MINIMUM COST DESIGN OF A BUNKER CONSTRUCTED FROM WELDED STIFFENED PLATES

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ABSTRACT

The main structural parts of a steel bunker are systematically optimized for minimum cost. Pressure distribution due to the stored material in bin walls is nearly hydrostatic, therefore the optimum positions of horizontal stiffeners are calculated using the condition that all the parts of the base plate strips should be stressed to yield strength. The optimum number of stiffeners is determined in bin and hopper walls to reach a minimum cost. Transition beams are loaded by hopper reactions and should be designed for bending as horizontal welded I-beams. Total material and fabrication costs are determined for three optimized bunker structural solutions having different ratios of bin height/width. In the investigated numerical example of a cement bunker the structural version of bin height/width ratio of 1 and height of 6 m has the minimum total cost. The cost of bunkers with ratios of 0.5 and 1.5 is 63 and 6% higher, respectively.

IIW Thesaurus keywords: economics; costs; computation; design, steel; reinforcement; structural members; hoppers; optimisation; comparisons; MMA welding; GMMA welding; reference lists

1 INTRODUCTION

The aim of the structural optimization is to achieve savings in weight and cost at the design stage by changing some significant structural characteristics. A cost function should be minimized, which contains variables expressing the structural characteristics. These characteristics are as follows: loads, materials, profiles, geometry, topology, fabrication, transportation, erection, maintenance.

Our aim is to show this design procedure in the case of a welded stiffened bunker (Fig. 1). The structural characteristics of a bunker are as follows.

Loads: self-weight, pressure of the stored material, wind and earthquake effects. The specialty of the pressures from stored material is that they vary across the height of the bin, this variation being near hydrostatic.

Structural material is steel of yield strength 235 MPa.

Structural types: single or combined in a group, square, rectangular, polygonal or prismatic.

Structural parts (Fig. 2): stiffened plate walls for bin and hopper, columns, vertical edge beams, transition beams.

Profiles: we use trapezoidal stiffeners for bin and hopper walls and square hollow sections for columns and vertical edge beams, as well as welded I-profiles for transition beams.

Geometry is determined by main dimensions as follows: width and height of bin, slope and height of hopper, width of outlet, height of columns.

Fabrication: all connections are welded.

From these characteristics we select the following: we consider a single square bunker. We use only horizontal stiffeners, since in our previous study [1] we showed that

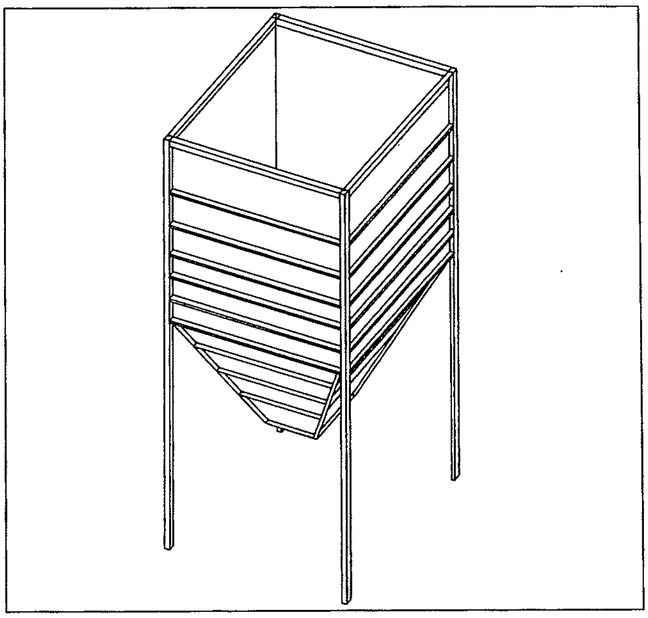

Fig. 1. Welded square bunker with horizontal stiffeners.

plates loaded by hydrostatic pressure are more economic with horizontal stiffeners than with vertical ones.

The distances between stiffeners for bin wall should be non-equidistant, since our previous study [1] showed that the non-equidistant arrangement is more economic than the equidistant one. The hopper walls can be stiffened by equidistantly arranged horizontal stiffeners, since it can be assumed that the hopper walls are loaded with constant normal pressure. The thickness of trapezoidal stiffeners should be varied, since they are loaded by different bending moments.

Furthermore, the bin width and height can be varied, so that the volume of the stored material should be constant. A similar variation has been studied in the case of circular silos [2, 3].

