SECOND-ORDER SHAPE OPTIMIZATION OF A STEEL BRIDGE

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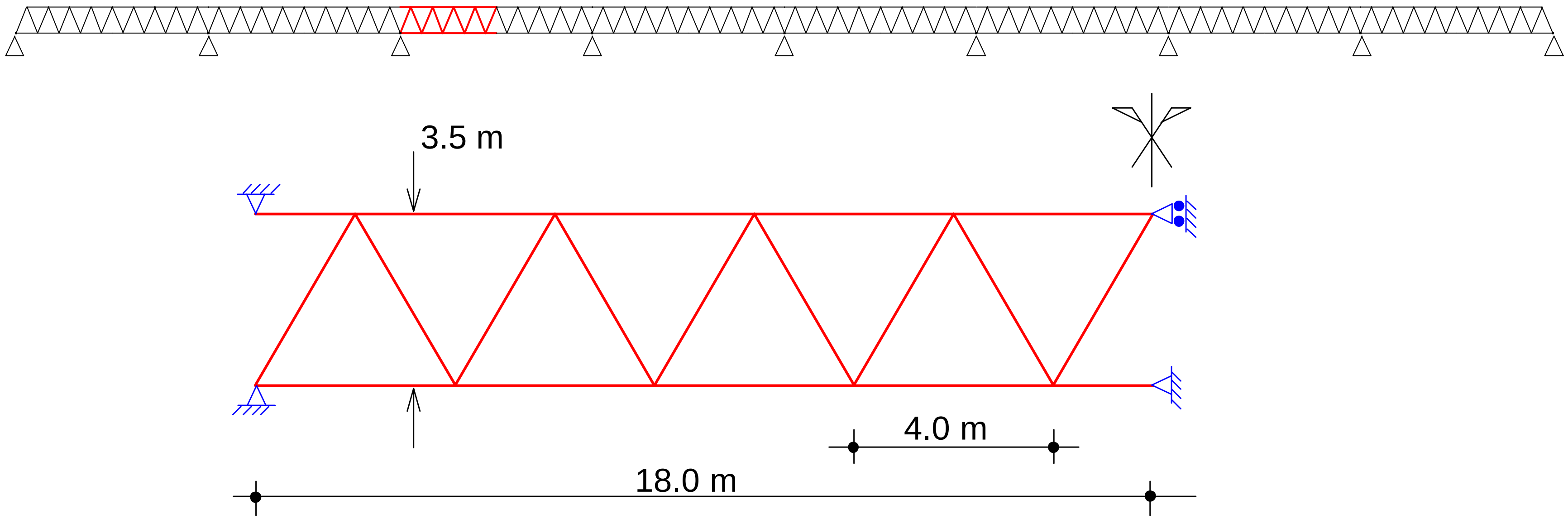
PROBLEM

- Minimize the cost of a steel bridge
- Member sizing and shape optimization



STRUCTURAL BEHAVIOR

- Linear elastic
- Fixed nodes (normal direction)
- Local Euler buckling
- Portuguese structural codes

OPTIMIZATION APPROACH

- Nonlinear program
- Second-order approximation
- Integrated formulation
- All the problem variables are present in the nonlinear program
- No sensitivity analysis

OPTIMIZATION SOFTWARE

- NEWTOP
- General purpose code
- Lagrange-Newton method
- Symbolic manipulation of all the functions

NONLINEAR PROGRAMMING

Minimize $f(\underset{\sim}{x})$

subject to

$$\underset{\sim}{g}(\underset{\sim}{x}) \le \underset{\sim}{0} \quad \rightarrow \quad g_i(\underset{\sim}{x}) + s_i^2 = 0$$

$$\underset{\sim}{h}(\underset{\sim}{x}) = \underset{\sim}{0}$$

- Variables / functions ➡ real and continuous
- All the functions are generalized polynomials, such as:

$$f(\underset{\sim}{x}) = 5.9\,x_1^2 x_4^{-3} - 3.1 x_2 + 2.7\,x_1^{-1} x_3 x_5^2 - 1.8$$

GENERALIZED POLYNOMIALS

$$f(\underset{\sim}{x}) = 5.9\,x_1^2 x_4^{-3} - 3.1 x_2 + 2.7\,x_1^{-1} x_3 x_5^2 - 1.8$$

- A symbolic manipulation is performed
- Expression parsing and evaluation is simplified
- Exact first and second derivatives can be easily calculated
- All these operations can be efficiently performed

