DESIGN, ANALYSIS AND FABRICATION OF WELDED STRUCTURES

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Contents

Summary

Basic problems of mechanics of welded steel structures are treated: residual welding stresses and distortions, torsion of thin-walled rods, overall buckling of compression rods, lateral-torsional buckling of beams, stability of beam-columns, local buckling of plates, vibration and damping, fatigue of welded joints, effect of post welding treatments for fatigue. Fatigue design of fillet welds connecting a welded I-section cantilever to a column is treated. In stability problems the effect of initial imperfections and residual welding stresses is considered.

Structural optimization is the modern design system, which enables cost savings and selection of innovative structural versions. The structural volume, mass or cost is formulated as the objective function, design and fabrication constraints are taken into account according to up-to-date design rules. Mathematical methods for constrained function minimization are summarized and applied to minimum mass and cost design of welded beams, tubular trusses, frames, stiffened plates and shells. By means of the simple formulae derived by optimization of welded I- and box beams it is possible to compare the characteristics of various types of sections and beams, which can be useful for designers.

A plate stiffened on one side and a cellular one are compared to each other in the case of longitudinal stiffeners and uniaxial compressive force and it is concluded that the cellular plate is more economic because of its larger torsional stiffness.

The problem relating to the economy of shell structures how to achieve cost savings by using thinner stiffened shells instead of thick unstiffened ones is treated for different cases of loading and form of shells. A ring-stiffened circular cylindrical shell is more economic than an unstiffened one in the case of external pressure, since these shells are very sensitive against buckling for this load.

1. Introduction

Welded structures are widely applied in all industrial fields. The following photos illustrate this fact.

Photo 1. Wind turbine tower

Photo 2. Press frame

Photo 3. Crane

Photo 4. Offshore platform

Photo 5. Bridge

Photo 6. Chemical plant

Photo 7. Pressure vessel

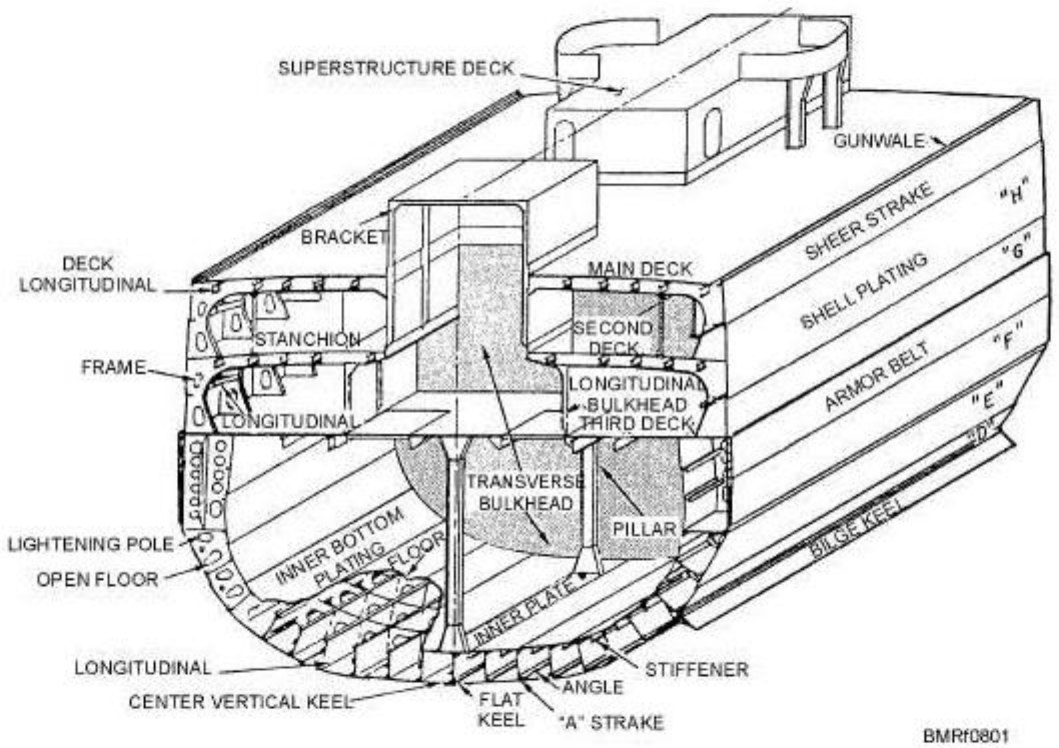

Photo 8. Ship

The most suitable means to treat the design of welded structures is the optimum design system. Structural optimization is a design system for searching better solutions, which better fulfil engineering requirements. The main requirements of a modern load-carrying structure are the safety, fitness for production and economy. The safety and producibility are guaranteed by design and fabrication constraints, and economy can be achieved by minimization of a cost function.