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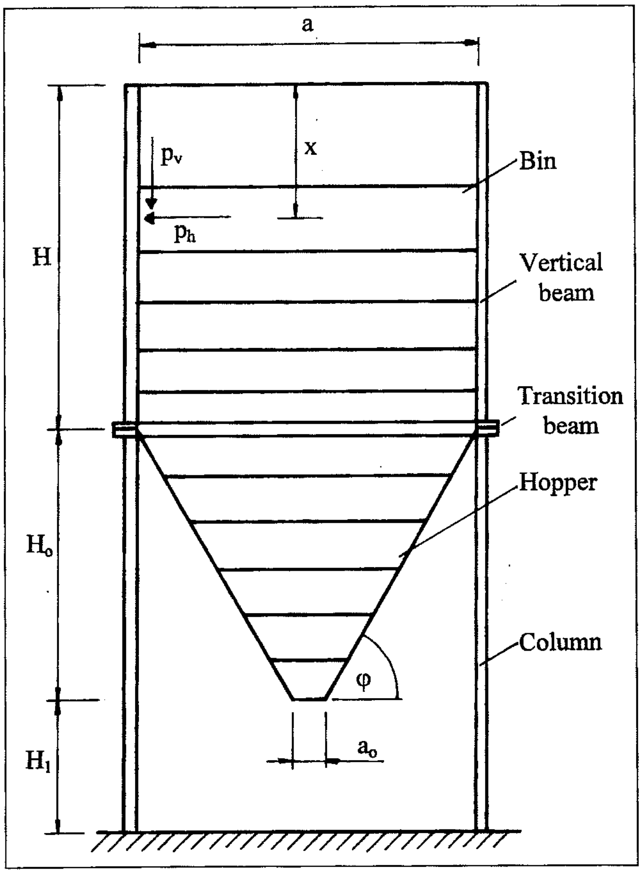

Fig. 2. Main structural parts of a welded square bunker and the pressure components.

Among the relevant literature the following. books [4-5-6-7-8] as well as articles [9, 10] should be mentioned. The authors of this document have not found any studies on minimum cost design of bunkers.

Summarizing the above mentioned design aspects, we optimize the positions of horizontal stiffeners in bin walls, calculate the required stiffener thicknesses, determine the optimum number of bin and hopper stiffeners by minimizing the cost, and calculate the total cost of a bunker. This procedure is repeated for three bunkers with different widths and heights (for ratios H/a = 0.5, 1.0 and 1.5) and the optimum value of H/a is determined, which gives the minimum total cost. The cost function contains the material and fabrication cost as shown in our recent studies [3, 11].

2 OPTIMUM POSITIONS AND NUMBER OF HORIZONTAL STIFFENERS OF BIN WALLS

Bin walls are loaded by nearly hydrostatic pressure due to stored material (Fig. 3). The maximum pressure intensity can be calculated using the Janssen formula [6 or 12]

$$p_{h\,max} = k p_{v\,max} \tag{1}$$

$$P_{vmax} = \frac{\rho_m a}{4k\mu}\left[1 - \exp(-H/x_0)\right]; \qquad x_0 = \frac{a}{4k\mu} \tag{2}$$

where ρ_m is the density of stored material, μ the friction coefficient of the material on the wall, k the pressure coefficient, a the bin width (Fig. 2).

The optimum positions of horizontal stiffeners can be obtained under the condition that each part of the constant-thickness base plate should be loaded to yield stress. Since it can be seen that the base plate parts have side ratios greater than 3, they can be calculated as strips with fixed edges (Fig. 3). Thus, the stress constraint for a base plate strip is

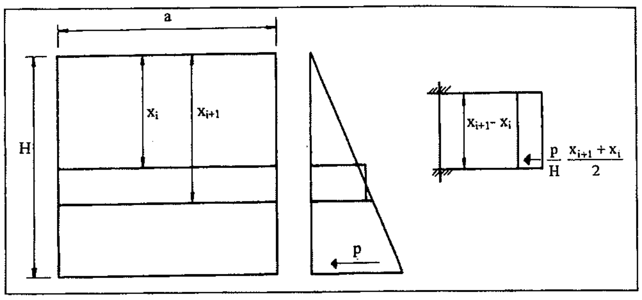

Fig. 3. Base plate strip subject to bending. x_{i+1} and x_i are the stiffener positions.

$$\sigma_{max} = \frac{p(x_{i+1} + x_i)(x_{i+1} - x_i)^2}{4Ht_b^2} \le f_y; \qquad i = 1 \ldots n \tag{3}$$

where $p = \gamma p_{h\,max}$, γ is the safety factor, t_b is the thickness of bin, f_y is the yield stress.

The optimum positions of stiffeners can be calculated by solving the following set of non-linear equations expressing that all base plate parts should have the same thickness

$$t_i \ge \left(\frac{p x_1^3}{4Hf_y}\right)^{1/2} \tag{4}$$

$$(x_2 + x_1)(x_2 - x_1)^2 = x_1^3$$
$$(x_{i+1} + x_i)(x_{i+1} - x_i)^2 = x_1^3 \qquad i = 1 \ldots n \tag{5}$$
$$(H + x_n)(H - x_n)^2 = x_1^3$$

Having obtained the optimum positions of n stiffeners, each stiffener should be designed as a simply supported beam for a bending moment of

$$M_{Si} = \frac{pa^2}{64H}(x_{i+1} - x_{i-1})(x_{i+1} + 2x_i + x_{i-1}) \tag{6}$$

