DESIGN OPTIMIZATION OF STEEL FRAMES WITH BUILT-UP TAPERED SECTIONS USING SIMULATED ANNEALING METHOD

By

Tamer Mohamed Mahmoud Seleem

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
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in
Structural Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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Under the Supervision of

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Key Words:
Design optimization; Simulated annealing; Tapered members; Design steel frames.

Summary:
Design of steel frames with non-uniform cross-section members is always a complex problem. In this study, an algorithm is presented for the optimum design of steel frames with tapered built-up I sections based on simulated annealing (SA) method. Flexural and axial constraints of the AISC 2005 code (Allowable Stress Design- ASD) are applied. The strength constraints take into account the lateral-torsional buckling resistance of frame segments between the adjacent lateral restraints. Each frame member consists of one or more segments; each segment has a linearly varying depth, while the flange width is constant for each segment, it may vary from segment to segment each segment. The depth at the start and end of each segment, top and bottom flange thickness and, flange width are all design variables used in the formulation of the design problem. Frame members are totally laterally restrained at joints, extra restraint points can be optionally added between joints. By applying the algorithm several design cycles are performed, the values of the design variables are changed at each design cycle. The cost function is presented by the total frame weight. The search terminates when the temperature (search step size) has fallen substantially where, no more economical frame weight can be obtained. All design variables treated as discrete values, hence, the problem is classified as a discrete design optimization problem. Because the problem has too many design variables, heavy computation capacity is needed. Web depths are the dominant design variables, the simulated annealing (SA) method is used to search for the optimum web depth, and the process is continued until convergence is obtained. Verification and numerical examples are presented to demonstrate the practical application of the algorithm; also a comparison is made with another algorithm used in the literature.

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Dedication

This thesis is dedicated to the soul of my father and to my mother, who always encouraged and supported me all the way long.

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Abstract

Design of steel frames with non-uniform cross-section members is always a complex problem; computer is widely used in such design problems. In this study, an algorithm is presented for the optimum design of steel frames with tapered built-up I sections based on simulated annealing method. AISC 2005 code (Allowable Stress Design- ASD) flexural and axial constraints are applied to all frame members in the formulation of the design problem. The strength constraints take into account the lateral-torsional buckling resistance of frame segments between the adjacent lateral restraints. Each frame member consists of one or more segments; each segment has a linearly varying depth, while the flange width is constant for each segment, it may vary from segment to segment, the depth at the start and end of each segment is treated as a design variable, top flange thickness, bottom flange thickness and, flange width are all design variables used in the formulation of the design problem. Frame members are totally laterally restrained at each frame joint, extra restraint points can be optionally added between joints, they are restraining the I section at flanges; one flange or both flanges can be restrained. By applying the algorithm several design cycles are performed, the values of the frame design variables are changed at each design cycle. The cost function is presented by the total frame weight. While searching for the optimum solution the temperature (search step size) decreases linearly because of the cooling factor (f), the search terminates when the temperature has fallen substantially where, no more economical frame weight can be obtained. All design variables treated as discrete values, hence, the problem is classified as a discrete design optimization problem. Because the problem has too many design variables, heavy computation capacity is needed. Web depths are the dominant design variables, the simulated annealing (SA) method is used to search for the optimum web depth, and the process is continued until convergence is obtained. Exact analysis is performed during all design cycles to check the validity of the proposed solutions. Verification and numerical examples are presented to demonstrate the practical application of the algorithm; also a comparison is made with another algorithm used in the literature. The cooling factor (f) effect on the optimization process is also studied.

Chapter 1 Introduction

With lots of advantages, lightweight steel portal frame structures with tapered members have been broadly used and become one of major structures used in these years. The span and the height of the structure are become more and more large, tapered members become more and more usual since they allow significant material savings and consistent design.

Despite these advantages, the use of tapered members suffers from the lack of appropriate simple but accurate design formula in most codes of practice. Taper effects are rather badly accounted for. [1] In the present study a design computer algorithm is created to design continuous beams subject to flexure and shear effects and to design portal frames subject to flexure, shear and, axial loadings.

1.1. Main advantages of Steel Structures

Steel is a universally used material. It is used either separately or combined with other material, e.g. reinforced concrete. Its popularity may be attributed to the combined effects of several factors, the most important of which are, it possesses great strength, exhibits good ductility, ease in fabrication, and is relatively cheap. In addition, steel is the ultimate recyclable material. Several advantages are listed in Table 1-1 below.

