OPTIMIZATION OF A TRANSFER CARRIAGE ALONG CRANE GIRDERS

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Drever International S.A., located in Liège and part of SMS Siemag Group, is a market leader for continuous annealing furnaces and galvanizing plants for steel and stainless steel strips. Liège University and Drever International collaborate for many years in R & D. For the heat treatment of the strips (automotive qualities), it is necessary to use a transfer carriage in order to translate along crane girders an induction furnace (with a weight of about 60 tons) and a mobile cooler system (having a weight around 20 tons). This carriage, which has several overhangs, consists of I beams and box girders and integrates devices to compensate torsional effects. The design of this equipment is guided by the respect of strict deflection criteria, imposed by the production conditions. An optimization of the presently used carriage was required, especially in terms of total weight. A study aimed at proposing several new carriage configurations and discussing their respective advantages and drawbacks has been initiated and, as a result, the most promising configuration has been selected and carefully designed, including the fabrication and erection constraints. The use of tubular sections appeared quickly as an evidence, leading at the end to a very significant decrease of the weight and fabrication costs, while satisfying requests in terms of resistance, deformation and stiffness. In the paper, the way on how tubes have been used to achieve the industrial goals is presented and illustrated.

Keywords: Tubular profiles, crane girders, component method.

1. Introduction

Generally, optimization of any structure can be carried out in terms of the weight reduction, simplification of joints and details, reduction of the number of specific parts and assemblies, actions on a substructure, manufacturing, transportation, assembling, etc. There is no perfect solution which can satisfy all these criteria, but the parametric study is necessary in order to select a solution that fits the most all these requirements, what is conducted in this work as well. Eight new solutions are proposed as improvements of the current solution and studied parametrically.

2. Initial Solution

2.1. *Layout of the structure*

The initial solution can be described as a grillage structure, in terms of its layout and dimensions. It consists of a system of mutually perpendicular beams/girders subjected to gravity

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loads. The only part of the structure that is out of the horizontal plane are brackets, with the purpose to compensate torsional effects. For clear understanding, designation of all parts of the structure is given in Figure 1.

Sides of the structure (right/left) are assigned in relation to the view from the operator side. The carriage structure is supported by a pair of rails placed on top of crane runway beams. Each runway beam forms a frame together with columns. The distance between the frames is 9000 mm, measured axis-to-axis between the rails.

The crane carriage assembly is composed of the carriage structure itself plus secondary structural assemblies that allow access to the equipment during maintenance periods and they are not part of the detailed study, however their weight and loads acting on them have to be taken into account for the carriage structure analysis. The secondary assemblies are: three floor assemblies (upper floor assembly, carriage floor assembly, lower floor assembly) including their columns, four bogie platform assemblies and several ladders. The crane carriage assembly is intended to translate from the park position to the operating position for a distance of 10855 mm.

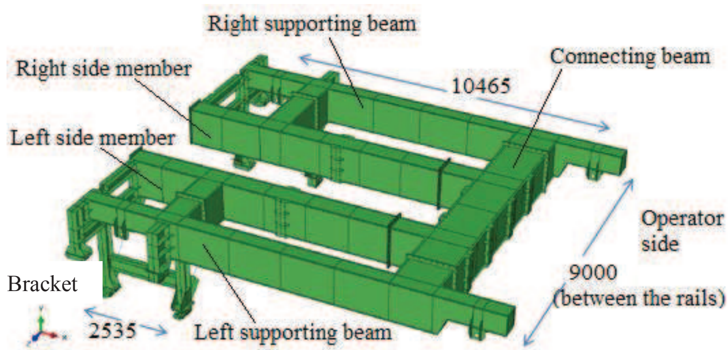

Figure 1. Layout of the carriage structure itself (dimensions in mm)

Cross-sections selected for the supporting beams, side members and connecting beam are welded built-up box sections with constant height, except for the supporting beams that are tapered, to allow placing of the roller bogies. All above mentioned beams are made of plates with constant thickness along the longitudinal axis. The cross-sectional sizes of the main structural members are given in Table 1, following the designation given in Figure 2. It should be mentioned that the beams are stiffened by means of transverse stiffeners (diaphragms), in order to prevent distortion of the box, shear buckling of the web, etc.