We consider trapezoidal stiffeners according to [13] with given dimensions of a_1 = 90 and a_3 = 300 mm, and apply the local buckling constraint for the inclined webs according to Eurocode 3 [14]

$$a_2 \le 38 t_s \varepsilon; \varepsilon = (235/f_y)^{1/2} \tag{7}$$

Considering a stiffener cross-section as shown in Fig. 4 the distance of the gravity center G is

$$z_G = \frac{h t_s (a_1 + a_2)}{a_4 t_F + (a_1 + 2a_2) t_s} \tag{8}$$

where

$$h = \left[(38 t_s \varepsilon)^2 - 105^2\right]^{1/2} \tag{9}$$

The moment of inertia is

$$I_y = a_4 t_F Z_G^2 + a_1 t_s (h - Z_G)^2 + \frac{a_2^3 t_s \sin^2\alpha}{6} + 2a_2 t_s\left(\frac{h}{2} - Z_G\right)^2 \tag{10}$$

$$\text{where} \quad \sin^2\alpha = 1 - \left(\frac{105}{38 t_s \varepsilon}\right)^2 \tag{11}$$

The required stiffener thickness tS can be calculated from the stress constraint

$$\frac{M_{Si}}{I_y}(h - Z_G) \le \frac{f_y}{\gamma_{M1}} \quad \text{or} \quad \frac{M_{Si}}{I_y} Z_G \le \frac{f_y}{\gamma_{M1}}; \gamma_{M1} = 1.1 \tag{12}$$

The optimum number of stiffeners can be determined from the condition that the cost of the whole bin wall should be minimum. The cost function includes the mate-

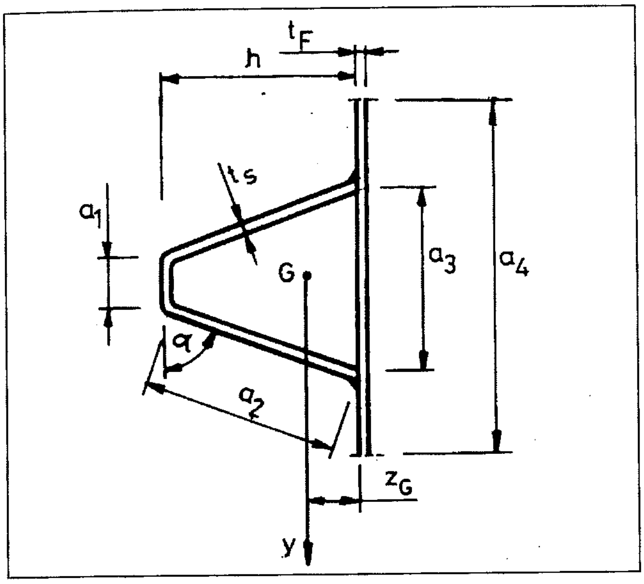

Fig. 4. Cross-section of a trapezoidal stiffener.

rial and fabrication costs as we have used it in our recent studies [3, 11]

$$\frac{K}{k_m} = \rho V + \frac{k_f}{k_m}\left[C_1 \Theta_d (\kappa \rho V)^{05} + 1.3\, T_2\right] \quad (13)$$

where ρ is the material density, k_f and k_m are the fabrication and material cost factors, respectively, κ is the number of structural elements to be assembled, V the volume of the structure, Θ_d the difficulty factor expressing the complexity of a structure (planar or spatial, using simple plates or profiles), the coefficient for the preparation time is C_1 = 1.0 min/kg$^{0.5}$. To give internationally usable results, the ratio k_f/k_m is varied over a wide range. For steel k_m = 0.5-1.4 \$/kg, for fabrication including overheads k_f = 0-60\$/manhour = 0-1\$/min, thus, the ratio may vary in the range of 0-2 kg/min, the value of 0 corresponding to the minimum weight design. The welding time is given by

$$T_2 = \sum_i C_{2i} a_{wi}^n L_{wi} \quad (14)$$

The factor of 1.3 expresses that the additional time for chipping, slag removal and electrode change is approximated by $T_3 = 0.3T_2$. The formulae for $C_2 a_w^n$ are given for various welding technologies and weld types. a_W is the weld size, and L_W is the weld length [11].

It is assumed that the base plate is butt welded from plate strips of width 1500 mm or less.

In the following, detailed numerical calculations are given only for a bunker of H/a = 1 and H = 6,000 mm. For other values of H/a results are summarized only, to show the optimum ratio corresponding to the minimum cost of the whole bunker.

Numerical results for a bin of H/a = 1 and H = 6,000 mm

Cement is selected as the stored material with a density ρ_m = 1,600 kg/m^3 = 1.6 x 10^{-5} N/mm^3. With the values k = 0.6 and μ = 0.4, using Eqs. (1) and (2) we obtain x_0 = 6,250 mm and p_{hmax} = 0.036 N/mm^2, $p = \gamma p_{hmax}$ = 0.054 N/mm^2.

A stiffener is welded to the base plate with 2 fillet welds of size $a_W = 0.7t_S$. Welding times are calculated using the following data: GMAW-M welding technology (Gas Metal Arc Welding with gas mixture). For (14) the following formulae are used:

a_W = 4-15 mm	V butt welds	$C_2 a_W{}^n n = 0.1861 a_W^2$
a_W= 0-15 mm	fillet welds	$C_2 a_W n = 0.3258 a_W^2$

and L_W is calculated in mm. The difficulty factor is chosen as Θ_d = 3.

The results of computations for n = 7 and 8 are summarized in Table 1.

It should be noted that an additional stiffener on the bin wall top is also considered, which has the same thickness as the uppermost one. It can be seen that the minimum cost is achieved by using n = 8. A further increase of the number of stiffeners is limited by the minimum distance between stiffeners, which should be greater than a_3 = 300 mm.

