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A Biomimetic Structural Form: Developing a Paradigm to Attain Vital Sustainability in Tall Architecture

Osama Al-Sehail

Abstract**—**This paper argues for sustainability as a necessity in the evolution of tall architecture. It provides a different mode for dealing with sustainability in tall architecture, taking into consideration the speciality of its typology. To this end, the article develops a Biomimetic Structural Form as a paradigm to attain Vital Sustainability. A Biomimetic Structural Form, which is derived from the amalgamation of biomimicry as an approach for sustainability defining nature as source of knowledge and inspiration in solving humans' problems and a Structural Form as a catalyst for evolving tall architecture, is a dynamic paradigm emerging from a conceptualizing and morphological process. A Biomimetic Structural Form is a flow system whose different forces and functions tend to be "better", more "fit", to "survive", and to be efficient. Through geometry and function—the two aspects of knowledge extracted from nature—the attributes of the Biomimetic Structural Form are formulated. Vital Sustainability is the survival level of sustainability in natural systems through which a system enhances the performance of its internal working and its interaction with the external environment. A Biomimetic Structural Form, in this context, is a medium for evolving tall architecture to emulate natural models in their ways of coexistence with the environment. As an integral part of this article, the sustainable super tall building 3Ts is discussed as a case study of applying Biomimetic Structural Form.

Keywords**—**Biomimicry, design in nature, high-rise buildings, sustainability, structural form, tall architecture, vital sustainability.

I. INTRODUCTION

A brief dip into the history of tall architecture's trajectory shows the extraordinary role of structure, which has increased remarkably during the last decades and caused a tremendous shift in the theme and morphogenesis of tall architecture, changing its stereotypes significantly. However, this role seems unaware of or separate from the sustainability equation, particularly from the environmental perspective, as one of the essential prerequisites in the current practices of tall architecture design [1], [2]. As well, the speciality of tall architecture per se classifies many of the sustainability strategies developed for low-rise buildings as unsuitable for it because of its shape and size and the sheer density of occupation [3]. This raises queries about the efficacy of current sustainability practices in tall architecture generally, and whether sustainability can be realized aside from its structure. From this perspective, the intention of this research focuses on the essential interdependence between the structural form of tall architecture and its sustainability and embraces biomimicry as a mode to reveal a new level of sustainability in tall architecture. In this light, the research advances two postulates to frame its hypothesis: Natural structural forms serve as a model, measure and mentor for promoting sustainable innovation designs, and structural form is the real catalyst of the evolution of tall architecture over time. The research puts forwards the premise of *Biomimetic Structural Form* as an "efficient paradigm" through which *Vital Sustainability* can be gained. This contextualizes the leading question: How can a Biomimetic Structural Form be revealed as an efficient paradigm in developing Vital Sustainability in tall architecture, and what is the process of its emergence? This involves implicitly asking what a Biomimetic Structural Form is and why it can be considered a potential and reliable paradigm to design sustainable tall architecture.

This research interprets sustainability in tall architecture as a critical occurrence in which there is a level of intrinsic discrepancy between the two phenomena (tall architecture and sustainability), which can obviously be seen in the basic requirements of high-rise buildings when compared with their counterparts, low-rise buildings [4]. This contradiction necessitates exiting from the circle of the standard sustainable solutions and innovating a new mode of sustainability in tall architecture and a new paradigm to accomplish it. For this purpose, this research posits Biomimetic Structural Form as a paradigm to reach Vital Sustainability in tall architecture. Terminologically, a Biomimetic Structural Form is derived from fusing a structural form, as a catalyst of evolving tall architecture, and biomimicry, as a design approach for sustainability. Through a conceptualizing and morphological process and the use of computational design means, a Biomimetic Structural Form emerges as a flow system in which forces and functions tend to move more efficiently and survive better. At the same time, those elements that are abstracted as geometry and function from natural structural forms and which define their performance are formulated as parameters guiding its materialization. A Biomimetic Structural Form, as a result, emulates natural structural forms in their sustainable performance, producing what is called Vital Sustainability, whereby tall architecture has the capacity to achieve the sustainability of its internal workings and its interaction with the external environment. As a goal, Vital Sustainability can be realized at the entire environmental and

Osama Al-Sehail is a PhD student in the Faculty of Environmental Design, University of Calgary, Calgary, AB T2N1N4 Canada; he was a Design Director in Group Consult International – Dubai, UAE (e-mail: osama.alsehail@ucalgary.ca).

structural performance levels of an individual tall building.

The research shows Vital Sustainability as part and parcel of tall architecture's existence and presents Biomimetic Structural Form as an alternative to the conventional structural system, which has become within the present developments of technology and design methods an obstacle impeding the evolution of tall architecture. This in turn reflects on evaluating current standard practices of sustainability as complements working within the framework of the Biomimetic Structural Form to enhance partial performance of the system. The research, in brief, is a both a theoretical and a practical project that argues that sustainability in tall architecture is an inevitable evolution requiring a new approach that takes into consideration its typological singularity.