INPUT FILE

```
### Main title of the nonlinear program
      Symmetric truss with two load cases (kN,cm)
Min.
    +565.685 * t5 ^ 2 + 100 * t8 ^2 ; # truss volume (cm3)

s.t.i.c.
    Min. area 4:   - t4 ^ 2 + 0.15 < 0 ;

s.t.e.c.
    Equil 16:  + 141.421 * t5 ^ 2 * disp16 - 100 = 0 ;

END_OF_FILE
```

- All the software is coded in ANSI C

LAGRANGIAN

$$L\left(\underset{\sim}{X}\right) = f\left(\underset{\sim}{x}\right) + \sum_{k=1}^{m} \lambda_k^g \left[g_k\left(\underset{\sim}{x}\right) + s_k^2 \right] + \sum_{k=1}^{p} \lambda_k^h h_k\left(\underset{\sim}{x}\right)$$

VARIABLES

$$\underset{\sim}{X} = \left(\underset{\sim}{s}, \underset{\sim}{\lambda}^g, \underset{\sim}{x}, \underset{\sim}{\lambda}^h\right)$$

SOLUTION

- Stationary point of the Lagrangian

SYSTEM OF NONLINEAR EQUATIONS

$$\nabla L\left(\underset{\sim}{X}\right) = \underset{\sim}{0} \quad \Rightarrow \quad \left| \begin{array}{ll} 2 s_i \lambda_i^g = 0 & (i = 1, \ldots, m) \\ g_i + s_i^2 = 0 & (i = 1, \ldots, m) \\ \dfrac{\partial f}{\partial x_i} + \sum_{k=1}^{m} \lambda_k^g \dfrac{\partial g_k}{\partial x_i} + \sum_{k=1}^{p} \lambda_k^h \dfrac{\partial h_k}{\partial x_i} = 0 & (i = 1, \ldots, n) \\ h_i = 0 & (i = 1, \ldots, p) \end{array} \right.$$

- The solution of the system is a KKT solution when

$$\boxed{\underset{\sim}{\lambda}^g \geq 0}$$

LAGRANGE-NEWTON METHOD

- The system of nonlinear equations

$$\nabla L(\underset{\sim}{X}) = \underset{\sim}{0}$$

is solved by the Newton method

- In each iteration the following system of linear equations has to be solved

$$\underset{\sim}{H}\left(\underset{\sim}{X}^{q-1}\right)\Delta\underset{\sim}{X}^{q} + \nabla L\left(\underset{\sim}{X}^{q-1}\right) = \underset{\sim}{0}$$

