SCIA scientific software

White Paper

Overall Optimal Design of Structures

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Breakthrough technology with discrete parametric batch processing in SCIA • ESA PT 2007

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Content

Introduction

Most CAE software products announce: “Our software helps you to make an optimal design of your structures”. It this achieved in reality?

In common sense one talks about optimisation of structures, but in fact one optimises only a few chosen structural parts. A design engineer searches for the minimal size of the cross-section that satisfies the design code, he/she tries to find the minimal number of bolts needed in a specific steel connection, he/she is searching for minimal required area of reinforcement steel in a concrete beam. All structural parts are designed optimally, yet it does not mean that the whole structure is optimal for instance from the point of view of cost of material, time of construction, price of labour, etc.

An optimal design of a structure is found when many variants are tried and compared. Everybody will agree, but how many times it is a real case in the construction industry ? Normally the designer works under the pressure of the client and there is not much time for working out variants.

A typical example concerns a reinforced concrete beam. At the start the dimensions of the cross-section are preselected, then the internal forces are calculated and the reinforcement is designed, optimally of course. Yet who plays a little bit more with the height and width of the beam to find an optimal price of the whole beam, which is composed out of the price of concrete and the price of steel?

Almost everybody is able to do it with existing software tools, it is only the question of testing of number of variants, comparing of them and finding the most suitable one. In fact, it could be realistic for small projects, but not for real big projects.

Optimisation of global systems

The research on optimisation is mainly lead by automotive and aerospace industries. The emphasis is mainly on the computational fluid dynamics domain and structural optimisation area, especially on the shape optimisation.
There are many mathematical methods, which can satisfy the needs of the construction and building industry. Normally the system has to be described with a number of parameters. Then one has to set the target of the optimisation – what is the goal, what should be minimized of maximized. And it is required to be able to calculate this goal from any set of parameters. If one does so, then one has defined what is normally "goal function" or "price function".

Once a set of parameters and the goal function are defined, one can use standard mathematical optimisation methods, it does not matter if we optimise the weight of a space shuttle or the traffic in the streets.

Optimal design of structures

Having powerful software tools for the design of structural parts and mathematical methods for optimisation of systems being clear, why then is the optimisation of structures not widely used?

The current CAE software systems are not equipped well enough for the structural optimisation. Which necessary functions are needed ? It consists of:

1. Functions for optimal design of specific structural members like a steel beam, concrete beam, steel connection, foundation block, etc. Usually the minimal dimensions, size or number are searched. The member must satisfy the criteria of the appropriate code.
2. There must be a possibility to parameterise the structure. The designer has to decide, what is fixed in the structure and what can be changed – spans, heights, dimensions of cross-sections, thickness of plates and walls, loads ... Each feature which can vary must be able to be described by one independent parameter.
3. There must be a possibility to define the goal function. It can be the weight of needed steel, volume of concrete, weight of reinforcement, but it can be also maximal displacement or whatever else.
4. The software system must be able to evaluate the goal function for the specific set of parameters. It means that a function, which is able to read the set parameters and return a goal value, must be available.
5. The optimisation solver is needed. This is a tool, which generates the different sets of parameters, calculate goal function, and finally proposes the optimal set of parameters.

With a CAE system equipped with all such functions, the way to optimisation is open. We are proposing a breakthrough technology that gives a much better design methodology, on top of a general CAE program, which enables a gradual change.

Current status:		**New vision: automatic optimisation**
- Primary design of structural system & dimensions - Analysis + code checks - Assessment of results; changes are introduced, re-do analysis until design is found OK	⇨	- User defines parameter values, limits, constraints and goal - Optimization in batch mode - Variants are proposed with details on goals & constraints; engineer may decide which one and refines design

