are evidences for the early human practice of nature-inspired design.

4.2 Modeling Methods of Spider Web as Fiber Orientation

Figure 4 illustrates a research conducted by Thomas [17] to extract basic parameters for modeling and defining of spider web. The method illustrated in the figure was used for accurate definition and analysis of some parameters of research interest on a spider web such as:

1. Web area - the area fenced by the outermost gluey spiral,
2. Number of spans on the web,
3. Quantity of sticky spiral turns on the web,
4. Quantity of non-sticky spiral turns on the web,
5. Ratio between number of sticky and non-sticky spiral turns and
6. Web dimension or the distance between successive sticky spiral turns measured along a radius in the eastern, southern, and western regions of the web.

To formulate the spider web geometry, the length as the spiral moves a distance from the inside point to the outer side turn was divided by the number of turns minus one (Fig. 4) [17].

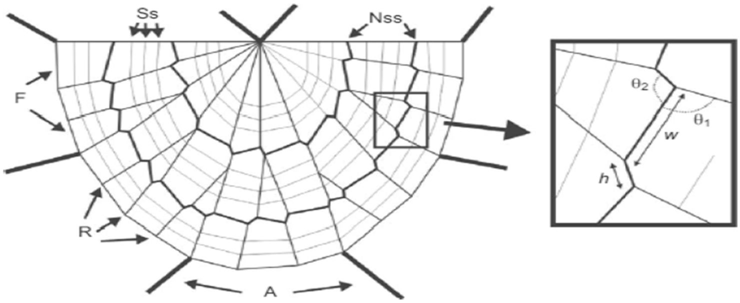

Fig. 4. A simplified Nephila orb web. Where A is the anchor filaments, F is frame filaments, R is the short radii, Ss and Nss are sticky and non-sticky spiral filaments respectively, h is for height (length of Nss spiral and radius junction) and width (w) of the Nss zigzag spiral pattern and the angle between the Nss and the radius (θ_1) and the angle between the Nss spiral and the junction (θ_2).

For each web, they [17] designated the area crossed by the eight southern-most radii and measured the following parameters from the seven fenced segments of each of the Ns spiral turns. Lost or radically altered directions in the segments were designation overlooked, and those measurements are summarized as;

1. The height to width ratio of the Nss spiral, zigzag shape (h/w) and the zigzag index of the Nss spiral can be calculated by the addition of the two angles of the Nss spiral, which it makes with its intersection at the radius divided by 180°, (i.e. $(\theta_1 + \theta_2)/180$).
2. Nss spiral was detectable by its zigzag/weave shape, where the distance of the intersection between the radius and the Nss spiral was used to build the height of the weave profile and the inter-radial length built the width of the web.
3. The intersection contained the Nss spiral fibers covering about the radius with smaller sticky silk filaments used to avoid slipup condition between the non-sticky spiral and the radius.
4. From uniaxial tensile test results (Fig. 5) [17]), it has been observed that there exists high non-linear stress-strain with high initial Young's modulus (stiffness) followed by a lower post-modulus curve.

Few efforts have been proposed to model spider orb webs with a proper analytical explanation for non-broken web type. Orb webs possess a stronger radial threads compared with the spiral threads because they are free of stress concentrations. This makes spider web unique for use as nature-based design to be mimicked for localized damage maintenance. Orb spiders optimize their web either by increasing the number of spiral threads for dense web (for trapping small insects) or modify it by adjusting the number of radial filaments. Familiarizing the environmental conditions or decreasing the cost of

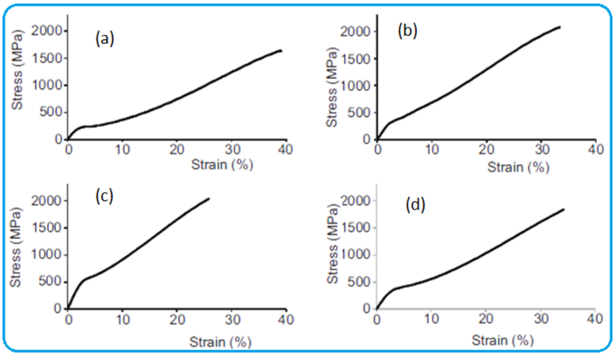

Fig. 5. Stress-strain response curves of spider webs fibers of (a) non-sticky spiral, (b) Radial, (c) frame, and (d) anchor filaments.

making the web without decreasing the damage tolerance of the web is also one of the techniques of optimization [18].

