HIGH STRENGTH STEEL IN TUBULAR TRUSSES

Teemu Tiainen, Kristo Mela, Timo Jokinen, Markku Heinisuo

Tampere University of Technology, Faculty of Business and Built Environment, Finland
teemu.tiainen@tut.fi, kristo.mela@tut.fi, timo.jokinen@tut.fi, markku.heinisuo@tut.fi

1 INTRODUCTION

Trusses are widely studied applications in structural optimization, e.g. [1] - [6]. Despite their wide use in buildings such as roof and floor girders surprisingly few references can be found dealing with fire resistance of tubular trusses, as concluded in [7]. Optimization of office building steel structures in fire has been studied in [8] but no trusses were considered.

This paper presents optimized results for two Warren-type welded tubular trusses. They are optimized in ambient conditions and in ISO 834 fire for 30 minutes using intumescent protection. The criteria are weight and fabrication cost separately. Many methods for cost calculations of steel structures have been presented [9] - [13]. In this study the method presented in [14] is used including the costs based on all fabrication activities and use of real estate (workshop). Steel grades are varying as: S355, S500 and S700 and hybrid solutions are included, as well. In hybrid solutions the strength of chords is higher than in the braces. Steel grade S355 is the reference case. The trusses are simply supported and loaded with a vertical uniform load. Only planar cases are studied. Symmetric Warren-type trusses are considered with and without verticals.

Constraints follow strictly the requirements of Eurocodes in ambient and fire conditions both for members and joints. The structural analysis model is made following the geometrical model including eccentricities at the gap joints. Only gap joints are considered. Design variables are the height of the truss, the locations of the joints between braces along the chords, and the member sections, chosen from a catalogue of cold-formed square tubular tubes, meaning sizing and shape optimization as categorized in [15]. In addition, the fire resistance requirement adds an extra design variable of intumescent paint thickness.

The scope is to consider whether it is economical to use high strength steel (HSS) instead of regular steel grade S355 in typical “standard” solutions for buildings: roof trusses with fixed roof inclination 1:20.

2 TRUSS CASES

One span simply supported two truss types 1 and 2 of *Fig. 1* are considered with a span of L = 36 m. Supports are located at the ends of the truss. Two uniform design loads at the top chord are in room temperature 23.5 and 47.0 kN/m. In fire the loads are 7.6 and 15.2 kN/m, respectively. The amount of diagonals is fixed (8) in each truss.

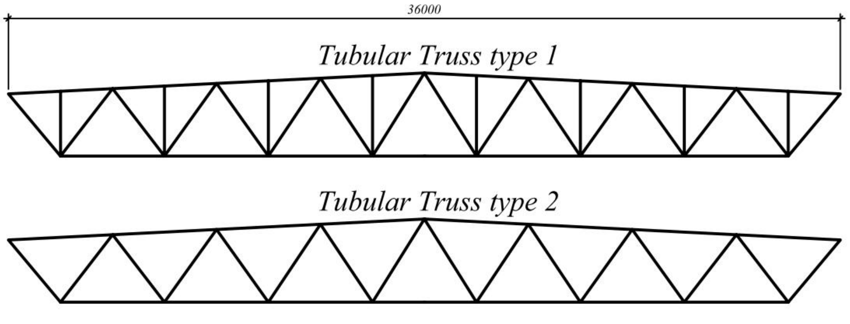

Fig. 1. Warren-type trusses, type 1 and 2

Design variables are taken as:

- Height of the truss measured from the bottom surface of the bottom chord to the top surface of the top chord at the mid-span of the truss, height range 0.5 – 5.0 m;
- Locations of the joints along the chords, a_1 – a_7 as shown in Fig. 2. Location of the joint is measured from the mid-points of the gap along the chord. At the support exists no eccentricity, location range 0.5 – 5.0 m;
- Gap length g, which is supposed to be same at each joint, gap range 10 – 50 mm, step 1 mm;
- Cross-sections of the members taken from *Table 1*.