3 OPTIMUM NUMBER OF HORIZONTAL STIFFENERS OF HOPPER WALLS

The hopper wall pressures are calculated using formulae given by [12] (Fig. 5). Pressures from the material in the hopper (Fig. 5a) are given as

$$P_n = \frac{0{,}6 \rho_m k a \sin^2 \varphi}{\mu^{1/2}}; \; q = p_n / 2 \quad (15)$$

Pressures from the material above the hopper can be calculated as (Fig. 5b)

$$P_{n1} = (p_v c_b \cos^2 \varphi + p_h \sin^2 \varphi)\left(1 + \frac{\sin \varphi}{4\mu}\right); \; q_1 = p_{n1} / 2 \quad (16)$$

c_b = 1,5

Table 1. Optimum positions of horizontal stiffeners and costs of the stiffened bin walls in the case of n = 7 and 8, considering an additional top stiffener for different values of k_f/k_m (kg/min).

n	x_i (m)	t_s (mm)	t_F (mm)	K/k_m(kg) for $k_f/k_m = 0$	K/k_m(kg) for $k_f/k_m = 1$	K/k_m(kg) for $k_f/k_m = 2$
7	1.44 2.34 3.09 3.75 4.36 4.94 5.48	7 7 8 8 8 8 8	7	3,909	5,936	7,963
8	1.33 2.16 2.85 3.47 4.04 4.56 5.06 5.54	6 7 7 8 8 8 8 8	6	3,729	5,767	7,805

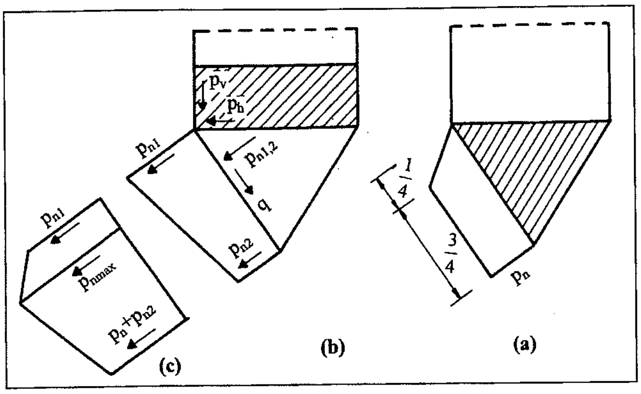

Fig. 5. Pressure distribution on a hopper wall.
(a) pressure from the material stored in the hopper;
(b) pressures from the material above the hopper;
(c) summarized normal pressure distribution.

$$p_{n2} = p_v c_b \cos^2\varphi, q_2 = p_{n2}/2 \tag{17}$$

The summation of the two pressures results in a pressure distribution shown in Fig. 5c, where

$$P_{nmax} = P_n + P_{n1} - \frac{P_{n1} - P_{n2}}{4} \tag{18}$$

Instead of this distribution, we calculate approximately with a constant normal pressure p_{nmax}. This approximation is on the side of safety. For a constant normal pressure an equidistant arrangement of horizontal stiffeners can be used (Fig. 6). Thus, we should determine the optimum number of stiffeners, which gives the minimum cost for the hopper wall.

Numerical results for a hopper wall of the bunker of H/a = 1, φ = 60°

With Eq.(15) p_n = 0.04098 N/mm², using (1) and (2), we obtain p_v = 0.0617 and p_h = 0.036 N/mm². With (16), (17) and (18) p_{n1} = 0.0784, p_{n2} = 0.0231 and p_{nmax} = 0.10559 N/mm². Multiplying by the safety factor γp_{nmax} = 0.1584 N/mm².

It is possible to calculate the required constant base plate thickness t_h assuming that a plate strip has fixed edges. From

$$\frac{\gamma p_{n\max} a_s^2}{12 t_h^2 / 6} \le \frac{f_y}{\gamma_{M1}} = 213 \text{ MPa}$$

we obtain

$$t_h \ge a_s \left(\frac{\gamma p_{n\max}}{2 f_y / \gamma_{M1}} \right)^{1/2} = 0.01928 a_s$$

a_s being the distance between stiffeners (Fig. 6).

The required trapezoidal stiffener thicknesses are calculated similarly to the case of bin wall stiffeners using Eqs (7-12), but instead of M_{si} we use

$$M = \frac{\gamma p_{n\max} a_i^2 a_s}{8}$$

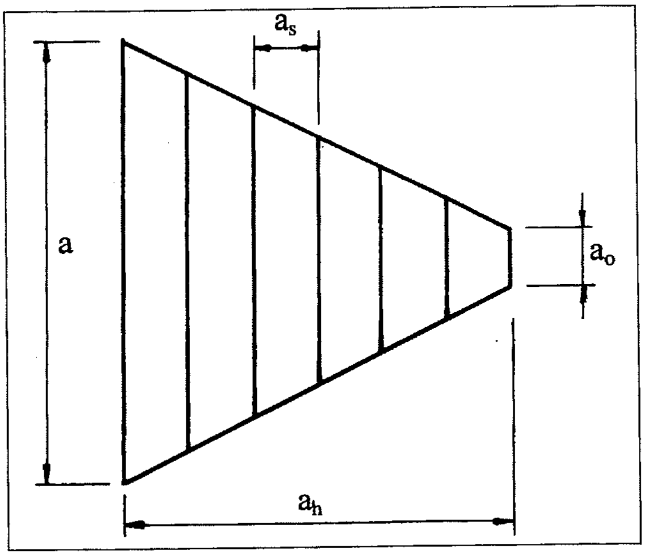

Fig. 6. Equidistant arrangement of horizontal stiffeners of a hopper wall.