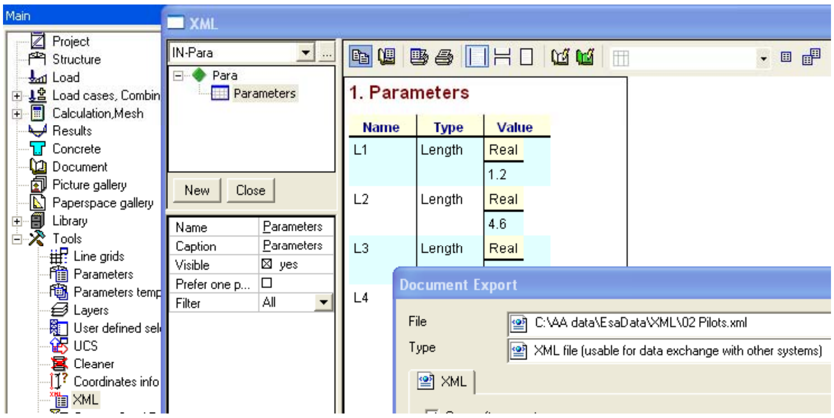
Optimisation in SCIA • ESA PT

SCIA • ESA PT 2007 incorporates all needed functionality described above.

Steel and concrete members can be designed optimally. Optimisation of steel-cross sections is common practice since many years; the optimal design of reinforcement was made available more recently. Also several steel connections may be optimised. The design of the minimal needed reinforcement in plates and walls is available. SCIA • ESA PT also allows defining all needed member optimisations, remembering them and repeating them after the change of the input data for a structure.

The parameterisation of the structure is a basic feature of SCIA • ESA PT modelling. Almost any entity, any feature of the designed project can be defined by a user defined parameter. Parameters are assigned to variables, starting from dimensions of structural members and cross-sections, loads and masses, over the time of pooring concrete, up to for instance the diameter or cover of steel reinforcement.

SCIA • ESA PT has a general text XML interface, which allows modifying structural data from “outside” and also reading any needed value for a project. In a XML document the user defines what design values should be incorporated. All ESA output documents are live, refreshable when the project is changed and recalculated. The XML document plays the role of the goal functions without limitations. How the XML file is defined is shown in a practical example hereafter



SCIA • ESA PT also operates in the “hidden” mode. The project may be modified from outside of SCIA • ESA PT, the calculation process can be launched from outside of SCIA • ESA PT, all defined documents may be refreshed and updated from outside and finally all values in the document can be read from outside. For that purpose we have an extra application ESA_XML.exe, which is easy connected to any external software application.

The simplest optimisation solver is the one that generates all possible sets of input parameters and calculates a goal function from all of them. Then the minimal (or maximum) goal value is found with the optimal set of input parameters. This operational mode is simple and reliable. If one calculates all possible variants, then one definitely finds the optimum. The only problem is that for systems with many parameters, the number of variants dramatically increases.
This kind of “batch optimiser” is now available in SCIA • ESA PT. The user only defines limits for his parameters and the step of variation for the parameters. All variants are calculated and diagrams of the results are generated within the spreadsheet Excel.

The last function in optimisation is the real optimisation solver. Such a solver needs the same input as the “batch optimiser” – with limits and steps for the parameters. But in this case not all variants are calculated, only a few variants are “tipped”; from the results of the goal function the optimal set of parameters is derived. The magic of the quality of this solver is how good they are at “tipping”. The better the solver the least calculation of variants is needed.
SCIA co-operates with the Prague University of Civil Engineering on this topic. At the current state the university optimisation solver is connected to SCIA • ESA PT. The solver uses a

stochastic algorithm of “Simulated Annealing” based on general genetic algorithms. It enables also potentially multi-parametric optimisation, what means that more result values can be controlled. The method guarantees finding more "optimal" solutions, because it searches for local extremes, which have a sense from engineering point of view.

Practical examples of optimisation

One distinguishes 4 different types of structural optimisation:

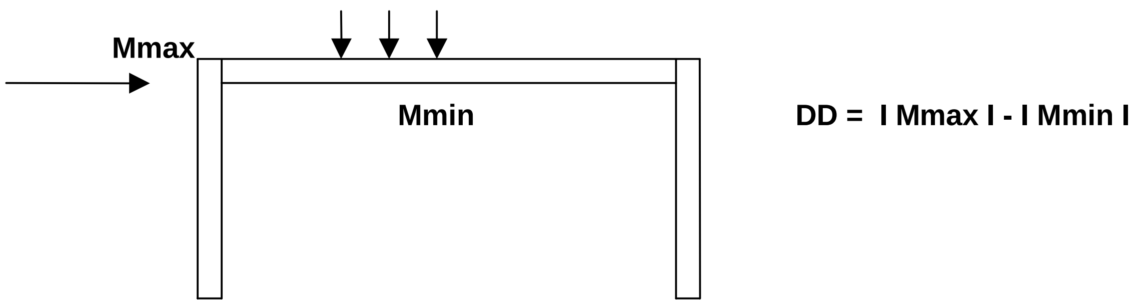
- **Topology** optimisation, which means finding a structure without knowing its final form; it means that members or FEM mesh parts will be removed/added during calculation of the variant solutions
- **Shape** optimisation: the topology of the structure is known a-priori but there can be some parts in which e.g.high stress can cause problems, thus shape parameters will be optimised to minimize stresses.
- **Size** optimisation: a structure is defined by a set of sizes, dimensions or cross-sections; these are combined to achieve the desired optimal criteria.
- **Topography** optimisation, which means searching a proper shape of a structure (e.g. tent, membrane, bridge).

Many examples of structural optimisation are manifest in the daily engineering practice, a few are mentionned hereafter

Searching the optimal relation between stiffnesses of beams and columns
Finding the optimal thickness of concrete plates
Determing the optimal dimensions of concrete beams
Finding the optimal shape of a post-tensioned tendon
Optimisation of the position of foundation piles
Sensitivity analysis of the subsoil parameters
Designing the least cost steel connection
Minimizing the weight of a steel structure for a pre-set type of frames
Searching the optimal definition of bridge spans
Finding a maximum carrying load for a crane under various geometrical positions

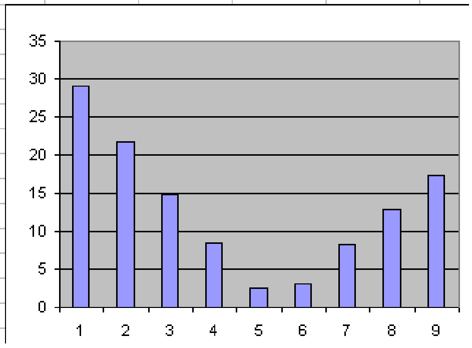
To illustrate the discrete parametric batch processing in SCIA • ESA PT a few illustrative small examples are outlined:

A. <u>Find such dimensions of a beam and a column in a frame to have the same bending moment at the end and in the middle of the beam</u>.



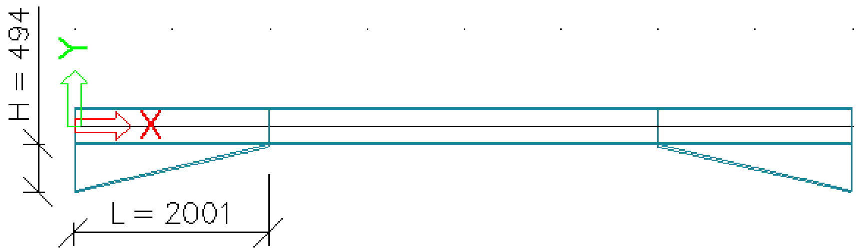
The batch process leads to the following output table:

Hbeam [m	Hcol [mm]	Max [kNm	Min [kNm]	DD [kNm]
380	280	136,03	-107,013	29,017
380	290	132,287	-110,584	21,702
380	300	128,773	-113,919	14,855
380	310	125,483	-117,023	8,461
380	320	122,407	-119,906	2,502
380	330	119,54	-122,575	3,035
380	340	116,868	-125,043	8,175
380	350	114,378	-127,323	12,945
380	360	112,064	-129,423	17,358



B. <u>Optimise the length and depth of a haunch</u>

Consider a beam with haunches; the beam is a HEA section, the haunch is from an IPE section. The dimensions of the haunch are parameterised; the profile of the main beam is optimised with a standard SCIA • ESA PT member optimisation.

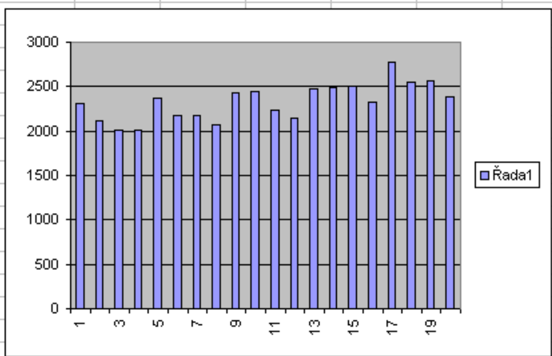


In each run the haunch is modified, the structure is calculated and the beam is optimised. The total weight is reported; with an assumed price for 1 kg of steel (e.g. 2,1 Euro), the price of the material for beam & haunches is reported.

