An Overview of Applications of Biomimetics in Civil Engineering

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Abstract—Biomimetics is a development that offers reasonable solution to the problems faced by humans by imitating the nature thereby deriving maximum benefits of nature and improved sustainability. We have been striving for green buildings and use of green materials for the same. This paper attempts to present a review of its applications in Civil engineering in general as well as in various types of constructions to make the structures eco-friendly, including copying the nature for designing the shapes as well for actual constructions. The nature inspired techniques used are natural ventilation, harnessing non-conventional energy, lighting, climate control and data optimization using soft computing techniques like artificial neural networks and genetic programming. More and more concepts should be explored and copied from the nature for the benefit of humans as well as natural environment.

Keywords—Biomimetics, green material, green building renewable energy, civil engineering, genetic programming, artificial neural networks.

I. INTRODUCTION

The term biomimetics comprises Greek words ‘bios’ and ‘mimesis’, which mean ‘life’ and ‘to imitate’ respectively. Biomimetics is also termed as bionics or biomimicry and is possibly popularized by an American natural science writer Janine Benyus through her revolutionary book titled ‘Biomimicry’. She describes it as a new science that studies nature’s models and imitates or derives inspiration from the natural designs and processes to help solving human problems and issues. As its name suggests the aim of biomimetics is to mimic or imitate the nature (i.e. different plants, vegetation, insects and animals from various ecosystems) in order to provide efficient solutions to the engineering problems [1]. Studying the hydrophobic surface of a lotus leaf to develop self-cleaning paints is an example [2].

Biomimetics is an emerging and rapidly developing field, which focuses on alternative ways of implementing sustainable engineering solutions through, or inspired by, nature. Various engineering institutions and individuals, depending on their field, describe biomimetics as a set of scientific or design principles [1, 3]. It is an intriguing innovation that is becoming increasingly relevant and significant in a carbon-conscious, ever expanding and rapidly developing world. There is huge potential and ability in the field of biomimetics to solve the difficulties in urbanization and industrialization faced by humans by imitating the nature as it has given a new direction to think in engineering applications especially civil engineering. Mixture of simplicity and complexity makes biomimetics a useful tool in innovating construction materials and designs for sustainable development [1, 4].

Biomimetics works as an effective and efficient design methodology founded on the principles of environmental sustainability [4, 5]. It offers a theory that can be referred to as model, mentor and measure. As a model, it helps emulating natural design in relation to forms, processes and systems. As a mentor for design, it offers a new way of viewing and valuing nature. As a measure, it uses an ecological standard to judge the sustainability of our innovations [6].

There are many complex processes involved in various civil engineering phenomenon such as hydrology, hydraulics, meteorology, structural engineering which involves large number of parameters, relation between which is not clearly known. If sufficient data are available, biomimetic soft computing techniques of Artificial Neural Networks, Genetic Programming can be employed to determine relationship between the parameters.

II. APPLICATIONS IN CIVIL ENGINEERING

Estimation and forecasting of important hydrological parameters such as rainfall, evaporation, sea levels, ocean wave heights have been successfully done by researchers using Artificial Neural Networks (ANN) and Genetic Programming (GP). These techniques are also useful for analysis of stresses, failure of materials in structural engineering field provided that useful and sufficient length of data are available. ANN is inspired from working of the human brain while GP works on the Darwinian principle of ‘Survival of the fittest.’ GP uses the natural evolution process of crossover, mutation and reproduction to generate best equation to fit the data. It is still under the process of its maximum utilization. Software is available for implementing the ANN and GP.

Biomimetics could offer sustainable alternative solutions to conventional design practice, as its basis is to reduce the energy consumed by the system by combining functions and reducing wastage. It can be applied not only to design the shape of the development but also to provide solutions in the in construction related operations and processes of development, as well as to the selection of the materials used for constructions [7].

A. Materials

1. Artificial Aggregates

Coarse aggregate in the conventional concrete are replaced by newer ones by mimicking the natural coarse aggregate. The material is a mixture of waste paper sludge, ash and rubber wood dust. They are produced in the form of pellets of the same size and shape, which becomes aggregate after hardening. Its use in concrete is found to yield acceptable compressive strength as compared to the normal concrete mix. Thus it has a good potential to mimic the natural coarse aggregate in concrete, which would prevent environmental degradation to a large extent [8].