The results are summarized in Table 2. Note that we use a minimum stiffener thickness of 6 mm.

It can be seen that the costs decrease when the number of stiffeners increases, except in the case of k_f/k_m = 2. We decide that the optimum number of stiffeners is 7.

4 OPTIMUM DESIGN OF TRANSITION BEAMS

We consider the transition beams (Fig. 2) as simply supported with a span length of *a*. They are subject to bending from the horizontal pressure acting on the lowest part of the bin and from the horizontal component of pressures acting on the hopper. Bending moment from the first action is

$$M_1 = \frac{p(H - x_n) a^2}{16} \tag{19}$$

We approximate the pressure distribution as shown in Fig.7. The horizontal reaction from the normal pressure is

$$H_2 = \left[\frac{\gamma p_{n\max}}{3} + \frac{\gamma (p_n + p_{n2})}{6} \right] a_h \sin \varphi \tag{20}$$

The maximum bending moment from H_2, assuming a load distribution shown in Fig.7, is

$$M_2 = \left(F_1 + \frac{F_2}{2} \right) \frac{a}{2} - F_1 \left(\frac{a - a_0}{6} + \frac{a_0}{2} \right) - \frac{F_2 a_0}{8};\ F_1 = \frac{H_2 (a - a_0)}{4};\ F_2 = H_2 a_0 \tag{21}$$

For tangential pressures *q* we assume a distribution similar to that for normal pressure.

The horizontal reaction from tangential pressure acting on the hopper is (Fig. 8)

$$H_3 = \frac{\gamma p_{n\max} + \gamma (p_n + p_{n2})}{4} a_h \cos \varphi \tag{22}$$

Table 2. Hopper base plate thicknesses and costs for different numbers of stiffeners. Dimensions in mm, costs in kg and k_f/k_m in kg/min.

n	a_s	t_h	K/k_m		
			k_f/k_m=0	k_f/k_m=1	k_f/k_m=2
5	900	18	3,716	4,915	6,114
6	771	15	3,430	4,745	6,061
7	675	13	3,248	4,661	6,074

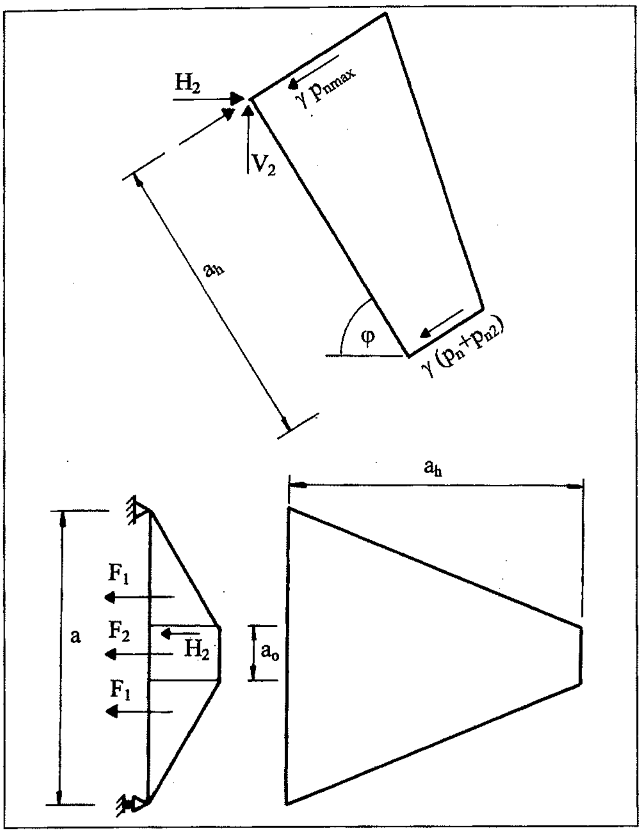

Fig. 7. Pressure reactions on a transition beam.

The maximum bending moment from H_3, assuming the same distribution as for H_2, is

$$M_2 = \left(F_3 + \frac{F_4}{2}\right)\frac{a}{2} - F_3\left(\frac{a-a_0}{6} + \frac{a_0}{2}\right) - \frac{F_4 a_0}{8};\ F_3 = \frac{H_3(a-a_0)}{4};\ F_4 = H_3 a_0 \quad (23)$$

The transition beam is designed as a horizontal symmetric welded I-beam loaded by bending in a horizontal plane by the maximum bending moment of

$$M = M_1 + M_2 - M_3 \quad (24)$$

Numerical results for the bunker of H/a = 1

Considering the bin wall with 8 stiffeners M1 = 55 x 10^6 Nmm. H_2 = 318.4 (N). M_2 = 1,046 x 10^6 Nmm, H_3 = 168.9 (N), M_3 = 555 x 10^6, M = 546 kNm.

