Truck Floor Design for Minimum Mass and Cost Using Different Materials

Károly Jármai and József Farkas

Abstract In the chapter the floor structure of a truck produced by a company in Hungary has been investigated. The structure consists of steel members, or extruded Al-alloy longitudinal and cross members as well as a tread deck plate. Using an optimum design process, namely the Hillclimb optimizer, significant mass and cost savings may be achieved by decreasing the deck plate thickness and changing the profile, dimensions and number of cross members. Comparison is made using the combination of the steel and aluminium, or using only steel alone. Design constraints relate to fatigue stress range of welded joints, to local buckling of extruded or normal profiles and to fabrication size limitations. A special loading case is also considered when a wheel is staying on a curb and the floor is distorted.

1 Introduction

There are some trucks for beverage transport, where the truck structure has a steel chassis consisting of two longitudinal beams. The subframe is constructed from two longitudinal beams bolted on steel beams. They can be made from *Al*-alloys, or structural steel. The Al-alloy floor structure has three layers as follows (Fig. 1): cross members welded to subframe, the longitudinal members welded to cross members, tread deck plate distributing the pallet loads. The material of cross members is an *Al*-alloy AlMgSi0.7 according to German standard DIN 1725 [1] of $R_{p.0.2}$ = 215 MPa according to DIN 1748 [2] (international alloy type 6005A). The tread deck plate material is an *Al*-alloy AlMg2.5 (international alloy type 5052). These main structural parts are framed by side rails, which carry the loads from

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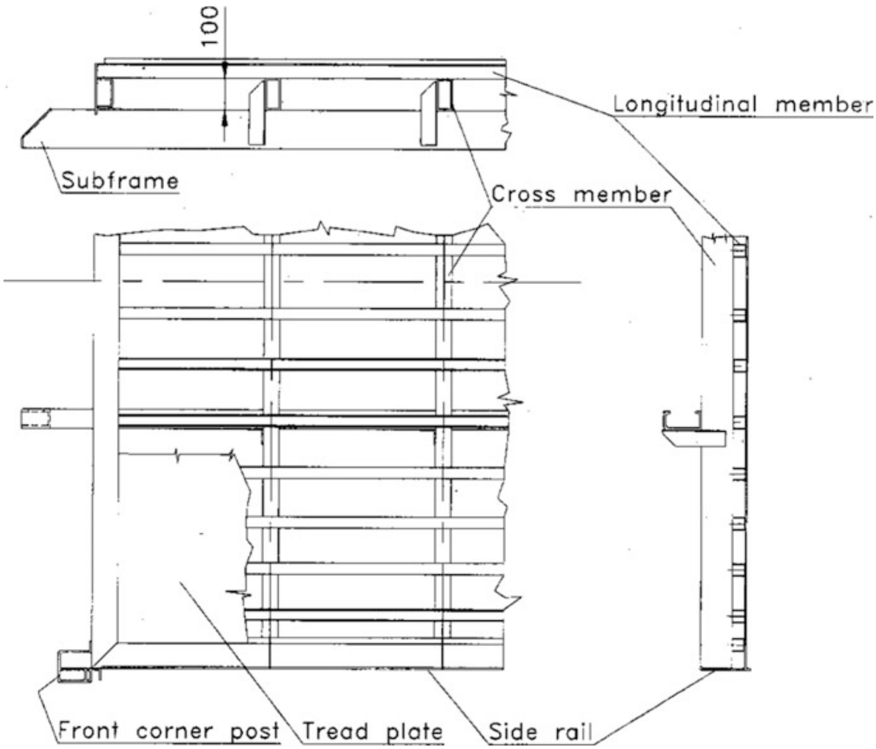

Fig. 1 Truck floor structure

roof, sidewalls and doors. We have made an optimization using aluminium, or normal steel in the floor structure. Due to the fact that the fatigue limit for the steel at Eurocode 3 up to 690 MPa and at IIW recommendation up to 960 MPa does not change, it does not worth to use higher strength steels, only normal structural steel.