2. Cement

Production of every ton of Portland cement, which is an important and essential ingredient of modern day concrete as a construction material, emits about 1 pound CO_2. Brent Constantz, a bio-mineralization expert from Stanford University (California), utilized biomimetics by observing the construction of the coral reeves. He found coral reef as an application technology for cement manufacturing. It is formed by CO_2 gas and ocean water, which have a natural reaction that gives rise to calcification. Thus this process uses CO_2, a huge waste resulting from all human activities, as a raw material to create the coral structure. Manufacturing of artificial coral reef using waste gas from a local power plant and dissolving it in water was undertaken [9]. Constantz and his company Calera use CO_2 as a feedstock for cement production. Calera's calcium carbonate produced from CO_2 is in the form of a fine, free-flowing white powder as shown in Fig. 1.

Fig. 1: Calera's Supplementary Cementitous Material [10]

It can function as supplementary cementitous material (SCM) that can be used in the traditional concrete mixes where the environmentally sustainable calcium carbonate can replace a portion of Portland cement, helping reduce the overall carbon footprint of traditional concrete without compromising on the strength [10].

3. Paint

The phenomenon of self-cleansing in case of the lotus leaves and flower was known in Asia since ages. The lotus effect refers to the very high repellence between the leaves of the lotus flower and water. Water droplets pick up dirt particles from the leaf surface due to complex nanoscopic architecture of the surface [11].

In 1805, Thomas Young developed a mathematical model [Ref. Fig. 2] linking material features to the shape of a liquid drop on the material via the equation,

$$\gamma_{SG} = \gamma_{SL} + \gamma_{LG} \cos\theta_c$$

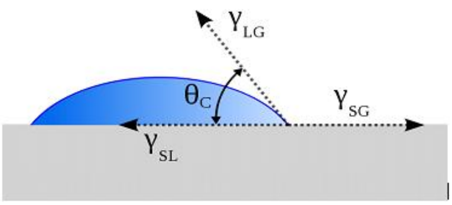

Fig. 2: Contact angle of a liquid droplet wetted to a rigid solid surface [11]

Where, γ_{SG} = Solid–gas interfacial energy
γ_{SL} = Solid-liquid interfacial energy
γ_{LG} = Liquid-gas interfacial energy

By the mid-nineties, Wilhelm Barthlott developed industrial products and trademarked this principle as the Lotus-Effect [11]. This structure is very useful and now widely used for different applications such as self-cleansing paint, known as Lotusan. Fig. 3 depicts the analogy between the lotus leaf and Lotusan paint as well as the concept of self-cleansing [2, 11].

Fig. 3: Analogy between the lotus leaf and Lotusan Paint [12]

4. Ornilux Glass

Millions of birds are killed each year by flying into the reflective glass of multistoried buildings of the office and apartments. The reflections of trees, landscape and the sky can make it appear as if the glass is not there. Green building has increased the need for additional glass for interior day lighting creation. The result is an increased frequency of bird deaths each year. The Arnold Glass Company, through the use of biomimetics, looked to spider webs and their ability to avoid destruction by bird flight. Spider webs include a reflective component in the UV range that deters birds from flying into their webs, yet they attract insects such as moths towards their reflective light. This UV component increases the spiders foraging success and avoids destruction at the same time. Arnold Glass has created a product called ORNILUX (Ref. Fig. 4) that integrates this UV reflective pattern into its glass. This resulted in 76% fewer bird collisions in field-testing [9, 13].