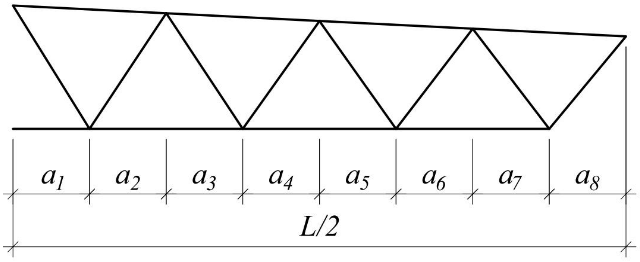

Fig. 2. Locations of the joints

Table 1. Cross-section catalogue

Number	*BxHxt [mm]*	*Number*	*BxHxt [mm]*	*Number*	*BxHxt [mm]*	*Number*	*BxHxt [mm]*
1	25x25x3	15	80x80x4	29	120x120x5	43	160x160x10
2	30x30x3	16	80x80x5	30	120x120x6	44	180x180x6
3	40x40x3	17	80x80x6	31	120x120x8	45	180x180x8
4	40x40x4	18	90x90x3	32	120x120x10	46	180x180x10
5	50x50x3	19	90x90x4	33	140x140x5	47	200x200x8
6	50x50x4	20	90x90x5	34	140x140x6	48	200x200x10
7	50x50x5	21	90x90x6	35	140x140x8	49	200x200x12.5
8	60x60x3	22	100x100x4	36	150x150x5	50	250x250x6
9	60x60x4	23	100x100x5	37	150x150x6	51	250x250x8
10	60x60x5	24	100x100x6	38	150x150x8	52	250x250x10
11	70x70x3	25	100x100x8	39	150x150x10	53	250x250x12.5
12	70x70x4	26	110x110x4	40	150x150x12.5	54	300x300x10
13	70x70x5	27	110x110x5	41	160x160x6	55	300x300x12.5
14	80x80x3	28	120x120x4	42	160x160x8		

Firstly, the geometrical presentation using the design variables was constructed to a special truss module [16]. Different solutions are got by varying the design variables. The structural analysis model was derived from the geometrical model by the module using the local joint models shown in *Fig. 3*. The idea in this study was to follow strictly the present Eurocodes by generating the stiff eccentricity elements (e) to the joints and hinges to the ends of the braces. Linear elastic analysis was done using the beam elements of [17]. After that the resistances of the members and joints and all requirements originating from the joint design were checked. These checks were as constraints and the feasibility of the solution was checked in the optimization.

The joint checks include “penalty factors” for HSS welded tubular joints appearing in EN 1993-1-12. The full-strength welds are used at the joints. In fire design the national approval of intumescent NULLIFIRE S607 [18] is used to define the required protection thickness for members in 30 minutes of ISO 834 fire. It was supposed that the gas temperature was the same all around the members. The temperatures at joints are supposed to be same as highest of the joined members and design rules for joints are supposed to be same as in ambient conditions, but using reduced steel strength at elevated temperatures following EN 1993-1-2.

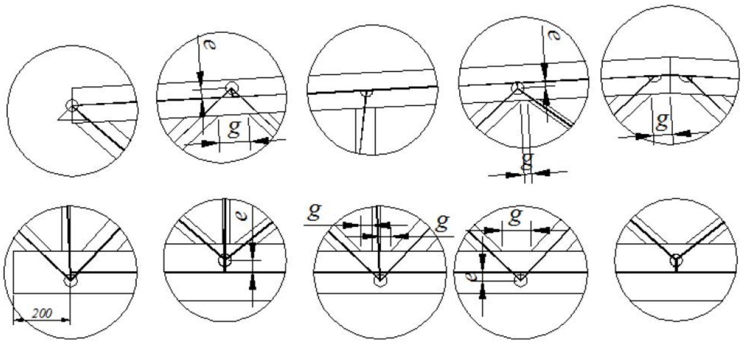

Fig. 3. Local analysis models of joints

3 OPTIMIZATION AND RESULTS

Some design variables are continuous and some are discrete. There were about 20 design variables and 160 constraints in the problem. The criteria are weight and fabrication cost of the truss separately. The weight is easy to calculate using the exact presentation of the truss. The costs are calculated summing up material, blasting, sawing, welding (including tack welding and assembly of members) and painting costs. The used cost calculation method was developed for the regular steel. In this study the cost factors for HSS are used with the reference S355 for sawing and welding of S500 and S700 steel grades. The cost factors for fabrication are: sawing S500 factor 1.15, S700 factor 1.30; welding S500 factor 1.25, S700 factor 1.50, respectively. For labour, real estate, maintenance and energy Finnish cost level (2012) was used. The reference tube material S355 cost was 0.80 €/kg and material cost factors S500: 1.15 and S700: 1.30 were used. The cost for fire paint was 20 €/mm/m^2.