II. METHODOLOGY

The methodology of the research outlines the trajectory of developing the theme of the Biomimetic Structural Form in tall architecture. It includes constituting the epistemological framework of a Biomimetic Structural Form through qualitative examination and review of the literature and case studies in tall architecture, structural form, biomimicry, and sustainability. The research determines two aspects of the knowledge extracted from nature and transferred to the design: Geometry and function. Through embracing the principles of the Constructal Law, the research links the structural performance and the geometry and function of natural structural forms. Building this part depends mainly on a correlation analysis that involves determining the strength of the relationship between the two variables (geometry and function) and structural form. This analysis is done through reviewing the literature on the Constructal Law and analysing natural structural forms in this field. Building a Biomimetic Structural Form as a prototype is what frames the practical portion of this research. It contains two interconnected overlapping processes: First, a Challenge to Biology Method, which represents the conceptual part of the process and begins with identifying the natural structural model and ends with the evaluation of the prototype; and secondly, a Computational Design Process, which is the morphological part in the equation of building a Biomimetic Structural Form. It is important to consider here that building a prototype cannot be done without designing its vehicle (a tall building), and that this requires assuming the default requirements of its function and environment. Evaluating the performance of the Biomimetic Structural Form occurs at three levels: Structural performance, influence of the Biomimetic Structural Form on the sustainability of the structural system, and the influence of the Biomimetic Structural Form on the entire performance of the tall building. Achieving the first and second levels is required to define the sustainability of the structural system, which combines with the third level to achieve vital sustainability. As part of the practical portion, the research discusses the design of 3Ts—the design proposal for a super-tall building in Mississauga, Ontario, Canada, as a case study for building a prototype.

III. STRUCTURE IN TALL ARCHITECTURE

There is no doubt about the prominence of structure in the equation of architecture, which represents *firmitas* in Vitruvius's trilogy *(firmitas*, *utilitas* and *venustas*). For Angus Macdonald, "It is the most basic quality … It is concerned with the ability of the building to preserve its physical integrity and survive in the world as a physical object" [5]. Simply, a structure as a concept is the basic meaning for architecture in its wide usage, which can be recognized from the linguistic explanation of the word "architecture" as a complex or carefully designed structure of something [6]. In tall architecture, the leverage of the structure seems more dominant because of its role in defining the main characteristic of tall architecture—the height. Historically, various complex factors have impacted the evolution of tall architecture, such as economics, aesthetics, technology, politics, etc., where the structure was the means to get to the end. Without exaggeration, it can be said that the structural development of tall buildings is a nonstop evolving process in which a distinct structural history of tall architecture is equal to the history of tall architecture itself [7].

IV. STRUCTURAL FORM

The role of structure in the equation of the evolution of tall architecture cannot be separated from its form since a structural form, unreservedly, is the real face of this evolution. At the same time that structure generates and develops the forms of tall architecture, the forms themselves, conversely, formulate the structure, which elucidates to a large extent its commonness as one term—structural form— abundantly in the literature that deals with the structure and development of tall architecture. Edmond Saliklis in *Evaluating Structural Form: Is It Sculpture, Architecture or Structure?* describes structural form: "[it] is mathematically based, it seeks the greatest efficiency, economy and elegance that the designer can create … it is not random, it is not generated by trial and error, it is not subject to changes in taste or fashion, it is not symbolic of some anthropomorphic idea" [8].

From an engineering perspective, the term structural form in tall architecture refers fundamentally to the structural system; it can be visualized as a vertical cantilever beam with its base fixed in the ground [7]. Its function is to transfer lateral and vertical loads through its system components, which are connected with each other in efficient ways. Structural forms are classified into different categories according to the type of stresses that may arise in their members from the application of loads [9]. Instances such as a rigid frame, outrigger, tube, and buttress core system exemplify this system. Architecturally, the visualization of the structural form is not very different from the above, but it sheds more light on its morphological characteristics. In this context, it is categorized as either an orthogonal or conventional structural form or a non-orthogonal or unconventional structural form. Box-forms are what differentiate the first type, while pyramidal, leaning, and free forms, etc. are instances for the second [10]. In this research, the structural form in tall architecture equals the meaning of architectural structural form.

V. EVOLUTION OF THE STRUCTURAL FORM

The evolution of the structural form from the beginning of tall architecture till the 1980's was moving in a constant rhythm whereby its development was limited to inserting specific improvements on the earlier modes to enhance structural performance or increase the height of buildings [7]. From the 1980's, according to Ali and Moon, "the new generation of tall buildings broke the monotony of the exterior tower form and gave rise to novel high-rise expressions" [7]. This mutation in the evolution of structural form resulted in what was later known as unconventional structural form. For comparison, the ordinary picture of the conventional system is repetitive floor plates and beams along the building's height connecting the central core to the surrounding exterior columns. Euclidean geometry with its orthogonal elements and plane surfaces distinguishes the attributes of this system, it is being understood that two contradictory qualities are required: stiffness and efficiency. As Hensel et al. state, "stiffness implies that structural members are optimised so that they do not easily bend, and members are arranged into whole structures that are rigid and inflexible, [whereas] efficiency characterises the preferred mode of achieving structural stiffness with a minimum amount of material and energy… any elasticity of the material from which it is made must be minimised, and elastic deformation of the structure under load is carefully calculated" [11]. Hence, designing a conventional structural form assumes a ceiling of limitations that the behaviour of the structural form will be able to respond to and concentrates mainly on the mono-parametric structural behaviour of the material form, which consists mostly of a one-way causal relation [11]. Contradictory, unconventional structural forms are revealed in various attributes where non-Euclidian geometry and non-orthogonal elements and features are dominant. The unconventional structural form brings to the light the shift in the ways of handling this kind of system, new definitions of their parameters, and new structural design tools. Craig Hartman observes that in novel tall architecture, the structural design process begins not with columns and beams (the conventional picture of the structural form), but rather with an intuitive understanding of the interrelationship between the forces at play that make a form an essential part of the structural solution [1]. Realizing a structural form with this quality provides flexibility to deal with the design of tall architecture freely when the parameters are considered as leverages. To exemplify this point, in the design of the Burj Khalifa, the world's tallest building, the spiral telescopic structural form participates effectively in providing unique solutions for the essential issues in this kind of projects, such as wind loads, sway, circulation, safety, etc. [12].