The 2D based modeling techniques conducted by Yuko et al. [19] for orb-web consisted of *R* radial threads and *S* spiral threads. In this study, the nodes are designated by a set of (r, s) as shown in Fig. 6. A 2D vector **X**r indicates the location of this set, where r = 0, 1, 2,…., R−1 and s = 1,2, ……, S, $X_{r,0}$ = (0,0) is independent of r. The (r, s) element of the radial and spiral threads connect two adjacent nodes $X_{r,s}$ and $X_{r,\ s-1}$ and another set of adjacent nodes $X_{r,\ s}$, and $X_{r-1,\ s}$ respectively. The natural length of all (r, s) radial threads is equal to K while that of the (r, s) spiral thread k_s depends on s because of geometrical restrictions:

$$k_s = \alpha s K \equiv 2sK\,\sin(\pi/R) \tag{5}$$

which means, without any tension, the node position is given in (θ, r) coordinates by

$$X_{r,s} = 2r\pi/R,\ sK) \tag{6}$$

The spring constant of the radial thread is independent of the element and represented:

$$\bar{U} = \mathrm{U/K} \tag{7}$$

While that of spiral thread depends on the **s** and is designated in Eq. (8) because the spring constant is inversely proportional to the natural length.

$$\bar{u}_s = u/k_s \tag{8}$$

An effort for modeling and conducting a finite element analysis (FEA) was reported in [20] for an ideal web with a diameter of spiral contour 25 cm and this model contained four types of filaments (spiral, radial, frame, and anchorage) as given in Fig. 7. Different mechanical and physical properties characterize these threads. The finite element analysis and post-processing (FEMAP) software was used to model the spider web and ABAQUS non-linear FE code was used for detail analysis. The mechanical and physical properties of the spider thread are given in Table 1 [20].

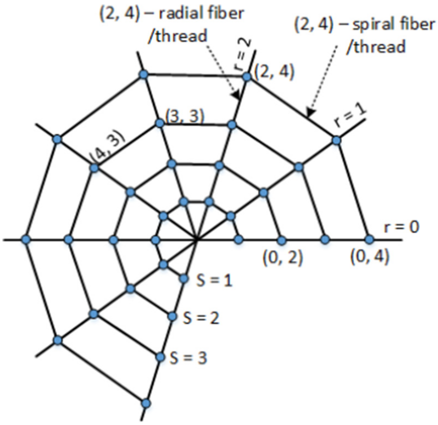

Fig. 6. Model of orb-web of spider consisting of 10 radial and 4 spiral threads (R = 10, S = 4).

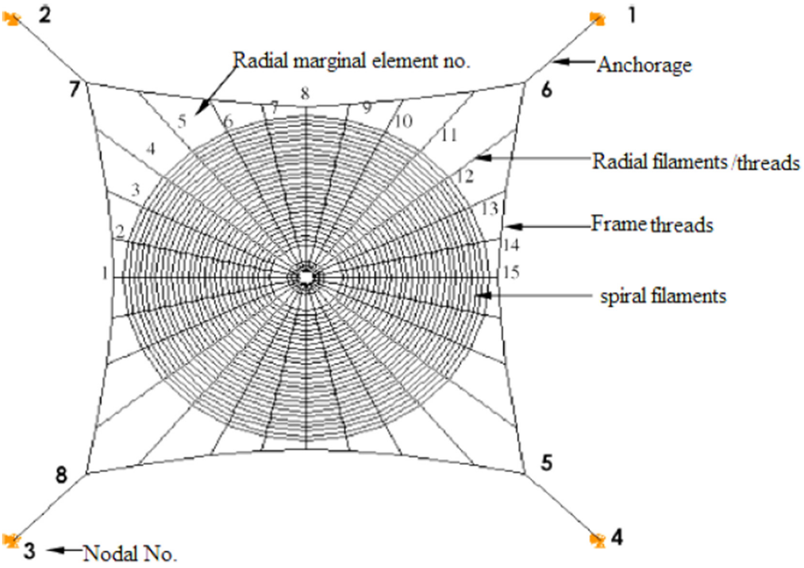

Fig. 7. Finite element model of a spider web.

