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Fast Three-phase Mass Minimization of Truss and Shell Structures with Stress and Stiffness Constraints

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Abstract: The paper describes a new iterative optimization procedure and its simple to use computer implementation, allowing to minimize the mass of truss and shell structures under static load while satisfying the stress and stiffness constraints and keeping the mesh topology of the structure. The procedure first fulfils the stress constraint, then the stiffness constraint. Finally, the continuously found design variables can be replaced by discrete values from user's catalogue. Seven optimized structures are described, and results are discussed in detail. Compared to other optimization procedures, the described technique is an order of magnitude faster and suitable for everyday use in design practice of even large structures.

Keywords: steel structures; mass minimization; FE analysis; truss elements; shell elements; fully stressed design; stress constraint; stiffness constraint

1. Introduction

Generally, for the success of every iterative optimization procedure it is necessary that it rapidly converges to the goal in the feasible region and that the goal is as close as possible to the global minimum. Its location is usually unknown; the success of the optimization depends on using an appropriate starting point, that is, on initial values of the design variables and on the optimization path, that is, on the way they iteratively change.

Specifically, minimizing the mass of a structure means using such an appropriate procedure to determine the value of design variables so that the total mass is minimal while still meeting all constraints imposed on the structure.

This task is not new at all: All the traditionally well-known software packages like ABAQUS, ADINA, ALTAIR, ANSYS, GENESIS, NASTRAN, ... - to name just some from the beginning of alphabet - contain also optimization modules mostly based on finite element analyses. They allow the user to specify the widest variety of optimization goals, methods and constraints.

However, almost all the well-known methods and software products have in common that mastering of the issues is a very time-consuming process followed by a lengthy preparation of input data based on extensive manuals, often also by specific tuning with the structure to be optimized. Even worse is using a non-adaptive optimization procedure as a black box which rarely guarantees finding the global minimum. This all is why the mass minimization of structures has not yet become as obvious as standard FE-calculations.

This article does not dare to evaluate the very broad current state of optimization techniques, with new developments coming every day. For the sake of brevity, reference is made at least to the outstanding newest list of references in [1], ranging from

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mathematical foundations [2], through optimization techniques [3] to the latest works, especially in the field of truss structures. Similarly, an extensive list of references up to 2008 can be found in [4].

The aim of this paper is to describe a new heuristic iterative procedure **FSDOPT** (**F**ully **S**tressed **D**esign + **OPT**imization) and its implementation in the computer program of the same name. The program is easy to use, it allows the user in everyday design practice fast minimization of the mass of a statically loaded structure consisting of truss and shell elements while satisfying the most common, i.e. stress and stiffness requirements. By repeatedly running of the procedure with different control parameters does the user get a sense for the behaviour of the structure and a hope for the result that can approach the global minimum.

The effectiveness of the program is verified and compared on benchmark academic examples and on large truss structures from practice published recently as well; following diverse techniques are compared: genetic algorithm with domain-trimming [5], modified Lagrange functions in MathCAD environment [6], a promising DFSD technique without details [7], Big Bang – Big Crunch method [8-10], artificial immune system [11], search algorithm based on FSD [12]. A shell structure of the author is optimized as well.

2. Basic characteristics

For the minimization procedure described here, neither the goal function nor the penalty function nor constraints are to be defined explicitly: The goal is simply to minimize the total mass of a structure with fixed topology as a sum of masses of all structural elements, the penalty function does not exist, the stress constraints are represented by allowable stress for each group of elements, the stiffness constraint is represented by limited displacement of nodes.

Formally, for completeness, the optimization task can be mathematically expressed as follows:

Find $X^T = \{X_1, X_2, \ldots, X_n\}$ (1)

minimizing $M(X) = \sum_{i=1,n} \rho_i L_i X_i$ (2)

subject to constraints $g_j(X) \leq {}_{max}g_j \quad j = 1,2,\ldots n_c$ (3)

and ${}_{min}X_i \leq X_i \leq_{max} X_i \qquad i = 1,2,\ldots n$ (4)

where X_i is the design variable of the i-th element meanings cross-section area of the truss element and thickness of the shell element, n is the number of structural elements, M is the objective function (the mass of the structure), ρ_i is the material density of the i-th element, L_i is for the i-th element length of the truss element and the surface area of the shell element, inequality constraints g_j represent the member stresses and node displacements with the maximum ${}_{max}g_j$, n_c is the number of inequality constraints, ${}_{min}X_i$ and ${}_{max}X_i$ are the minimum and maximum values of the design variable X_i.

Structural elements can be treated individually (each with a separate design variable) or in N groups (all elements in a group having a common design variable). The assignment to groups depends on the conditions of the particular design and on the decision of the user of the program, e.g. to distinguish the upper and lower flange, to emphasize the geometrical symmetry, to reduce the assortment. In such a case the values of N design variables are looked for, $N \leq n$.