In this kind of problem the particle swarm optimization (PSO) algorithm has proven to be suitable [17]. PSO [19] is a stochastic heuristic method relying on a swarm of individuals moving in the design space. Optimization runs were done using following PSO parameters: Inertia 1.4, factor to reduce the inertia 0.8, number of iterations without best found enhancement to change the inertia 3, penalty factor 2. The criteria function and the constraints were replaced with an unconstrained problem using the penalty factor. This approach can lead to a situation in which the best found solution is no longer feasible. Therefore, the best found feasible solution is kept in memory.

After convergence studies the final results were calculated using 400 iterations, 300 individuals and 8 runs for each case for type 2 and 500 iterations, 400 individuals and 8 runs for type 1. The weight optimal type 1 truss is shown in *Fig. 4*. This is a typical shape of the found optimal trusses. The first span near the support was larger than others at the top chord. It was found, too, that the use of constant gaps at the joints was not a good choice. The two diagonals near the supports tend to be large, so the gap at their joint should be small to reduce the eccentricity at the joint. The eccentricity here tends to be so large that the eccentricity moment should be divided to the joined members following EN 1993-1-8. The gaps at the mid-parts of the truss were at the top limit 50 mm in many solutions indicating that using larger gaps better solutions may be found.

Using manual sizing with evenly distributed joints and height $H=L/10$ = 3.6 m, the truss with the weight 1870 kg was obtained for this case (type 2, S355/S355, steel grade S355 both at chords and at braces, load 23.5 N/m). This is a typical result which can be derived in practice when a program to check the feasibility of the truss is available for the designer. Thus, using the shape optimization about 10 % savings in weight can be achieved in this case.

Tables 2 and 3 include the best found results for type 1 and type 2 trusses, respectively. Result marked with star denotes that the best cost and weight structures are different designs.

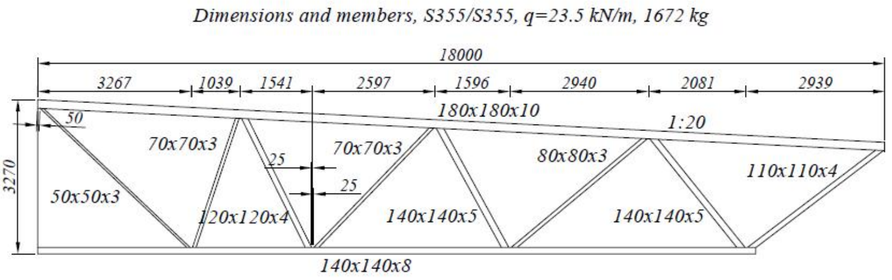

Fig. 4. Weight optimal type 2, material S355 all members

Table 2. Best found solutions for type 1 trusses

Material		Load [kN/m]	Best found	
Chords	Braces		Cost [euro]	Weight [kg]
S355	S355	23.5	1526	1430
S500	S500	23.5	1676	1251
S700	S700	23.5	1562	1004
S500	S355	23.5	1736	1458
S700	S355	23.5	1722	1322
S700	S500	23.5	1560	1060
S355	S355	47.0	2661	2605
S500	S500	47.0	2715	2182
S700	S700	47.0	2553*	1777*
S500	S355	47.0	2797*	2498*
S700	S355	47.0	2876*	2317*
S700	S500	47.0	2804*	1964*

Table 3. Best found solutions for type 2 trusses

Material		Load [kN/m]	Best found	
Chords	Braces		Cost [euro]	Weight [kg]
S355	S355	23.5	1652	1616
S500	S500	23.5	1681	1385
S700	S700	23.5	1566	1110
S500	S355	23.5	1493	1290
S700	S355	23.5	1570*	1225*
		23.5		
S700	S500		1569	1146
S355	S355	47.0	3400	3334
S500	S500	47.0	3142	2582
S700	S700	47.0	2613	1897
S500	S355	47.0	2882	2614
S700	S355	47.0	2641*	2082*
S700	S500	47.0	2589	1933

When comparing best solutions no systematic rule can be found to say which type, 1 or 2, is better. With the large load (47.0 kN/m) and with the materials S355/S355 and S500/S500 type 2 is much heavier and costly than type 1. The mean of height of the truss was in optimal trusses $L/10.7$ for type 1 and $L/10.4$ for type 2, which are near traditional engineering assumptions.