VI. SUSTAINABILITY IN TALL ARCHITECTURE

Different from other impacts on tall architecture, sustainability, as a global trend and one of the major prerequisites in architectural design at the present time, has a great influence on tall architecture and its design. According to Sev and Tugrul, a new generation of high-rise buildings is being designed for sustainability [10]. Despite this influence, what is distinctive about sustainability in tall architecture is the argument about whether high-rise buildings can ever be greener than low-rise buildings [4]. For Honnorat, "with today's technology, a tower will always be more energy-hungry… [Simply,] if you're going to wash or take a shower on the 80th floor, you have to bring the water up there … [when] you take your shopping up to your apartment in an elevator, that will consume more energy than if you lived on the ground floor" [4]. Understating the role of sustainability in the context of tall architecture can be done mostly through a positioning of the environment that implicitly involves the two other pillars (the economy and the society), as shown in Fig. 1, by examining what is currently known as Green Tall Architecture. Nevertheless, it must be borne in mind that the quantitative and qualitative effects of the economy on tall architecture are essential and occasionally prior to the environmental design as a consequence of the investments involved in tall architecture.

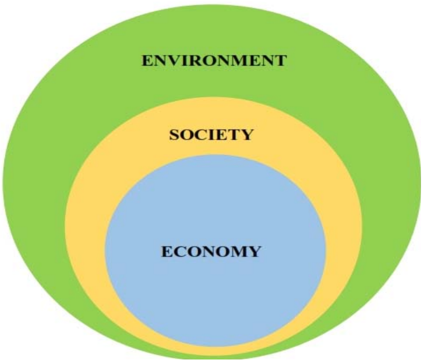


Fig. 1 The relationship between the three pillars of sustainability [13]

From another perspective, tall architecture could, by contrast, seem a sustainable solution. This view takes into account the large increase in the world's urban population (up to 66% of the world's population by 2050 according to the United Nations' prediction), which is linked with the expected rise in the planet's temperature of between 2 and 5 degrees Fahrenheit by the end of this century as a result of the greenhouse effect and increased carbon dioxide from human activities [14], [15]. A tall building could enable many people to live, work, and spend their leisure time or access public services in a relatively small area and result in more efficient uses of mass transportation. This would, gradually, increase tall architecture's role in supporting the sustainable growth of cities. However, this view does not change the difficulties in attaining sustainability at the level of an individual tall building. Also, considering the operation of tall architecture as a major direction of sustainability and ignoring the influence of structure in the equation of sustainability is a contradiction of the reality. To demonstrate this point, Sarkisian argues that "the carbon emissions associated with building construction range from 10 to 20% of the total carbon produced to operate it for a 50-year building life" [1]. To envision the design of net-zero energy buildings, he adds, "the carbon associated with the initial construction will represent 100% of the total carbon emitted … it typically takes 20 years for the carbon associated with typical building operation to outweigh the initial carbon required to build the structure" [1]. In this light, the research highlights the necessity for a new perception to deal with the subject of sustainability in tall architecture taking into consideration the specialty of tall architecture and the role of structural form in its evolution, the level of sustainability that is intended to be obtained, and the process to achieved that target. From this perspective, the research emphasizes the role of structural form in tall architecture and embraces biomimicry as an approach for sustainability. Consequently, it puts forward a Biomimetic Structural Form as a paradigm to attain Vital Sustainability.

VII. Biomimicry as an Approach for Sustainability

Borrowing from nature or biomimicry is not a novelty; nature has always been a source of materials and ideas, for instance in the great works of Leonardo da Vinci (1452-1519), Sir George Cayley (1773-1857), Joseph Monier (1823-1906), Frank Lloyd Wright (1867-1959), Buckminster Fuller (1895-1983), and Frei Otto (1925-2015) [19]. Although their attempts reflected some of the basics of biomimicry, sustainability as a target of biomimicry was unaccounted for at that time. Biomimicry in its current standpoint belongs to the work of Benyus through her seminal book *Biomimicry: Innovation Inspired by Nature*, in which she frames the underlying principles of biomimicry, or what is also called biomimetics, by dealing with nature as the source of knowledge and inspiration. She defines biomimicry, which is derived from a combination of two Greek words, *bios* (life) and *mimesis* (imitation), as "a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems, for example, a solar cell inspired by a leaf" [16]. Three interpretations to realize the role of nature are done in this regard: Nature as a model, nature as measure, and nature as a mentor [16]. Benyus develops her conviction about the efficiency of nature's solutions by describing the way nature has developed its solutions over billions of years and has uncovered a high level of effectiveness [16]. Consequently, if we were to design a built environment in accordance with these principles, we would be well on the way to living within the ecological limits of nature and achieving our goal of sustainability [16].