The procedure consists of three phases (Fig. 1). The first two are active ones: The searched values are determined from continuous design variables, fulfilling first the stress constraints in Phase 1, then the stiffness constraints in Phase 2. In Phase 3, the resulting values found continuously can be replaced by discrete values from the user's catalogue file. Neither phase is mandatory.

The execution of the program is controlled by the master optimization part. It is based on actual displacements, stresses and mass data obtained by iterative FE-analyses carried out with changing values of design variables.

For the master optimization part, the minimum, maximum and starting value of the design variables (4) and the value of the allowable stress (3) for each of N groups of finite elements are entered. If necessary, parts of the structure can be excluded from optimization by prescribing the same minimum and maximum value for corresponding design variables. Entered can be the total displacement (3) allowed for a specified node or for all nodes.

For analyses slightly modified parts of the well-established general purpose finite element structural analysis program [13] are used. Corresponding standard FE-data are entered, including two types of finite elements: 3D 2-node truss elements with axial forces only and 3D 4-node shell elements (ELEMENT TYPE 1 and 6 in [13]). The structure can be loaded by node forces, surface pressure, temperature, temperature gradient, self-weight, all combinable in load cases [13].

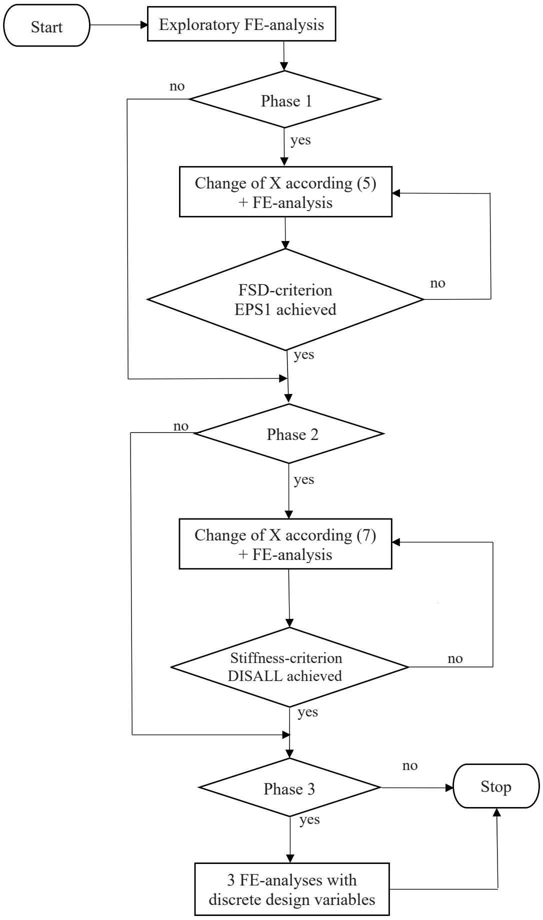

Figure 1: Flowchart of the three-phase procedure.

3. Procedure, Phase 1

Input control parameters for Phase 1 are METHOD, EXP1, EPS1.

In Phase 1 the stress requirements (3) are fulfilled by achieving the FSD state (Fully Stressed Design). The outgoing vector X of design variables (1) serves as a starting vector for Phase 2.

FSD is an early optimization technique, very efficient when only stress limitations are prescribed. The goal can be reached within a few iterations. FSD means the maximum possible use of the material of the structure in terms of stresses: According to the well-known definition, FSD means that the specified allowable stress is achieved in at least one element in each element group in at least one load case - unless this is prevented by the entered minimum and maximum values of design variables.

The vector X satisfying the FSD condition is created by repeated qualified changing of individual design variables:

$$X_i = X_{old,i} \cdot \alpha_i \tag{5}$$

for each of N groups.

α_i depends on calculated maximum stress σ_i (normal stress of truss elements, HMH-stress of shell elements) and allowable stress $\sigma_{max,i}$ as follows:
For **METHOD=1** (plane strain only) $\alpha_i = \sigma_i / \sigma_{max,i}$
For **METHOD=2** (bending only) $\alpha_i = (\sigma_i / \sigma_{max,i})^{0.5}$
For **METHOD=3** the calculation of α_i depends on ratio of plane stress and bending [14].

