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RESULTS AND TRENDS IN THE FIELD OF STRUCTURAL OPTIMIZATION

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Summary

Mass and cost reduction of structures needs structural optimization. Structural optimization has three main parts, structural analysis, synthesis and engineering evaluation. During the four decades at the University of Miskolc, where optimization studies have been performed, we have worked out the optimization of the following structures: crane girders, dogbone sections, silos, stiffened and cellular plates, tubular structures, sandwich and composite structures, etc. The fabrication cost calculation is very important for the optimum sizes. The optimization techniques used for optimization tend from direct search methods to sequential quadratic programming, using automatic derivation. Expert systems, genetic algorithms and neural networks are new promising fields of optimization.

1 OPTIMUM DESIGN OF SILOS

Silos are used for many engineering purposes. An elevated silo consists of the following structural parts: roof, circular cylindrical bin, transition ringbeam, conical hopper and supporting columns. The optimum design problem of silos is characterized by some specialities as follows. The structure is determined by two main dimensions i.e. the height H and the radius R of *the circular cylindrical bin* (Fig.1). The bin consists of several horizontal courses. The width of these courses is determined by the available plate width (e.g. 1500 mm).

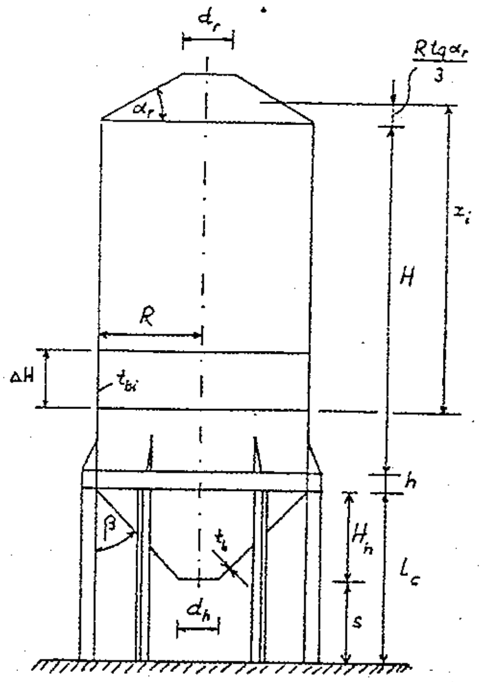

Fig. 1

The effect of a sudden temperature change as well as the dynamic filling and emptying effects are taken into account by multiplying factors. The local buckling of the cylindrical shell of variable thickness should be checked for two effects: a) for vertical compressive stresses due to the full load, b) for wind pressure acting on the empty silo.

The loads acting on *the transition ringbeam* cause compression, bending and shear in two planes and torsion. Since the open section beams have very small torsional stiffness, it is advantageous to use welded box ringbeams (FARKAS, JÁRMAI [1]). The ringbeam is optimized using the constraints on stress and local buckling of component plates.

The uniform thickness of *the conical hopper* can be calculated from the stress constraint. The slope angle of the hopper is determined by the friction angle of the stored material.

The number of *the supporting columns n* may vary in a range determined by the service conditions, i.e. by the prescribed distance between columns needed for lorries. The columns may have a square or circular hollow section, which is designed using the constraints on overall and local buckling.

Table 1. K/k_m (kg) values for four silos of equal storage capacity of 500 m^3 for $k_f/k_m=1$

R(m)	4.25	3.50	3.15	2.90
H(m)	7.50	12.00	15.00	18.00
H/R	1.76	3.43	4.76	6.20
roof	3769	2597	2073	1779
bin	8853	11627	13240	14295
ringbeam	6101	4943	4170	3597
hopper	4356	3065	2583	2169
columns	2681	2231	2068	1952
total	25760	24463	24134	$\boxed{23792}$

Closed formulae have been derived for the optimal dimensions of SHS or CHS columns. The objective function (K) is formulated as a cost function, which includes the material (K_m) and fabrication (K_f) cost, k_m and k_f are the specific material and fabrication costs. For material Fe 360 and Fe 510 type steels are used with yield stress 235 and 355 MPa, respectively. Results in Table 1 show that the highest H/R ratio gives the minimum cost.

2 OPTIMUM DESIGN OF SANDWICH BEAMS WITH FIBER REINFORCED COMPOSITE LAYERS

The poor damping capacity of aluminium beams can be improved by using a rubber layer. The disadvantage of such sandwich beams was the relatively high dynamic deflection due to the shear deformation of the rubber layer. For the present study our aim was to decrease this large deflection by using fiber-reinforced plastic (FRP) layers. To investigate the static and dynamic behaviour of sandwich beams constructed from aluminium square hollow section (SHS) and rubber and FRP layers, we have used 3 specimens as shown in Fig.2. Static bending tests and vibration damping measurements serve to describe the most important characteristics of the investigated models. For the calculations the static and dynamic bending theory of sandwich beams with thick faces is applied.

