CHAPTER 1

INTRODUCTION

The use of trusses as the key structural systems in the construction of industrial and residential buildings has increased in many developing countries. The majority of the material used to fabricate the truss structures is steel because it provides an economical solution in terms of short erection time and high strength-to-weight ratio. In designing a steel truss, it is essential to obtain an optimum section for each of the truss members that minimizes the overall costs of the truss construction. The cost minimization objective can generally be expressed as a function of various governing parameters, such as the self-weight of the truss members as well as their cross sectional areas to be minimized, with certain constraints on the structural behavior of the designed truss. In this process, a logical combination of several fields, e.g. minimization algorithms, finite element method, nonlinear analysis, etc. must be involved.

In the current structural steel design procedures (e.g. AISC-ASD, LRFD, PD), a whole truss would be analyzed prior to the determination of the member cross-sections. Because of the fact that some of the input data are not known in advance, some parameters, such as the member cross sections, have to be assumed. It is therefore necessary to check for the strength and the stability of the whole structure after the analysis process. In case that any of the structural member does not satisfy the checking criteria, the cross-section of that member needs to be changed, resulting in the change of the total self-weight as well as the stiffness of the truss. As such, the previous analysis results are somehow shifted, and can no longer be used for designing the truss. These approaches do not give an accurate indication of the factor against failure, because they do not consider the interaction of strength and stability between the structural system and its member at the same time. Furthermore, in the current specifications the individual member strength equations are not concerned with the system compatibility. There is no verification of the compatibility between the isolated member and the member as part of a frame. As a result, there is no explicit guarantee that all members will sustain their design loads under the geometrical configuration imposed by the frame system.

The current design methods also lack certain considerations on the structural behaviors. That is, the stresses and displacements are determined by elastic analysis, while the strength and stability are determined separately by inelastic analysis. In order to partially overcome these limitations, two key considerations – material and geometry – must be accounted for in the process of truss analysis. By taking into account these sources of nonlinearities in truss analysis, one can predict not only the individual member strength but also the limit state strength and the stability of the whole truss. The capacity check for separate truss members is no longer required. This will simplify the design process considerably, and will be more convenient for automatic design.

In the current design procedure, a bar passing all the checking conditions may not be the most economical answer. This leads to a sizing optimization problem, which is the selection of an optimal set of cross sections for the members of the truss. Several sizing optimization techniques are available in the context of engineering design optimization. However, there is no single technique that provides the most efficient, robust and accurate solution to all structural optimization problems.

The optimization technique that has received considerable attention in the past few decades is genetic algorithm (GA). Originated by Holland (1975), GA is a search strategy based on the rules of natural genetic evolution. GAs randomly create an initial set of possible solutions, each of which is represented as an equivalent string of genes or chromosomes that will be later combined with genes from other individual strings. As in a biological system subjected to external constraints, the fittest members of the initial population are given better chances of reproducing and transmitting parts of their genetic heritage to the next generation. It is expected that some members of the new population will acquire the best characteristics of both parents and, being better adapted to the environmental conditions, will provide an improved solution to the problem. The process is repeated many times, until all members of a given generation share the same genetic heritage (or the processing time is over). The members of these final generations, who are often quite different from their ancestors, possess genetic information that corresponds to the best solution to the optimization problem.

It has been shown that, by using a Darwinian-inspired natural selection process, GAs will gradually converge towards the best-possible solution (Turkkan 2003). Furthermore, GAs do not require gradient or derivative information. For this reason, it has been applied by researchers to solve discrete, non-differentiable, combinatory and global optimization engineering problems (Chen 1997). The algorithm is certified its well scientific theory but provides a mathematically less complex and full potential perspective in general applications. Nevertheless, when faced with a conflict between precision, reliability and computing time, the original GAs often result in an unsatisfactory compromise, characterized by a slow convergence and lack of precision. Many approaches have been proposed to improve the original GAs (Sakamoto and Oda 1993; Adeli and Cheng 1993; Soh and Yang 1996; Ramasamy and Rajasekaran 1996; Parmee *et al.* 1997; Leite and Topping 1998; Camp *et al.* 1998; Nair *et al.* 1998; Groenwold *et al.* 1999; Botello *et al.* 1999). The current study aims to investigate a suitable enhancement scheme of GAs for the sizing optimization of the planar steel trusses.