The table hereafter gives for calculated L (L haunch), H (Height haunch) the values of the beam weight (M) and price (P).

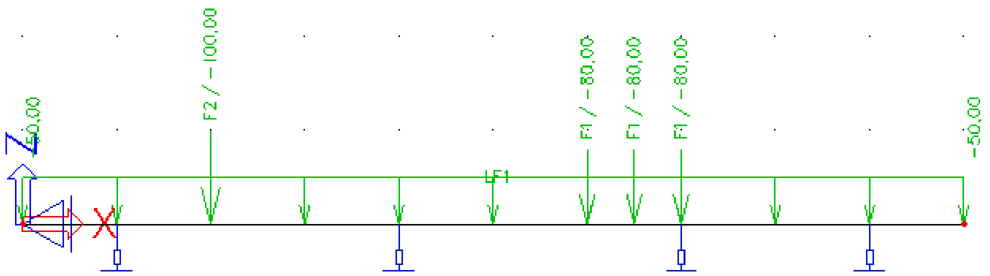
For each Haunch length, the optimum height is calculated. It means that several local minimum values are found.

LH [m]	HH [mm]	M	P
1	400	1102,018	2314,237
1	450	1006,248	2113,12
1	500	954,438	2004,319
1	550	959,148	2014,21
1,25	400	1127,892	2368,574
1,25	450	1033,3	2169,93
1,25	500	1039,187	2182,293
1,25	550	988,555	2075,965
1,5	400	1153,767	2422,91
1,5	450	1160,832	2437,747
1,5	500	1067,417	2241,575
1,5	550	1017,962	2137,72
1,75	400	1179,641	2477,247
1,75	450	1187,884	2494,556
1,75	500	1196,126	2511,865
1,75	550	1103,889	2318,166
2	400	1324,836	2782,155
2	450	1214,936	2551,365
2	500	1224,356	2571,147
2	550	1133,296	2379,921



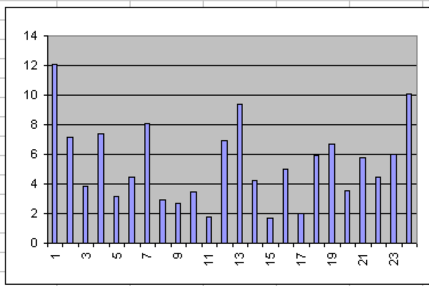
One finds that all variants satisfy from the point of view of code provisions, yet the price is varying in a quite wide range.

C. Optimisation of the position of piles.
The user has to design the foundation beam supported by piles. An ideal situation is when the reaction force in all piles is the same.

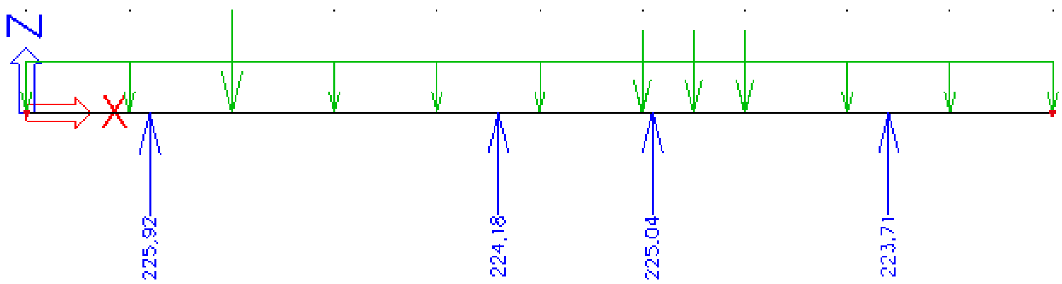


The user can set the limits for moving the supports, each variant is calculated and reactions are evaluated. The goal function can be a simple formula, which calculates the sum-of-squares of deviations from an average value of reaction.