HESSIAN MATRIX

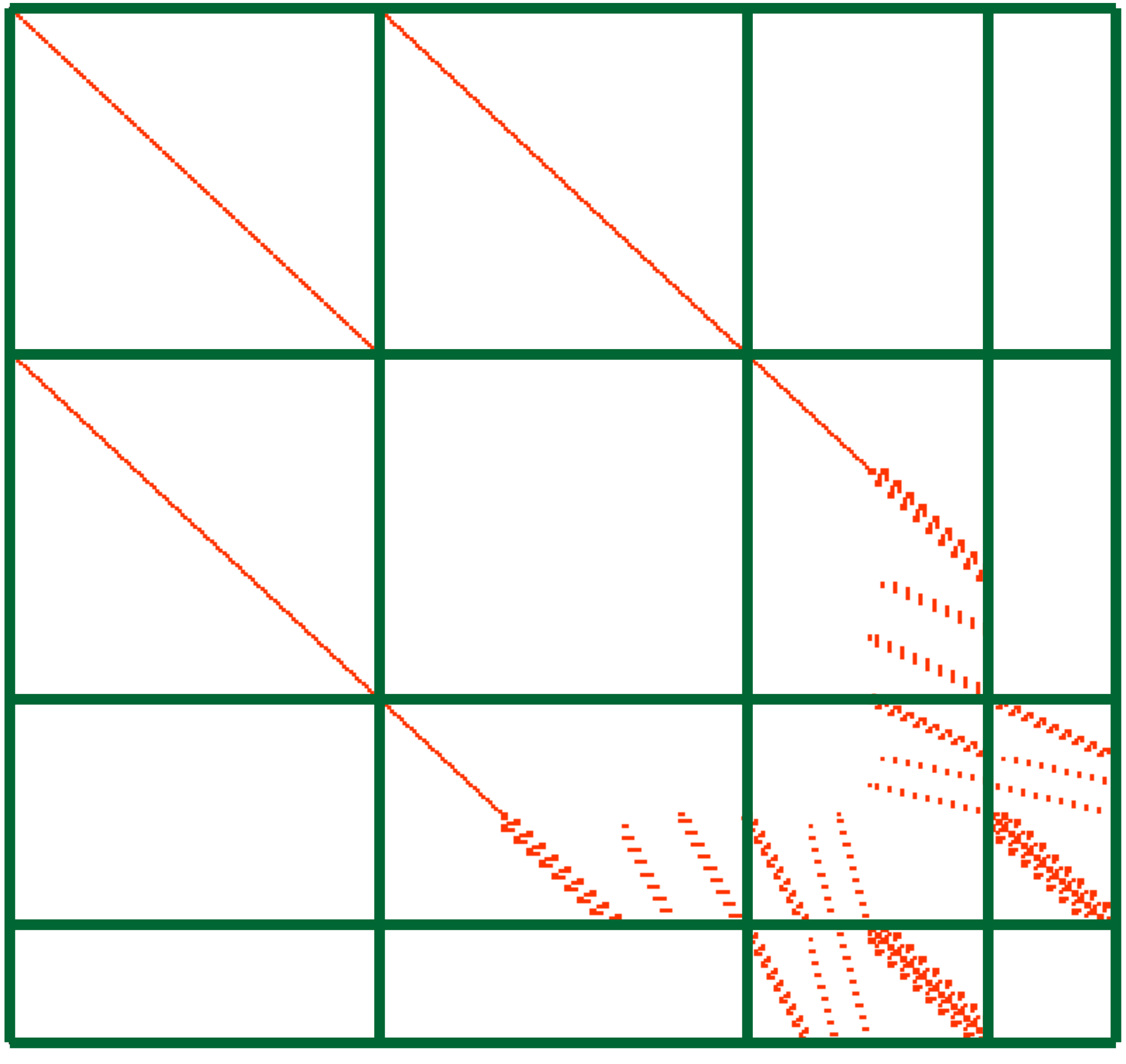
$\underset{\sim}{H} =$

	(m)	(m)	(n)	(p)
(m)	$Diag\left(2\lambda_i^g\right)$	$Diag\left(2s_i\right)$	$\underset{\sim}{0}$	$\underset{\sim}{0}$
(m)		$\underset{\sim}{0}$	$\dfrac{\partial g_i}{\partial x_j}$	$\underset{\sim}{0}$
(n)			●	$\dfrac{\partial h_j}{\partial x_i}$
(p)	*S Y M M E T R I C*			$\underset{\sim}{0}$

● $$\frac{\partial^2 f}{\partial x_i \partial x_j} + \sum_{k=1}^{m} \lambda_k^g \frac{\partial^2 g_k}{\partial x_i \partial x_j} + \sum_{k=1}^{p} \lambda_k^h \frac{\partial^2 h_k}{\partial x_i \partial x_j}$$

HESSIAN MATRIX SPARSITY PATTERN

$$\underset{\sim}{H} =$$



SYSTEM OF LINEAR EQUATIONS

- Gaussian elimination
  - adapted to the sparsity pattern of the Hessian matrix
- Conjugate gradients
  - diagonal preconditioning
  - adapted to an indefinite Hessian matrix

LINE SEARCH

$$\underset{\sim}{X}^{q} = \underset{\sim}{X}^{q-1} + \alpha \, \Delta \, \underset{\sim}{X}^{q}$$

- The value of α minimizes the error in $\Delta \underset{\sim}{X}^{q}$ direction
  - the value of α is often close to one
  - faster convergence
  - process may fail
- The value of α is made considerably smaller (e.g. α = 0.1)
  - stable convergence
  - more iterations - slower

NEWTOP COMPUTER CODE

- All the variables are scaled
- Constraints are normalized
- Elementary equality constraints are substituted:

$$x_i = c\,x_j \qquad \text{or} \qquad x_i = c$$

- The NLP is simplified
- Problems with a large number of variables can be solved

  (e.g., 4 000 design variables and 20 000 constraints)