Table 1-1 Advantages of steel structures

Item	**Comments**
Ease of erection	No formwork needed and minimum cranage required for the erection, many parts of the structure can be prefabricated away from the site, and it is largely self-supporting during erection.
Modifications	Either extensions or strengthening is relatively straightforward. Possible reuse after a structure is disassembled or scrap value even though not reusable.
Uniformity	The properties of steel do not change appreciably with time, as do those of reinforced-concrete structures.
Low self-weight	Permits large clear spans without intermediate columns
Dimensional control	Prefabrication in the workshop ensures accurate work and quality control.
Properties	structural steel has well-defined physical and mechanical characteristics [6]
Accuracy	design constraints using structural steel can be satisfied more accurately and at less computational cost compared with using other, more nonlinear, materials such as reinforced concrete material (AASHTO 1983) [6]

1.2. The Design Process

The design of structural steelwork is a process that is based on many contributing aspects: past experience of successful and unsuccessful construction, laboratory tests and results of research, combining to ensure structures do not fail. Structures can therefore be used efficiently and safely but at the same time must be economically built and maintained.

From this it can be understood that the design process must satisfy two conflicting aims; economy and safety. Achieving this compromise is not an easy task, consequently codes of practice have evolved to assist and guide the designer. However different national codes, for example British and American codes of practice treat the design problem differently. This may be because the behavior of steelwork frames, for instance, is not well understood because methods of design are still at an elementary stage of development. This may be due to the fact that the problem of design is much less specific than that of analysis.

The question of design or synthesis, involves generating member sizes which are satisfactory in all respects, under all loading conditions. In most cases, an unlimited number of designs will meet these requirements. More realistic designs are based strictly on a trial and error process. The design process starts with the analysis step. The analysis is performed on an initial member properties or what is called an initial solution, after analysis the whole structure is checked against design code requirements for strength and serviceability with any additional constraints required by the user, this is called the checking step. By the end of the checking step some parts of the structure will be under-designed (unsafe) and some others will be over-designed (safe), at this point all parts have to be safe by increasing sizes at where the structure is unsafe. The next step is to analyze the safe structure and a checking step is done again and over-design parts will be reduced in size to obtain more optimum structure. The steps are repeated several times until the optimum weight structure is reached and sizes cannot be reduced anymore.

1.3. What is Optimization?

The prime objective of structural engineers throughout design history has been to obtain the optimum structure under the prescribed design condition which can not only withstand external loads safely but also achieve economic solution.

Optimization is a procedure through which the best possible values of decision variables are obtained under the given set of constraints and in accordance with a selected optimization objective function.

Also it can be defined as Finding an alternative with the most cost effective or highest achievable performance under the given constraints, by maximizing desired factors and minimizing undesired ones. In comparison, maximization means trying to attain the highest or maximum result or outcome. From the previous section one can address several difficulties that may face the structural designer when utilizing conventional design. Firstly, the skill and experience of the designer, which could lead to completely different designs. Secondly, the complexity of the treated structure makes the process of performing several re-analyses and subsequent redesigns difficult. Thirdly, there is a difficulty in handling all possible loading cases. Fourthly, the intended usage of the structure might prevent the designer from achieving economical design. Fifthly, the alternative design and analysis techniques might confuse the designer in choosing the appropriate technique. Therefore, the use of computers has made reliable and accurate analysis much easier, and the speed with which alternative solutions can be analyzed makes it possible to achieve more economical designs than were attainable in the past. Design optimization is therefore an interesting research topic, and several suggestions and recommendations for design optimization have been made by design experts among them. Design optimization is concerned with the problem of the selection of geometric parameters and mechanical strength properties of the structural elements. This selection consists of a search for the external solutions, which satisfy the prescribed criteria, the search being conducted in an objective and rational way that does not rely on the intuition or special abilities of the designer. Thus, design optimization takes over that part of the design process, which consists of selecting sizes and subsequently checking that the required criteria have been met. The question arises whether the design optimization field can or should fully replace traditional designing procedures, that is, whether or not the task of optimization is to embrace all structural parameters so that the solution of an optimization problem should be equivalent to obtaining a complete design of a structure. This question will be answered in this research.

1.4. Main Features of a Structural Design Optimization Problem

In the case of simple elements or even the whole structure, it is possible and necessary to take into account all requested design criteria in the formulation of an optimization problem. This is exemplified by the classical simple design optimization problem. If the structural steelwork is more complex, however, the problem of including all design criteria in the optimization may prove impossible to solve by gradient-based techniques like linear and non-linear programming algorithms as search methods. In such cases it is advisable to include only some of the parameters in the formulation of the optimization problem. Unfortunately, however, very few physically meaningful problems in structural design, if any, can be formulated directly as linear programming (LP) problems without involving a degree of simplification. Most structural design problems involve highly non-linear constraint and objective function relationships. In addition, the relationships between the design variables, which are the members of the structure, are unknown. No one optimization algorithm can possibly be efficient or even successful in all cases of interest. If all design problems involve objective functions that were quadratic, with analytic derivative, then life would be simple. However, in design practice, it is well known that many problems are vastly more complicated than this. What is worse, often the function that we are attempting to optimize is not analytically available. It is only known in the form of a computer code that evaluates the function point by point.