Our aim is to decrease the material cost of the floor structure by changing the profile, dimensions and number of cross members, the thickness of deck plate as well as the material grades.

2 Load Cases

2.1 Loads in the Horizontal Floor Position

Two load cases should be considered in the design of cross members as follows: (a) loads due to pallets, roof, door and side walls in the horizontal floor position; (b) the same loading as in (a) but a wheel is staying on a curb, thus, the floor is distorted.

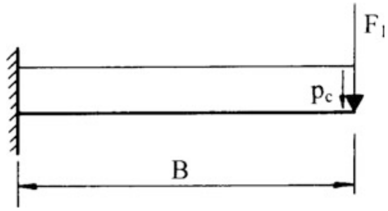

Fig. 2 Loads on the cantilever part of cross members

Loads acting on an outside cross member are as follows:

a corner column		205 N
roof	2060/4	515 N
upper door	1420/2	710 N
front wall	1033/2	516 N
		F_1 = 1946 N

Load from pallets: mass of a pallet is F_p = 8500 N, intensity of the uniformly distributed load is $p = F_p n_p/(BL)$, where the number of pallets placed on the half floor $n_p = 5$, B and L are the dimensions of a half cantilever floor surface. The uniformly distributed normal load acting on a cross member is $p_c = pL/(n_c–1)$, n_c is the number of cross members.

The maximum bending moment in a cross member is (Fig. 2)

$$M_{\max} = \frac{p_c B^2}{2} + F_1 B = \frac{F_p n_p B}{2(n_c - 1)} + F_1 B \tag{1}$$

Calculating with F_p = 8500 N, n_p = 5, B = 720 mm, F_1 = 1946 N one obtains bending moments for different numbers of cross members. This number is limited by the dimension of pallets (800 mm) to $n_{c.min}$ = 10. Since the original number of cross members is 14, we calculate with n_c = 14, 12 and 10. For these values of n_c one obtains

$$M_{14} = 2.578, M_{12} = 2.792 \text{ and } M_{10} = 3.1011 \text{ kNm}.$$

The corresponding shear forces are as follows:

$$Q = F_p n_p/(n_c - 1) + F_1;\; Q_{14} = 5215,\; Q_{12} = 5810 \text{ and } Q_{10} = 6668 \text{ N}.$$

2.2 Loads on the Distorted Floor

Measurements have been carried out on a truck loaded with pallets and with a wheel staying on a curb in a height of 91 mm. The measured deflections have

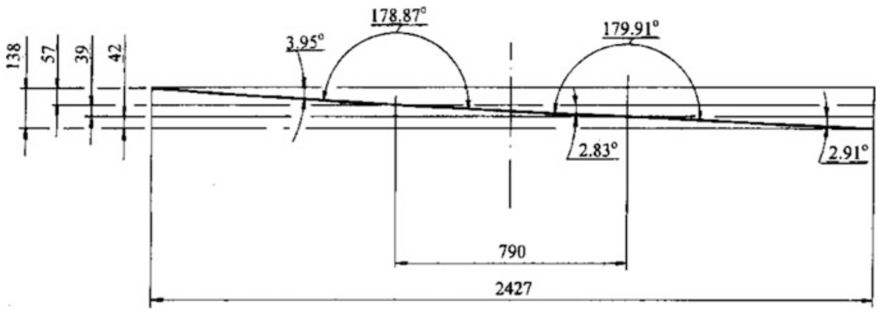

Fig. 3 Measured deflections of a distorted cross member, when a left truck wheel is staying on a curb

shown that the cross members near the wheel being lifted up are loaded by bending as it is seen on Fig. 3. This cross member can be modelled as a cantilever beam of its whole length L_c loaded by a force F corresponding to a deflection w. This deflection can be approximately calculated as $w = 138 - L_c\varphi$, where L_c = 2427 mm, $\varphi(rad) = 2.91°\pi/180° = 0.0508$, thus, w = 15 mm. Furthermore

$$F = \frac{3EI_x w}{L_c^3}; M_{c.\max} = FL_c \tag{2}$$

where E = 7 x 10^4 MPa is the elastic modulus of aluminium, E = 2.1 x 10^5 MPa for steel, I_x is the second moment of area.