TRUSS OPTIMIZATION

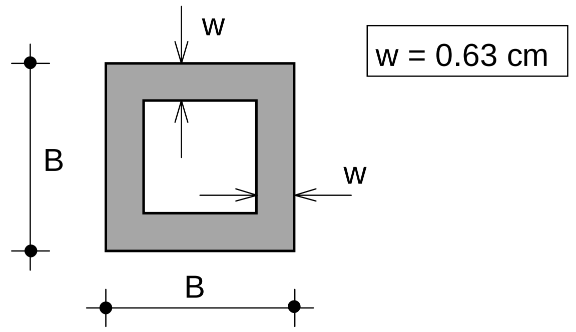
- Cost minimization (often similar to volume minimization)

  - Sizing ⇨ cross-sectional areas may change
  - Shape optimization ⇨ nodal coordinates may change

Simultaneously

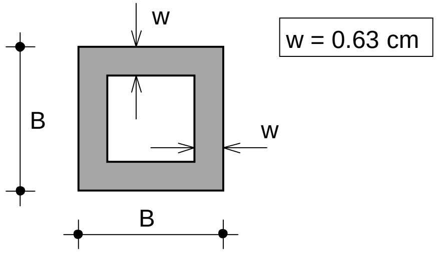
VARIABLES

- Integrated formulation
- Design variables and behavior variables simultaneously present in the nonlinear program
  - ♦ Cross-section dimensions (e.g., width, diameter, area)
  - ♦ Some nodal coordinates
  - ♦ Nodal displacements



SUBSTITUTED VARIABLES

- In most cases the area (A) and the moment of inertia (I) depend on a single parameter (B)



$$A = C_0^A + C_1^A B + C_2^A B^2$$

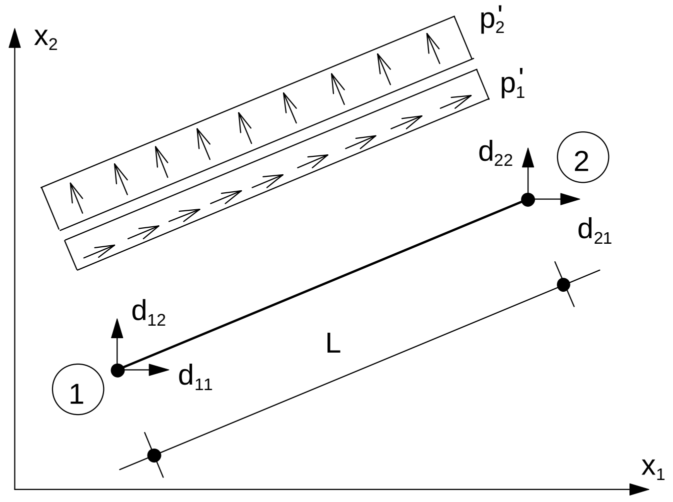
$$I = C_0^I + C_1^I B + C_2^I B^2 + C_3^I B^3 + C_4^I B^4$$

- ♦ Coefficients C_i^A and C_j^I are fixed
- ♦ Variables A and I can be substituted in all the functions that define the mathematical program

ADDITIONAL VARIABLES

$$k_{ij} = \cdots + EAL^{-1} + \cdots$$

$$L = \sqrt{\left(x_{21} - x_{11}\right)^2 + \left(x_{22} - x_{12}\right)^2}$$



- Additional variables ⇨ L_i

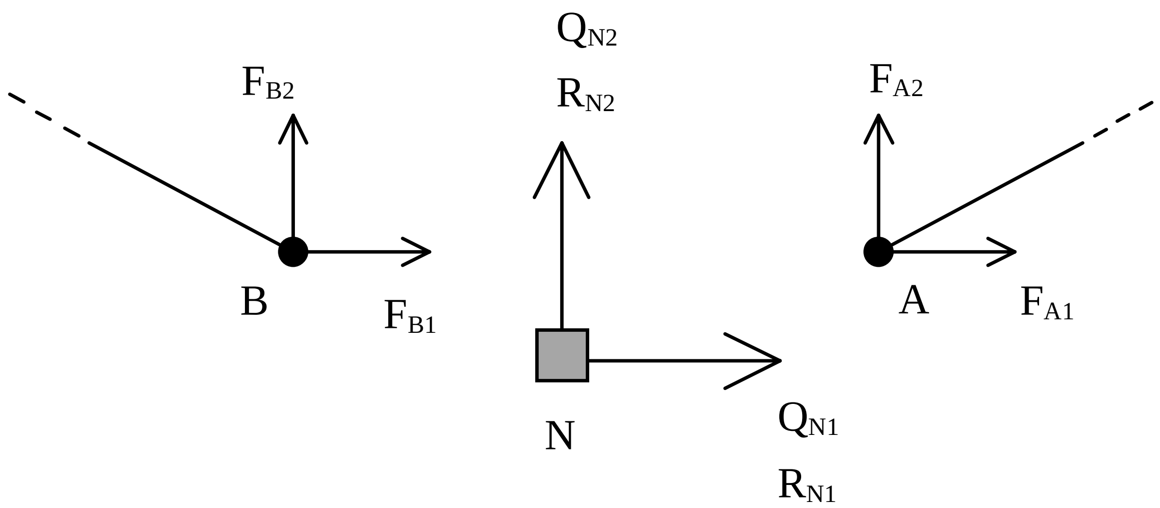
$$-L^2 + x_{11}^2 + x_{12}^2 + x_{21}^2 + x_{22}^2 - 2x_{11}x_{21} - 2x_{12}x_{22} = 0$$