Table 1. Dimensions of cross-sections

Section	b_{f1}	t_{f1}	b_{f2}	t_{f2}	h_w	t_w	d
	mm	mm	mm	mm	mm	mm	mm
1-1	1320	15	1320	15	1135	15	1190
2-2	680	15	680	15	1135	12	556
3-3	524	15	524	15	1135	12	400
4-4	524	25	524	15	600	12	400
5-5	800	15	800	15	1135	12	676
6-6	300	20	300	20	260	12	/
7-7	300	25	300	25	250	20	/
8-8	300	20	300	20	260	12	/

Sections 1 to 5 are built-up boxes, while sections 6 to 8 are welded I-shape sections. All structural members are made of steel S235.

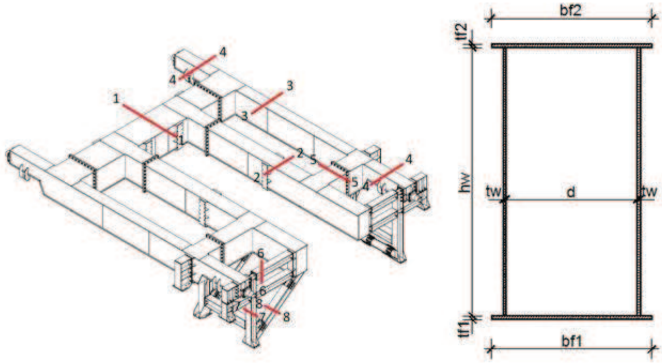

Figure 2. Designation for Table 1.

Four roller bogies transfer the vertical loading to the runway structure and allow the translational movement. Each roller bogie consists of two rollers and each is equipped by a gearbox and a motor. To compensate torsion, there are eight rollers supported in the horizontal direction. Longitudinally, the distance between the vertical roller bogies is 10465 mm while the distance between the horizontal rollers is 2535 mm (see Figure 1). For clear understanding, Figure 3 is given to show how the brackets and horizontal rollers compensate torsion, by means of horizontal reactions.

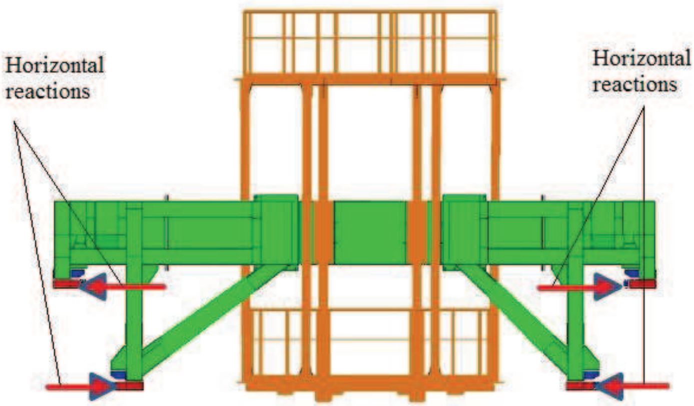

Figure 3. Horizontal reactions compensating torsion

2.2. *Design assumptions*

The initial solution was designed according to FEM 1.001: Rules for the design of hoisting appliances, based on the allowable stress method. Actions on the structure and combinations of loads are based on FEM 1.001 as well.

The number of stress cycles during the design working life of the structure is 20000, thus the fatigue assessment is not necessary (Hrabowskia et al 2012), (Hrabowskia et al 2015). Climate effects are not considered because the structure is located inside a building. The deflection limit for this equipment is strict, equal to span/1250, in this case 7.17 mm.

According to the code, the structure is classified as A3. Respecting the classification, the amplifying coefficient is γ_c=1.05. Even though the structure does not have any hoisting device, the dynamic coefficient has to be taken into account with is minimum value, hence ψ=1.15.