3 Geometric Characteristics of Cross Members

The cross-section loaded by bending and shear consists of a cross member and a part of the deck plate (Fig. 4). We calculate an effective width of the deck plate 50t, t is the thickness. In the case of a rectangular hollow section (RHS) the geometric characteristics of this cross section are as follows [3]:

$$A = A_1 + A_2;\ A_1 = 2ht_w + 2bt_f;\ A_2 = 50t^2 \tag{3}$$

$$y_G = \frac{A_1}{A}\left(\frac{h+t}{2} + c\right); \quad y_c = h + c + \frac{t}{2} - y_G \tag{4}$$

$$I_x = \frac{h^3 t_w}{6} + \frac{bt_f h^2}{2} + A_1\left(y_c - \frac{h}{2}\right)^2 + A_2 y_G^2 \tag{5}$$

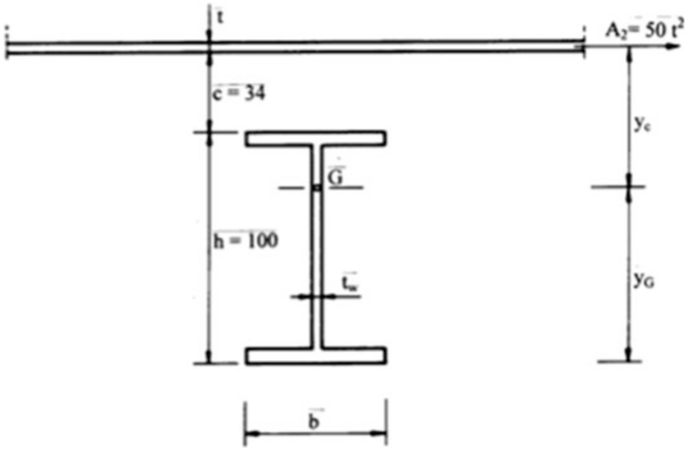

Fig. 4 Cross-sections of cross members

In the case of I-profile (Fig. 4) the characteristics are as follows:

$$A_1 = ht_w + 2bt_f \tag{6}$$

$$I_x = \frac{h^3 t_w}{12} + \frac{bt_f h^2}{2} + A_1\left(y_c - \frac{h}{2}\right)^2 + A_2 y_G^2 \tag{7}$$

In our previous calculations [4] we have made comparisons using the rectangular hollow section, I- and C-profiles. It was found that the best cross section is the I-beam. That is the reason why the I-profile has been chosen.

4 Design Constraints

4.1 Constraints on Fatigue Stress Range for the Horizontal Floor Position

$$\sigma_1 = \frac{M_{\max}}{I_x} y_{\max} \le \frac{\Delta\sigma_N}{\gamma_{Mf}}; \quad y_{\max} = \max(y_G, y_c) \tag{8}$$

$$\tau_1 = \frac{Q}{A_w} \le \frac{\Delta\tau_N}{\gamma_{Mf}}; \tag{9}$$

where $A_w = ht_w$ for I-profile.

Since the cross members are welded to longitudinal subframe beams, they should be designed considering the fatigue of welded joints. According to Hobbache [5] the fatigue stress range for number of cycles 2 x 10^6 in the case of transverse stiffener welded on girder web (detail 512 for structural aluminium alloys) is $\Delta\sigma_C = 28$ MPa. Calculating with a realistic number of cycles $N = 2 \text{ x } 10^5$,

$$\log \Delta\sigma_N = \frac{1}{3} \log \frac{2x10^6}{2x10^5} + \log \Delta\sigma_C = 1.78049; \quad \Delta\sigma_N = 60.3\,\text{MPa} \tag{10}$$

For steel $\Delta\sigma_C = 80\,\text{MPa}$ (detail 512 for structural steel, the same as for Al) $\Delta\sigma_N = 172.3\,\text{MPa}$. With a safety factor of 1.25.

