CONCEPTUAL DESIGN IN STRUCTURAL ENGINEERING: AN EVOLUTIONARY COMPUTATION APPROACH[1]

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Abstract

This paper describes a new design paradigm, evolutionary structural design, that involves the entire design process, including conceptual and detailed design stages. In this paper, first a brief overview of the fundamentals of evolutionary computation is provided. Next, the concept of evolutionary structural design and its principia are discussed. Inventor 2001 is described in the following section. It is an experimental research and design system based on evolutionary computation. The system has been developed by the authors at George Mason University for applications in the design of tall buildings. Inventor 2001 allows for the conducting of evolutionary structural design, including the generation of structural concepts and the detailed design, analysis of internal forces, dimensioning, and optimization. Selected specific research results are also provided, including a discussion of the discovered emergent structural shaping patterns that are surprisingly consistent with the state of the art in structural shaping of steel skeleton structures of tall buildings. Finally, the initial research conclusions are provided.

1. Introduction

Structural design practice is undergoing significant changes, mostly driven by the ongoing Information Technology revolution. In the past, the use of computers in structural design was limited

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mostly to the detailed design stage, understood here as the analysis, dimensioning, and numerical optimization of structural systems. During the last 15-20 years, however, significant progress can be observed in design science, in computer science, and in computer engineering. In the area of design science, the significant research effort, mostly promoted and supported by the National Science Foundation (NSF) and by the National Aeronautics and Space Administration (NASA) in the USA, has already resulted in an improved understanding of the entire design process, including its conceptual design stage. In computer science, the area of evolutionary computation has matured up to the level where engineering applications, including structural design applications, are becoming not only feasible, but also desired for both engineering reasons (novel, safer, and simply better designs) and for economic reasons (less expensive and with improved constructability). Progress in computer engineering has resulted in the reduction of computing costs by a factor of 10,000 and in new generations of engineering computer workstations, which are much faster (by the order of 10^9) and easier to use than computers available only 15-25 years ago.

Integration of results from the above mentioned domains of Information Technology creates a synergy that may entirely change the nature of the use of computers in structural design and may lead to a new design paradigm, called by us "Evolutionary Structural Design," discussed in Section 3. Subsequently these changes may lead to rapid progress in the development of various design support tools and to a new structural design practice.

The Information Technology and Engineering School at George Mason University was established about 15 years ago to promote fundamental IT research and its transfer to engineering. Since the School's establishment, one of the most prominent research areas is evolutionary computation with work being conducted in the Evolutionary Computation Laboratory within the Computer Science Department. Also, research on the conceptual structural design was initiated in the Civil, Environmental and Infrastructure Department about 10 years ago. The integration of research in these two areas has led to several projects on the evolutionary structural design, supported mostly by the NASA Langley Research Center. The selected results of these projects are reported in this paper.

In this paper, a brief review of the fundamentals of evolutionary computation is presented. Next, the basic concepts of evolutionary structural design are discussed. Inventor 2001, an evolutionary design support tool, is also described as are examples of the results produced in various design experiments conducted in the area of the structural design of steel skeleton structures of tall buildings. Finally, the research conclusions are presented.

2. Evolutionary Computation

The concept of evolution has been originally proposed in biology as the mechanism behind the changes in the form and behavior of all living organisms [1]. However, the processes of long-term evolution can be also observed in engineering [2], and principia of evolution can be used in computer programs. Therefore, evolutionary computation (EC) may be used as a computational paradigm for a generation of structural design concepts that might never have been previously considered.

