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Seismic resistant optimum design of a welded steel frame supporting a pressure vessel

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Keywords: Welded steel frame, seismic design, structural optimization, tubular structures.

Pressure vessels are expensive and dangerous devices, which need safe supports. Their fracture caused by earthquake can be very dangerous. Thus, the design constraints should be very strict.

A simple supporting frame consists of 4 columns and 4 beams (Fig. 1). The pressure vessel is fixed at the middle of the beams. The horizontal seismic load is calculated according to Eurocode 8 (2003). Since the horizontal forces cause large bending moments in the horizontal plane and the beams should transfer at the frame corners large bending moments, they suitable profile is a welded box section or tubular hollow section. Therefore the columns are constructed with box section as well. The welded corners are assumed to be rigid.

Eurocode 8 prescribes a strict limitation of the horizontal sway at the middle of the beams. This sway has four components as follows: the sway of the vertical frames, deformation of the beam due to bending in horizontal plane, displacement of the beam due to angular deformation of the frame corner and another displacement caused by torsion.

In an optimum design procedure the safety and fitness for production are guaranteed by design and fabrication constraints, the economy is achieved by minimization of a cost function (Farkas & Jármai 1997, Farkas & Jármai 2003).

The fabrication (assembly and welding) cost of frame corner joints is proportional to the size of columns and beams, thus the minimum cost design is identical to the minimum mass design. Since the investigated frame is symmetric, the unknowns to be optimized are the thicknesses t_1 and t_2 for columns and beams, respectively as well as a common width $h_1 = h_2$ of the square hollow section (SHS) of the columns and beams.

The constraints relate to the sway limitation and to the stability of frame members against compression and bending according to Eurocode 3 (2002).

Calculation of the seismic force is according to Eurocode 8 (2003): the pressure vessel mass m should be multiplied by $0.85 \times 0.2091 = 0.1777$. The pressure vessel mass is 300 kN, the seismic horizontal force acting on a beam is $F_b = 0.1777 \times 75 = 13.3$ kN.

Constraint on elastic sway limitation is given as:

$$u_e \leq \frac{0.0075H}{\gamma_1 q \nu} = \frac{0.0075x4000}{1.4x5.5x0.4} = 9.74 \text{ mm.} \qquad (1)$$

Importance class for power plants is IV (EC8 Table 4.3). Structural height $H = 4000$ mm. The recommended safety factor for importance class IV is $\gamma_1 = 1.4$. The reduction factor $\nu = 0.4$. Behaviour factor $q = 1.1 \times 5 = 5.5$ according to Eurocode 8 (2003) Table 6.2 and Figure 6.1.

Numerical data: $E = 2.1 \times 10^5$ MPa, $G = 0.8 \times 10^5$ MPa, $H = 4000$, $L = 4000$ mm, $F = 75$ kN, $F_b = 13.3$ kN. The objective function is the structural volume $V = 4A1H + 4A2L$ or the structural mass $m = \rho V$, $\rho = 7.85 \times 10^{-6}$ kg/mm^3.

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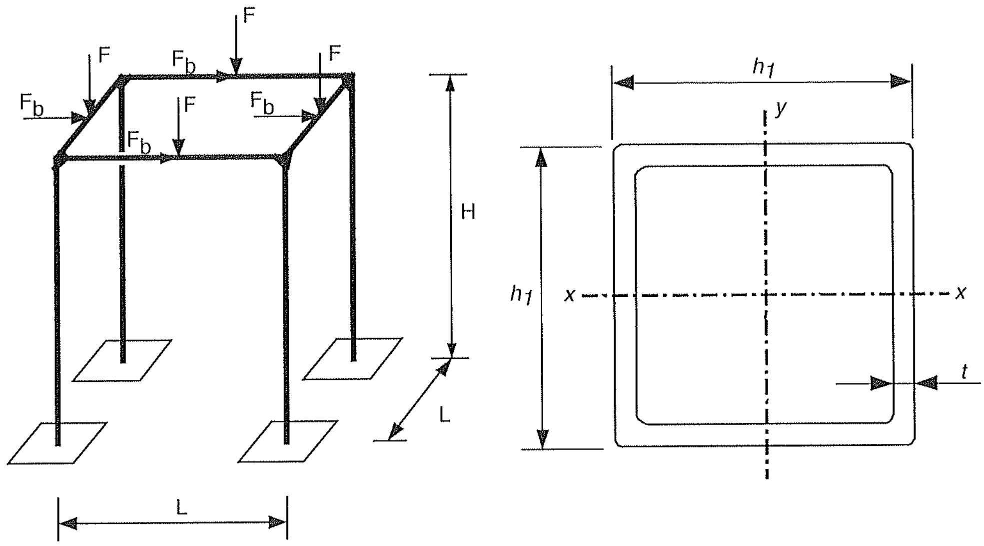

Figure 1. Supporting frame with vertical and horizontal forces; dimensions of a square hollow section.

The suitable SHS for columns and beams are selected using a cold-formed SHS catalogue BS EN 10219:1997. Since the minimum thickness is limited by the local buckling constraint, only that thicknesses can be used, which are larger than this limit, e.g. for $h_1 = 220$, $t = 6.3$, for $h_1 = 250$, $t = 8$, for $h_1 = 260$, $t = 8$ and for $h_1 = 300$, $t = 10$ mm. Therefore the number of SHS to be investigated is limited.

The governing constraint is that on sway limitation, the stress constraints are always fulfilled. The common width is h_1 and the thicknesses are t_1 for columns and t_2 for beams.

The optimum sizes are as follows: $h_1 = 250$, $t_1 = t_2 = 8$ mm, the minimum mass is $m = 1890$ kg.

The detailed calculation of sway due to bending deformations of the frame in vertical and horizontal plane and due to the torsion of the beams is presented. The objective function is the structural volume or mass, since the minimum cost design coincides with minimum mass design.

The optimum cross-sections are selected from a discrete series for SHS using a systematic search. The sway limitation is the governing constraint. Calculating the sway components it is found that the deformation due to torsion of beams and the sway from the angular deformation of frame corners can be neglected.

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