The above three alternatives provide a fast convergence of the solution assuming constant loading. If the load is constant and the structure is statically determined, after the first (exploratory) FE-analysis the values of the design variables are adjusted so that already the second FE-analysis confirms the FSD state. However, when loaded by self-weight or thermal effects, the load varies because it depends on the changing values of design variables. This worsens convergence so it is advisable to try METHOD=2 with an other exponent:

$$\alpha_i = \left(\frac{\sigma_i}{\sigma_{max,i}} \right)^{EXP1} \tag{6}$$

Phase 1 ends when the relative change of the value of each design variable during achieving the allowable stress in its group is smaller than EPS1. Thus, leaving Phase 1 and entering Phase 2, stress constraints are met with required accuracy EPS1, stiffness constraint is not considered yet.

A small value of EPS1, e.g. 0.0001, leads to a very accurate FSD. However, for achieving the final objective in Phase 2 (minimum mass while satisfying both stress and stiffness constraints) it is sometimes appropriate to try larger values, e.g. 0.01, thus, not to start from the exact FSD. Using an even larger value, Phase 1 is totally disabled and Phase 2 will start straight away with input values of design variables.

4. Procedure, Phase 2

Input control parameters for Phase 2 are NINFO, DISALL, CINP, EXP2, CMULT.

In Phase 2 the values of design variables from Phase 1 fulfilling the stress constraints are iteratively changed so that also the stiffness constraint is fulfilled. This is inputted by DISALL, representing the maximum allowable total displacement of node NINFO. The displacements of other nodes are not evaluated. If node NINFO is not specified, the DISALL constraint applies to all nodes. If DISALL is not specified, or if it is already fulfilled with values of the design variables specified or detected in Phase 1, directly Phase 3 follows.

The iteratively used redimensioning equation for the design variable Xi has the heuristic form

$$X_i = X_{old,i} \cdot \left(1.0 - C \cdot \left(\frac{Dis_{1,i} - Basdis}{Basdis} \right) \cdot \left(\frac{\sigma_{gr,i}}{\sigma_{max,i}} \right)^{EXP2} \right) \quad (7)$$

for each of N groups.

$Dis_{1,i}$ is the maximum displacement with temporarily increased only one design variable X_i, $Basdis$ is the maximum displacement found in previous iteration, $\sigma_{gr,i}$ is the maximum stress calculated in previous iteration in i-th design group, $\sigma_{max,i}$ is defined above.

This equation determines the new value of the i-th design variable by combining the current C value, the current quasigradient information $(Dis_{1,i} - Basdis)/Basdis$ and the current stress ratio $\sigma_{gr,i}$ / $\sigma_{max,i}$ in i-th group with a constant exponent EXP2.

The quasigradient information is obtained by observing the effect of increasing the value of only one design variable X_i at a time. In "classical" numerical obtaining of the gradient information, the value increases only slightly. In FSDOPT, the resulting effect is obtained in synergy with the actual value of C. It is found that when the value of the design variable is slightly increased and the value of C is very large, roughly the same result is obtained as when the value of the design variable is massively increased and the value of C is correspondingly smaller. In FSDOPT, the quasigradient information is obtained by a temporary increasing of the value of the design variable X_i to twice its actual value.

When the redimensioning equation is first used at the beginning of Phase 2, $C = \mathrm{CINP}$. Depending on the combination of CINP and EXP2, there is a jump change in the values of the design variables found at the end of Phase 1, hence a jump in stresses, displacements and masses.

In general, if some iterative step produced a displacement greater than DISALL, i.e. the structure is too elastic ("elastic domain"), the redimensioning equation is used with updated quasigradient information and with updated value of

$$C = C_{old} \cdot CMULT \quad (8)$$

This procedure increases the values of the design variables, consequently also the mass, and decreases the stresses and displacements.

If some iterative step produced a displacement smaller than DISALL, i.e. the structure is too stiff ("stiff domain"), the program proceeds in a faster way: The quasigradient information is not updated and the redimensioning equation uses the values found when the structure was last too elastic. However, C is used as updated to

$$C = C_{old} \cdot \left| \frac{(Dis_{old} - DISALL)}{(Dis_{old} - Dis_{max})} \right| \quad (9)$$

Dis_{max} is the displacement (either of node NINFO or maximum) detected in the iteration just completed, Dis_{old} is the Dis_{max} value detected in the previous iteration. This procedure decreases the values of the design variables, consequently also the mass, and increases the stresses and displacements. This optimization path represents an alternative to the optimization path in the "elastic domain".

The iterative adjustment of the values of the design variables in Phase 2 ends on satisfying the stiffness constraint.

Numerical results prove that the total number of iterations is an order of magnitude less than with other methods. The user can repeatedly run the program with different input control parameters to easily verify how they affect the convergence rate and quality of the optimizing process. Therefore, no procedure is used in program to jump out from an eventual local minimum.