EC is a modern search technique inspired by the biological processes of evolution and selection. Concepts and mechanisms of Darwinian evolution and natural selection are incorporated in evolutionary algorithms. EC can be also understood as an optimization process in which a population of solutions undergoes a process of gradual change as indicated below:

1. Generation of the initial population of solutions ("parents")
2. Selection of parents to be reproduced
3. Reproduction
4. Selection of surviving members of a population
5. Repeat steps 2-4 indefinitely

The basic evolutionary process described above contains the minimal set of features of a process necessary to be a Darwinian evolutionary algorithm (EA). Even these simple EAs have surprisingly useful properties, especially attractive when dealing with difficult global optimization problems. They perform particularly well when applied to problems with nonlinear, stochastic, temporal, or chaotic components, where traditional optimization techniques like gradient descent, hill climbing, and purely random search are generally unsatisfactory. It is in this context that much of the work on engineering

applications has taken place historically: using simple EAs for numerical design optimization. The two main issues in applying EAs to any problem are:

1. Selecting an appropriate representation.
2. Providing an adequate evaluation function for estimating the "fitness" of generated individuals (points in the search space).

In the most straightforward representation, each gene represents a dimension of the search space. Each dimension can represent an appropriate set of values, discrete or continuous, a feature can take. In the simplest case, these representations use binary genes denoting the presence or absence of a feature. In these representations, each individual consists of a fixed-length binary string of genes, or a genotype, representing some subset of a given set of features. Often, in complex engineering applications, multi-valued attributes are more natural to use [3].

The second important step in successful application of EAs in engineering designing is choosing an appropriate fitness evaluation function to a problem domain. Evaluation functions provide EAs with feedback about the fitness of each individual in the population. EAs use this feedback to bias the search process in order to improve the population's average fitness. Naturally, the details of a particular fitness function are problem specific.

The two most commonly used reproductive mechanisms include mutation and recombination (or crossover). Mutation models single parent reproduction and operates by cloning a parent and then providing some variation by modifying one or more genes in the offspring's genome. Mutation is modeled by the mutation operator, acting on the offspring's genome, which defines the manner in which genes are to be modified and a mutation rate that specifies the amount of variation, i.e. how many genes on average will be modified. Recombination models multi-parent reproduction in which subcomponents of the parents are cloned and reassembled to create offspring genome(s). Traditionally, the recombination operator for fixed-length linear genomes takes the form of simple crossover operators where crossover points mark the linear subsegments on the parents' genomes to be copied and reassembled [4].

Common attributes shared by evolutionary processes which are relevant to engineering design processes include [5]:

- Little, if any, a priori knowledge of the search environment
- Excellent search capabilities due to efficient sampling of the design search space
- Ability to avoid local optima
- Ability to handle high dimensionality
- Robustness across a wide range of problem classes
- Provision of multiple feasible solutions
- Ability to locate the region of the global optimum solution

The evolutionary process may become a fundamental engineering design process and subsequently may be utilized in various design support tools. It offers true potential in the context of a holistic approach to engineering design understood here as that incorporating all aspects of developing a design, including qualitative (conceptual) and quantitative (numerical) aspects.

3. Evolutionary Structural Design

During recent years, several projects on evolutionary structural design have been initiated. The concept of integrated evolutionary structural design has been pioneered by Parmee [6]. Also, Grierson [7] initiated research on the design of architectural and structural layouts of office buildings using a multi-criteria genetic algorithm in a Pareto optimization. The last two authors of this paper began research in 1997 on the next generation of evolutionary design tools supporting an integrated "morphogenic" design process [8]. One such tool, Inventor 2001, is presented in the following section. For a more detailed the state of the art review see [3].

The structural design process is understood here as a process that starts when a need for a new structural system, or for a modification of an existing system, is realized. It ends when the final description of a future system, also called the "final design," is produced. The final design has two major components: a design concept and a detailed design. The design concept represents a qualitative or abstract part of the final design and is usually presented in abstract terms, for example: a