2.3. *Loads*

Taking into account the design assumptions, and respecting the code requirements, the following loads are taken into account:

- self-weight of the carriage structure plus self-weight of secondary structural assemblies;
- working loads: inductive furnace and air cooler plenum with a weight of 60 t and 20 t respectively, two ducts with a weight of 5 t each and the inductor;
- inertial forces due to horizontal motions.

These loads are combined in four possible load combinations.

2.4. *Results*

The structure was designed to fulfill the ultimate limit states and serviceability limit states criteria. The SLS criterion was governing for the design, while at the ULS the utilization was around 60%.

Today, the total weight of the carriage structure is 36,268 kg what is the basis for all further comparisons.

3. Pre-design Proposals

In order to find a solution that is lighter than the initial solution and additionally respecting the fabrication complexity and erection constraints, eight solutions are proposed at the pre-design level. A variety of structural systems is covered by these eight solutions, like bowstring structures, planar trusses, box trusses. All proposed solutions are graphically presented in Figures 4-7.

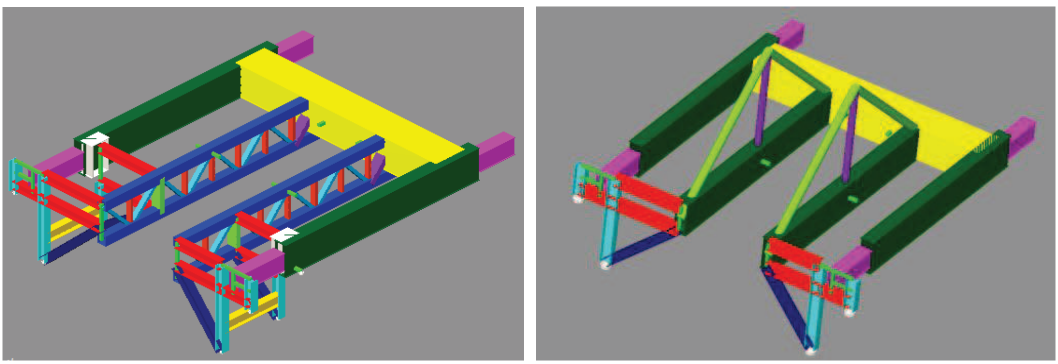

Figure 4. Solution 1 and Solution 2

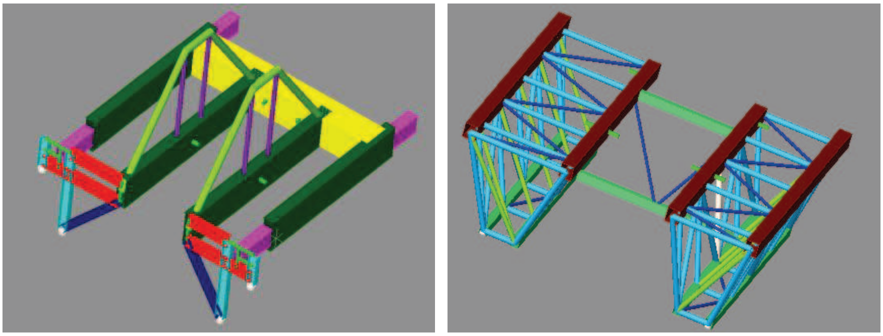

Figure 5. Solution 3 and Solution 4

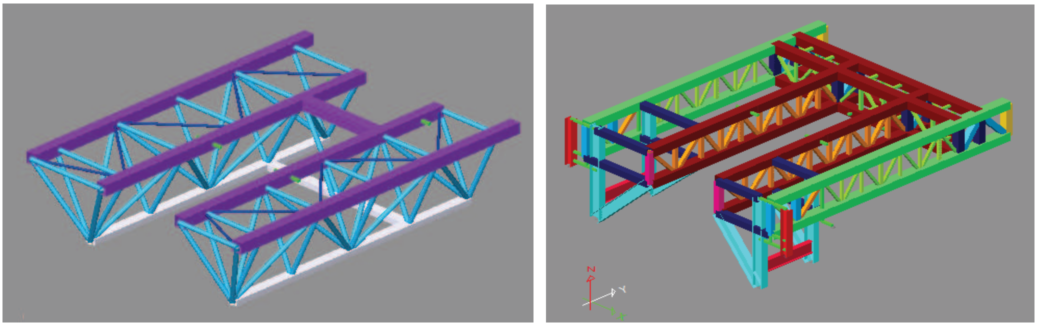

Figure 6. Solution 5 and Solution 6

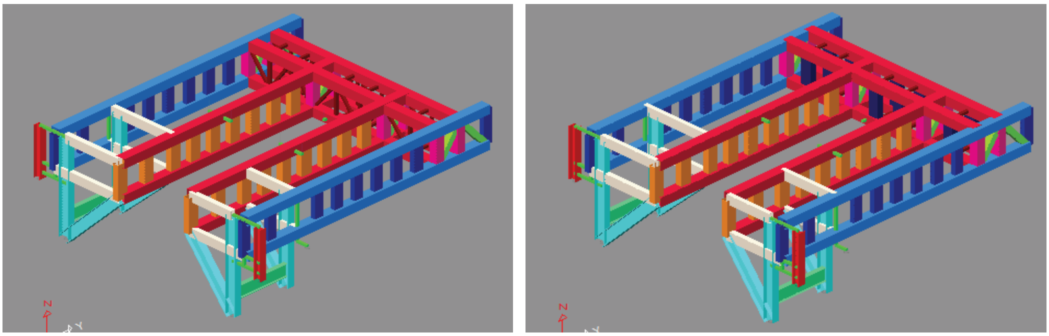

Figure 7. Solution 7 and Solution 8

For all eight solutions, the following phenomena are studied parametrically:

- vertical displacements;
- vertical reactions;
- horizontal reactions;
- elastic stresses;
- buckling reduction factors

but also, additionally, the influence of the following particularities on the overall stiffness of the structure:

- geometry and stiffness of the bowstring structure for Solution 2 and Solution 3;
- coupling of parallel planar trusses for Solution 6 and Solution 8;
- stiffness of certain openings in Viereendel trusses for Solution 7;

- modeling of connections in the structural analysis for Solution 6;