5. Procedure, Phase 3

Phase 3 takes into account a list of existing or preferred cross-section values provided by the user. It is not always practical to strive for a global minimum at all costs in Phase 2, especially not at the cost of prohibitively prolonging the optimization process. For if the working directory contains a user's cross-section catalogue file, the continuously and possibly with great effort in Phase 2 obtained values of design variables for each of N groups will anyway be replaced in Phase 3 by discrete values from the user's catalogue file.

In Phase 3 three final analyses are carried out: In the first, second and third analysis each design variable X_i is replaced by the nearest (larger or smaller), nearest larger and nearest smaller discrete value from the user's catalogue file, respectively.

Thus, the first analysis provides values that are not very different from those determined continuously. The second one provides smaller displacements and stresses but bigger mass. Finally, the third one provides bigger displacements and stresses but smaller mass of the structure.

The magnitude of the corresponding changes depends on the size of the intervals between discrete values in the cross-section catalogue file. The user can compare the results of the three analyses and opt for the solution that suits him best.

6. Numerical examples

Seven examples cover planar and space truss structures and space shell structure.

For the sake of brevity the author refers to the details in the cited literature.

FSDOPT evaluates the total displacement of the nodes (formed by the components in all three directions) whereas in solved examples the stiffness constraint is often defined as the displacement limit of one component (mostly in vertical direction). In such cases the value of the total displacement DISALL was entered appropriately increased in order to achieve the fulfilment of the required stiffness constraint in one direction.

6.1 Mass minimization of truss structures

6.1.1 Planar structure with 10 truss elements [5]

The planar structure (Figure 2) represents a classical optimization benchmark example used by many authors. 6 nodes, 10 truss elements in 10 independent groups, L=9.144 m, modulus of elasticity E=68950 MPa, material density ρ=2767.99 kg/m^3, stress constraint defined as maximum stress of all elements=172.375 MPa, stiffness constraint defined as maximum displacement of all nodes in both directions=0.0508 m, cross-sectional areas from 64.52E-6 to 22580.6E-6 m^2, P_1=667.2 kN, P_2=222.4 kN.

In [5] 7 methods are referenced, with the mass achieved from 2118.52 to 2295.91 kg. From the same source,„the best solution required nearly 4000 iterations to reach the best discovered solution with an initial population size of 500 solutions prior to any domain reductions".

Using FSDOPT, the structure was optimized starting with maximum cross-section area for each element. After reaching the FSD state, the optimization path continues in Phase 2 and ends in only 35 iterations with M=2159.68 kg and maximal displacement exactly as constrained, that is 0.0508 m (Figure 3).

The mass M is often closely related to the achieved value of the maximum displacement, and therefore, when comparing the results of different authors, it is important to compare the results really achieved (not the rounded ones). When solving this benchmark task in [5], in input the maximum displacement was constrained to 0.0508 m, but the reported result M=2118.52 kg corresponds to the achieved displacement of 0.0509 m [16]. The difference between 0.0508 and 0.0509 m is 0.1 mm only, but when for FSDOPT 0.0509 m was prescribed (and achieved) instead of 0.0508 m, the previous value of M=2159.68 kg decreased by 4 kg …

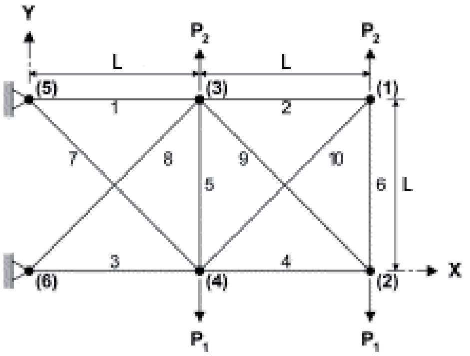

Figure 2: Benchmark structure with 10 2D truss elements.

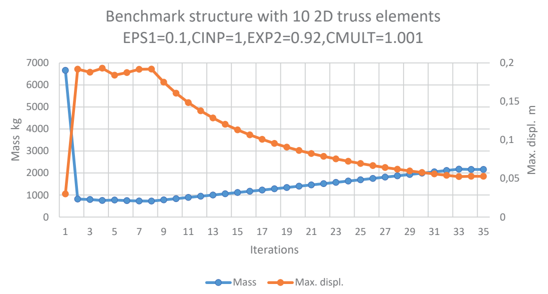

Figure 3: Optimization path of the benchmark structure with 10 2D truss elements.