For aluminium

$$\frac{\Delta\sigma_N}{\gamma_{Mf}} = \frac{60.3}{1.25} = 48.2\,\text{MPa} \tag{11}$$

For shear it is

$$\Delta\tau_C = 28;\ \Delta\tau_N = 44.3; \frac{\Delta\tau_N}{\gamma_{Mf}} = \frac{44.3}{1.25} = 35.44\,\text{MPa} \tag{12}$$

For steel

$$\frac{\Delta\sigma_N}{\gamma_{Mf}} = \frac{172.3}{1.25} = 137.8\,\text{MPa} \tag{13}$$

For shear it is

$$\Delta\tau_C = 80;\ \Delta\tau_N = 126.8; \frac{\Delta\tau_N}{\gamma_{Mf}} = \frac{126.8}{1.25} = 101.44\,\text{MPa} \tag{14}$$

It should be mentioned that we calculate with the bending moment also from static load F_1 in the fatigue constraint as an approximation in the safe side.

4.2 Constraint on Fatigue Stress Range for the Distorted Floor Position

$$\sigma_2 = \frac{M_{c.\max}}{I_x} y_{\max} = \frac{3Ew}{L^2} y_{\max} \leq \frac{\Delta\sigma_{N1}}{\gamma_{Mf}} \tag{15}$$

In the case of distorted floor position the maximum bending moment arises at the end of the cross member, where it is welded to subframe by fillet welds. For this joint, according to [5] (detail No.413) $\Delta\sigma_{C1} = 22$ MPa and a realistic number of cycles $N = 10^5$ it is

$$\frac{\Delta\sigma_{N1}}{\gamma_{Mf}} = \frac{59.7}{1.25} = 47.7\,\mathrm{MPa} \tag{16}$$

4.3 Constraints on Local Buckling of Profiles

Web of I-section (unreinforced)
For aluminium

$$h/t_w \le 22\varepsilon/g; \tag{17}$$

For steel [6]

$$h/t_w \le 69\varepsilon/g; \tag{18}$$

$$\begin{aligned} g &= 0.65 + 0.35\tfrac{y_0}{y_c} \quad \text{when} \quad 1 \ge \tfrac{y_0}{y_c} \ge 0 \\ g &= 0.65 + 0.30\tfrac{y_0}{y_c} \quad \text{when} \quad 0 \ge \tfrac{y_0}{y_c} \ge -1 \end{aligned}$$

$$y_0 = y_G - \frac{t}{2} - c \tag{19}$$

$$y_c = h + c + \frac{t}{2} - y_G \tag{20}$$

Flange of I-section (unreinforced)
For aluminium alloy

$$b/t_f \le 14\varepsilon \tag{21}$$

For steel

$$b/t_f \le 28\varepsilon \tag{22}$$

For aluminium

$$\varepsilon = \sqrt{\frac{250}{\sigma_{\max}/\gamma_{M1}}},\ \text{for steel}\ \varepsilon = \sqrt{\frac{235}{\sigma_{\max}/\gamma_{M1}}} \tag{23}$$

4.4 Fabrication Constraints: Size Limitations

Some constant dimensions are prescribed by the original structure as follows:

$$h = 100, \quad c = 34\,\text{mm} \tag{24}$$

The web thickness is limited to

$$t_{w.min} = 3.4\,\text{mm} \tag{25}$$

to guarantee the quality of welding.

The tread plate thickness is limited to

$$t_{min} = 2\,\text{mm} \tag{26}$$

Since the cross members should be welded to side rails, the extruded shapes should not have any reinforcing ribs or bulbs, since they are in the way of welding.

It should be mentioned that the extruded I-profiles with or without reinforcing ribs or bulbs optimized for pure bending have the same minimum cross-section area, thus, the use of ribs or bulbs does not result in mass savings.

5 Optimization Characteristics and Results

The objective function is the cross-sectional area of the cross members and deck plate part (Eq. 3).

The unknown variables are the dimensions of profile flanges b and t_f.