Biomimicry as practice can be embodied in three interconnected principles: *ethos, (re)connect and emulate*, which are demonstrated by Baumeister in the *Biomimicry Resource Handbook: A Seed Bank of Best Practices.* About ethos, Baumeister explains, "[it] forms the essence of our ethics, our intentions, and our underlying philosophy for why we practice biomimicry" [17]. A (re)connect, she adds, is "a practice and a mindset that explores this relationship between humans and the rest of nature" [17]. In other words, it restores the balance with nature. The last principle, to emulate, is the action of biomimicry on how to be proactive in achieving the vision of humans fitting in on Earth [17]. It is imperative here to understand emulation in biomimicry as the process of mimicking deep patterns or principles rather than directly copying or slavishly imitating the natural models [17]. Thus, studying a spider to learn about sensing, fiber manufacture, adhesion, or tensegrity, is, actually, a study of design principles and a living lesson in them. This involves realizing biomimicry as a conscious emulation of nature's genius, where the intent to learn from nature is what distinguishes biomimicry as a method. As Baumeister emphasizes, "biomimicry implies conscious forethought, an active seeking of nature's advice before something is designed" [17]. To move from shallow to deeper biomimicry requires engaging in an ongoing conversation with the organism and biomimicking what we learn on at least three levels representing what is known as biomimicry taxonomy [17]. The biomimicry taxonomy of the life principles is a function-based organizational scheme consisting of three design levels: Natural forms, processes, and ecosystems that show how organisms meet different challenges [17]. These principles can be realized as innovative strategies, sustainable benchmarks, and aspirational ideas that redefine and guide our choices in biomimetic design [17]. Consequently, Baumeister believes, "If we can biomimic at all three levels—natural form, natural process, and natural system (ecosystem)—we shall begin to do what all well-adapted organisms have learned to do, which is to create conditions conducive to life" [17].

VIII. Biomimicry and Structural Form

Biomimicry has growing resonances in architecture. Pawlyn in *Biomimicry in Architecture* demonstrates how it offers architects a whole new approach to design, transcending the direct mimicking of natural forms in order to understand the sustainable principles that lie behind those forms and systems. As an environmentally sustainable method, six imperatives express its architectural implementation: Build more efficient structures, manufacture materials, create zero-waste systems, manage water, control the thermal environment, and, finally, produce energy for buildings [18]. Historically, a natural structural form was one of the main sources in understating a principle of the structural form in tall architecture. One of the early attempts in this field was the work of Nachtigall and Wisser, who investigated the structure-functional compression between the grass blade and a television tower and concluded that the dead load in trees increases with mass and height and structural resistivity occurs only by cross-sectional area (Fig. 2) [19]. Khan, one of the most famous structural engineers of tall architecture in the 20th century, emphasizes that well-detailed and efficient structures possess the natural elegance of slenderness and reason [8]. The interest of applying biomimicry in tall architecture during the last decades lies in the different lenses that are proposed to address the design [20]. Additionally, potentials of the natural models make one contemplate seriously how to benefit from them in solving problems. For example, in the same context of structural form, the bone as a structural system shows no predetermined breaking points and no waste of material, and the safety factors for it and the tendons together are between 2 and 6 compared to 1.67 and 1.92 in most structural systems in tall architecture [19], [21].

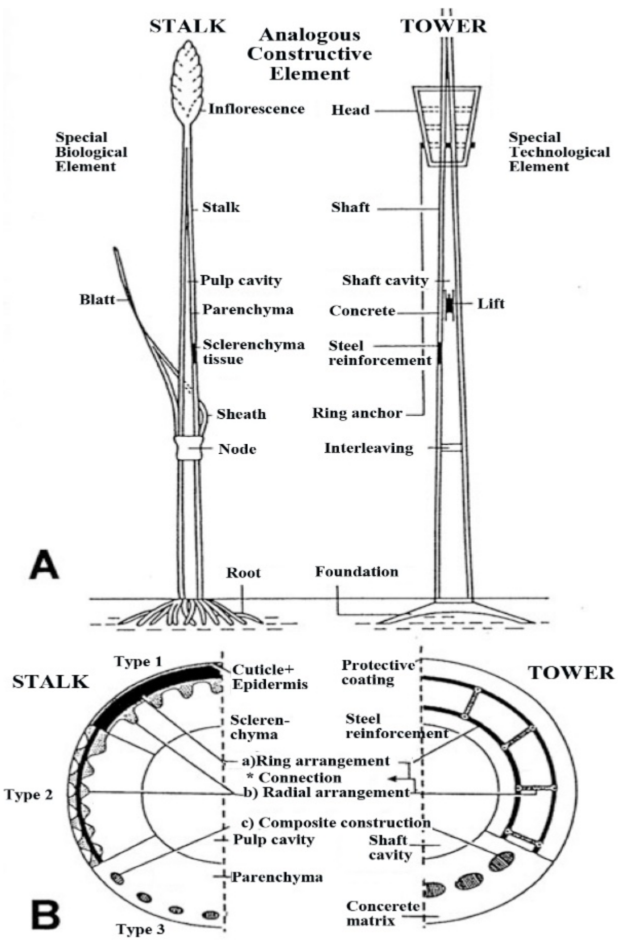


Fig. 2 Comparison between the grass blade and television tower by [19]

Understanding biomimicry in the design of the structural form requires being keenly aware the following issues: First, the design of the structural form in tall architecture is not a linear process, as it is in low-rise buildings where the design constraints aggravate exponentially with increasing the height of buildings. Succinctly, at a height of 400 m, for example, the wind flow is more like what an airplane would experience; the wind pressure increases the overturn factor of the building to the power of two, and the building's motion that humans can feel rises to the power of three [4]. Second, applying biomimicry in developing a structural form does not include only its form or system but also the elements and details that comprise it. Further, there is a tolerance in natural structural forms that makes their systems adaptable in certain ways to resist forces; for example, as Gruber states, "biological structures usually allow large deflections, which is not acceptable in architecture.… The flexibility and softness of plant parts protects them from large forces." [19] Lastly, as Pohl and Nachtigall introduce in *Biomimetics for Architecture & Design: Nature—Analogies—Technology,* nature has no blueprints for its structures, so biomimicry is not a direct copy from nature to the world of technology [22].