6.1.2 Planar structure with 19 truss elements [6]

Simple planar truss structure. 10 nodes and 19 truss elements in 10 groups as follows (Figure 4): 1,11; 2,12; 3,13; 4,14; 6,16; 5,15; 7,17; 8,18; 9,19; 10. d=3000 mm, h=2600 mm, F=400000 N, modulus of elasticity E=206000 MPa, material density ρ=7.8E-6 kg/mm^3, stress is constrained to 345 MPa for all groups, vertical displacement in node 8 is constrained to 14 mm. Cross-section areas have

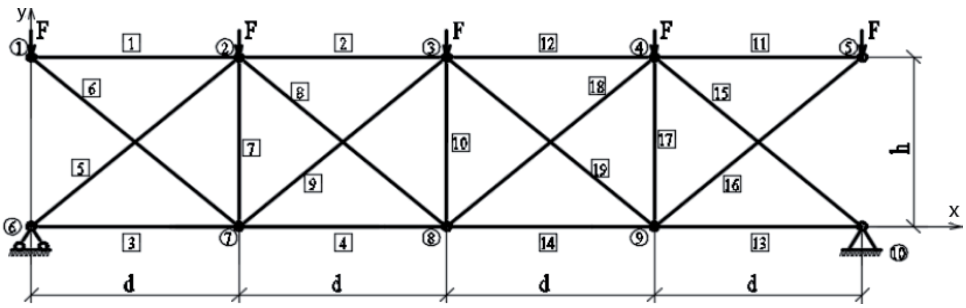

Figure 4: Structure with 19 2D truss elements.

lower and upper limits of 13.631 and 34077.193 mm^2.

The solution in [6] was carried out in universal mathematical package MathCAD. The algorithm was designed to minimize the total mass of this small structure taking into account possible buckling of elements with prescribed tubular form.

To make the comparison with FSDOPT possible, the method [6] was used with omitted influence of buckling phenomena, leading to mass M=2080.63 kg, which seems to be at least very close to the global minimum. The number of FE-analyses was not explicitly given, it depends on unconditional minimization method used [17].

(FSDOPT does not account for buckling directly. However, in repeated optimization runs, for compressed elements a reduced stress limit can be set.)

Phase 1 in this simple example with a constant load always proceeds the same result regardless of the specified value of EPS1 and regardless of the starting cross-section areas (here maximum for all elements was used). Already in the second analysis the FSD state is reached (Figure 5).

A typical short optimization path with 11 iterations ended with M=2436.73 kg. With a longer optimization (using CINP=0.001, EXP2=666, CMULT=1.02) M=2214.31 kg was achieved.

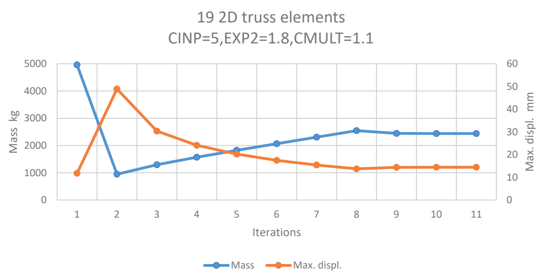

Figure 5: Short optimization path of the structure with 19 truss elements.

6.1.3 Planar structure with 25 truss elements [7]

Simple planar truss structure with 14 nodes and 25 aluminium truss elements optimized separately, thus 25 groups each containing one truss element (Figure 6). Six bays, each 9.144 m long for a total length of 54.864 m. Top and bottom chords, the height of the structure is 9.144 m. Total vertical load=800.4 kN. Stress is constrained to 172 MPa for all elements. Vertical displacement in the middle is constrained to 0.0508 m. For minimal and maximal cross-section areas 1E-8 and 1 m^2 are used. Modulus of elasticity E=69000 MPa, material density ρ=2700 kg/m^3.

From [7] only basic data of the example have been overtaken; the used optimization technique DFSD (Direct Fully Stressed Design) is only briefly stated that it fulfils both the stress and displacement constraints in a single one iteration and is applicable for statically determinate structures only. However, the method itself is not described and no further research is known in the field.

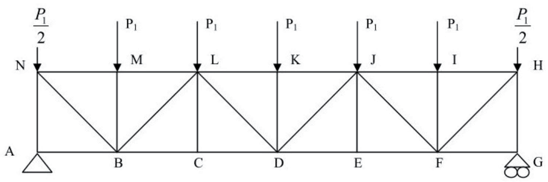

Figure 6: Structure with 25 2D truss elements.

Also in this simple example with a constant load, in Phase 1 already in the second analysis the FSD state is reached: 21 finite elements show the allowable stress value of 172 MPa and 4 finite elements are redundant (they have a minimal cross-section area and practically zero stress).

The speed of convergence and the quality of the final result in Phase 2 are affected by the control parameters used, so it is advisable to try several combinations. Here the fastest path with only 9 iterations (Figure 7) ends with mass M= 8773.77 kg which is very close to the best result of M=8770.41 kg achieved with CINP=1,EXP2=2,CMULT=1.01.