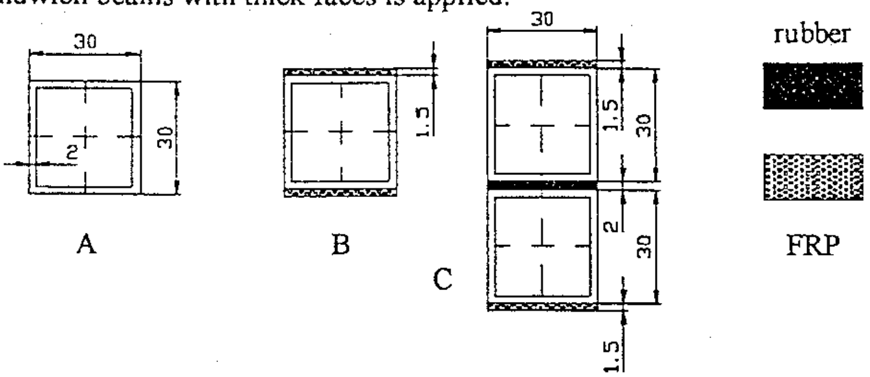

Fig. 2. Tested specimens

In the static tests the maximum deflection is measured at the midspan of simply supported beams loaded by a concentrated force at midspan. Three specimens have been manufactured and tested (Fig.2).

In order to determine the eigenfrequencies and vibration damping or loss factors the Brüel-Kjaer vibration measuring devices have been used in our laboratory. The loss factors are obtained by using the half-power bandwidth method. The formula for the loss factor at the ith eigenfrequency f_i is $\eta_i = \Delta f / f_i$ where Δf is the frequency bandwidth. Table 2 gives the measured results.

Table 2. Measurement results: eigenfrequencies and loss factors

Specimen	A			B			C		
i	1	2	3	1	2	3	1	2	3
f_i (Hz)	32	196	536	33	200	543	52	255	648
η_i	0.0125	0.0028	0.0015	0.012	0.0032	0.0028	0.052	0.057	0.053

The static bending stiffness of a SHS aluminium beam can be increased significantly by using FRP layers. This increase was in the case of our investigated specimens about 35%, without any increase in weight. The FRP layers do not increase the vibration damping, the loss factor is only about 1%. The static behaviour of a SHS profile with FRP layers can be calculated by the reduced bending stiffness. The damping can be increased significantly by applying a rubber layer of high damping capacity [2]. In our case the loss factor has been quadrupled (comparison between specimens A and C). Due to a soft rubber layer the static bending stiffness decreased by 52%. The static and dynamic behaviour of specimen C can be calculated with sufficient accuracy by the bending theory of sandwich beams with thick faces. The optimization is performed taking into account the face beams stresses, the local buckling of the webs, the deflection and the damping factor of the beam.

3 DOGBONE SECTIONS

A hollow flange beam (HFB) consists of a straight web and two hollow flanges. The shape of flanges can be triangular, circular or square one. To compare these structural versions with welded I-beams an optimization procedure is developed. The optimum cross-sectional dimensions are determined which minimize the cross-sectional area and fulfil the design constraints on stress due to bending and on local buckling of web and compression flange.

Hollow flanges can be used instead of simple plate flanges in welded beams (Fig.3). A special triangular hollow flange beam (TFB), called also „dogbone", is developed by the Australian firm Palmer Tube Technologies Ltd (DEMPSEY [3]). The section is cold-formed from flat strip. The triangular flanges are closed by two electric resistance welded seam.

We have worked out an optimization method to compare the TFB-s with circular CFB and square SFB and with welded I-beam. The main advantages of HFB over simple welded I-beams are as follows: (a) the local buckling strength of beam parts is higher, therefore the thicknesses can be smaller; (b) the whole beam is higher, therefore the beam deflection is smaller; (c) the torsional stiffness is much larger, therefore the lateral-torsional buckling strength is larger.

The problem of lateral-torsional buckling of TFB is investigated by PI & TRAHAIR [4]. They have proposed a reduction of the torsional stiffness due to web distortion. We show that the Eurocode 3 (EC3) formulae give smaller values for lateral-torsional buckling factors, thus, the EC3 method can be used for comparison.

In the optimization the optimum cross-sectional dimensions are sought which minimize the cross-sectional area and fulfil the design constraints on maximum stress due to bending as well as on local buckling of the web and the compression flange.

First the cross-sectional characteristics are derived for an arbitrarily hollow flange shape and the optimization procedure is described, then the optimum cross-sectional areas and moments of inertia are expressed and compared for the above mentioned four beam shapes.

