ADVANCED TEMPUS COURSE

on

NUMERICAL METHODS IN COMPUTER AIDED OPTIMAL DESIGN

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LECTURE NOTES

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LECTURE NOTES: VOLUME 2

Contents

OPTIMUM DESIGN OF TUBULAR TRUSSES

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SUMMARY

A mathematical programming technique is used to determine the optimal sizes of a K-type truss of parallel chords with gap joints, welded from tubular hollow sections. The unknown variables are the diameter and the thicknesses of chord and brace members. The objective function is the volume (weight) of the whole truss. There are 9 inequality constraints considered: overall buckling of compression members, static strength of welded joints and geometric limitations on sizes. The Hillclimb method of Rosenbrock [2] is used in an illustrative numerical example.

1. INTRODUCTION

Most engineers who design structures employ complex general-purpose software packages for structural analysis. Therefore the major challenge faced by researchers in structural optimization is to develop methods that are suitable for general-purpose use and can be connected to other software packages [1].

Optimization is concerned with achieving the best outcome of a given objective while satisfying certain restrictions. The notion of improving or optimizing a structure implicitly presupposes some freedom to change the structure. The potential for change is typically expressed in terms of ranges of permissible changes of a group of parameters. Such parameters are usually called design variables in structural optimization terminology.

Design variables can be member sizes or cross-sectional dimensions, they can be parameters controlling the geometry of the structure, its material properties etc. Design variables may be continuous or discrete. Continuous design variables have a range of variation and can take any value in the range. Discrete design variables can take only isolated values, typically from a list of permissible values. Material design variables are often discrete. Design variables are commonly treated as continuous ones, because the optimization techniques usually can find the continuous optimum quicker, then the discrete one.

Due to manufacturing requirements discrete sizes of the structure are needed (commercially available cross sections, plate thicknesses etc.).

In most structural design problems we tend to disregard the discrete nature of the design variables in the solution of the optimization problem. Only when the optimum design is obtained do we adjust the values of the design variables to the nearest available discrete value. However, this procedure works well when the available values of the design variables are spaced reasonably close to one another. In some cases the discrete values of the design variables are spaced too far apart and we have to solve the problem with discrete variables. This is done by employing a branch of mathematical programming called integer programming. We´ve used the combinatorial backtrack discrete optimization technique [7], but we´ve developed a so called secondary search for the continuous techniques to find the best discrete optimum in the neighbourhood of the continuous one [1]. This is connected to all of the continuous techniques.

The choice of design variables can be critical to the success of the optimization process. In particular it is important to make sure that the choice of design variables is consistent with the analytical model.

The notion of optimization also implies that there are some merit function or functions that can be improved. The common terminology for such functions is objective functions. Objective function to be minimized can be the mass, cost, volume of the structure of whatever the designer thinks to be worth to minimized.

In structural optimization problems the constraints imposed on the design, such as stresses, displacements, stability, eigenfrequency, fatigue, damping of the structure and so on. Such constraints will affect the final design and force the objective function to assume a higher value than it would be without the constraints.

In general we divide the space of design variables into a feasible and infeasible domains. The feasible domain contains all possible design points that satisfy all the constraints. The infeasible domain is the collection of all design points that violate at least one of the constraints. Because we expect that some constraints influence the optimum design, we expect that some constraints will be critical at the optimum design. This is equivalent to the optimum being on the boundary between the feasible and infeasible domain. Inequality constraints in our standard formulation are critical, when they are equal to zero. These constraints are also called active constraints, while the rest of the constraints are inactive or passive.

The basic problem that we consider is the minimization of a function subject to equality and inequality constraints [3,5,6].

$$\begin{array}{lll} \text{Minimize} & f(x) & \\ \text{such that} & g_j(x) \geq 0 & j=1,...,M \\ & h_i(x) = 0 & i=1,...,P \end{array}$$

2. OPTIMIZATION OF THE TUBULAR TRUSS

The welded tubular structure is an economic and modern one [4]. There is a wide range of application fields: offshore structures, main frames of high buildings, bridges, vehicle body frames, columns, towers etc.