This study consists of two major parts. With the planar steel truss design as the primary objective, the first part deals mainly with the analysis of the truss structure, taking into consideration both types of nonlinearities – material and geometry – in the analysis process. It is expected that the proposed methods will be able to better predict the trusses in the working state, and will simplify the design process considerably. The second part of the study investigates sizing optimization of the truss using an enhanced genetic algorithm. This study practically sets the initial stage for the more complex structures, such as plane frames, spatial trusses, etc.

1.1. Literature Review

1.1.1 Methods of Truss Analysis

Early research works on stability and buckling of structures have mostly concentrated on the behavior of the structural members. Bleich (1952), Goodier (1942; 1964), Vlasov (1961) and Timoshenko and Gere (1961) are among the pioneers to study buckling of one-dimensional structural members. The methods of column deflection curves (Ellis *et al.* 1964), finite difference (Vinnakota *et al.* 1974) and finite integral (Brown and Trahair 1968) have been proposed for solving the differential equilibrium equation for columns and beams. The Rayleigh–Ritz (1981) method, based on a correctly assumed deflected shape, has also been proposed in the literature but was limited to simple problems where the deflected shape of the structures can be defined accurately.

Many researchers have presented various practical advanced analysis methods for steel frames taking into account the material and geometrical nonlinearities. For the geometrical nonlinearity, the stability functions, have been adopted to capture the second-order effects associated with P-δ and P-Δ moments in order to minimize the modeling and the solution finding time (Chen and Lui 1992). A softening plastic hinge model has been used to represent the degradation from elastic to zero stiffness associated with development of a hinge (White and Chen 1993). For the material nonlinearity, the Column Research Council (CRC) tangent modulus concept has been proposed to account for the gradual yielding due to the residual stresses (Liew *et al.* 1993), in which the modified incremental displacement method can be used as the solution technique (Kim *et al.* 1996). As an extension of the analysis, a sizing optimization of the steel frames can be performed by using the direct search method. The objective function in this problem is the weight of the structure, and the constraint functions are the load-carrying capacity, the lateral drift, deflection, and the ductility requirements (Kim *et al.* 2001).

The application of the new design method to three-dimensional trusses has also been presented in which the geometrical nonlinearity is considered using the updated Lagrangian formulation (Ovunc and Ren 1996) and the material nonlinearity is implemented using the Column Research Council (CRC) tangent modulus. The proposed analysis provides inelastic behavior and information on the failure mechanism (i.e., buckling or yielding). Because the analysis accounts for both material and geometrical nonlinearities, separate member capacity checks after the analysis are not required.

The advantages of the advanced analysis methods are (Choi and Kim 2002):

1. The analysis can practically account for all key factors influencing the behavior of a space frame: gradual yielding associated with flexure; residual stresses; geometrical nonlinearity; and geometrical imperfections.

2. The analysis overcomes the difficulties due to incompatibility between the elastic analysis of the structural system and the limit state member design in the conventional LRFD method. Separate member capacity checks encompassed by the

code specifications are not required, because the stability of separate members and the structure as a whole can be rigorously treated in determining the maximum strength of the structures.

3. The analysis can account for inelastic moment redistribution and thus may allow some reduction of the steel weight, especially for highly indeterminate space frames. This advantage is still expected to be effective for the semi-rigid planar trusses.

4. When the proposed optimal design method is used for the planar portal frame and the space two-story frame, the weights can be reduced by 8.0% and 3.7%, respectively, compared with the conventional design method.

Nonetheless, since various analysis methods that account for the material and the geometrical nonlinearities are available, these methods need to be carefully evaluated before using in the current study.

Fafitis (2002) has proposed a special method for nonlinear structural analysis. The novelty of the method is that only one stiffness matrix inversion is required without the need for updating and re-inverting the matrix at every load increment. This stiffness matrix is not necessarily the actual stiffness matrix of the structure. Instead, any stiffness matrix compatible with the geometry and the constraints of the structure can be used. The advantage of this option is that if the design of some members is revised, the already inverted and stored matrix can still be used for the analysis of the revised structure. Even with the limitation that the method is applicable for trusses with only the material nonlinearity, but its advantage in matrix processing may be useful for the current study.