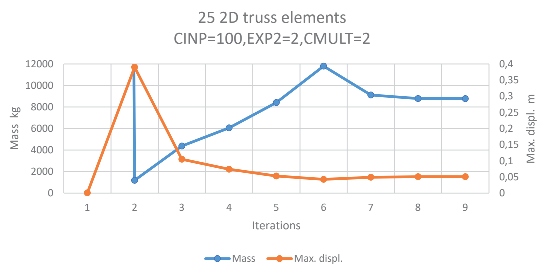

Figure 7: The fastest optimization of the 2D structure with 25 truss elements.

6.1.4 Planar structure with 29 truss elements [9]

Planar truss structure with 15 nodes and 29 steel truss elements in 29 groups (Figure 8).

P=300000 N, modulus of elasticity E=2.1E5 MPa, material density ρ=7850 kg/m^3, stress is constrained to 160 MPa in all elements, displacement is constrained to 0.050 m in all nodes. A user's catalogue file with 25 cross-section areas from 12.24E-4 to 97.59E-4 m^2 is used.

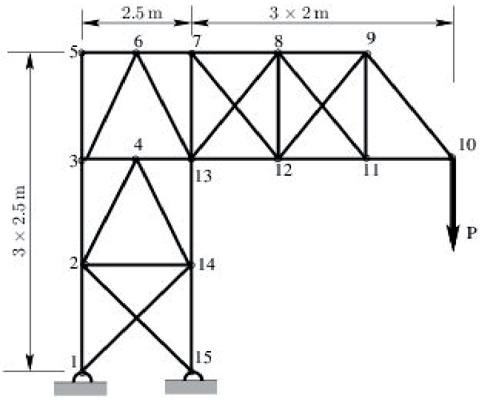

Figure 8: Structure with 29 2D truss elements.

According [9], from $25^{29} \approx 3.47 \times 10^{40}$ possible solutions of the problem, using Big Bang – Big Crunch method, in about 10000 FE-analyses [18] following results were achieved: M=1440.78 kg (stress constraint considered only) and M=1607.61 kg (both constraints included).

The optimization with FSDOPT (Figure 9) started with minimum cross-section areas for all elements. After 4th analysis (end of Phase 1, considering the stress constraint only) M=1394.77 kg, after 15th analysis (end of Phase 2, both constraints included) M=1601.39 kg. At last, three analyses (Phase 3) with discrete values from the user's catalogue file provided M=1602.88 kg (negligible changings), 1732.55 kg (stress and stiffness values decreased) and 1548.48 kg (stress and stiffness values increased).

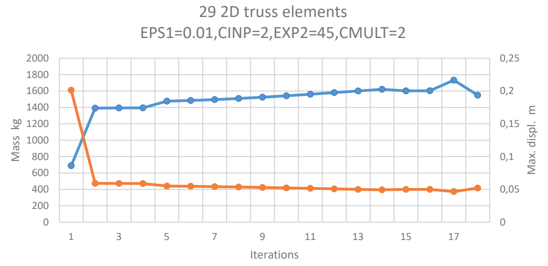

Figure 9: Optimization path of the 2D structure with 29 truss elements.

6.1.5 3D truss tower with 25 elements [10], [11]

Also this 3D structure with 10 nodes and 25 truss elements in 8 groups 1;2-5;6-9;10,11;12,13;14-17;18-21;22-25 (Figure 10) is widely used as benchmark by many authors. The foundation nodes are located at the corners of a square with a side length of 5.08 m, the height of the structure is also 5.08 m. Two load cases, stress limit 275.79 MPa in all groups, maximal displacement is constrained to 0.00889 m in every node in every direction. For minimal and maximal cross-section areas 0.6452 and 21.9354 cm^2 are used.

According to [11], to solve the same example, 74 analyses were needed. According to [10], to achieve the main author's result M=247.51 kg, 12500 analyses were necessary. Other 7 methods in [10] required from 3520 to 28850 analyses.

The optimization with FSDOPT (Figure 11) started with minimal cross-section areas for all elements. To demonstrate the effectiveness of Phase 2, a deliberately large value of EPS1=20 was used, caused the end of Phase 1 after two iterations with a state far away from FSD. Despite that, Phase 2 ended after only 28 iterations with displacement limit exactly fulfilled and stresses below limit; the mass achieved is by only 1.2 % bigger than the value in [10] with 12500 analyses.

6.1.6 3D truss tower with 160 elements [12]

3D structure with 52 nodes and 160 truss elements in 6 groups (Figure 12 [19]) is the largest of the 8 benchmark problems recently used to extensively compare the effectiveness of 11 minimization techniques [12]. The static indeterminate structure has a height of 16175 mm, a stress constraint of 147.15 MPa for all elements, a total displacement constraint of 80 mm for all nodes, 8 load cases incl. self-weight. A user's catalogue file with 42 cross-section areas from 184 to 9413 mm^2 was included.