IX. BIOMIMETIC STRUCTURAL FORM AND VITAL SUSTAINABILITY

Through embracing the principles of biomimicry, this research puts forward a Biomimetic Structural Form as a paradigm to attain Vital Sustainability in tall architecture; it grounds a Biomimetic Structural Form as an alternative to the conventional structural system in tall architecture and specifies, simultaneously, natural structural models as the source of its model, measure, and mentorship. The work outlines the emergence of a Biomimetic Structural Form from exploring the natural models up to its fulfilment as a paradigm in tall architecture. Grasping the knowledge that is derived from nature and the adequate mechanism to transfer it to human designs is a critical point in this trajectory. Through geometry and function, this matter is solved. Framing the knowledge within the geometry and functions, which reflect forms and behaviour of nature structural models, yields an appropriate mechanism to formulate their characteristics and features in architectural design. Through the principles of the Constructal Law as a guide in this regard, geometry and function fill a methodological gap in applying a biomimicry method in building a sustainable model.

About the geometry, the research distinguishes among three types with respect to their appearance and function in nature: *Constituting geometry*, which articulates and composes the entire system of the structural form; *supplementary geometry*, which appears as additional modes, such as bundling, tapering, wrapping, twisting, etc., to enhance and boost the main system of a structural form and its constituting geometry; and *components/elements geometry*, which describes a part of the structural form within the whole system, such as the geometry of a leaf within the geometry of its tree. The function, on the other hand, is related mainly to resisting different forces in structural form and realized as a flow system formulated as self-organizing and self-assembling over time to achieve an optimal fit and configuration against different forces, such as water, wind, gravity, etc. So, at the end, there are two powers that define any structural form in nature. To simplify these ideas, let's take as an example the tree as a structural form in nature. One can see that the function of the tree is not limited only to maximizing the flow of water, but also, in order to succeed in the real world, it must be able to withstand the stresses of the wind. Bejan and Zane see the tree as a physical flow architecture that morphs to meet two main objectives: Maximum mechanical strength against wind and maximum access for water coming from the ground to the parts of the tree [23]. This integrates with the geometry of the tree, which combines the proportional ratio of its trunk, decreasing as the tree rises, and its canopy, shaped according to the winds, which come at many speeds and trim parts of the trunk, branches, and leaves (Fig. 3) [23]. Through a generative design process, the paradigm of the Biomimetic Structural Form emerges as a flow system whose attributes are defined by function and geometry. A Biomimetic Structural Form within this context has the potential to be a dynamic paradigm emulating natural models in their ways of coexistence in the environment.

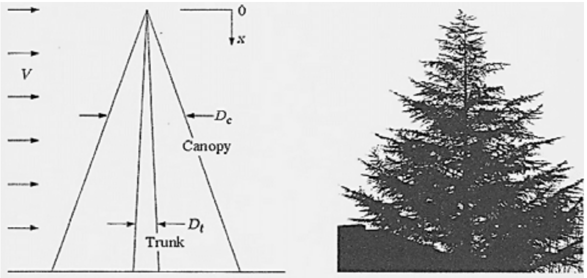


Fig. 3 Analysis of the structural form of the tree [23]

A Biomimetic Structural Form as a paradigm aims to find Vital Sustainability, which can be considered a basic level for surviving or an essential demand in tall architecture. From this point of view, a Biomimetic Structural Form is a step in the evolution of tall architecture that guarantees the retention of tall architecture as a typology. Likewise, Vital Sustainability at the level of the individual tall building is a qualitative shift toward comprehensive sustainable tall architecture by finding a foundation on which to set standard practices of sustainability. Realizing the theme of Vital Sustainability occurs at two levels: At the level of the entire performance of the tall building, such as enhancing functional and environmental performance, integrating different systems, providing a proper ground for complementary standard applications of sustainability, etc., and at the level of structural form, such as optimizing structural performance, decreasing the use of raw materials to an optimal level, creating a zero-waste system, etc. Remarkably, Vital Sustainability, through its two levels, becomes an indispensable quality in the design of the tall buildings. It is an inevitable evolution whereby tall architecture in its primary function and performance has the survival level of sustainability to remain and continue. Three directions define this quality; they are derived from the concept of survival or basic sustainability of Sutton [24]. Vital Sustainability in current life has become a survival demand; losing it means that the continuity of any products ceases. Also, Vital Sustainability in any system boosts the system's capacity to achieve the sustainability of its internal workings and its interaction with the external environment. Only natural systems show this level of sustainability; thus, they can be a unique model for inspiration in the design of tall architecture. In brief, Vital Sustainability in tall architecture is an inevitable evolution requiring a specific medium in which to occur. Through a combination of the structural form of tall architecture and biomimicry, a Biomimetic Structural Form (the medium) emerges as a paradigm to achieve Vital Sustainability in tall architecture.

X. CASE STUDY: THE DESIGN OF 3TS

Fig. 4 3Ts in the Mississauga skyline

3Ts—Three Twisting Towers—is a proposal for a super-tall building: 60 storeys and 300 m in height; it is part of the development of Square One—the heart of Mississauga— as a hyperdensity area striving to enhance its position as an attractive city. The design focuses largely on finding a landmark in the heart of the city as a strategy to put the city on the map of people's interest by taking into consideration the ethnic and cultural diversity of the inhabitants. As an objective, designing the 3Ts stands primarily on finding an optimal equation to fulfil the functional, environmental, and aesthetic requirements within the entire vision of Mississauga as a sustainable city. Biomimetic Structural Form was employed in the design of the project as a main approach, which displayed multi-levels of solutions, starting from the philosophy of the design and moving up to creating a sustainable super-tall building. As the design method, the *Biomimicry Design Spiral* with *Challenge to Biology* approach was applied [25].