There is a great variety among trusses in the topology, nodes, materials, manufacturing technologies and so on.

At the optimum design of trusses usually the section areas are regarded as unknowns, but at tubular members it is better to take into account the diameters and the thicknesses because of the special constraints.

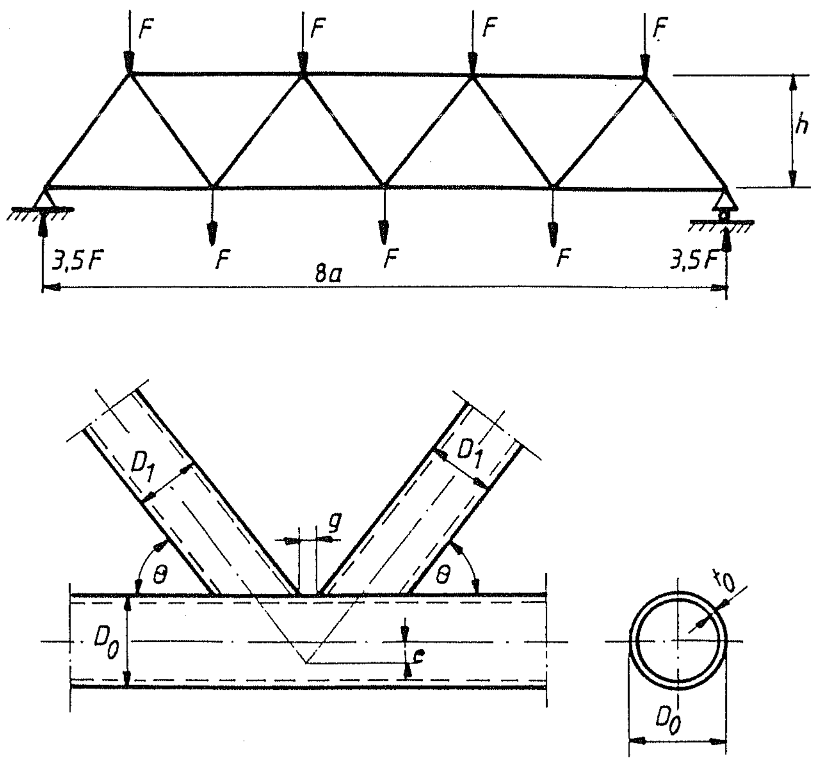

Fig. 1.

The aim of the optimization is to determine the minimal mass of the planar truss with symmetrical brace members subject to static loading.

Objective function is the volume of the truss with the diameter and thickness of the parallel chords D_0, t_0 and brace members D_1, t_1 and Ω which is equal to the height and node distance ratio h/a. There are five unknowns. For a given density the minimal volume gives the minimal, mass see Fig.1.

$$V / (2*a*\pi) = 7*D_0*t_0 + 4*D_1*t_1*\sqrt{1+\Omega^2}$$

Constraints are as follows:

We´ve used for the computation of the overall buckling of the trusses the rules of the Eurocode 3. [10], the new DIN 18800 has the same rule.

- Overall buckling of the chords:

$$\Gamma_s * F_{max.o} / (\pi*D_0*t_0) \leq \chi_0 * f_y$$

where χ_0 is the buckling coefficient,

$F_{max.o}$ is the greatest compression force in the chords,

$$F_{max.o} = 8 * F / \Omega$$

According to the Eurocode 3.

