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A Bio-inspired Study on the Impacts of Solar Loading on Building Facades

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A B S T R A C T

Daylight is one of the primary factors of thermal comfort. In warm regions, this factor is the cause of excessive heat absorption and energy loss due to further need for cooling solutions. Therefore, design of exterior facade as a sun-exposed structural envelope can play an effective role in indoors heat absorption. Natural structures use several solutions for optimal control and management of daylight. Mimicking these solutions can prove effective in achieving energy optimization and thermal comfort conditions. This paper aims to provide such solution by assessing and mimicking the structure of cactus and designing an efficient exterior accordingly for residential buildings located in hot climates. The results show that presence of suitably sized indentations and protrusions in the walls reduce heat absorption and energy consumption.

1. Introduction

Indoors thermal comfort condition is the function of four factors: temperature, humidity, solar radiation and air movement, the right combination of which can provide desirable conditions for humans [1]. Humans regularly use fossil fuels to provide desirable conditions in indoor spaces. In warm and dry regions however, controlling daylight is the best solution for this purpose [2-5]. Controlling the daylight means making effective use of solar radiation while eliminating its undesirable effects, such as excessive heat produced in summers, but sometimes the desire for making a bright space could become the cause of excessive heat absorption. Therefore this process has always been a popular subject of research. Natural structures achieve desirable thermal conditions without using any fossil fuels and only by using natural resources and renewable energies [6]. Many living structures perform their main activities during the night to reduce heat absorption during the day [7]. One of these living structures is the cacti specimens, which can survive dry and moisture-free environments using only minimal sources. Mimicking and assessing the features of these specimens can be invaluable for achieving principles and sustainable solutions for use in architecture.

The questions to be asked in this regard are: What physical features are required in a building to effectively control daylight in indoor environment? How can daylight be optimized? To answer these questions, first the current daylight optimization solutions aimed at reducing heat absorption of buildings are reviewed. Then the structure of cactus, as a living specimen that thrives in hot desert environment is analyzed. Afterwards, the results are used to design an envelope for buildings located in hot and dry environments.

So far, daylight control has been pursued through many approaches. Some researchers have optimized the design according to ecological rules stemming from the features of sun, wind, and earth [5]. But another approach is to mimic the natural structures with the aim of reducing energy consumption. This approach is also referred to as biomimicry. In this approach, the features inside natural structures are identified, analyzed and then adapted for similar problems in the human environment. There have been some studies for defining the principles of biomimicry [8,9]. Other studies have developed further details for the use of these principles in architecture [10-12]. However, identifying and assessing complex natural structures requires biological expertise, which may be an obstacle for engineers and architects [13]. Therefore, the goal of some studies has been to introduce appropriate natural structures to be mimicked in architecture. In these studies, natural structures in different levels are assessed in terms of performance, form and internal processes [14]. Research has shown that biomimicry is an effective solution for sustainable development by contributing to optimization of energy consumption [14-17]. Therefore, in this study, biomimicry is used as the primary approach to the subject of research.

Prior studies on the natural mechanisms that allow cactus to achieve living conditions include assessments of photosynthesis process [18,19] chemical activities [20], and properties of its physical structure. This paper is focused on details of physical structure and how they can be mimicked to achieve research objective.

2. Materials and Methods

The population of this study comprises all buildings located in warm and dry environments and exposed to excessive summer heat due to extreme daylight. Research tools are energy and biology related data obtained from library studies, which form the basis of design. For preliminary assessment, initial models are evaluated in the daylight energy simulation software (Honey Bee). Research findings are based on observation and form analysis of cactus structure, and results can be utilized depending on function and application.

3. Results & Discussion

In desert, where direct sunlight is a mostly adverse factor, it is necessary to reduce the area of surfaces exposed to direct sunlight as well as the heat reflection in the building. Natural evolution has solved this problem in the cactus rather well. The vertical form of cactus minimizes the amount of surface perpendicular to the sunlight and is a temperature reducing factor. The spines of cactus absorb and reflect solar radiation, reduce heat, and reduce the temperature as an intermediate layer [18]. In addition, there are many grooves on the cactus structure that reduce the directly received solar radiation, thereby cooling the cactus shell. These grooves create shadows in the cactus structure, which leads to successive surfaces of light and shadow. Combination of grooves and spines on the stems leads to reciprocal movement of air on the body of this plant. When the sun is directly on top of the plant, the cactus has the smallest possible sun-exposed surface and therefore minimum amount of sunlight [21]. Research has shown that presence of stems and spines in cactus leads to 2-3°C lower temperature than specimens without stems under similar conditions. Spines and stems also reduce the heat transfer coefficient (Lewis, et al., 1997 p. 615).

Figure 1: functional details of stems and spines in a cactus [22]

The majority of ribbed plants have proven to have some forms of repetitive architecture in their stem elements. An assessment of cacti structure shows that the groovy columns of the cactus stem are surrounded by a number of triangular stems. Assuming the triangle extrusion (height of triangle) as b and the distance of grooves from each other (base of triangle) as h, the results of studies have shown that when the protruding triangle and the main trunk have equal hardness, the ratio of h to b is equal to 1 [23].