The lateral-torsional buckling strengths are characterized by buckling factors in the function of L/h for simply supported beams of span length L and web height h subject to uniformly distributed normal load. The calculation of the torsional constants of closed thin-walled beams is treated e.g. in the book FARKAS & JÁRMAI [5].

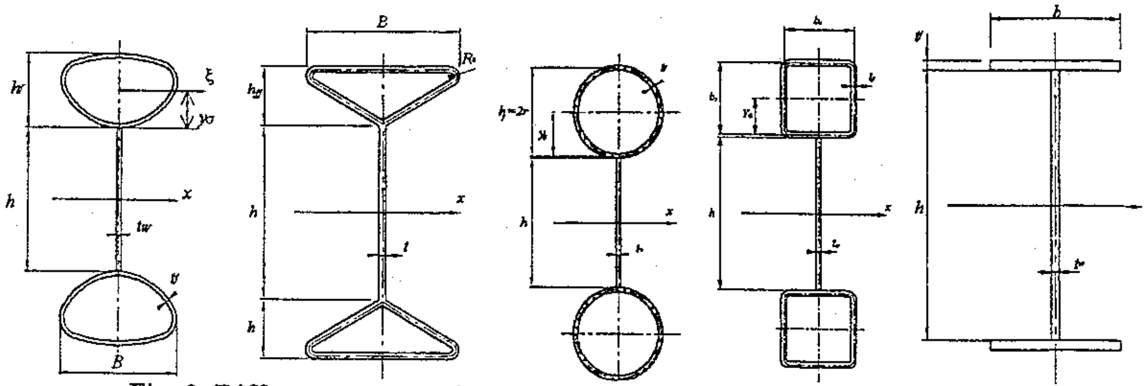

Fig. 3. Different cross sections, HFB, TFB, CFB, SFB and welded I-beam

Table 1. Comparison of lateral-torsional buckling factors χ_{LT}

φ	TFB	CFB	SFB	I-beam
1	0.5275	0.8974	0.5146	0.3536
2	0.3181	0.8052	0.3153	0.1346
3.33	0.2075	0.7052	0.2068	0.0702
10	0.0769	0.4031	0.0769	0.0216

It can be seen that the lateral-torsional buckling strength of HFB-s is larger than that of welded I-beam. The high values for CFB show that the torsional stiffness of circular hollow flanges is very large because of the high value of $\varsigma_{opt} = \frac{2h_f}{h} = 0.81$ compared with the lower ς_{opt} -values for TFB and SFB.

The minimum cross-sectional area design of four welded beam types considering the maximum stress due to bending and the limiting local buckling slendernesses gives a basis of comparison relating to the beam weight, deflection and lateral-torsional buckling strength. The cross-sectional area (weight) of HFB-s is smaller than that of I-beams. The moment of inertia about the major axis of HFB-s is larger, therefore the beam deflection is smaller than that of I-beams. The lateral-torsional buckling factor in function of $\varphi = L/10h$ is larger for HFB-s than that for I-beams (Table 1). These realistic comparisons give designers a basis for selection of suitable structural versions.

4 FABRICATION COST CALCULATIONS

In the early stage of optimization the mass of structures has been minimized. Nowadays there are also some optimization techniques, which can not handle complicated cost functions. To get an economic structure in the period of increasing fabrication costs, one should take into account as many elements of costs as possible. The cost of a structure is the sum of the material, fabrication, transportation, erection and maintenance costs. The fabrication cost elements are the welding-, cutting-, preparation-, assembly-, tacking-, painting costs etc. It is very difficult to obtain such cost factors, which are valid all over the world. If we choose times, as the basic data of fabrication phases, we can handle this problem. The fabrication time depends on the technological level of the country and the manufacturer, but it is much closer to the real process to calculate with. After computing the necessary time for each fabrication phase one can multiply it by a specific cost factor, which can represent the development level differences [5].

Using the COSTCOMP [6] program we can calculate the welding times. Times are usually general, but costs are different in various countries. Introducing the fabrication and material specific cost ratio k_f/k_m between 0 and 2 kg/min, it is possible to formulate the cost function from the times and to work out optimization in different economic conditions. Examples are shown applications for design of welded box beams and stiffened plates. The fabrication cost percents for welded box beam and stiffened plate are 29 - 35 and 46 - 71% of the total costs, respectively, thus they can have a significant effect on optimum dimensions. The discrete optima depend on the manufacturers, on the k_f/k_m ratio and the welding technologies.

5 NEW PROMISING AREAS

Expert systems, genetic algorithms and neural networks are new promising fields of optimization. Optimization algorithms can be built into expert system which help to find the best solution of a problem [7,8]. Neural networks can be used for function approximation. If the function-evaluation is heavy, than this approximation can be very powerful [9,10]. Genetic algorithms are very useful finding the solution of nonconvex optimization problems [11].

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