The dimensions of a welded I-beam optimized for minimum cross-sectional area are as follows [3]

$h = (1.5W_0/\beta)^{1/3}; 1/\beta = 69\varepsilon; \varepsilon = (235/f_y)^{1/2}$; $b = h(\beta/2\delta)^{1/2}; 1/ = 28\varepsilon$

and the thickness of web and flanges are $t_w = \beta h; t_f = \delta b$.

The required section modulus is $W_0 = \dfrac{M}{f_y / \gamma_{M1}}$

Using these formulae we obtain h = 645, t_w = 10, b = 290, t_f = 11 mm.

The cost of the beam is calculated using Eqs (12) and (13), and considering 4 fillet welds of size 5 mm, a difficulty factor 3, and the number of assembled structural parts being 3. For k_f/k_m = 1 we obtain $K/k_m \cong$ 982 kg.

5 VERTICAL EDGE BEAMS OF THE BIN

The required width of these square hollow section beams is determined by a geometric condition that the largest horizontal stiffener should be welded to them. For the

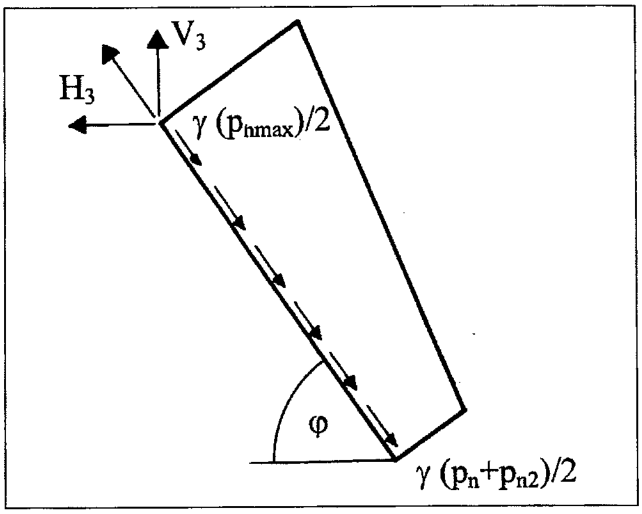

Fig. 8. Reactions from the tangential pressure on a hopper wall.

bin with 8 stiffeners, the maximum stiffener thickness is 8 mm, thus, using Eq. (9) we obtain hS = 286 mm. A square hollow section of 300 x 300 x 8 is required.

6 DESIGN OF COLUMNS

Calculation of the self-weight for a column

Optimized bin wall with 8 stiffeners	3,729 kg
Vertical edge beam 6 x 72,8	437 kg
Optimized hopper wall with 7 stiffeners	3,248 kg
Transition beam	640 kg
Total self-weight acting on a column	8,054 kg

The volume of the bunker is given by

$$V = a^2 H + \frac{(a^3 - a_0^3)\tan\varphi}{6} \quad (25)$$

Volume of the bunker of H/a = 1, $H = a$ = 6 m, a_0 = 0.6 m, φ = 60° is V = 278.29 m³.

The weight of the stored material is Q = 1,600 x 278.29 = 445 x 10^3 kg. $Q/4$ = 1,112.5 kN.

The effect of wind can be neglected.

The effect of earthquake is calculated according to [6].

The horizontal force is

$V_e = 0.2ZQ$

For a moderate damage Z = 3/8, thus Ve = 333.75 kN. This force is acting at a height of $H/2 + H_0 + H_1$ = 10.08 m. The compression force acting on a column due to earthquake is

N_e = 10.08 x 333.75/4a = 140 kN.

According to [14] two load combinations should be considered as follows:

(1) Permanent action (self-weight) + most unfavorable variable action (Q) multiplied by safety factors

1.35 x 80.54 + 1.5 x 1,112.5 = 1,778 kN

(2) Permanent action and all unfavorable actions, including earthquake, multiplied by 0.9

1.35 x 80.54 + 0.9 x 1.5(1,112.5 + 140) = 1,800 kN.

It can be seen that the second combination is the leading one.

We select for a column a square hollow section of 300 x 300 x10 mm. Assuming that the column is constructed with pinned ends, the length is 7.08 m. Check of the column according to [14] for overall flexural buckling:

$$\bar{\lambda} = \frac{7080}{118x93.91} = 0.6389;$$

$$\sigma = \frac{1800x10^3}{11500} = 156 \le 0.8171x213 = 174 \text{ MPa, OK.}$$

7 CALCULATION OF THE TOTAL COST OF THE BUNKER OF *H/A* = 1

We assume that kf/k_m = 1 kg/min and k_m = 1 \$/kg.

One stiffened bin wall with 8 + additional top stiffener	5,767 \$
One stiffened hopper wall with 7 stiffeners	4,661 \$
One vertical edge beam 300 x 300 x 8, length 6 m	528 \$
One transition welded I-beam	982 \$
One column 300 x 300 x 10, length 7.08 m	773 \$
Total cost of the structural parts of the bunker 4 x 12,711 =	50,844 \$

The costs of the connecting welds are as follows.