The optimum design procedure can be formulated mathematically as follows: the objective function should be minimized

$$f(x) \to \min, x = \left(x_1,...,x_n\right)$$

subject to constraints

$$g_j(x) \le 0, j = 1...p$$

where n is the number of unknowns and p is the number of constraints. The solution of this constrained function minimization problem needs effective mathematical methods.

The above description shows that the structural optimization has four main components: (1) *design constraints* relate to stress, stability, deformation, (2) *fabrication constraints* formulate the limitation of residual welding distortions, requirements for welding technology, limitations of plate thicknesses and main structural dimensions, definition of available profile series, (3) *a cost function* is formulated according to the fabrication sequence and contains the cost of materials, assembly, welding and painting, (4) *mathematical methods*.

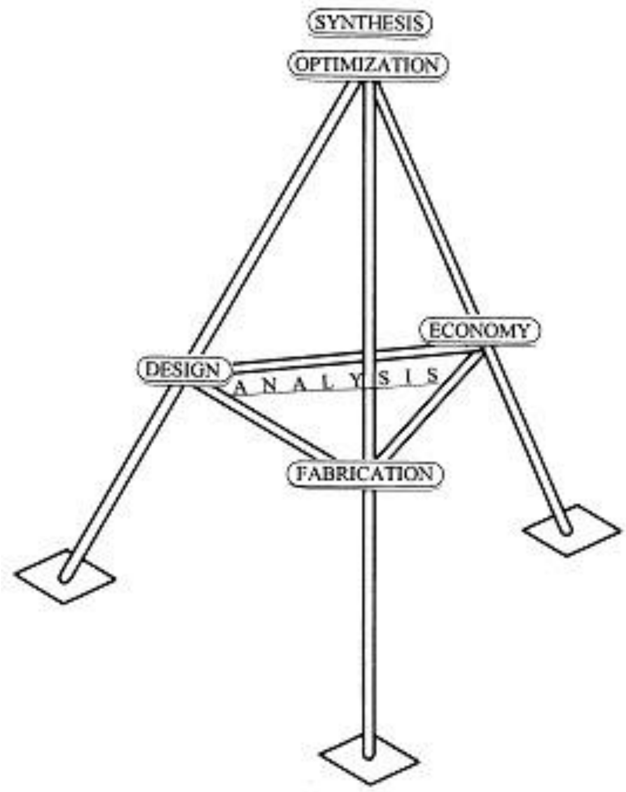

Figure 1. The structural optimization system

This system can be symbolized by a simple spatial structure as shown in Figure 1. This symbol also shows two important aspects: (1) when a requirement is missing, then the system does not work well, does not give better solutions; (2) close cooperation (harmony) should be realized between these main aspects, since they affect each other to a significant extent. Structural optimization is a general system, which can synthesize all the important engineering aspects.

At the analytical level the structural characteristics of the type of structure investigated should be analyzed as follows: loads, materials, geometry, boundary conditions, profiles, topology, fabrication, joints, transport, erection, maintenance, costs. Those variables whose changing will result in better solutions should be selected. A cost function and constraints on design and fabrication should be mathematically formulated in the function of variables.

At the level of synthesis the cost function should be minimized using effective mathematical methods for the constrained function minimization. Comparing the optimum solutions designers can select the most suitable one. This comparison can result in significant mass and cost savings in the design stage.