The two main aspects influencing the final cost are the weight of the structure and the amount of labor needed to fabricate it. Finally all these solutions can be classified in three groups according to their similarities (Table 2).

Group A covers solutions with the layout similar to the initial solution with some improvements, still using built-up box sections, Group B are box trusses composed of hollow sections and Group C are planar trusses composed of hollow sections.

Table 2. Groups of pre-design solutions

Group	Solution	Fabrication complexity	Material saving
A	1, 2, 3	Medium	Low to medium
B	4, 5	Very high	High
C	6, 7, 8	Medium	Low to medium

During the selection, Group A is neglected because the company strongly prefers to use commercial sections instead of built-up sections, mainly because of the fabrication tolerances that are sometimes difficult to satisfy in some countries. Solutions from Group B were not selected because of their fabrication complexity, what results in high fabrication costs. Within Group C, Solution 6 was selected as long as it provides higher material saving compared to Solution 7 and Solution 8. In addition, the assumption of rigid joints in Viereendel trusses is questionable in case of such big cross-sections (e.g. RHS 400x200x6 connected to RHS 400x400x100 used in Solution 7).

4. Improved solution

4.1. *Layout of the structure*

During the detailed design, Solution 6 was improved with the aim to decrease the number of braces, to avoid vertical brace members as much as possible and to simplify joints. The height of the trusses is 1500 mm, measured between the chord axes. The area of cross-sections is selected according to the stiffness required in order to satisfy the deflection criterion while the selection of cross-sections' shape and thickness is governed by the range of validity for the application of the rules for design of joints (Chapter 7 of EN 1993-1-8) in terms of width-to-height ratios, width-to-thickens ratios, width of braces to width of chord ratios, gap size, overlap size, cross-section class, allowed eccentricity, etc. Generally, the cross-sections have similar sizes than those selected the pre-design phase; adjustments have mainly resulted in a change of their shape (for example a rectangular hollow section instead of a square hollow section) or in a reduction of size and an increase of thickness.

