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Biomimicry and Theory of Structures-Design Methodology Transfer from Trees to Moment Frames

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Abstract

Currently, there are only three classical and a handful of emerging design methodologies available to structural engineers worldwide. None of these methodologies can explain the design concepts involved in the realization of natural structures such as trees, nor can they fully address the design needs of contemporary engineering structures. The recently developed Performance Control (PC) incorporates both the essence of the classical concepts and the newer procedures and addresses the observed performance of the structure during its known history of loading. PC attempts to mimic nature by applying the known theories of structures to the design of case-specific frameworks, rather than investigating their results for compliance against prescriptive criteria. Parametric examples have been provided to illustrate the applications of the conceptual design similarities between trees and manmade moment frames. It has been shown that an understanding of the structural performance of trees can enhance the structural design of moment frames, and that bioinspired PC can lead to minimum weight moment frames under lateral loading. The analogous performances of the natural and manmade structures may help explain the structural response of trees to similar loading scenarios.

Keywords: performance control, biomimetics, trees, moment frames, lateral loading

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1 Introduction

Nature makes purpose-specific materials one atom at the time, such as spider silk, wood *etc*. Humans have mimicked nature by creating synthetic materials also one atom at the time, *e.g*. Nylon, Kevlar, *etc*. It is therefore natural for humans to wish to understand how the same natural materials are used to create such magnificent structures as spider webs, trees, *etc*.

In the physical sense, the word ‘structure’ implies arrangement or putting together of material parts or elements in a purposeful manner and as such may apply to nano-systems, manmade objects as well as the entire universe. In the present context, structure is referred to manmade load bearing engineering frameworks. ‘Design’, in this context implies the thought or natural processes that may lead to the realization of a structure. Corporeal entities may therefore be characterized either as natural or manmade structures. Natural structures may be exemplified by such familiar objects as mountains and coral reefs, bird nests and eggshells, cobwebs and honeycombs, trees and plants, *etc*. Bridges, buildings, dams, transmission towers, pipelines, reservoirs, *etc*., are well known examples of engineering structures. While the history of earthly natural structures is as old as the planet itself, the history of modern structural engineering is hardly two centuries old[1,2]. While the ancient Egyptians, Greeks and Romans are credited with establishing the art of structural engineering the analytic understanding of the physical phenomena, underlying structural theories began during the Renaissance. Earthquake engineering, a sub-discipline of structural engineering, is only decades old and is still being evolved[3,4]. Both natural and manmade structures are realized through evolutionary design scenarios, both systems obey the same laws of nature and are subject to the same environmental conditions[5]. Loading energizes all structural systems, unloading discharges or reduces stored energy. The passage of time tests and deteriorates all structures. All structures are expected to withstand lifetime normal (service) as well as extraordinary (survival) environmental conditions. They are expected to

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endure certain degrees of damage and wear and tear. Natural, design-build methods tend to result in the most desirable (optimal) structural systems with respect to their functional response and environmental conditions, whereas the same cannot be claimed for manmade systems. Matteck[6] has shown that, “Trees optimize their mechanical design by adaptive growth, and react by self-repair to loads disturbing their optimum mechanical state.”

The purpose of this article is not to present a discourse on natural systems, but rather to propose a basis for a parallel approach between natural and synthesized design methodologies for type and loading specific structures. Nature does not preplan construction as humans do. Nature simply creates or builds as needed. Nature imposes its own laws of physics on things that it creates. Humans follow their limited knowledge of materials and applied mechanics and check the validity of computer generated end-results against prescribed criteria. Natural designs do not depend upon number crunching. Nature provides what is best for the purpose under the prevailing environmental conditions. Contemporary structural engineering relies mainly on investigating design related numerical output. The question that arises often is under what conditions and to what extent can humans mimic nature and impose their current knowledge of engineering sciences to what they plan to build? In other words, what are the differences and similarities between natural and human design philosophies and how can humans use natural design strategies, if it exists, to build engineering systems? The answer to these queries may be found in Vogel and Davis’s[7] assertion that the fundamental differences between natural and human strategies is in how these plans originate during the processes we refer to as design. Being mindful of such differences, the paper focuses on the similarities that may help improve manmade designs of engineering structures.

The article introduces a new facet of biomimicry or bioinspiration which attempts to unravel the natural design strategies involved in the structural performance of trees, rather than synthesizing new load bearing forms, substances and/or utilizing them as raw materials. The forthcoming parametric studies suggest that biomimicry can help transfer basic design concepts from trees to simple moment frames under lateral and/or combined loading conditions. Performance Control (PC) is a rational procedure that can help improve the design of manmade structures. The paper does not discuss the biological traits and evolutionary development of trees.

2 Natural systems, biomimicry and engineering structures

Biomimicry and adaptations from nature are the exercises in learning from nature and applying to manmade systems, and as such, are not new sources of inspiration for civil/structural engineers. Humans have been imitating nature since the beginning of time. The recorded history of learning from nature, mimicking a natural water tunnel, dates back to Ghanat (subterranean waterways) technology, in the Persian Empire, developed by an unknown genius some 3100 years ago[8]. The next noteworthy nature inspired structure, mimicking mountains and still standing, is the Step Pyramid in Egypt built by Imhotep, the first structural engineer/builder known by name in 2700 B.C.[9]. Humans are still using wood, dirt and rocks as basic building materials. Biomimicry and bioinspiration have already become part of formal architectural/civil engineering studies and have been utilized rather successfully to discover new materials, functional shapes and methods of achieving purposeful goals[10]. However, little has been said about similarities between natural and synthesized design strategies for functional structures and load bearing frameworks. Nature does not use processed or unnatural materials such as plastics, concrete and/or steel to build, it does not limit itself to such primitive design methodologies as elastic and/or plastic methods of approach. Civil/structural engineers are expected to design their structures to withstand loading combinations hypothesized by their peers. While biomimicry has helped engineers and architects achieve purposeful forms and functions for certain applications[11,12], it still remains to be seen if the underlying natural design concepts, in distinction to prescriptive methodologies, can be transferred into practical embodiments with true utility in manmade structures. In order to prepare for an answer, it seems reasonable to first identify as many natural characteristics as possible that may be in congruity with our current knowledge of the manmade world. Once the demand-response characteristics of a natural system are understood, they may be translated into feasible deign/demand requirements for prospective prototypes. An excellent account of transfer of mi-