The best way to decrease the weight of structures is to *decrease the plate thicknesses*. This is limited by several phenomena which should be avoided. Thus, in order to know the limits of the thickness minimization, the following problems should be investigated:

a) too thin plates exhibit too large fabrication imperfections due to shrinkage of welds after welding, thus, residual welding stresses and distortions should be analyzed (Section 3);
b) thin-walled structures, mainly open sections are very sensitive to twist. Restrained warping causes additional normal stresses, which can cause failures. Thus, the behavior of thin-walled rods due to bending, shear and torsion should be treated (Section 4);
c) too thin plates can buckle due to compression, bending or shear. Thin-walled columns and beams can fail due to overall buckling or lateral-torsional buckling. Thus, the main problems of structural stability should be investigated (Section 5);
d) too thin plates can vibrate due to pulsating loads, since their eigenfrequency is very low. Effective damping can be achieved by using sandwich structures with layers of materials with high damping capacity (Section 6);
e) decreasing plate thicknesses means to create structural parts with higher stress concentrations, which, in the case of pulsating loads, can cause fatigue failure of welded joints (Section 7);
f) to avoid residual welding distortions, buckling and vibration, stiffening can be used. Stiffened and cellular plates as well as stiffened shells should be treated (Sections 11 and 12);
g) stiffening by welded ribs can be too costly, therefore, the fabrication costs should be analyzed (see separate Chapter);
h) effective mathematical methods of optimization should be adapted and developed (Section 2).

The design of welded structures is treated according to these aspects.

2. Mathematical Methods for Structural Optimization

Modern structural optimization can be dated from the paper of Schmit in 1960, who drew up the role of structural optimization, the hierarchy of analysis and synthesis, the use of mathematical programming techniques to solve the nonlinear inequality constrained problems. The importance of this work is that it proposed a new philosophy of engineering design, the structural synthesis, which clarifies the methodology of optimization
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2.1. Design Variables, Objective Functions, Constraints and Preassigned Parameters

The objective function (more functions at multiobjective optimization), the design variables, the preassigned parameters and the constraints describe an optimization problem.

The quantities, which describe a structural system, can be divided into two groups: preassigned parameters and design variables. The difference between them is that the members of the first group are fixed during design the second group is the design variables, which are varied by the optimization algorithm. These parameters can control the geometry of the structures. It is the designer choice, which quantities will be fixed or varied. They can be cross-sectional areas, member sizes, thicknesses, length of structural elements, mechanical or physical properties of the material, number of elements in a structure (topology), shape of the structure, etc.

Design variables

Cross-sectional design variables can be the size, or dimension which are the simplest and the most natural design ones. The cross-section area of tension and compression members, the moment of inertia of bent members, or the plate thicknesses can be design variables of this kind.

The Young modulus, yield stress, material density, thermal conductivity, specific heat coefficient etc. can be *material design variables*. These properties have a discrete character, i.e. a choice is to be made only from a discrete set of variables.

Geometrical variables are the span length of a beam, the coordinates of joints in a truss or in a frame. Although many practical structures have geometry which is selected before optimization, geometrical variables can be treated by most optimization methods. In general, the geometry of the structure is represented by continuous variables.

Topological variables are related to structural layout, like number of supports, number of elements etc. These can be of discrete or continuous type. In truss systems the topology can be optimized automatically if we allow members to reach zero cross section size. The uneconomical members can be eliminated during the optimization process. Integer topological variables can be the number of spans of a bridge, the number of columns supporting a roof system, or the number of elements in a grillage system.

2.2. Constraints

behavior means those quantities that are the results of an analysis, such as forces, stresses, displacements, eigenfrequencies, loss factors etc. These behavior quantities form usually the constraints. A set of values for the design variables represents a design of the structure. If a design meets all the requirements, it will be called feasible design. The restrictions that must be satisfied in order to produce a feasible design are called constraints. There are two kinds of constraints, explicit and implicit ones.

Explicit constraints which restrict the range of design variables may be called size constraints or technological constraints. These constraints may be derived from various considerations such as functionality, fabrication, or aesthetics. Thus, a size constraint is a specified limitation, upper or lower bounds on a design variable.

Implicit constraints are constraints derived from behavior requirements are called behavioral constraints. Limitations on the maximum stresses, displacements, or local and overall buckling strength, eigenfrequency, damping are typical examples of behavioral constraints. The behavior constraints can be regarded as implicit variables. The behavioral constraints are often given by formulae presented in design codes or specifications. Other parts of the behavioral constraints are computed by numerical technique such as FEM. In any case the constraints can be evaluated by analytical technique. From a mathematical point of view, all behavioral constraints may usually be expressed as a set of inequalities.

The constraints may be linear or nonlinear functions of the design variables. These functions may be explicit or implicit in the feasible region X and may be evaluated by analytical or numerical techniques. However, except for special classes of optimization problems, it is important that these functions should be continuous and have continuous first derivatives in X .