The constraints are as follows: Eqs. 11, 12, 13, 14, 15, 21, 22, 24, 25, 26.

The optimization is performed for *I-profile* and for *three numbers of cross members* n_c = 14, 12 and 10.

Mathematical method: the Rosenbrock's Hillclimb algorithm is used [7].

Results are summarized in Table 1 and 2.

Table 1 Optimum sizes of the frame

	Original aluminium structure	Optimized aluminium	Optimized steel
Structural weight in kg	304.48	172.31	239.7
Structural cost in USD	927.44	550.27	247.40

Table 2 Result of the optimization

Profile		n_c = 14	n_c = 12	n_c = 10
Aluminium I-profile	b	55	60	65
	t_f	7.2	7.2	7.8
	A_1	1332	1404	1536
	m_c kg	104.41	95.18	89.20
	K_T $	927	927	927
	k_T $	0.54	0.63	0.795
	K_c $	304.74	291.78	260.64
Steel I-profile	b	30	30	35
	t_f	2	2	2.1
	A_1	660	660	747
	m_c kg	123.35	105.73	93.28
	K_T $	187	187	187
	k_T $	0.109	0.128	0.153
	K_c $	269.77	252.15	247.4

6 Mass Savings

The mass of the original tread plate of thickness t = 4.5 mm and dimensions 2280 × 6750 mm, taking the density of *Al*-alloy $\rho = 2.7 \times 10^{-6}$ kg/mm^3, for steel $\rho = 7.85 \times 10^{-6}$ kg/mm^3

$$m_{pl} = \rho t(2280 \times 6750) = 186.98\ \text{kg}.$$

For aluminium

Mass of the optimized *Al* plate of t = 2.0 mm is $m_{pl.opt}$ = 83.11 kg.

The mass of *Al* cross members can be calculated as

$$m_c = \rho A_1 n_c L_{cm}$$

where L_{cm} = 2440 mm is the length of a cross member. The calculated masses are shown in Table 2.

The original mass of the tread plate and cross members is

$$m = m_{pl} + m_c = 186.98 + 117.50 = 304.48\,\text{kg}.$$

The mass of the optimum *Al* solution is m_{min} = 83.11 + 89.20 = 172.31 kg, the mass saving is 132.17 kg for one truck (43%).

For the steel

Mass of the optimized steel plate of t = 2.0 mm is $m_{pl.opt}$ = 146.424 kg.

The mass of steel cross members can be calculated as

$$m_c = \rho A_1 n_c L_{cm}$$

The mass of the steel tread plate and cross members is

$$m = m_{pl} + m_c = 146.42 + 93.28 = 239.7\,\mathrm{kg}.$$

7 Cost Savings

For aluminium

Cost of tread deck plate

London Metal Exchange (LME) price of aluminium [8]	1.559 \$/kg
surcharge	0.9568 \$/kg
total	2.5159 \$/kg

Cost of cross members

Cost of the original plate (t = 4.5) 186.98 × 2.5159	470.44 \$
Cost of the optimized plate (t = 2 mm) 83.11 × 2.5159	209.09 \$

Cost of cross members

LME aluminium total	2.5159 \$/kg
extrusion work upcharge	1.3004 \$/kg
total	k_c = 3.8163 \$/kg

The total cost, including the proportional tool cost can be expressed as

$$K_T = k_c m_c + k_T$$

where

$$k_T = \frac{K_T}{50 n_c L_{cm}}$$

K_T is the tool cost, $50n_cL_{cm}$ is the total length of extruded bars for 50 trucks (one year production).

The results of the calculations are shown in Table 2.