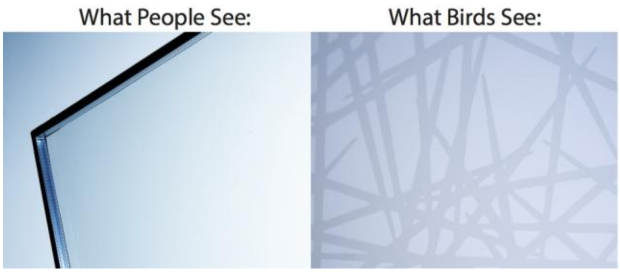

Fig. 4: Views of the Ornilux Glass [14]

B. Construction Design

Placing structures according to the anticipated mechanical impact can make huge material savings, and many plants, which defy extreme weather conditions, often display this. That is one of many biomimetic examples from nature where structures are used to create strength despite low weight. By means of the Additive Layered Manufacturing, many structural solutions can be copied from nature. Appropriate structures of metal or plastic can be united in lightweight construction with high mechanical demands. By using the concept of biomimetics in structural design, the properties of a product can be tailored to meet the exact optimum characteristics in strength, weight, flexibility, energy absorption, durability or whatever is the critical factor of your structure [15].

Integrating structural engineering with service engineering can be regarded, to some extent, as taking principles from biological systems and applying them to a large-scale conceptual design. Initial steps to connect biological concepts to structural design methodology are best focused on connecting more advanced structural forms with rather simplistic biological constructs for instance, a new method for form-finding of tensile structures informed by the growth principles that govern basic cell geometry. The patterns of cell growth and cell wall spatial arrangement are mechanisms driven by surface tension in the growth medium. Such mechanisms have been well understood by biologists for nearly a century, and a close examination of the cell growth literature exhibits a striking analogy to the mathematical form-finding methods that have been developed since the 1970's for tensile structures. By combining the principles of the force-density form-finding method with a series of rules derived from cell growth theory, a robust new form-finding method is possible. This method allows the specific tensile form to grow according to a series of rules, rather than be a result of arbitrary boundary conditions imposed by the designer [16].

The natural environment in fact inspires a number of structural systems, which are considered great man-made achievements. Suspension structures, such as long span suspension bridges, share the same structural principles with spider's webs. Membrane structures, such as modern stadia roofs and canopies behave very similarly to cell walls, gaining strength by being constantly in tension. The Pantheon of Rome is a biomimetic example, not in terms of its material but because of its structural behavior, which is similar to that of a seashell. Like seashells, the roof of the Pantheon gains its strength from its multi-dimensional curvature, which results in a structure not requiring extra reinforcing and hence being much lighter than conventional reinforced concrete spanning structures [7].

C. Construction

Imitation of natural processes is also a key factor in biomimetics. Most of the environmental hazards the world is facing today are as a direct or indirect result of power generation and use. Natural ecosystems have existed as minimum energy systems for millions of years, being driven primarily by solar energy. It is timely to determine whether the same principle could be applied to building structures, which themselves are artificial ecosystems where people live and work. Renewable sources could be incorporated into the method of construction, used for power supply, ventilation, climate control and lighting [7].

1. Natural Ventilation

Nature inspired building cooling system comes from the African termite mound. The African termite lives in tall mounds so strong that humans use dynamite to remove them when they are in the way. Relative to a termite's size, these mounds are equivalent to a mile-high skyscraper housing the population of New York. But their real genius lies in their remarkable environmental control system. Even in the oppressive heat of African savannah where temperatures vary from 104^0 F to 34^0 F in a single day. The design of these termite mounds keep them cool (around 85^0 F) without fans, chillers, or heat pumps. These tall mounds, which can reach 26 feet in height and 10 feet underground, are built like a smokestack, and the termites create small tunnels or openings at the bottom of the mound. These openings are oriented to catch the prevailing breezes, and as the air enters the mound it passes through chambers of wet mud, which lowers the temperature of the air through evaporative cooling. Because warm air rises, the air is drawn through the top of the stack through the 'stack effect' of convection. Architect Mick Pearce used the termite idea as the basis for his design of the Eastgate Building in Harare, Zimbabwe [7].

Like the termite mound, the design uses the mass of the building as a "heat sink" that insulates the building from the diurnal temperature swings outside. Working with

Ove Arup & Partners, he developed an air-change system that uses a central atrium to passively move air from the base of the building to the stacks on the roof. Along the way, it passes through hollow spaces under the floors and then into each office through baseboard vents. As the air warms, it is drawn out through 48 round brick funnels. During cool summer nights, fans send cooler outside air through the building seven times an hour to chill the concrete mass of the hollow floors. This project, which was completed in 1995, uses only 10% of the normal air conditioning required for similar buildings of its size [7]. Fig. 5 shows these details.