Welds connecting the vertical edge beams with bin walls (Fig. 9a). 3 fillet welds of size 4 mm, welding process SMAW (shielded metal arc welding). The length of welds connecting the base bin plate and the stiffeners is calculated approximately as 2*H*. *I*nstead of this length, we calculate with 5 welds having a length of *H*. Instead of 1.3, we multiply by 2, considering the time of assembly as well.

$K = 2 \times 0.7889 \times 10^{-3} \times 4^2 \times 5 \times 6{,}000 = 757$ \$

Welds connecting the stiffened hopper walls to an edge plate strip (Fig. 9b)

$K = 2 \times 0.7889 \times 10^{-3} \times 4^2 \times 4 \times 6{,}040 = 610$ \$

Welds connecting the hopper base plate to the transition I-beam (Fig. 9c)

$K = 2 \times 0.7889 \times 10^{-3} \times 6^2 \times 2 \times 6{,}000 = 682$ \$

Total cost of connecting welds 4(757 + 610 + 682) =	8,196 \$
Total cost of the bunker	59,040 \$

8 THE OPTIMUM *H/A* RATIO

In order to find the most economical structural solution we optimize bunkers having different *H/a* ratios, but the same storage capacity. Eq.(25) can be written in the form

$$V = \omega a^3 + \frac{(a^3 - a_0^3)\tan\varphi}{6} = 278.29 \text{ m}^3 \quad (26)$$

where $\omega = H/a; \varphi = 60^0$; $a_0 = 0.6$ m. Eq.(26) can be solved for *a* as follows

$$a = \left(\frac{278.35}{\omega + 0.28868}\right)^{1/3} \quad (27)$$

The height of the hopper is calculated using the following formula

$$H_0 = \frac{a - a_0}{2}\tan\varphi \quad (28)$$

Table 3 shows the main dimensions of bunkers with different *H/a* ratios

Results for H/a = 0.5

Bin walls with 3 stiffeners, base plate thickness 9 mm	cost 24,316 \$
Hopper walls with 9 stiffeners, base plate thickness 16 mm	41,172 \$
Transition I-beams: web 875 x 13, flanges 395 x 14	7,192 \$
Vertical edge plates 640 x 12 mm	852 \$
Columns: square hollow section (SHS) 350 x 8 mm	2,732 \$
Connecting welds	20,288 \$
Total cost	96,552 \$

Table 3. Bunker dimensions in m.

H/a	*a*	*H*	H_0
0.5	7.07	3.53	5.60
1.5	5.38	8.07	4.14

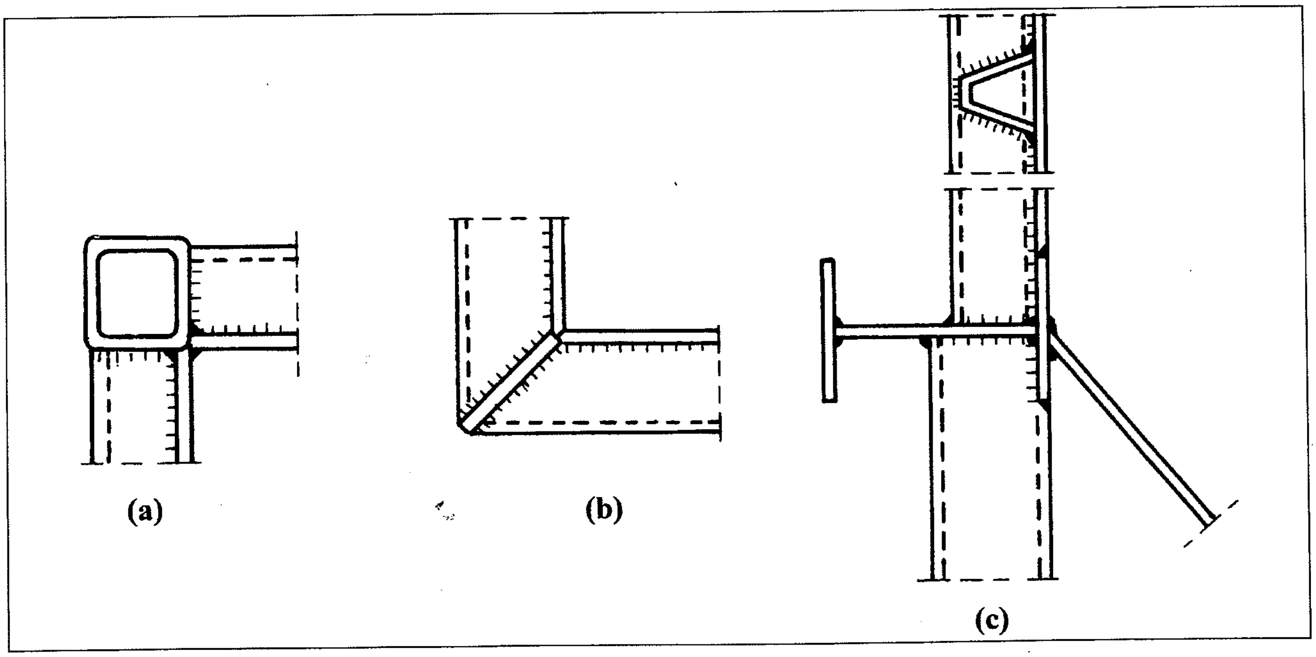

Fig. 9. Welded connections in a bunker. (a) Connection of stiffened bin walls to vertical edge beam; (b) connection of stiffened hopper walls to edge plate strip; (c) connection of hopper base plate, vertical edge beam and column to transition welded I-beam.