- Additional equality constraints ⇨ L_i definition

EQUILIBRIUM EQUATIONS

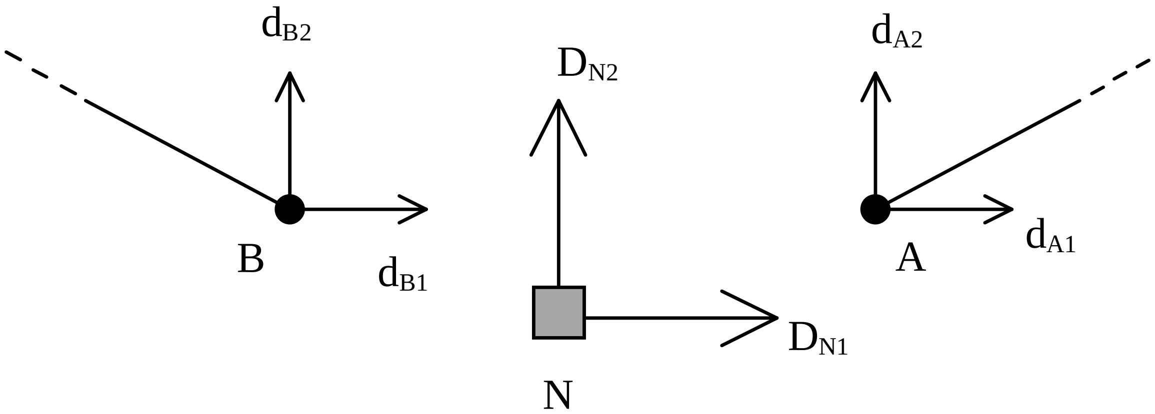
- Equality constraints:

$$\underset{\sim}{F}_A + \cdots + \underset{\sim}{F}_B + \cdots = \underset{\sim}{Q} + \underset{\sim}{R}$$