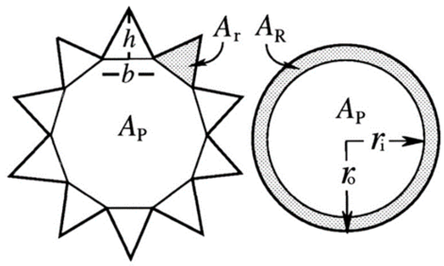

Figure 2: Cactus morphology and proportions (Niklas, et al., 1999)

Based on assessed features, numerous structures were modeled and simulated. Figure3 shows the several designs mimicked from cactus structures with similar proportion. Like the cactus trunk, these structures employ shadow and light due to indentations and protrusions to create air flow and thus reduce the summer sunlight's thermal load on the exterior body. These structures are assessed and evaluated based on the architectural factors and the required functions. Table 1 shows the proposed functions for each alternative.

According to the table, objectives such as shading, air conditioning by creating warm and cold surfaces on the exterior, use of indoor space by plan and availability of internal functions, and reduced thermal load are achieved in all designs. But factors such as potential green space on exterior shell to increase air quality, ample light and brightness for indoor space, and proper harmony with the environment are important objectives that are considered only in the first design. This this design can be regarded as an example of appropriate mimicry of cactus structure.

Based on the factors presented in Table 1, alternative 1 can be selected as the best design. Also, considering the physical features of Design No.2, it can be of note as an exterior for office space. Figures below show how this design may use the indoor spaces.

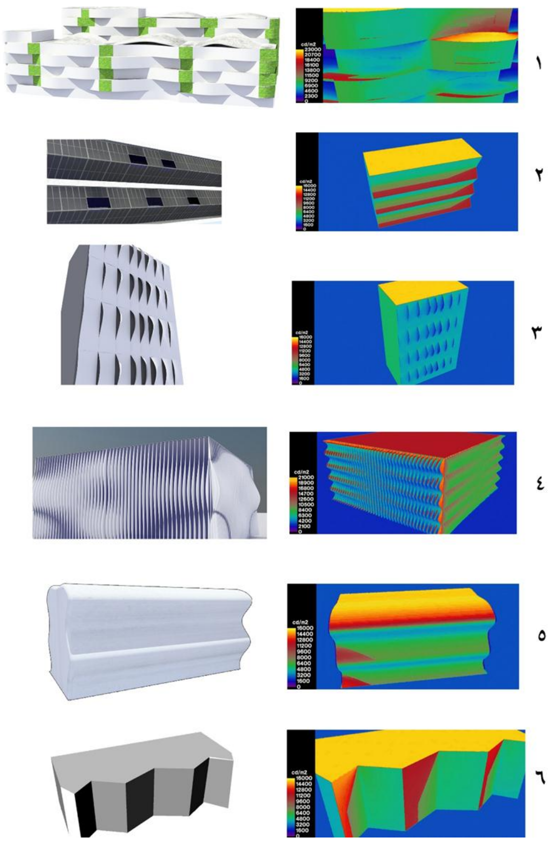

Figure 3: alternatives developed by mimicry of cactus structure

Main Factor	1	2	3	4	5	6
Shading						
Ventilation						
Plants						
Using Daylight for inside						
Utilization of indoor space						
Exploitation of density level						
Healthy						
Friendly Environment						
Reduce of Heating						

Table 1: factors affecting the environment sustainability of alternatives presented in Figure 3

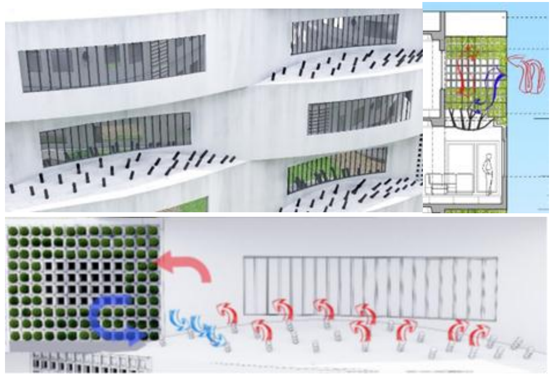

Figure 4: functional characteristics of the first design

4. Conclusions

Although many different features of cactus collectively contribute to its ability to survive in desert environments, identifying the physical structures associated with this ability and incorporating these structures in the exterior envelope of buildings, which is a decisive factor affecting its thermal load, can provide viable solution for energy saving in warm and dry environments during both summer and winter. Undoubtedly, there are many other potential features applicable to other level of design, for example, proper material design by biomimicry of cactus stems, design of optimized form atriums by biomimicry of cactus internal stems, etc., but assessment and taking inspiration from these features require access to laboratory facilities, and may be the subject of future works. Still, the designs presented in this paper, which were developed by biomimicry of cactus physical structure, can provide novel approaches for achieving energy-optimized buildings in line and harmony with economic and environmental features; features that are the main requirements of sustainable architecture and need to be incorporated into modern designs accordingly.

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