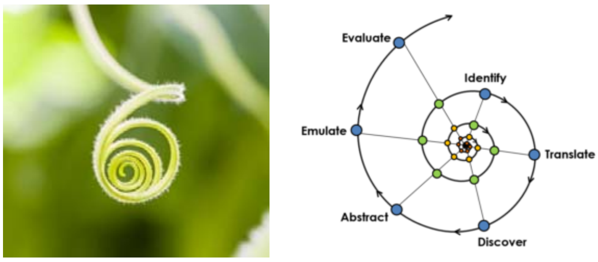


Fig. 5 Biomimicry Design Spiral with Challenge to Biology approach [25]

In the first stage—*Identify*—the objectives of the Biomimetic Structural Form and contextual issues surrounding it prior to the design were identified. They were later interpreted in the second stage—*Translate*—as ideas within the instances of biomimicry. In the third stage—*Discover*—exploring natural structural models and delineating their geometry and function were done. The natural structural model of the palm tree was chosen at this stage as a potential candidate for structural form that showed unique structural performance. Examining the structural form of the palm trunk discloses different modes of compositions and interconnections, which, in total, define the constituting geometry of the model. The central core—first mode—involves bundles of highly dense vascular strands that carry nutrients up and down the tree. Each strand in these vascular bundles is connected to the root system that penetrates the ground deeply as fibrous roots. Also, parts of these bundles constitute the roots of the fronds growing towards the external bark tissue, which formulate the phyllotactic spiral pattern of the trunk—second mode [26]. The external bark tissue has two layers of connections—third mode: The singular connections, which connect the fronds' base with surrounding frond bases, and the triple connections that recur every three frond bases, respectively (Fig. 6) [26]. Moreover, there are potentials to benefit from supplementary geometry that palms and some other plants show, such as twisting, taper and wrapping in order to provide stability, stiffness and resistance, climbing, and balancing of natural structural forms in their environments (Figs. 7 and 8). This information shaped the inputs of the next stage—*Abstract*, which is, technically, a reverse engineering process which aims to transfer the geometry and function to physical formulas in the design of the Biomimetic Structural Form.

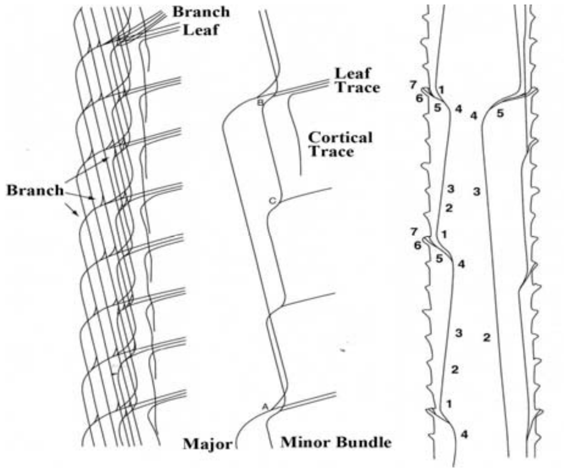


Fig. 6 The singular and triple connections in the bark tissue of the palm tree [26]

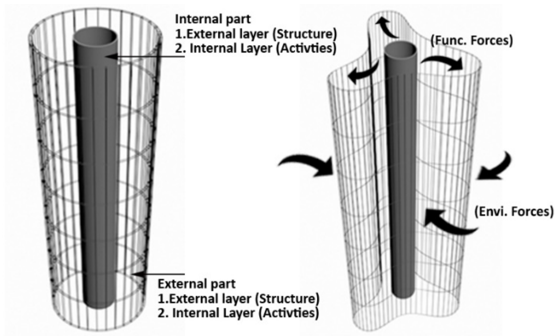
Fig. 7 Bundle system and trunk tissue pattern in the trunk of the plam tree [27], [28]

Architecturally, the initial paradigm of a Biomimetic Structural Form included building the flow system and defining its geometry. As a flow system, the function of the building includes two types of movements (flows): The flow of people and activities, which was recognized mainly as vertical flow through the height of the building from up to down and vice versa, and the flow of the forces that link mainly with the structural system and are collected from the entire building for channelling to the ground. Reflecting the configuration of the flow systems of the palm tree, the Biomimetic Structural Form was outlined as two layers: The internal included the flow of people and activities, while the external was for the flow of the loads (Fig. 9).