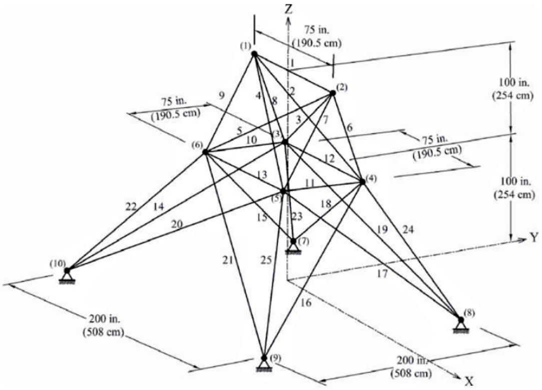

Figure 10: 3D tower structure with 25 truss elements.

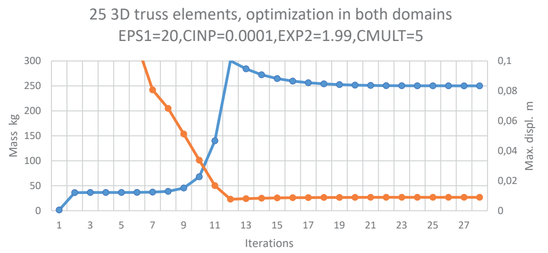

Figure 11: Optimization path of the 3D structure with 25 truss elements.

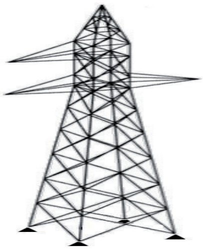

Figure 12: Large 3D tower structure with 160 truss elements.

According [12], for this benchmark problem 11 optimization procedures yielded the total mass ranging from 1164 kg (26432 FE-analyses) to 871 kg (1767347 FE-analyses).

Using FSDOPT, the FSD state in Phase 1 in 4 iterations was reached (Figure 13). In Phase 2, the mass of 798.3 kg and a maximum displacement of 79.99 mm were obtained, with only 9 iterations needed together. Three solutions in Phase 3 followed, with discrete values from the user's catalogue file, the first and the third one yielded a reduction in mass but exceeded both the stress and stiffness constraints. The middle one provided a mass of 863.43 kg with maximum stress of 137.28 MPa and a maximum displacement of 74.24 mm only (Figure 13).

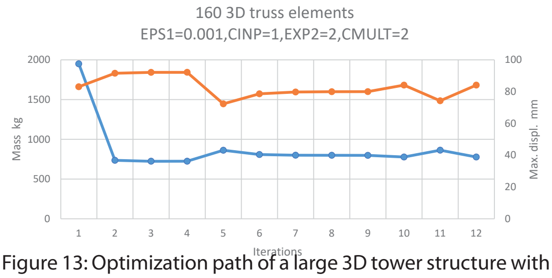

Figure 13: Optimization path of a large 3D tower structure with 160 truss elements.

6.2 3D 4-node shell structure (Figure 14)

3D press frame from production praxis with stress and stiffness constraints, 2990 mm high, composed of 141 nodes and 118 4-node shell elements in 15 groups (12 active ones, 3 with fixed thicknesses), loaded by operational forces and self-weight. Stress constrained to 43 MPa, maximal total displacement of nodes constrained to 1 mm. Thicknesses of shell elements can vary from 30 to 150 mm. The optimization started with maximal thickness in all groups=150 mm, except two groups with fixed thickness=40 mm and one group with fixed thickness=50 mm.

Included loading by self-weight is worsening convergence. However, using METHOD=3 [14], 5 FE-analyses were sufficient in Phase 1 to achieve the FSD state with prescribed accuracy EPS1.

First, as an example of fast minimization, the optimization path in "stiff domain" is shown (Figure 15). In Phase 2, the stiffness constraint is fulfilled and the stresses are below the limit in 16 iterations. However, here the mass M=4018.24 kg is slightly bigger than that provided by longer minimization in "elastic domain", which probably ends very close to the global minimum.

The best solution M=3746.05 kg has been achieved with optimization path in both domains (Figure 16). In Phase 2 only 8 iterations were needed to fulfil both stress and stiffness constraints.

Due to the uniqueness of the structure, comparison with other authors was not possible.