Design space, feasible region

We may regard each design variable as one dimension in a design space and any particular set of variables as a point in this space. In cases with two variables the design space reduces to a plane problem. In the general case of N variables, we have an N-dimensional hyperspace.

Considering only the inequality constraints the set of values of the design variables that satisfy the equation $g_j(\mathbf{x}) = 0$ forms a surface in the design space. These are boundary points. This surface cuts the space into two regions: one where $g_j(\mathbf{x}) < 0$ (these are interior points) and the other where $g_j(\mathbf{x}) > 0$ (these are the exterior points). The set of all feasible designs forms the feasible region. The solution of the constrained optimization problem in most cases lies on the surface. The solution can be local or global optimum.

Any vector $\mathbf{x}$ that satisfies both the equality and inequality constraints is called a feasible point or vector. The set of all points which satisfy the constraints constitutes the feasible domain of $f(\mathbf{x})$ and will be represented by X ; any point not in X is termed non-feasible.

2.3. Objective Function

The selection of an objective function can be one of the most important decisions in the whole optimum design process. Mass is the most commonly used objective function due to the fact that it is readily quantified, although most optimization methods are not limited to mass minimization. The minimum mass is usually not the cheapest. Cost is of wider practical importance than mass, but it is often difficult to obtain sufficient data for the construction of a real cost function. A general cost function may include the cost of materials, fabrication, welding, painting, maintenance, etc.

2.4. Divisions in Optimization Techniques

The different single-objective optimization techniques make the designer able to determine the optimum sizes of structures, to get the best solution among several alternatives. The efficiency of these mathematical programming techniques is different. A large number of algorithms are available. Each technique has its own advantages and disadvantages; no one algorithm is suitable for all purposes. The choice of a particular algorithm for any situation depends on the problem formulation and the user.

The general formulation of a single-criterion nonlinear programming problem is the following:

minimize

$$f(x) \qquad \mathrm{x}_1, x_2, ..., x_N \tag{1}$$

subject to $g_j(x) \le 0, \quad \mathrm{j}=1,2,...,P$ (2)

$$h_i(x) = 0 \quad i = P+1, ..., P+M \tag{3}$$

$f(x)$ is a multivariable nonlinear function, $g_j(x)$ and $h_i(x)$ are nonlinear inequality and equality constraints respectively.

The optimization models can be very different from each other.

- *Analytical and numerical*
- *Unconstrained and constrained*
- *Single- and multivariable*
- *Single- and multiobjective*
- *Discrete and non-discrete*
- *Structure free and structure dependent techniques*
- *Single- and multilevel optimization*

2.4.1. Methods without Derivatives

Optimization techniques, which require the evaluation of function values only during the search, called methods without derivatives (zero-order methods). These methods are usually reliable and easy to program. It often can deal effectively with non-convex functions. The price to pay for this generality is that these methods often require thousands of function evaluations to achieve the optimum. Thus these methods can be considered as most useful for problems, in which the function evaluation is not computationally expensive and we can rerun the programs from different points to avoid local optima.

Complex method
This method is a constrained minimization technique which uses random search so it does not require derivatives. Although the complex method was designed to be applied to nonlinear programming problems with inequality constraints, we include the method in this section because of its use of random search directions.

Flexible tolerance method
This method is a constrained random search technique. The Flexible Tolerance algorithm improves the value of the objective function by using information provided by feasible points, as well as certain non-feasible points termed near-feasible points.

Hillclimb method
This method is a direct search one without derivatives. Rosenbrock's method is an iterative procedure that bears some correspondence to the exploratory search of Hooke and Jeeves in that small steps are taken during the search in orthogonal coordinates. However, instead of continually searching the co-ordinates corresponding to the directions of the independent variables, an improvement can be made after one cycle of co-ordinate search by lining the search directions up into an orthogonal system, with the overall step on the previous stage as the first building block for the new search coordinates.

2.4.2. Methods with First Derivatives

Methods with first derivatives (first order methods), which utilize gradient information, are usually more efficient than zero-order methods. The price paid for this efficiency is that gradient information must be supplied, either by finite-difference computations or analytically. These methods are not efficient, if the function has discontinuous first derivatives. However in most cases first order methods can be expected to perform better than zero order methods.

Penalty methods: SUMT, exterior, interior penalties
Penalty methods belong to the first attempts to solve constrained optimization problems satisfactorily. The basic idea is to construct a sequence of unconstrained optimization problems and to solve them by any standard minimization method, so that the minimizers of the unconstrained problems converge to the solution of the constrained one.