Compared to the pre-design proposal, where SHS 400x400x8 and SHS 400x400x10 were selected for the chords, the design stage replaces them with SHS 350x350x12.5. A more compact cross-section was required to comply with the rules for design of joints, what is also an advantage to use the same cross-section for all chords as well as the fact that SHS 350x350x12.5 is more available on the market. A graphical illustration of the layout is given in Figure 8.

In order to simplify the production, a special care was taken about the joints in order to obtain gap joints rather than overlap ones. From the manufacturing point of view, K-type joints are preferred to KT-type joints, hence vertical braces have been avoided as much as possible. As it can be seen in Figure 8, the vertical braces are present now only at the intersections between the perpendicular trusses and around the supports. This is conducted mainly to increase the thickness of diagonal braces. In overlap joints, the vertical brace has smaller size, therefore it overlaps the diagonal braces. Some joints in the pre-design proposal were spatial, what is also not desirable. With the aim to avoid this complex detail, brace members in the connecting beam have been rearranged, by changing their directions in one of the vertical parallel planes. An illustration is given in Figure 8. This leads to the fact that all joints in the structure can be considered as planar joints, what simplifies the production and the design as well. Cross-sections used for the improved solution are presented in Table 3.

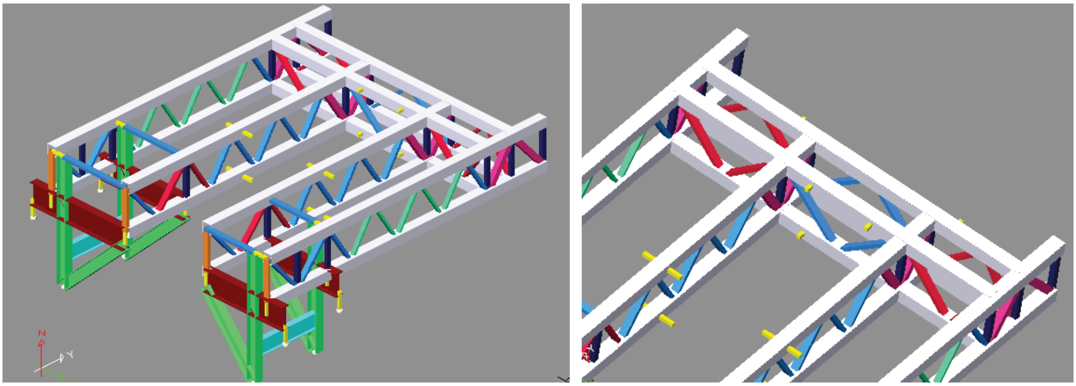

Figure 8. Improved solution - 3D view (left) and connecting beam (right)

Table 3. Cross-sections used for the improved solution

Part	Section
Chords	SHS 350x350x12.5
Braces	RHS 200x100x6, RHS 200x100x8, RHS 160x80x5, SHS 150x150x6, SHS 200x200x10
Brackets	HEB 360, HEA 800, IPE 550

4.2. *Design*

The finite elements model used to analyze the structure consists of continuous chords and pin-ended braces. As a result, the brace members are loaded in axial compression/tension while the chords are subjected to the combined effects of axial forces, bending moments and shear forces. To keep the consistency with the initial solution, loads and combination of loads are calculated according to FEM 1.001, while the design checks are performed in accordance with Eurocode.