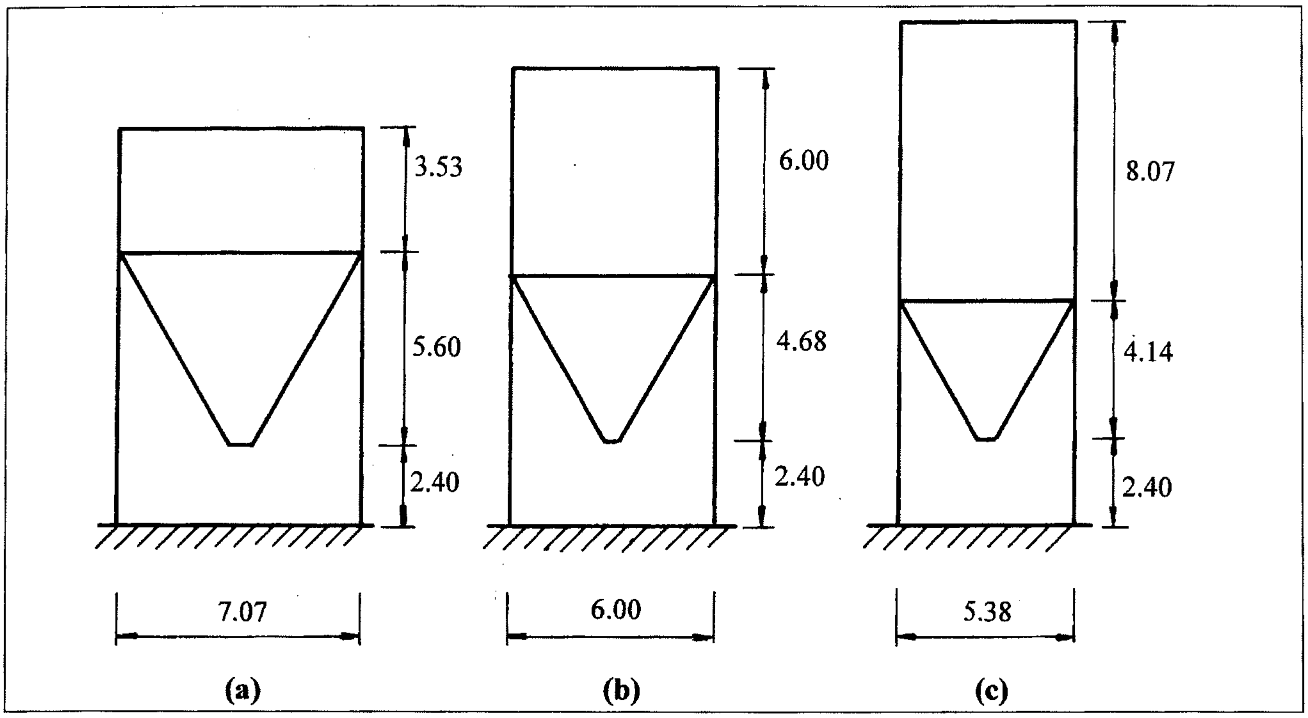

Fig. 10. Main dimensions of bunkers in m with different *H/a*-ratios: (a) 0.5, (b) 1.0, (c) 1.5.

Results for H/a =1.5

Bin walls with 7 stiffeners, base plate thickness 8 mm	cost 28,236 $
Hopper walls with 6 stiffeners, base plate thickness 14 mm	14,612 $
Transition I-beams: web 570 x 9, flanges 260 x 10	2,944 $
Vertical edge beams: SHS 350 x 8	2,756 $
Columns: SHS 350 x 8	2,236 $
Connecting welds	11,736 $
Total cost	62,520 $

The main cost data for the three structural versions (Fig. 10) are summarized in Table 4.

It can be seen that the bunker with a *H/a* = 1 ratio can be built at minimum cost. The bunker with *H/a* = 0.5 results in a high cost because of large hopper dimensions.

9 CONCLUSIONS

The bin and the hopper of a welded square bunker can be optimized for minimum cost. The pressure distribution on the bin walls is nearly hydrostatic, therefore the optimum position of horizontal stiffeners should be calculated. The hopper walls are subjected to a nearly constant normal pressure and, on the basis of the detailed cost calculation, the optimum number of horizontal stiffeners can be determined.

Important structural parts are the transition beams loaded in bending by hopper reactions and designed as horizontal welded I-beams.

The most economic solution is achieved by comparing costs for bunkers with different *H/a* ratios. The best version is the bunker with a ratio of *H/a* = 1. The difference between the costs of bunkers with ratios *H/a* = 1 and 0.5 is 63%.

Table 4. Comparison of the main cost data in $.

H/a	0.5	1.0	1.5
Bin	24,316	23,068	28,236
Hopper	41,172	18,644	14,612
Other parts and welds	31,064	17,328	19,672
Total	96,552	59,040	62,520

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