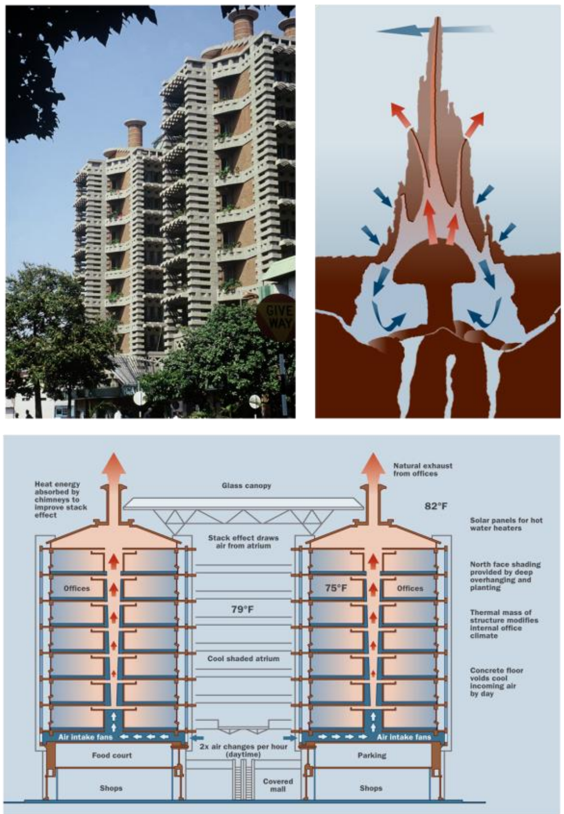

Fig. 5: Eastgate Centre Natural ventilation System & termite mound [17]

2. Biomimetic Solar Cell

Solar energy drives natural ventilation and the lighting, thereby reducing energy loads during the whole-life operation of the building. The use of solar energy could also be implemented during construction. The building cannot totally provide its own energy needs. Adaptations on the building's external envelope or structure could harvest, store and provide energy when needed [7].

Scientists at Princeton University achieve major gains in light absorption and efficiency of solar cells after being inspired by the wrinkles and folds on leaves (Refer Fig. 6). They created a biomimetic solar cell design using a relatively cheap plastic material that is capable of generating 47% more electricity than the solar cells with a flat surface. They used ultra-violet light to cure a layer of liquid photographic adhesive, altering the speed of curing to create both shallower wrinkles and deeper folds in the material, just like a leaf [18].

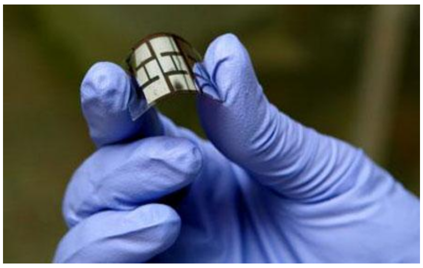

Fig. 6: Biomimetic Solar Cell [18]

The team reported in the journal, 'Nature Photonics' that these curves on the surface made a sort of wave-guide that channeled more light into the cell, leading to greater absorption and efficiency. The researchers found that the greatest gains were at the longest (red) end of the light spectrum. Solar cell efficiency typically tapers off at that end of the spectrum, with virtually no light absorbed as it approaches infrared, but the leaf design was able to absorb 600 percent more light from this end of the spectrum. Plastic solar cells are tough, flexible, bendable and cheap. They have a wide-range of potential applications, but their biggest downfall is that they're much less efficient than conventional silicon cells. A team at UCLA was recently able to achieve an efficiency of 10.6 percent, which put the cells into the 10 - 15 percent efficiency range considered necessary for commercialization. The Princeton teams expects that their leaf-mimicking design could push that efficiency even further because the method can be applied to almost any plastic material. The curing process also makes the cells stronger because the wrinkles and folds relieve mechanical stresses from bending. A standard plastic solar panel would see an efficiency dive of 70 percent after bending, but the leaf-like cells saw no diminished effects. This tough flexibility could lead to the cells being incorporated in electricity-generating fabrics or windows and walls [18].