- Reactions are only present in constrained dof 's

COMPATIBILITY EQUATIONS



$$\underset{\sim}{d}_A = \underset{\sim}{D}_N$$

$$\underset{\sim}{d}_B = \underset{\sim}{D}_N$$

- Variables d are substituted
- D_{Ni} is fixed in constrained dof 's

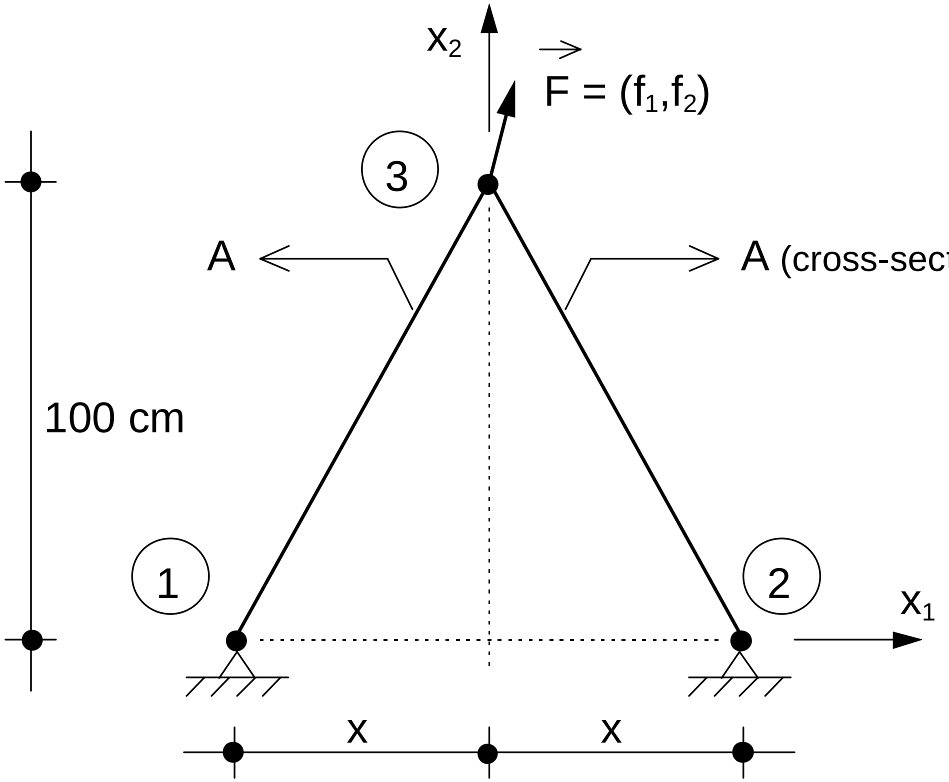
NON LINEAR PROGRAM

- Objective function: cost ⇨ $f(\underset{\sim}{x}) = \sum_{i=1}^{NB} c_i A_i L_i$

- Equality constraints:
  - for each bar with variable length:
    - ➔ one equation defining L
  - for each non-prescribed degree of freedom:
    - ➔ one equilibrium equation

- Inequality constraints:
    - minimum width ⇨ $B \geq B_{\min}$
    - allowable stress (tension and compression)
    - local Euler buckling
    - side constraints in nodal coordinates ⇨ $x_{\min} \leq x_i \leq x_{\max}$