L1 [m]	L2 [m]	L3 [m]	L4 [m]	R1 [kN]	R2 [kN]	R3 [kN]	R4 [kN]	R [kN]
1,1	4,6	6,1	8,2	217,397	221,908	225,697	233,858	12,083
1,1	4,6	6,1	8,3	219,58	223,745	226,094	229,441	7,18
1,1	4,6	6,1	8,4	221,58	225,586	226,678	225,015	3,812
1,1	4,6	6,2	8,2	219,897	223,372	225,472	230,119	7,402
1,1	4,6	6,2	8,3	222,036	225,238	225,811	225,776	3,127
1,1	4,6	6,2	8,4	223,997	227,104	226,342	221,418	4,443
1,1	4,7	6,1	8,2	220,634	222,376	224,541	231,309	8,102
1,1	4,7	6,1	8,3	222,825	224,165	224,958	226,913	2,961
1,1	4,7	6,1	8,4	224,833	225,964	225,556	222,508	2,675
1,1	4,7	6,2	8,2	223,167	223,803	224,279	227,611	3,436
1,1	4,7	6,2	8,3	225,314	225,623	224,637	223,286	1,797
1,1	4,7	6,2	8,4	227,283	227,448	225,183	218,946	6,896
1,2	4,6	6,1	8,2	221,671	220,56	224,111	232,517	9,368
1,2	4,6	6,1	8,3	223,888	222,369	224,484	228,119	4,222
1,2	4,6	6,1	8,4	225,921	224,182	225,043	223,714	1,688
1,2	4,6	6,2	8,2	224,201	221,999	223,874	228,786	4,992
1,2	4,6	6,2	8,3	226,373	223,836	224,188	224,463	1,966
1,2	4,6	6,2	8,4	228,366	225,673	224,695	220,126	5,942
1,2	4,7	6,1	8,2	224,954	220,993	222,953	229,96	6,673
1,2	4,7	6,1	8,3	227,179	222,753	223,345	225,584	3,543
1,2	4,7	6,1	8,4	229,219	224,523	223,918	221,2	5,772
1,2	4,7	6,2	8,2	227,516	222,395	222,678	226,271	4,45
1,2	4,7	6,2	8,3	229,697	224,185	223,011	221,967	5,963
1,2	4,7	6,2	8,4	231,697	225,981	223,532	217,649	10,084



When we minimize this function, all piles are loaded with the same force.



Ongoing research work

The Prague University of Civil Engineering has an extensive research program on optimisation. The research work is focused on algorithms, which are suitable for practical civil engineering problems, with typical discrete input functions (e.g. set of available materials, rolled sections or steel bars), together with a complicated dependency of the final goal function on those input variables. Moreover, as a structure must fulfil many various criteria, it is necessary to handle either multi-criteria problems or constraints, which are usually difficult to be described in close mathematical form. Several optimisation algorithms are developed, yet the optimisation of real life structures still demands a very large computation time. Methods that realize a breakthrough concerning this problem are based on numerical approximations, resulting in minimizing the number of calculations, and are called response surface methods. From artificial intelligence usually methods are used like neural networks, e.g. the so-called radial basis function network.

One of the advantages of the presented optimisation methods is, that they search not for the global extreme of a goal function, but for local extremes, and, therefore, more local extremes are found. Each of them has a meaning and it is up to the designer to assess those variants from the practical point of view, constructional aspects, a.o..

The other approach for handling high computational time is the approach of parallel or distributed computing. Most of the users of the SCIA software have a computer network, consisting out of PC's, which are in use during much less than 24 hours per day. Many hours during the day and definitely during the night they are either switched off or not really running computational tasks. So, algorithms that are able to use this free capacity will be very helpful. A scenario where the designer - who is at a certain state of his design of a structure - defines ranges, limitations, demands etc. The optimisation algorithm runs overnight, and when coming to the office in the morning, he considers one or more variants of the designed structure, which were computed as optimal solutions.

Benefits for structural engineers

Optimal design of structures will change the design process intensively; a "dream of the future" is becoming reality. As mathematical methods are developing and speed of computers is increasing, optimisation will bring a completely new quality to the practical design process.

Reference

Matej Leps, Single and multi-objective Optimization in Civil Engineering with Applications, PhD Thesis, Technical University Prague, 2004