The total cost of the original deck plate and cross members is K = 470.44 + 457.00 = 927.44 $

and that of the optimum (10 cross members of I-profile) K_{min} = 209.09 + 341.18 = 550.27 $

The cost savings for one *Al* truck is 377.17 $ (39%)

For steel

Cost of tread deck plate

London Metal Exchange (LME) price of steel	0.375 $/kg
surcharge	0.231 $/kg
total	0.606 $/kg

Cost of the optimized steel plate (t = 2 mm) 241.623 × 0.606 146.424 $

Cost of cross members

LME steel	0.606 $/kg
cutting and welding costs	0.475 $/kg
total	k_c = 1.081 $/kg

The total cost, including the proportional tool cost can be expressed as

$$K_T = k_c m_c + k_T$$

where

$$k_T = \frac{K_T}{50n_cL_{cm}}$$

K_T is the tool cost, $50n_cL_{cm}$ is the total length of welded bars for 50 trucks (one year production).

The results of calculations are shown in Table 2.

The total cost of *the Al deck plate* optimum (10 cross members of I-profile) K_{min} = 209.09 + 341.18 = 550.27 $

and that of the optimum (10 cross members of welded I-profile) K_{min} = 146.42 + 100.98 = 247.40 $

The cost savings for one steel truck is 302.87 $ (55%).

8 Conclusions

In the case of a truck floor welded from *Al* alloy extruded profiles and a deck plate, the systematic optimum design process can result in significant savings in mass and cost compared to the original design. A cross-section is optimized consisting of an extruded cross member and an effective part of the deck plate. The objective function is the cross-sectional area, the design constraints relate to a fatigue stress range of welded joints and local buckling of extruded profiles. Fabrication aspects regarding the size limitations are also considered.

In addition to the loading by pallets in horizontal floor position the case of distorted floor position is also taken into account, when a truck wheel is staying on a curb. The bending moments arising in this position have been calculated on the basis of experimental measurements of deflections.

Optimization shows that the thickness of deck plate can be decreased from 4.5 to 2.0 mm, the original number of cross members can be decreased from 14 to 10, and the original cross member shape (RHS) can be replaced by I- or a C - profile having optimum dimensions. These changes can result in 141 kg mass and 377.17 $ cost savings for a truck structure.

It should be emphasized that, in spite of the torsion of the whole floor in the second loading case, the cross members are loaded by bending, since the torsion is restrained by longitudinal members and by the deck plate. In the case of torsion the RHS profile would be, of course, more advantageous than the open profiles.

Higher tool cost of the RHS for n_c = 12 and 10 is caused by the large width of the profiles, since the height is limited to 100 mm. It can be seen that the higher tool cost does not significantly affect the result.

Using a welded steel deck plate and transversal stiffeners, one can make optimization on the same way. In spite of the mass increment comparing to the aluminium optimum, using steel elements one can reduce the total cost of the structure significantly, with 55%, although for a vehicle the mass is significant in fuel consumption.

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References

1. DIN 1725–1983. Aluminiumlegierungen. Knetlegierungen. https://www.beuth.de/en/ standard/din-1725-1/2650507
2. DIN 1748–1981. Strangpressprofile aus Aluminium und Aluminium-Knetlegierungen—Zulässige Abweichungen. www.beuth.de/en/standard/din-1748-4/928185
3. FarkasJ, Jármai K (2013) Optimum design of steel structures, Springer Verlag, Heidelberg 288p. ISBN 978-3-642-36867-7. http://dx.doi.org/10.1007/978-3-642-36868-4
4. Farkas J, Jármai K, Dúl R (2001) Minimum cost design of a truck floor welded from aluminium-alloy profiles, Welding in the World, Pergamon Press, Vol 45, No 9–10, pp 19–22. ISSN 0043-2288
5. Hobbacher A. IIW Recommendations for fatigue design of welded joints and components. IIW-doc. IIW-1823–07, ex XIII-2151r3-07/XV-1254r3-07
6. Eurocode 3. Part 1.1 (2005) Design of steel structures. General rules and rules for buildings. European Committee for Standardization. Brussels
7. Rosenbrock HH (1960) An automatic method for finding the greatest or least value of a function. Comput J 3(3):175–184. doi:10.1093/comjnl/3.3.175
8. London Metal Exchange http://www.lme.com/metals/ Accessed 17 Sept 2016

http://www.springer.com/978-3-319-51188-7

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