NUMERICAL EXAMPLE



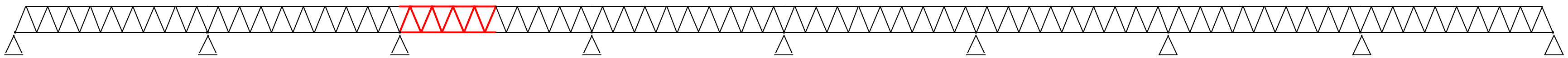
$$\| \vec{F} \| = 200\, kN$$

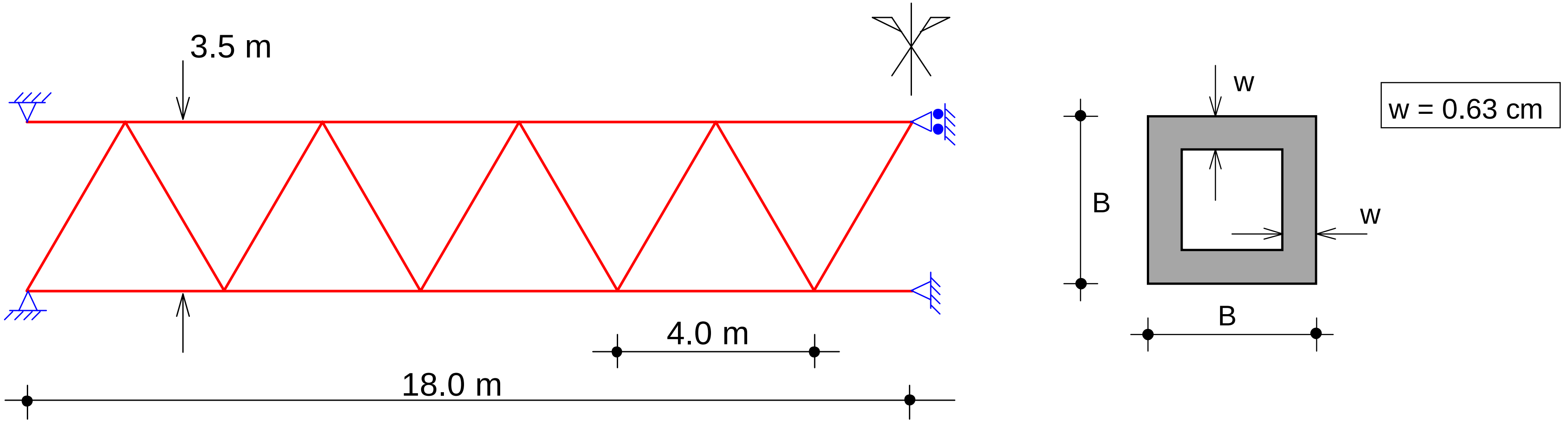
$$f_2 = 8\, f_1$$

$$\sigma_{max} = 100\ kN/cm^2$$

- Variables: A , x
- Svanberg's solution confirmed

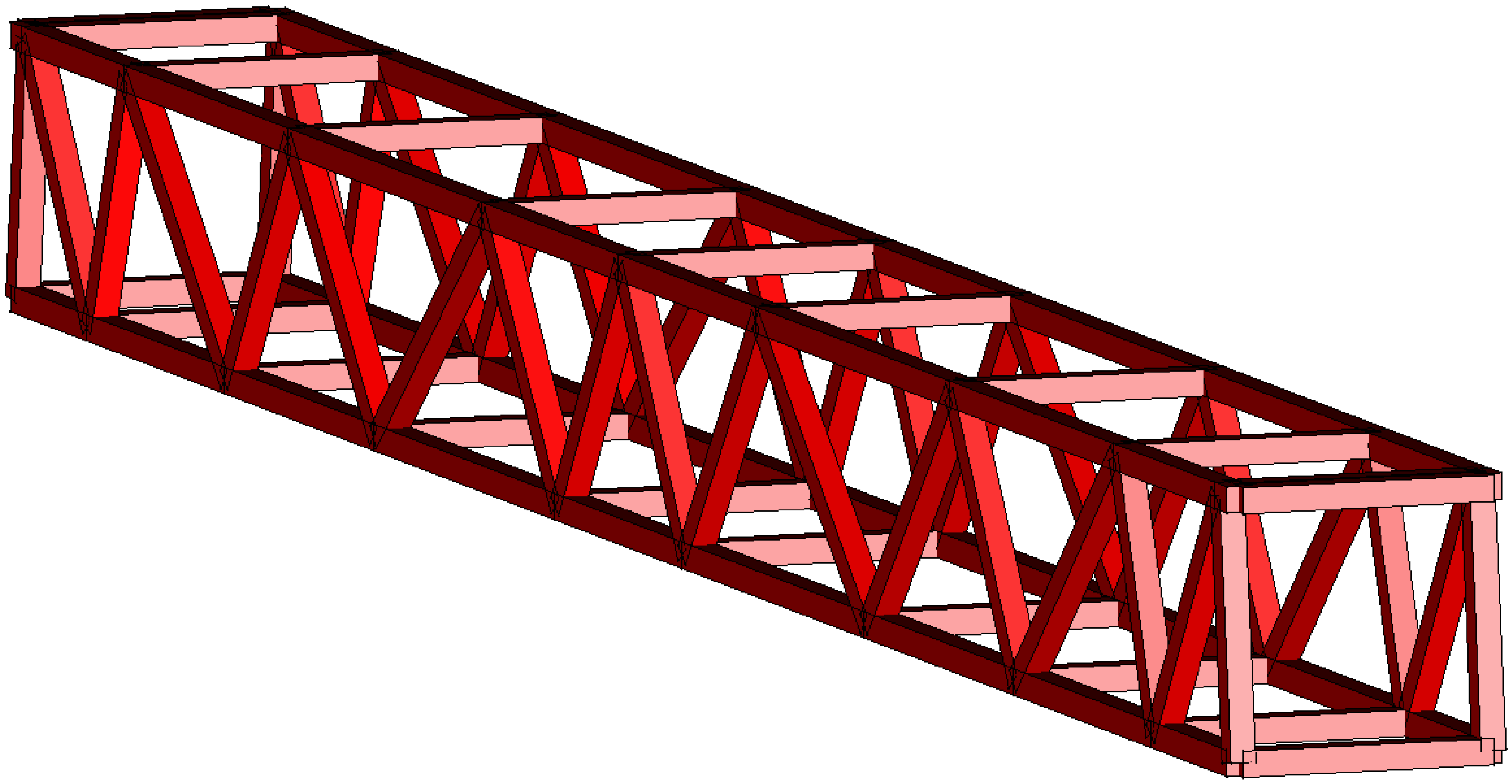
STEEL BRIDGE



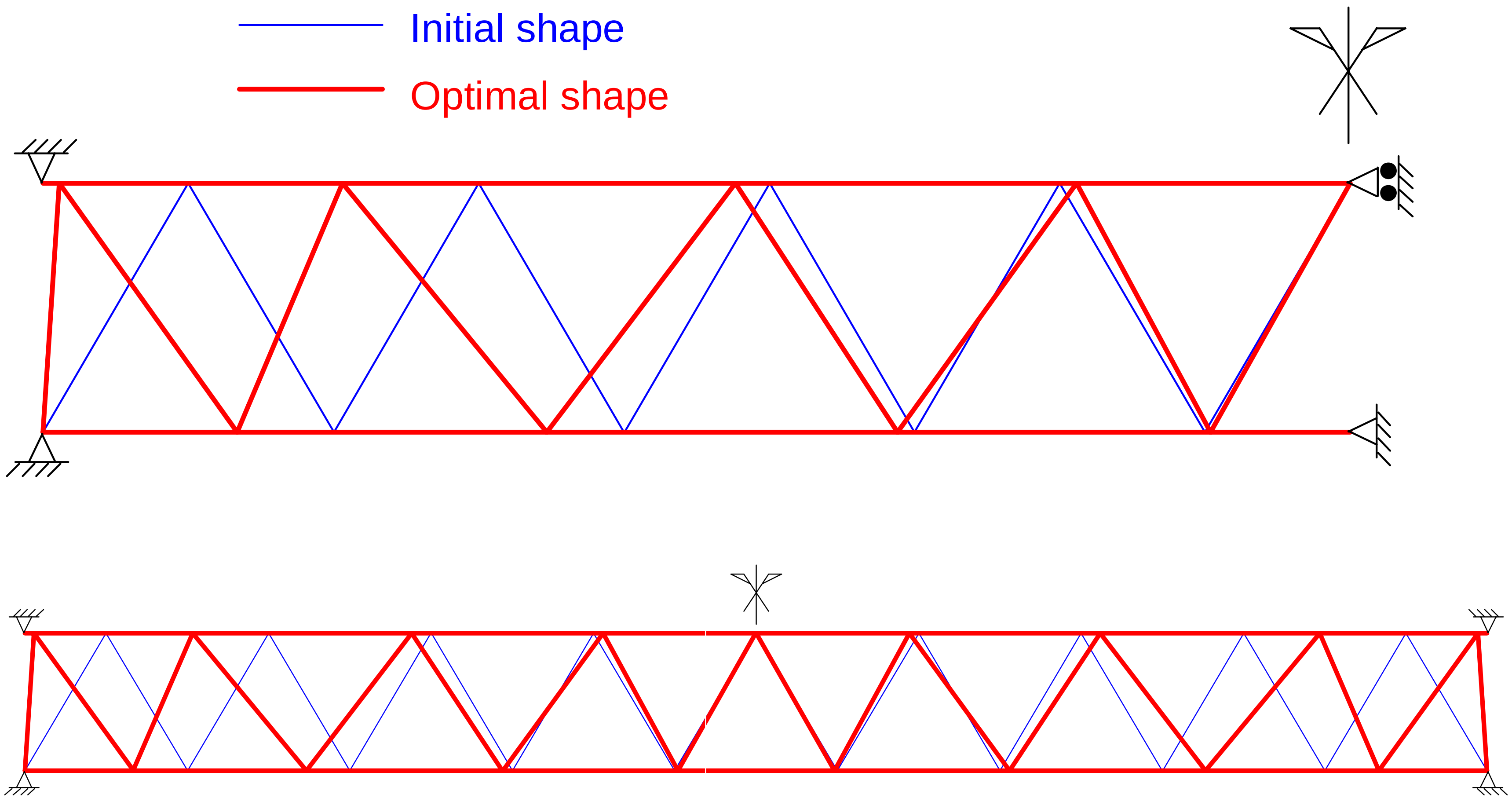


- Group I - horizontal bars
- Group II - diagonal bars

STEEL BRIDGE



OPTIMAL SHAPE



NUMERICAL RESULTS

- Optimal solution - sizing only
  - Volume = 170 dm^3
- Optimal solution - sizing and shape optimization
  - Volume = 146 dm^3 (14 % smaller)
  - CPU time (PC): less than 10 seconds

CONCLUSIONS

- Significant economy in a structure that will be repeated
- Efficiency and accuracy
- Optimal structure is easy to build
- Friendly user interface is still required
- Move limits in nodal coordinates need some tuning