Davidon-Fletcher-Powell method
The variable metric method of Davidon was extended by Fletcher and Powell. This method is one of the best general-purpose unconstrained optimization techniques making use of the derivatives that are currently available.

Leap-frog method
The dynamic trajectory method, more commonly known as the leap-frog method, was originally proposed for the unconstrained minimization of a scalar function $f(\mathbf{x})$ of n real variables $\mathbf{x} = (x_1, x_2, \ldots, x_n)$. The algorithm was modified to handle constraints by means of a penalty function formulation. The method possesses the following characteristics: it uses only function *gradient* information $\nabla f(\mathbf{x})$, requires no explicit line searches, is extremely robust and handles steep valleys and discontinuities in functions and gradients with ease. The method seeks *low local minima* and can thus be used as a basic component in a methodology for global optimization. Although for very high accuracy, it may not be as efficient as classical methods when applied to smooth and near-quadratic functions, it is particularly robust and reliable in dealing with the

presence of numerical noise in the objective and constraint functions.

Snyman-Fatti-method
The global method described here, namely the Snyman-Fatti (*SF*) multi-start global minimization algorithm with dynamic search trajectories for global continuous unconstrained optimization, was recently reassessed and refined to improve its efficiency and to be applicable to constrained problems. The resultant improved computer code has been shown to be competitive with of the best evolutionary global optimization algorithms currently available when tested on standard test problems.

2.4.3. Methods with Second Derivatives

The second-derivative methods, among which the best-known is Newton's method, are originated from the quadratic approximation of $f(\mathbf{x})$. They make use of second-order information obtained from the second partial derivatives of $f(\mathbf{x})$ with respect to the independent variables.

Newton's method
A classical second order method is the Newton's method. This technique begins with the second order Taylor series expansion.

Sequential quadratic programming
Sequential quadratic programming or SQP methods are the standard general purpose algorithms for solving smooth nonlinear optimization problems. The key idea is to approximate also second-order information to obtain a fast final convergence speed. Thus we define a quadratic approximation of the Lagrangian function $L(\mathbf{x},\mathbf{u})$ and an approximation of the Hessian matrix by a so-called quasi-Newton matrix.

2.4.4. Optimality Criteria Methods

Optimality criteria (OC) methods are based on Kuhn-Tucker (KT) necessary conditions of optimality. The advantage of these techniques, that they are computationally very efficient. It is a disadvantage, that they depend on the behavior of the structure and their convergence is not always guaranteed.

2.4.5. Discrete Optimization Techniques

In practical design, cross-sectional variables may be restricted to some discrete values. Such are the rolled steel members, which are produced in distinct sizes with unevenly spaced cross-sectional properties. In such cases the design variable is permitted to take on only one of a discrete set of available values. However, as discrete variables increase the computational time, the cross-sectional design variables are usually assumed to be continuous.

Backtrack method
The backtrack method is a combinatorial programming technique, which solves nonlinear constrained function minimization problems by a systematic search

procedure. The advantage of the technique is that it uses only discrete variables, so the solution is usable.

2.4.6. Evolutionary Techniques

Genetic algorithm

Genetic Algorithms (GAs) are numerical optimization techniques inspired by the natural evolution law of Darwin. A GA starts searching the design space with a population of individuals (designs), which are created over the design space at random. In the basic GA, every individual of the population is described by a binary string called chromosome. In the chromosome the genes can represent the physical sizes of the structures, the material properties, etc. The GA uses three main operators: selection (reproduction), crossover and mutation to direct the density of the population of designs towards the optimum point.

Differential evolution

Differential Evolution (DE) is a novel direct search method, which is a member of a broader class of optimization algorithms called Genetic Algorithms (GAs). DE also interprets the objective function value at a point as a measure of that point's fitness as an optimum. After being guided by the principle of survival of the fittest as in GA, an initial population of vectors is transformed into a solution vector through repeated cycles of mutation, recombination, and selection.

Particle swarm optimization

The algorithm models the exploration of a problem space by a population of individuals; the success of each individual influences their searches and those of their peers. In our implementation of the PSO, the social behavior of birds is mimicked. Individual birds exchange information about their position, velocity and fitness, and the behavior of the flock is then influenced to increase the probability of migration to regions of high fitness.

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