1.1.2 Genetic Algorithms

Genetic algorithms (GAs) are stochastic search techniques based on the mechanics of natural selection and natural genetics. GAs combine survival of the fittest among string structures with a structured yet randomized information exchange to form a search algorithm. In order to surpass their more traditional cousins in the quest for robustness, GAs are different from other traditional optimization and search procedures in four very fundamental ways (Goldberg 1989):

- GAs work with a coding of the parameter set, not the parameters themselves;
- GAs search from a population of solutions, not a single solution;
- GAs use payoff (objective function) information, not derivatives or other auxiliary knowledge; and
- GAs use probabilistic transition rules, not deterministic rules.

The fittest members of the initial population are given better chances of reproducing and transmitting parts of their genetic heritage to the next generation. A new population is then created by recombination of parental genes. After it has replaced the original population, the new group is submitted to the same evaluation procedure, and later generates its own offsprings. The process is repeated many times, until all members of a given generation share the same genetic heritage. From then on, there are virtually no differences between individuals.

The members of these final generations, who are often quite different from their ancestors, possess genetic information that corresponds to the best solution to the optimization problem (Holland 1975).

An essential characteristic of GAs is the coding of the variables that describe the problem. For a specific problem that depends on more than one variable, the coding is constructed by concatenating as many single variable codings as the number of the variables in the problem. The length of the coded representation of a variable corresponds to its range and precision. By decoding the individuals of the initial population, the solution for each specific instance is determined and the value of the objective function that corresponds to this individual is evaluated. This applies to all members of the population. There are many coding methods available, such as binary, gray, non-binary, etc. (Jenkins 1991a; 1991b; Hajela 1992; and Reeves 1993). The most common coding method is to transform the variables into a binary string of specific length.

The basic parameters of GAs include population size, probability and type of crossover, and probability and type of mutation. By varying these parameters, the convergence of the problem may be altered. Thus, to maintain the robustness of the algorithm, it is important to assign appropriate values for these parameters (Pezeshk and Camp 2003). Much attention has been focused on finding the theoretical relationship among these parameters. Schwefel (1981) has developed theoretical models for optimal mutation rates with respect to convergence and convergence rates in the context of function optimization. De Jong and Spears (1990) have presented theoretical and empirical results on the interacting roles of population size and crossover in genetic algorithms. Cvetkovic and Muhlenbein (1994) have investigated the optimal population size for uniform crossover and truncation selection.

The initial population, which might have been very far from the satisfactory solution, can adapt itself toward the optimized solution. Conversely, mutation tends to disorganize the convergence of the problem; therefore, the mutation rate, in conjunction with the population size, is crucial to the overall performance of GAs (Pezeshk and Camp 2003).

1.2. Research Objectives

The current study consists of two main parts. The first part investigates advanced analysis methods for the planar steel trusses, taking into account both types of nonlinearities – material and geometry. The second part examines possible enhancement of GAs for sizing optimization of the planar steel trusses. It is expected that the proposed algorithm will be able to better predict the behavior of the trusses in the working state, and simplify the design process.

The key objectives of the current study can be listed as follows:

- To incorporate the material and geometrical nonlinearities into the existing analysis methods in order to better predict the planar steel trusses in the working state.

- To implement the modified structural analysis method into the sizing optimization problem of planar steel trusses using GAs.
- To examine possible GA enhancement schemes to be used for sizing optimization of the planar steel trusses.

1.3. Scope of Research

The current study aims at the development of a structural analysis program for the planar steel trusses that accounts for the material and geometry nonlinearities without considering the out-of-plane effects.

In order to incorporate the output from the structural analysis program with the optimization process, a penalty function shall be employed to account for three types of constraints – the ultimate load carrying capacity, the serviceability and the ductility – in accordance with the AISC\LRFD specification.

The current study aims at also the utilization of an enhanced genetic algorithm for sizing optimization of the planar steel trusses. The objective function is computed as the total self-weight of the truss members, which are selected in accordance with the practical section table in the AISC\LRFD design specification. The efficiency of the program shall be assessed using standard benchmark problems.

Note that the objective function used for the sizing optimization of the planar steel trusses is its weight (or equivalently, its total volume) instead of its cost. Even though the cost is a function of the weight, using the cost as the objective function is more complicated since it entails certain aspects, such as maintenance, machinability, number of connections, material, etc., that there is no exact relationship for. Further, cost can vary considerably from one time horizon to the next. Consequently, in this study the problem is formulated using the weight as the objective function.