pre-stressed concrete beam, or a steel K-truss. It is usually described using symbolic (qualitative) attributes, for example: type of connection (rigid, flexible, etc.) or kind of material (steel, concrete, etc.). The detailed design contains all numerical (quantitative) information about the future engineering system, for example: its dimensions and other quantitative characteristics. When the entire design process is considered, two stages can be distinguished that take into account the nature of the results (qualitative or quantitative). The first stage produces a design concept, or design concepts, is usually called the "Conceptual Design Stage," or simply "Conceptual Design." The second stage that produces a detailed design is usually called "Detailed Design Stage," or "Detailed Design." Usually, the design process is conducted sequentially. Both the conceptual and detailed design stages are completed independently, often by different designers. In the traditional structural design the first stage is usually conducted by a designer who arbitrarily selects, or develops, a design concept, evaluates it and decides about its feasibility. In the second stage, the selected design concept is used to produce the final design through the process of analysis, dimensioning and numerical optimization. Currently, various computer design support tools are available only for the second stage of the structural design process, for example a system called SODA [9].

In the traditional structural design, only a very limited number of design concepts are produced and subsequently evaluated by a designer. Sometimes, several design concepts are selected and concurrently evaluated. More often, a single design concept is developed and evaluated. If it is found infeasible, it is modified, or evolved, by the designer and evaluated again. Because of this practice, evolution seems to be a natural way for engineers to produce design concepts, although only manually and considering only a small number of design concepts. When evolutionary computation is used to produce designs an integrated design process can be developed. In this case, the conceptual and detailed design processes are integrated and a human designer can be eliminated from the loop while the evaluation and selection of design concepts are automated. Thus, the human designer receives complete final designs containing both design concepts and the detailed designs with all numerical information. The evaluation of such final design concepts is easy because the quantitative design features can be formally assessed.

4. Inventor 2001

Inventor 2001, an experimental evolutionary computation support tool, has been developed at George Mason University in the Information Technology and Engineering School [10]. It is intended for design experiments in the domain of structural designs of tall buildings and produces both the design concepts as well as detailed designs. The system has six major components:

1. Evolutionary Computation Component.
2. Feasibility Filter.
3. Structural Analysis, Design and Optimization Component (SODA).
4. Wind Forces Analyzer (WindLoad).
5. Evaluator.
6. Visualization Component.

Steel skeleton structures are considered by Inventor 2001 as planar transverse designs. Three-bay structures that have 16-36 stories are the subject of interest. Allowable bay widths include 20, 24, or 26 feet, and story heights may be 10, 12, or 14 feet. Representation of designs of steel skeleton structures in tall buildings includes six types of diagonals (K, X, \ and /, simple X, and V), two types of beams (rigid and hinged), and two types of ground connections (rigid and hinged).