Fig. 5 illustrates best found criterion values. In both types the weight is significantly reduced by using HSS but only type 2 benefits clearly when cost is used as criterion. Weight savings using S500 and S700 in all members compared to S355/S355 trusses are 84 % - 87 % and 61 % - 69 %, respectively. The cost savings using HSS are evident in certain solutions. Especially, type 2 trusses with the higher load, cost savings are over 20 % in using S700/S700 and in hybrid S700/S500 compared to the type 2 solutions using regular steel (S355).

From *Fig. 5* it can be seen that the least costly option in with higher load is S700 truss and S500/355 hybrid with lower load. Relative difference between best found and pure S355 truss is 2-4 %.

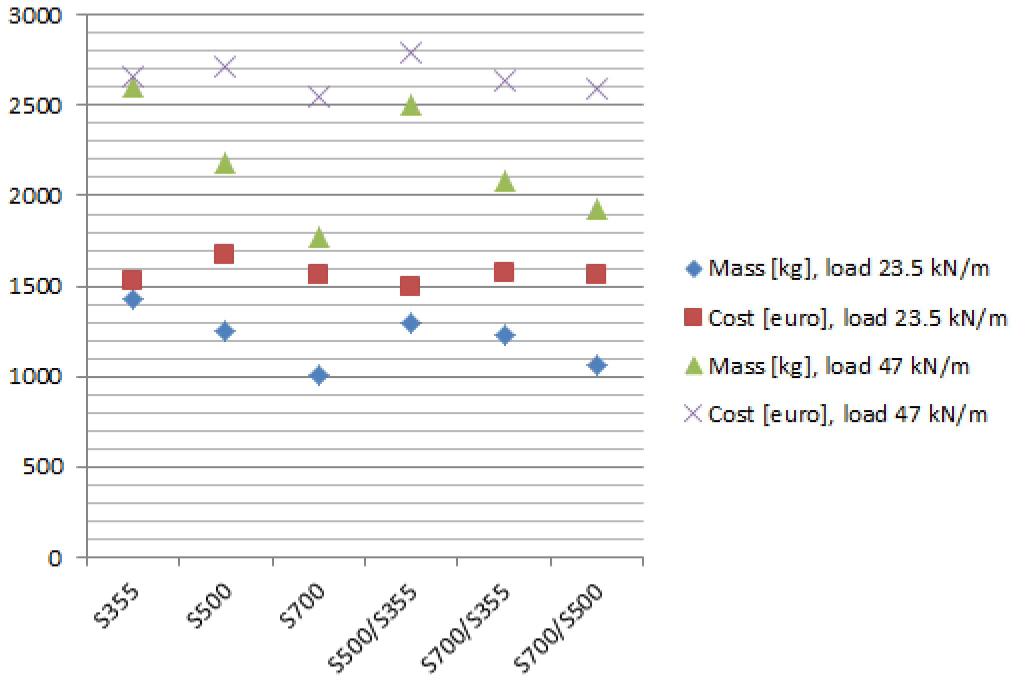

Fig. 5. Best found truss cost and mass values for each strength combination.

In the fire design optimization, the extra variable of fire protection thickness was introduced. The protection thickness had discrete values of 0, 1, 1.5, 2.0, …, 4.0 and 4.5 mm. With type 2, R30 optimization was done with same parameters as in ambient temperature, 400 particles, 300 iterations and 8 runs using the lower load 23.5 kN/m with the fire protection. In *Table 4* are compared costs and weights of best found trusses with and without fire resistance requirement. It can be seen that weights of the trusses are very similar but the costs are about twice as much when the fire requirement is present. The weight S700/S500 hybrid solution without fire is heavier than the solution with R30 fire requirement. This shows the stochastic nature of PSO method.

Table 4. Comparisons with R30 truss and without fire resistance requirement, Type 2, both are cost optimal solutions.