3. Concentrated Solar Power Plants.

Concentrated Solar Power (C.S.P.) plants are probably the most technologically advanced and efficient form of generating solar energy on a large scale. Currently there is only a handful in the world, and one of them (inventively called PS10) majestically stands in Andalucía, Spain. Fig. 7 shows 100 m tall mast surrounded by rows of giant mirrors know as the heliostats, each roughly the size of half a tennis court. The heliostats reflect the sun's energy onto the central tower where it is then converted into enough electricity to power 6,000 homes. C.S.P.'s could potentially generate enough clean, renewable energy to power the entire US, based on the assumption that two commodities are available in abundance: land and sunlight. The resulting layout resembled a spiral, very similar to certain patterns found in nature. Inspired by this discovery the team looked for more examples to follow in nature; they chose the sunflower [19].

Fig. 7: Concentrated Solar Power Plant PS10, Spain [20]

The petals of a sunflower are arranged in a special spiral pattern commonly found in nature and known as a Fermat Spiral, a design that has fascinated mathematicians for centuries. Each petal is turned at a magical angle of 137 degrees with respects to its neighbour. This has allowed the footprint to be further reduced up to 20% of the original PS10; but even better, the spiral pattern reduces the actual number of heliostats needed and the shading they cast on one another, increasing the total efficiency of sunlight reflection [19].

D. Shape

Our environment's ever shifting nature has allowed both plant and animal life to evolve and adapt to be able to survive. This amazing process has long been a source of inspiration for designers, engineers and architects for their building projects. This is because these designs are not just aesthetically pleasing but are also practical and innovative as some of them also take on the adaptive features of the things they were based on [21]. Some of them are as follows:

1. Bird's Nest Stadium

The Beijing National Stadium or better known as the Bird's Nest Stadium was designed by Swiss architecture firm Herzog & de Meuron for the 2008 Summer Olympics and Paralympics in Beijing, China. As the name implies, the stadium looks like a giant bird's nest made out of 110,000 tons of steel [21]. Refer Fig. 8.

Fig. 8: Bird's Nest Stadium, China [21]

2. Lotus Temple, India

Iranian architect Fariborz Sahba, who took the lotus flower as his inspiration for the project, designed the Lotus temple in New Delhi, India. The temple (Photograph shown in Fig. 9) is the site of worship for followers of the Bahá'í Faith [21].

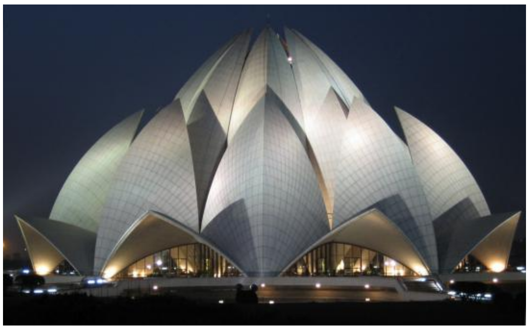

Fig. 9: The Lotus Temple, India [21]

3. Taipei 101, Taiwan

Taipei 101 is located in the Xinyi District in Taiwan's capital city, Taipei. The building was designed by C.Y. Lee & Partners and was inspired by the indigenous slender bamboo that the country sees as an icon of learning and growth [21]. Refer Fig. 10

Fig. 10: Taipei 101, Taiwan [21]

III. CONCLUDING REMARKS

The genius of nature is all around us from the coral in the ocean to the land ecosystems in the form of insects, animals, trees, plants and vegetation. Living organisms operate under a sustainable set of operating conditions, which have been evolving since eternity. By looking at them and mimicking the designs and/ or their behavior, we have the opportunity to create marvels for the benefits of the humans as well as nature from this knowledge bank as the best research laboratory in nature. In this era of modernization, all of us are striving and talking about sustainable development, conservation and preservation of natural resources and eco-friendly activities. Biomimetics would be very useful in the endeavour. There has to be a paradigm shift in our understanding and concepts about implementation of the built environment. If we learn through these organism models, we would survive happily on this planet for billions of years.

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