The conclusion drawn from the study on the FEA of spider web are the following:

1. Initial tensions of the threads have significant effects on the transverse toughness of spider webs, and the broken threads contribute to the local effects. Within the localized damage, the spider web can function as a net for grasping prey without significant defects.
2. The impact load due to insect was simulated, and the web responds dynamically. The steady-state response magnifies approximately 3700 times to static response at

Table 1. Mechanical and physical properties of spider threads.

Types of threads	Diameter of threads (μm)	Modulus of elasticity (MPa)	Breaking stress (MPa)	Initial tension (μm)
Spiral	2.4	500	800	10
Radial	3.93	2600	1200	132
Frame	7.23	5555	1250	924
Anchor	8.03	7000	1300	1320

its first natural frequency with minimal damping ($\zeta = 0.0001$) and about 15 times (i.e. 0.1526) with damping.

3. For spider web, the proposal of "the path with the greatest stiffness carries the greatest load" is valid in such net structures.
4. The aerodynamic damping has a significant impact in reducing the amplitude of the dynamic response of the web, so that aerodynamic damping is one of the critical parameters to absorb the web vibration.
5. The application area of simulated results suggested for light structures like cable-stayed bridges as nature inspired design for reinforcing bridge structures.

5 Observed Research Gaps

There are many industrial applications created by nature-inspired design. Many scholars are working to meet the needs of aviation, automotive, construction, medical treatment, military, telecom, and different engineering area by emulating nature at a different level of process and system that require product design through nature-inspired design techniques. Biomimicry, biomimetic, and bio-inspired design principles are methods of acquiring technical knowledge from natural systems. There are attempts to distinguish them for detailed methods and techniques to integrate into product development [15].

After a careful review of recent and on-going researches, the following research directions are identified with possible research gaps.

1. Many products and systems are still engineered with conventional methods imply that there are limitations to meet the dynamics of industries and human needs.
2. Poor initiatives are observed in using and cultivating nature-inspired principles for fiber orientation to reinforce composite structures.
3. Limited tools, equipment, and machinery are available for real trucking and mimicking of nature for engineering application and production.
4. Though the iterations and evolutions that took place through billions of years have nature cultured in terms of optimal design, many optimization methods and processes are not still nature emulated.
5. Graphic inspirational methods are the most practiced methods to copy building designs or engineering systems. These are limited to copying the visual appearance of nature as it is. Conceptual inspiration, on the other hand, is a technique for

acquiring knowledge of nature's rules, principles, or patterns to be integrated for engineering systems. It is not well-practiced as of visual methods.

6. Design and production by computational inspirations (algorithmic bio-mimicry) are very limited in industrial applications and much more enforcement is required for evolutionary technologies.
7. Limited applications of web-like structures are employed to predict mechanical behavior and accurately to detect and locate damages for non-linear stress response-oriented design.
8. To date, there is a small claim to use nature mimicry for fiber orientation to reinforce the composite structures.

6 Concluding Remarks

Enhancement for engineering design-by-analogy or nature-inspired design has been the foundation of many pioneering designs for all human history. However, the visual, conceptual, and computational methods of inspiration to mimic nature remains much to be understood for endless innovation of products and processes for engineering applications. Fiber orientation plays a significant role in determining the mechanical properties of composite structures.

A spider web performs with a very flaw-tolerant system and provides opportunities for beating failure with lacking failing. Even if a few threads are damaged, the crack or failure propagation is localized. This reduced damage can be repaired, rather than replacing, and this is one of the unique features to mimic from nature of the spider web design for robust and damage-tolerant design of mechanical structures. To better understand the mechanical performance of the spider web structure, more advanced analysis and simulation works are sought. Due to their non-linearity, FEMAP and ABAQUS are proposed as practical tools for modeling and simulation of spider web.

From this study, spider web fiber orientation for composite reinforcement is suggested for practical applications using the analogy of nature-inspired design. An effort has been done to visualize the broader nature-inspired design techniques for modeling and analysis. The common practice regarding fiber orientation for product development assessed with the current knowledge of designer thought and the practiced approaches for the nature-inspired design are examined for further integration techniques. Then the future direction for nature-inspired design is proposed from the superior design-by-analogy viewpoint.

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