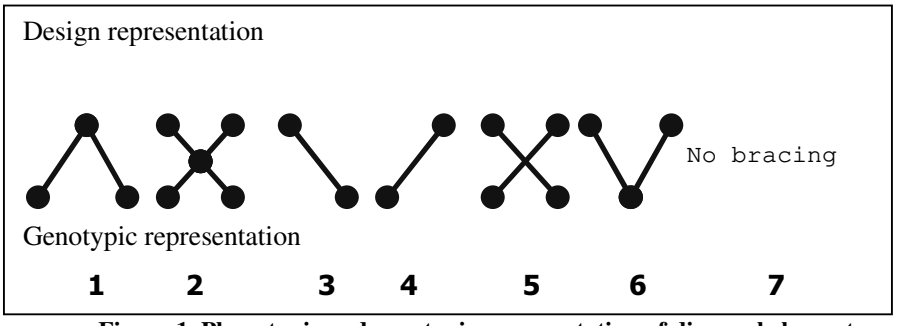

Figure 1. Phenotypic and genotypic representation of diagonal elements

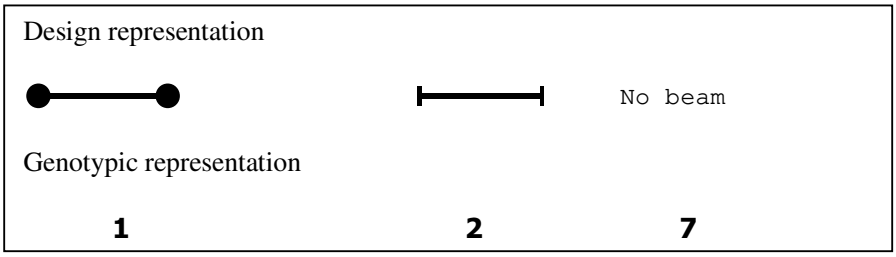

Figure 2. Phenotypic and genotypic representation of beams

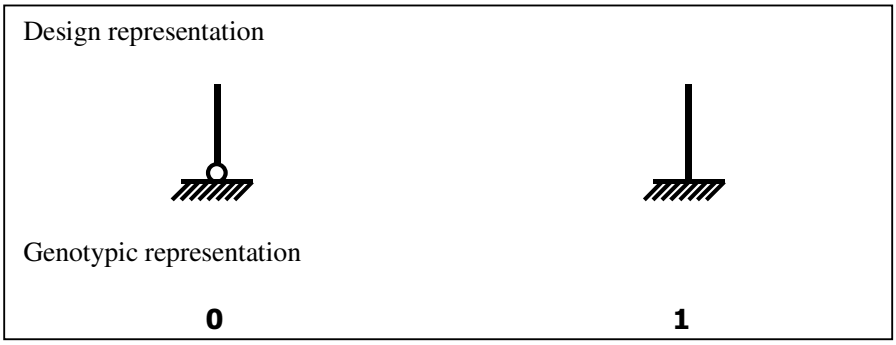

Figure 3. Phenotypic and genotypic representation of ground connections

Several requirements can be imposed on the structural system designs: symmetry, one or more vertical trusses, and one or more horizontal trusses. The structural analysis of generated designs is conducted by SODA. In the analysis, dead, live, and wind loads, as well as their combinations are considered. The structural elements are designed using several groups of sections for beams, columns, and diagonals, i.e. 61 groups of sections for each structural system. In SODA, the structural analysis can be conducted using either first order or P-Δ analysis; however, in the experiments described in this paper only the first order analysis was used.

Evolutionary algorithms operate on genotypes representing the following elements of the steel skeleton systems: beams, diagonals, and ground connections. These elements are described by multi-valued attributes that are integer encoded as genotypes. In the process of evolution, fixed-length representations are used for evolved steel skeleton structure designs. However, the length of the genotype depends on the height of the building. Six genes (attributes) represent each story. Three of these attributes are seven-value attributes (diagonals, see Figure 1) and the remaining three are three-value attributes (beams, see Figure 2). The four last genes in a genotype describe ground connections. These genes can have only two values (see Figure 3). Thus, depending on the height of a building, our genotypes may contain from 100 genes (16 stories) to 220 genes (36 stories).

5. Design Experiments and Results

The objective of the experiments described in this paper was to determine the feasibility of evolutionary computation as an optimization procedure in design of steel structural systems, as well as a search for novel structures and/or substructures emerging during evolutionary processes. Our objective has been accomplished through the analysis of the results of a number of design experiments involving the following class of structural systems:

- Number of bays: 3 bays
- Structure height: 36 stories
- Bay width: 20 feet
- Story height: 14 feet
- Distance between transverse systems: 20 feet
- Requirements: No requirements imposed or symmetry
- Analysis method: First order

Evolutionary processes were started using initial designs selected from a set of 12 feasible designs chosen by authors. The initial group of 12 parents consisted of designs that were considered

as (sub-)optimal, as well as designs that were characterized as rather poor for this class of buildings. Three examples of the initial set of designs are shown in Figure 4.