Fig. 8 Supplementary geometry (Taper, Twist and Wrap) in plants [29]-[31]

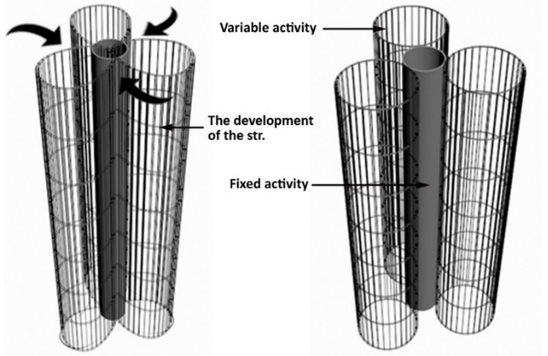
Morphologically, two kinds of the geometry were applied: Constituting geometry for formulating the different layers of flow systems and supplementary geometry for enhancing the form of the whole system. Many structural systems were examined at this stage to define the optimum for each flow system. A steel diagrid system was appointed for the external layer of the external part, which clearly exhibits its appearance as the natural tissue of the palm trunk. It demonstrates different levels of attributes such as redundancy, hierarchy, multi-directional action, recurrence, growth, modules, etc. The external layer of the internal part is formed from a steel framed tube, which is interconnected with the first layer (the diagrid system) by repetitive steel framed floors, generating a kind of the bundle system. Each layer geometrizes different flows of the functions: The external part bounds the flow of activities as variable, while the internal part bounds vertical circulation and services as fixed. Besides, supplementary geometry such as Taper, Wrap and Twist was used to formulate the whole geometry of the Biomimetic Structural Form in order to enhance its architectural and structural performance.

Through a generative design process using the 3D Max and Revit software, the model of the Biomimetic Structural Form is revealed as a prototype, which commences the *Emulate* stage. Three different steps frame this last stage—*Evaluate*: evaluating the design against the initial objectives, evaluating the design against nature's rules for sustainability, and reflecting the ideas and lessons that emerged in each step to develop the design in the next steps. In the design of the 3Ts, the evaluation involved the evaluation of the results of each stage independently and the evaluation of the whole prototype with new parameters, resulting in three different models until the final prototype was reached.



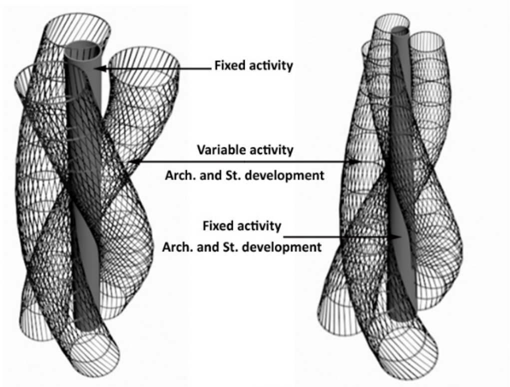
(1) Identify the two flow systems and define the consisting geometry

(2) The deformation as per forces and the functional requirements: irregular form



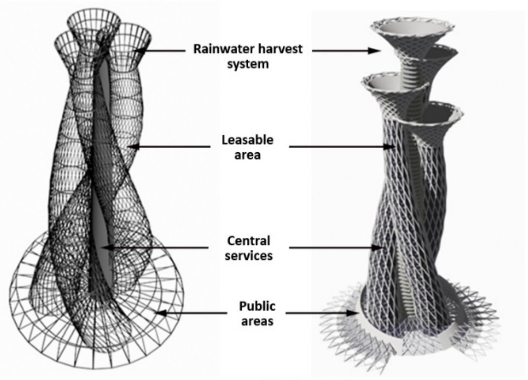
(3) The geometrization of the form and function as three isolated elements

(4) Uniform geometry: balancing between the function and geometry



(5) Supplementary geometry – twist

(6) Supplementary geometry – taper



(7) The appearance of the top and bottom

(8) Final design

Fig. 9 The development of the flow systems and geometry of the Biomimetic Structural Form

Fig. 10 The final design of the 3Ts

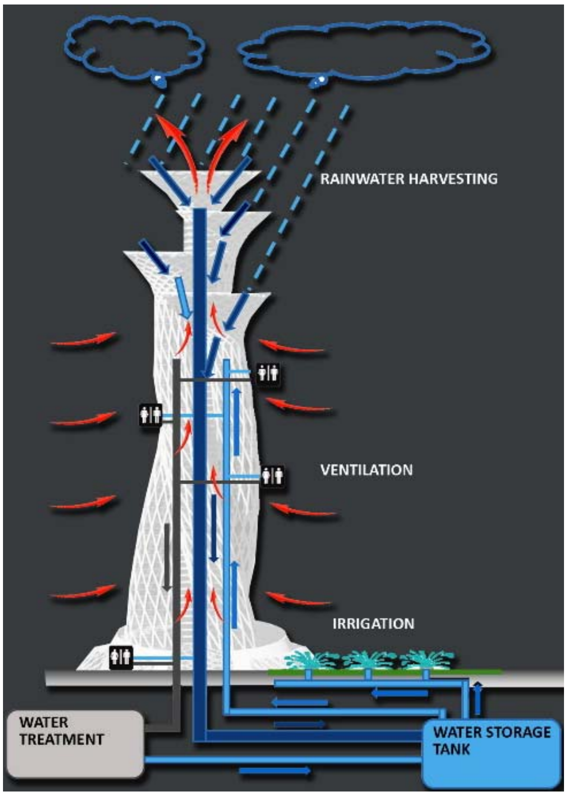


Fig. 11 Section showing the integrated systems with the Biomimetic Structural Form of the 3Ts