Material		*Load (kN/m)*	*Cost (Euro) with R30 requirement*	*Cost (Euro) without fire*	*Weight (kg) with fire requirement*	*Weight (kg) without fire*	*Cost ratio*	*Weight ratio*
Chords	*Braces*							
S355	S355	23.5	5362	3775	3998	3813	1.42	1.05
S500	S500	23.5	8223	4252	3692	3307	1.93	1.12
S700	S700	23.5	6692	3620	2711	2639	1.85	1.03
S500	S355	23.5	7155	3872	3407	3327	1.85	1.02
S700	S355	23.5	8315	3680	3388	2697	2.26	1.26
S700	S500	23.5	6795	3775	2815	2970	1.8	0.95

SUMMARY

Without fire requirements, it can be concluded that weight ratios using S500 and S700 steel in all members of tubular trusses compared to S355/S355 trusses are 84 % - 87 % and 61 % - 69 %, and hybrids are between. The smaller numbers are for the load 47.0 kN/m and the larger numbers are for the load 23.5 kN/m. The cost savings using HSS are smaller but clear with the higher load. Generally, shape optimization means savings compared to pure sizing optimization, which can be done in practice by trial and error without optimization tools. The optimization means a systematic tool to find the best solutions in the sizing and shape optimization problem of trusses.

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REFERENCES

[1] Jarmai, K, Snyman, J, Farkas, J, “Application of novel constrained optimization algorithms to the minimum volume design of planar chs trusses with parallel chords”, Engineering Optimization, 36:457–471, 2004.

[2] Saka, M, “Optimum topological design of geometrically nonlinear single layer latticed domes using coupled genetic algorithm”, Computers and Structures, 85:1635–1646, 2007.

[3] Farkas, J, Jarmai, K, “Optimum strengthening of a column-supported oil pipeline by a tubular truss”, Journal of Constructional Steel Research, 62:116–120, 2006.

[4] Kripakaran, P, Gupta, A, Baugh, J, “A novel optimization approach for minimum cost design of trusses”, Computers and Structures, 85:1782–1794, 2007.

[5] Iqbal, A, Hansen, J, “Cost-based integrated design optimization”, Structural and Multidisciplinary Optimization, 32:447–461, 2006.

[6] Mela, K, “Mixed Variable Formulations for Truss Topology Optimization”, PhD thesis, Tampere University of Technology, 2013.

[7] Ozyurt, E, Wang, Y, C, “Resistance of T- and K-joints to tubular members at elevated temperatures”, In Proc of *Applications of Structural Fire Engineering*, Wald, Burgess, Horova, Jana, Jirku (eds), CTU Publishing House, Prague, pp. 179-185, 2013.

[8] Bzdawka, Karol, “Optimization of Office Building Frame with Semi-Rigid Joints in Normal and Fire Conditions”, PhD thesis, Tampere University of Technology, 2012.

[9] 1 Tizani, W, Nethercot, D, Davies, G, Smith, N, Mc-Carthy, T, “Object-oriented fabrication cost model for the economic appraisal of tubular truss design”, Advances in Engineering Software, 27:11–20, 2006.

[10] Watson, K, Dallas, S, Van der Kreek, N, Main T, “Costing of steelwork from feasibility through to completion”, Journal of Australian Steel Construction, 30:2–9, 1996.

[11] Pavlovcic, L, Krajnc, A, Beg, D, “Cost function analysis in the structural optimization of steel frames”, Structural and Multidisciplinary Optimization, 28:286–295, 2004.

[12] Klansek, U, Kravanja, K, “Cost estimation, optimization and competitiveness of different composite floor systems - part 2: Optimization based competitiveness between the composite i beams, channel-section and hollow-section trusses”, Journal of Constructional Steel Research, 62:449–462, 2006.

[13] Farkas, J, Jarmai, K, Analysis and Optimum Design of Metal Structures. A. A. Balkema, Rotterdam, 1997.

[14] Haapio, J, “Feature-Based Costing Method for Skeletal Steel Structures based on the Process Approach”, PhD thesis, Tampere University of Technology, 2012.

[15] Uri Kirsch. Structural optimization, Springer-Verlag, 1993.

[16] Mela, K, Heinisuo, M, Tiainen, T, ”D4.5”. RUOSTE, RFSR-CT-2012-00036. 2012.

[17] Jalkanen, J, “Tubular Truss Optimization Using Heuristic Algorithms”, PhD thesis, Tampere University of Technology, 2007.

[18] NULLIFIRE S607 intumescent paint for tubular and I section and WQ beam protection, *Product declaration.* TRY. 2008 (in Finnish).

[19] Kennedy, J, Eberhart, R, “Particle swarm optimization”, In *IEEE International Conference on Neural Networks*, Vol. 4, pp. 1942–1948, 1995.