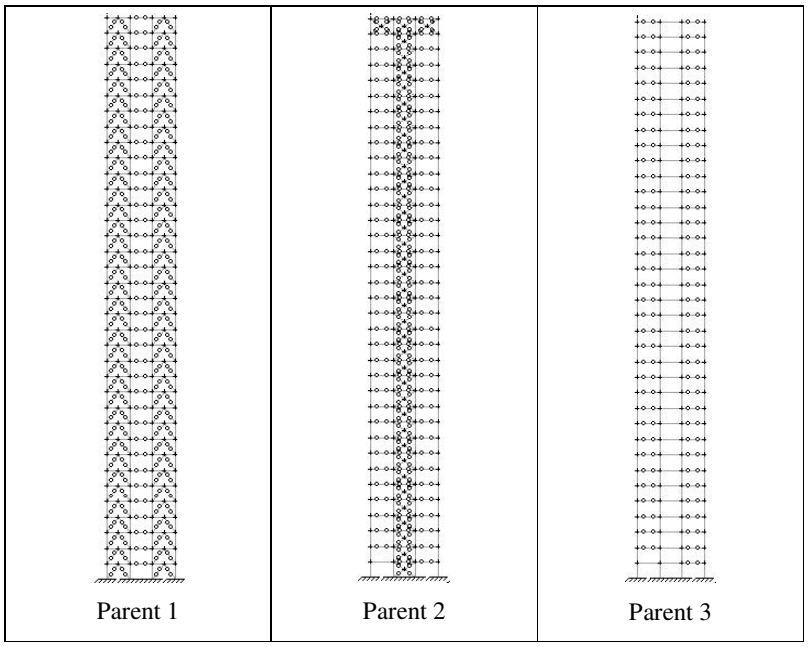

Figure 4. Examples of initial parents for evolutionary processes

In the performed experiments, various EA parameters have been used. Population sizes used in experiments consisted of either 3, 9, or 12 designs. The offspring population consisted of 5 individuals per parent. Mutation and crossover rates were set as either fixed values throughout the entire evolutionary processes (from range 0.10-0.90), or randomly defined by the system at each generation. Design experiments were performed as both short evolutionary processes (100-1,000 generations), medium-length processes (1,000-5,000 generations), and long-term processes (more than 5,000 generations). Interesting comparisons between short-term and long-term processes have been presented in [11]. Typical 'best-so-far' curves for several independently evolving populations of steel structural systems are presented in Figure 5. As one can easily see, evolution generates fitter solutions throughout the run and hence optimizes the structural system designs. What can also be noticed in this figure, is the fact that the optimization progress rate is sensitive to the initial conditions (initial parent population).

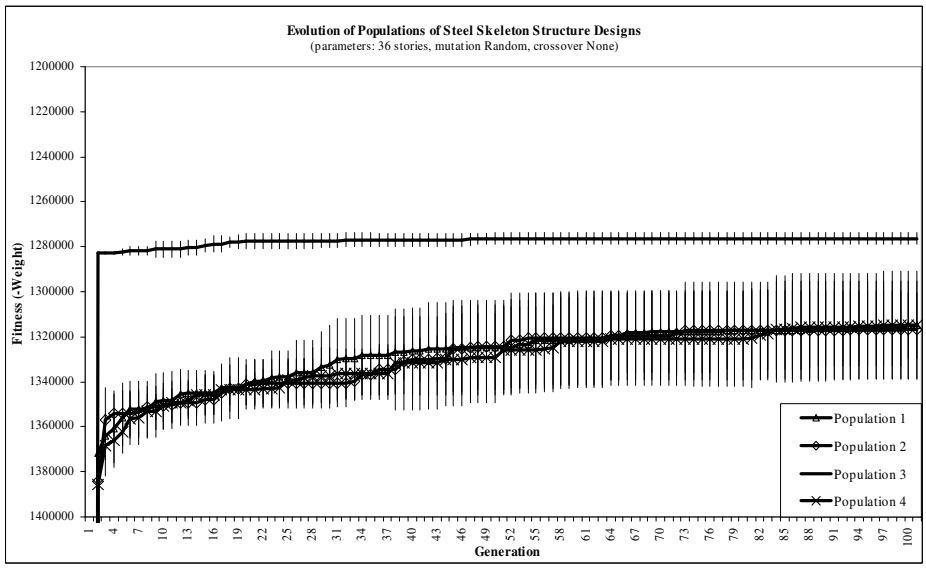

Figure 5. Examples of initial parents for evolutionary processes

In addition to testing the outcomes of various experiments from the optimization viewpoint, a search for novel designs of steel skeleton structures in tall buildings has been conducted. This search considered both qualitative aspects of the designs' topologies and quantitative changes of characteristic attributes describing the structure (like total weight, number of K bracings, etc.). During the qualitative analysis, emerging patterns at the level of entire structures, as well as multistory substructures, were sought.