$$\chi_0 = 1 / (\Phi_0 + \sqrt{\Phi_0^2 - \bar{\lambda}_0^2}) \; ; \quad \bar{\lambda}_0 = \lambda_0 / \lambda_E \; ; \quad \chi_0 \leq 1$$

$$\lambda_E = \pi \sqrt{E / f_Y} = 76.4$$

$$\lambda_0 = k * L_0 / i_0 \; ; \quad \bar{\lambda}_0 = 188.809 / D_0$$

k = .85 the coefficient of the effective length,

$L_0 = 2 * a = 6000$ mm,

$i_0 = \sqrt{I/A}$ the radius of inertia,

$$\Phi_0 = 0.5 * [1 + \beta *(\bar{\lambda}_0 - 0.2) + \bar{\lambda}_0^2] \; ; \qquad \beta = 0.34$$

if $\bar{\lambda}_0 \leq 0.2$ then $\Phi_0 = 1$

- Overall buckling of the braces:

$$\Gamma_s * F_{max.1} / (\pi*D_1*t_1) \leq \chi_1 * f_y$$

where χ_1 is the buckling coefficient,

$F_{max.1}$ is the greatest compression force is the chords,

$F_{max.1} / F = 3.5 * \sqrt{(1 + \Omega^2)} / \Omega$

$108.2702 * \sqrt{(1 + \Omega^2)} / (\Omega * D_1 * t_1) - \chi_1 \leq 0$

According to the Eurocode 3.

$\chi_1 = 1 / (\Phi_1 + \sqrt{\Phi_1^2 - \bar{\lambda}_1^2})$; $\bar{\lambda}_1 = \lambda_1 / \lambda_E$; $\chi_1 \leq 1$

$\lambda_E = \pi \sqrt{E/f_Y} = 76.4$

$\lambda_1 = k * L_1 / i_1$

$\bar{\lambda}_1 = 188.809 / D_1$

$k = .85$ the coefficient of the effective length,

$i_1 = \sqrt{I/A}$ the radius of inertia,

$\Phi_1 = 0.5 * [1 + \beta *(\bar{\lambda}_1 - 0.2) + \bar{\lambda}_1^2]$; $\beta = 0.34$

if $\bar{\lambda}_1 \leq 0.2$ then $\Phi_1 = 1$

Local stability constraints

$D_0 - 50 * t_0 \leq 0$ (limit slenderness of the chord)

$D_1 - 50 * t_1 \leq 0$ (limit slenderness of the brace)

Geometric constraints

$D_1 - D_0 \leq 0$ (manufacturing constraints)

$0.2 * D_0 - D_1 \leq 0$

$D_1 * \sqrt{(1 + \Omega^2)} - D_0 * (1.5 - 0.1 * \Omega) \leq 0$

Strength of the nodes

At the welded chords for the plastification of the upper flange there is a recommendation according to [8,9], which was developed by a series of measurements.

$F_{max.1} \leq 8.9 * f_{y0} * t_0^2 / \sin\theta * D_1 / D_0 * \sqrt{D_0/(2*t_0)} * f(n)$

$\sin\theta = \Omega / \sqrt{(1 + \Omega^2)}$

The coefficient concerning to the force of the chord is as follows

$f(n') = 1.3 - 0.4 / (D_1/D_0) * F_{max.0} / A_0 / f_{y0}$

$f(n') = 1 + 0.3 * n' - 0.3 * n'^2$

$$n' = 247.4747 / (\Omega * D_0 * t_0)$$

If $f(n') \geq 1$ then $f(n') = 1$

Constraint on the punching shear

$$375.0589 - t_0 * D_1 * (1 + \sqrt{(1 + \Omega^2)} / \Omega) \leq 0$$

Ω	D_0[mm]	t_0[mm]	D_1	t_1	A[mm²]	active constraint
0.80	170.6	3.4	108.9	3.0	5753.9	lateral buckling of chords
0.90	164.6	3.3	118.7	2.5	5366.7	
1.00	156.7	3.3	120.3	2.4	5280.7	
1.10	154.9	3.1	120.9	2.4	5104.3	
1.20	151.1	3.0	122.7	2.5	5077.0	
1.22	150.0	3.0	122.3	2.4	5061.9	
1.23	150.0	3.0	122.4	2.4	5049.1	
1.24	149.5	3.0	122.5	2.5	5050.9	
1.25	149.2	3.0	122.1	2.5	5058.7	
1.30	149.8	3.0	123.3	2.5	5137.5	

Table 1.