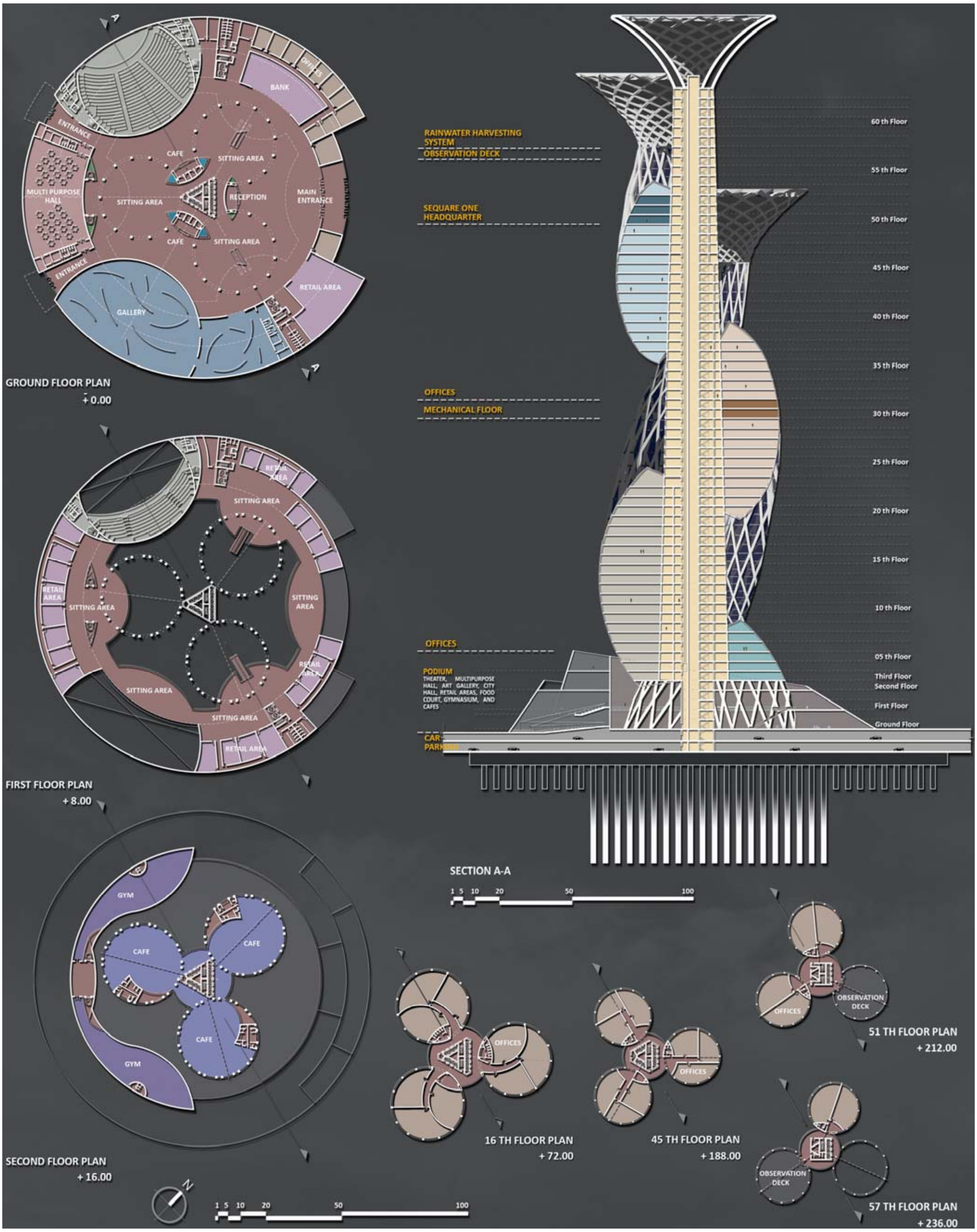


Fig. 12 Plans and section of the 3Ts

Evaluating the Biomimetic Structural Form was based on extrapolating and examining the general ideas of Vital Sustainability. Structurally, the results indicated to decrease the quantity of structural material between 20 and 40%, which was initially achieved by using the steel diagrid system as a main structural system; freeing the structure form from the internal columns; and minimizing the required structural elements to the optimum. This reflects in turn on the waste percentage and the classification of the material of the Biomimetic Structural Form as recyclable material. At the level of energy performance, the curvature shape of the Biomimetic Structural Form and the salient elements of its diagrid system provide a unique solution to control the effect of the sun's rays on the internal spaces throughout the year. As for natural light, the design shows a high level of performance and minimizes the need for artificial light during the day.

As illustrated in Fig. 11, the rainwater harvesting system, which is represented by the three flower-shaped elements on the top of the building, the recycling and reuse system located within the central core of the project and the natural ventilation system, which depended on finding different pressure areas inside and outside the building, were integrated into the Biomimetic Structural Form. At the end, the initial assessment revealed about a 30% reduction in carbon footprint. All these attributes culminate in the aesthetic and symbolic achievement of the Biomimetic Structural Form, which is represented by the three petals of the field bindweed flowers—a kind of wild flower common in Mississauga—as symbol of how nature gathers the Mississauga residents into one community.

XI. CONCLUSION

The importance of the "A Biomimetic Structural Form" lies in its specificity in dealing with the subject of sustainability at the level of the individual tall building. A Biomimetic Structural Form transfers sustainability as a value from being a matter requiring solutions to a necessity in developing tall architecture. Thus, sustainability is unfolded as a manifestation of the continuous evolution of tall architecture. The current research distinguishes between two levels of sustainability: *Vital Sustainability* and *Comprehensive Sustainability*, where achieving the second requires the existence of the first initially. For this purpose, a Biomimetic Structural Form is applied as a paradigm to attain Vital Sustainability. Furthermore, the research in developing its hypothesis employs biomimicry as an approach to sustainability and nature's genius as a source of knowledge and inspiration. Through geometry and function, the research defines what kind of knowledge can be derived from nature and determines the proper mechanism to apply it in the design of tall architecture. In brief, this research is multidisciplinary; it explains how tall architecture can emulate organisms in their sustainable performance and provides, architecturally, an innovative practical method for carrying out such emulation.

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