Figure 6 presents a part of a structural system of a tall building where emergent 3-story substructures have been identified. The rightmost part of this figure presents a photo of a recently built tall building in Hong Kong that uses exactly the same pattern of structural bracing as the one found in our experiments. Emergent behavior during the evolutionary processes has also been observed on several other levels. As our experiments have shown, interesting patterns usually occurred during rapid changes in the value of the fitness function. To further investigate this issue, characteristic attributes describing the structure have been analyzed at such time steps of rapid fitness gain. It has been found that significant improvements were possible by "large scale" replacements of various members of the structural system. For example, in one of the instances a significant number of X bracings was replaced with K bracings, accompanied by the similar change in the number of fixed beams and hinged beams.

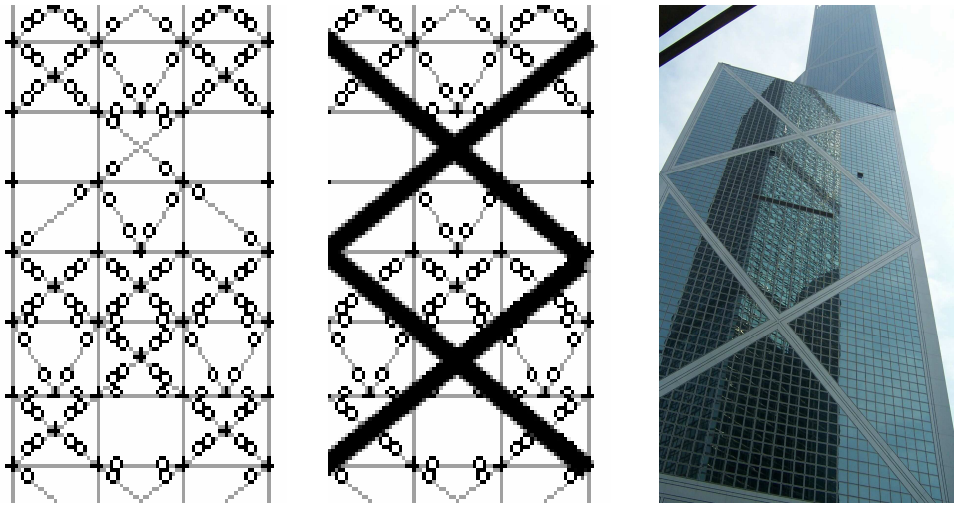

Figure 6. Emerging substructures in evolving designs compared to the state-of-the-art

Another interesting behavior exhibited by the evolutionary design processes consisted in not only forming multistory substructures but generating various types of substructures that were subsequently embedded in different places of the steel skeleton system. Thus, evolution has "learned" to generate substructures with very few diagonal elements in the top part of the building where forces are the smallest. In the middle part of the structure, there have been other substructures consisting of more elements; and in the bottom part where the forces have maximum values, the substructures were very dense with bracing elements. A more detailed analysis of this phenomenon can be found in [12].

6. Conclusions

Evolutionary computation is an emerging paradigm for calculations both during the conceptual and detailed design stages. It is particularly attractive in the area of structural design, as demonstrated in this paper. Ultimately, evolutionary computation may lead to the development of a new generation of evolutionary design support tools that will allow full automation of the structural design. In this case, the designer will be able to consider a large number of final and complete designs produced in a short time. This ability will ultimately lead to more novel structural designs and to reduced design and construction costs.

Acknowledgment:

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