3. NUMERICAL EXAMPLE

Compression force	$F = 23000$ N
the safety factor for static loading	$\Gamma_s = 1.5$
the force with the safety factor	$\Gamma_s * F = 34500$ N
the yield stress of the steel	$f_y = 355$ MPa
horizontal distance between the nodes	$a = 3$ m
the Young module	$E = 210$ GPa

The range of Ω is $0.80 \div 1.30$

The computation results for different Ω are shown on Table 1. using 0.1 as a step length for Ω. Around the optimum we've chosen smaller steps to determine the optimum more accurately.

Fig. 2. shows the values of the objective function.

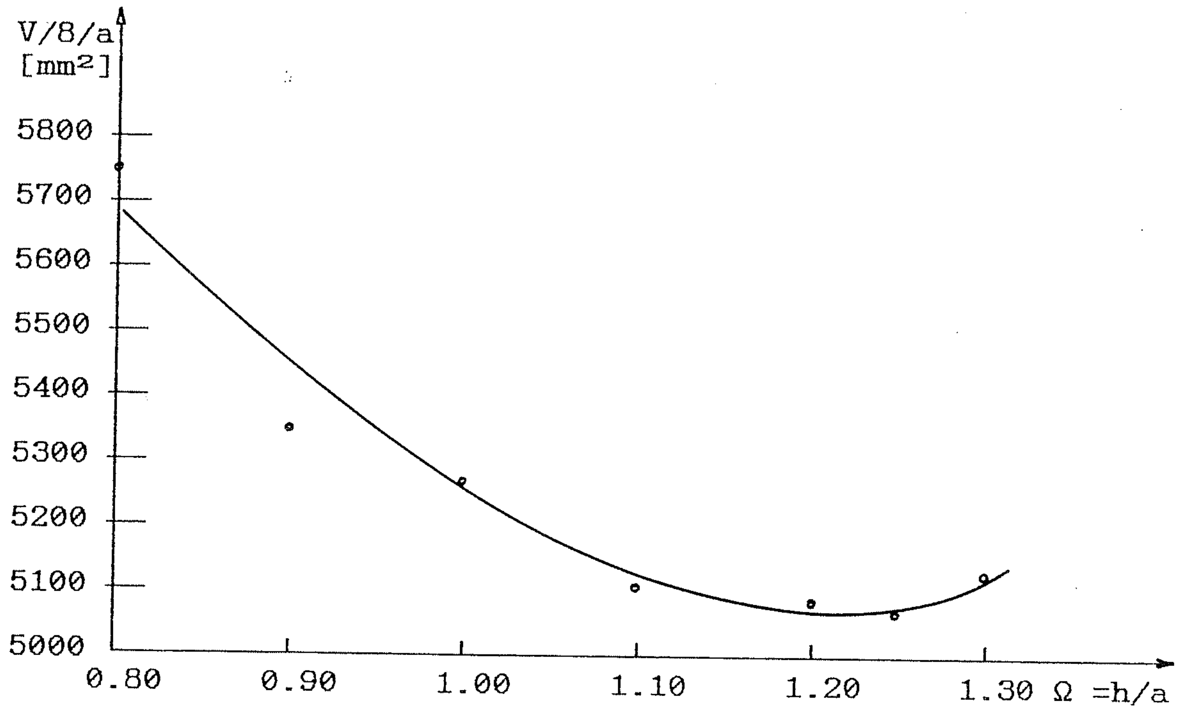

Fig. 2.

Fig. 2. shows, that the optimum of $\Omega = h/a$ is at 1.23.

The optimal sizes of the truss members are as follows

Chord diameter is 150.0 mm, thickness is 3.0 mm.
Brace diameter is 122.4 mm, thickness is 2.4 mm.
Volume of the structure V/(8*a) is 5049.1 mm².

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