It should be mentioned that the design resistance of the weld connecting the braces to the chord, stated by clause 7.3.1(4) of EN 1993-1-8, should not be less than the design resistance of the cross-sections of those braces in order to allow for non-uniform stress-distributions and sufficient deformation capacity to allow for redistribution of unavoidable bending moments. For steel grade S235 and the partial safety factors recommended by Eurocode ($\gamma_{M0}=1$; $\gamma_{M2}=1$) the minimum throat thickness of a single sided fillet weld is $a \geq 0.923t$. Since the majority of brace members in the structure have thickness 6 mm or less, this means that the welding can be performed in one pass in order to produce the requested full-strength welds.

There is lack of design recommendations in Chapter 7 of EN 1993-1-8 for some cases which are present in this structure, e.g. unidirectional K and KT joints, KT joints where a vertical brace is the overlapping member and bolted splice joints with end plates. This can be solved using advanced finite element approach or following the guidance given in (Wardenier et al. 2010), (Packer et al. 2009) and (Tata Steel 2013).

4.3. *Results*

Deflections governs the design. The maximum vertical displacement calculated in the numerical model is 6.85 mm, what is within the strict limit of 7.17 mm.

Design of cross-sections, stability of structural members and design of joints are generally satisfied with a significant reserve of utilization. An exception is the joint at the support, that needs to be stiffened with the flange plate (15 mm thick) in order to prevent the chord face failure loaded by three braces in compression (unidirectional KT joint).

Finally, the total weight of the carriage structure is 30,179 kg. It includes the weight of structural members, plates and 10% of the weight in addition. This paper does not analyze in detail joints between the brackets and trusses, sub-assemblies intended to fix roller bogies to the structure, sub-assemblies for fixing the platform columns and caissons, etc. In order to compensate this and estimate the final weight of the structure, all these parts are accounted as 10% of the structural weight. The summary is given in Table 4.

Table 4. Improved solution - summary of the weight

Item	Weight (kg)
Structural members	26797
Plates	702
10% of extra structural weight	2680
Total	30179

As an overview of the contribution of the various structural parts to the total weight Table 5. is given. The braces contribute only with 11.93% to the total weight, but on contrary they require more labor for the production than other parts of the structure.

Table 5. Contribution of the parts of the structures to the total weight

Part of the structure	Weight (kg)	Contribution (%)
Chords	15536	57.98
Braces	3198	11.93
Brackets	8063	30.09
Total	26797	100.00

5. Comparison between the initial and improved solution

The main comparison between these two solutions in terms of total weight is given in Table 6. Solution 6 was selected among eight pre-design proposals mainly because of the fabrication (with the aim to replace built-up box sections with commercial hollow sections) what resulted at the end in a considerably lighter structure. Generally, there are two reasons in this case that allowed the weight reduction. The height of the trusses is 1500 + 350 = 1850 mm while the height of the box girders in the initial solution is 1165 mm, what means that the improved solution has higher stiffness-to-weight ratio compared to the initial solution. Basically, this height was selected in order to compose the truss with a proper geometry. The second reason is related to the type of beams, since a truss girder provides more possibilities for the optimization than a built-up box. For instance, a built-up box girder is made of plates, and its cross-sectional dimensions are often constant along the axis, or changed at certain nodes. On contrary, each member of a truss can be adopted with different cross-sectional sizes between the nodes.

Table 6. Total weight – comparison

Solution	Weight (kg)	ΔG (kg)
Initial solution	36268	/
Improved solution	30179	-6089

6. Conclusions

On the basis of the results and their interpretation given in the previous chapters, the following conclusions can be drawn:

- The final reduction of the weight compared to the initial solution is 6089 kg, what means that truss girders made of tubular sections provide more possibilities for the material savings than built-up boxes;
- Design of cross-sections and stability of structural members are not governing for the design of this structure and the utilization ratio is mainly below 0.5;
- Design of joints strongly influences the design, in terms of layout and dimensions, in order to satisfy the validity limits given in EN 1993-1-8;
- The improved solution imposes smaller loads to the crane runway beams compared to the initial solution. Optimization of the runway structure could be a subject of future studies.

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