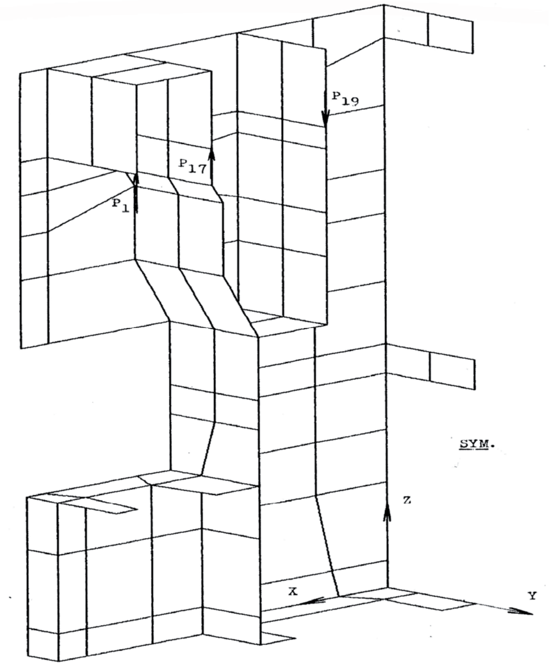

Figure 14: Press frame model composed of 118 shell elements.

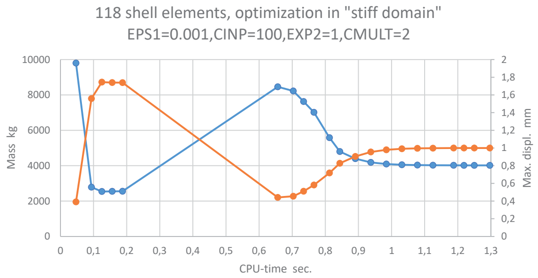

Figure 15: Optimization path of a press frame modelled by shell elements.

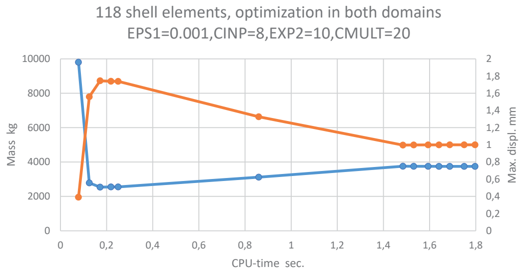

Figure 16: Optimization path of the press frame, minimum mass achieved.

The same press frame structure was optimized also using finer FE-mesh consisting of 517 nodes and 472 shell elements obtained by splitting every original shell element to four elements. Upon solving this structure with large bandwidth the CPU-time consumed increased 50-times. Using renumbering [15], the CPU-time consumption decreased under comfortable 1/10. In all solutions the results were practically the same. This indicates that the optimization can be successful even with a sparser FE-mesh.

7. Conclusions and future developments

This paper deals with mass minimization of structures consisting of truss and shell finite elements with static loading and stress and stiffness constraints. A 3-phase iterative heuristic technique is implemented in the author's program FSDOPT allowing also a less experienced user in everyday design practice to find quickly the best suited design without lengthy study of extensive manuals to known universal optimization software packages.

The program is easy to use. By selecting just a few control input data, different starting points and different optimization paths can be set. By repeatedly running of the program with changed control parameters does the user get a sense for the behaviour of the structure and a hope for the result that can approach the global minimum.

Numerical examples presented in the paper confirm the intuitive notion that the more or less exact FSD state found in Phase 1, fulfilling the stress constraint, can be used as a suitable starting point for Phase 2.

Based on FSD, the simple iterative optimization technique in Phase 2, using a heuristic redimensioning equation (7), fulfils the stiffness constraint while the stresses are below the limit. It is believed the technique is able to provide a mass close to the global minimum. In Phase 3 the previously found continuous design values can be replaced by discrete values from the user's catalogue of cross-section values.

Using the program can help to identify redundant parts of the structure.

Compared to other methods, the described 3-phase technique achieves roughly the same or even better results than recently published methods. Moreover, it is an order of magnitude faster in terms of the number of iterations needed, so it is not limited to academic examples.

In addition, the number of necessary iterations also depends on the required accuracy of meeting the stiffness constraint in Phase 2. Currently, a tight fixed tolerance of +/- 0.01 % of DISALL is used in the program. However, also in diagrams shown can be seen that this requirement is sometimes too strict, it prolongs the optimization process (see e.g. Figure 11). This may not be necessary from the point of view of the functionality of the structure, especially when the continuous optimization process is finalized by Phase 3 using discrete values from the user's catalogue file. Therefore, an option will be included to input the possibly broader tolerance for fulfilling of the stiffness constraint. This could further reduce the number of iterations needed.

The author plans further refinement of the heuristic technique used in Phase 2. The global minimum mentioned in Example 6.1.2 will be used as a benchmark.

Further deployment of the program would be welcomed, especially to minimize the mass of large truss and shell structures.

Program details

The executable version of FSDOPT has been created using G95 FORTRAN compiler for Windows and run on a notebook with an Intel® Core™ i3 processor operating on 2.30 GHz.

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