Structural analysis of two metal *de Dion* roof trusses in Brussels model schools

M. de Bouw, I. Wouters & L. Lauriks
Department of Architectural Engineering (æ-lab),
Vrije Universiteit Brussel, Belgium

Abstract

From 1830 onwards state education was one of the priorities of the new Belgian monarchy. In 1875 the *Ligue de l'Enseingement* and architect E. Hendrickx put forward the *École Modèle* as a new school building typology where the *préau* – a spacious central covered courtyard – organized the entire school happening. This prototype served as a guideline for over 55 schools built by famous architects in every community of Brussels between 1875 and 1920.

To span the *préau*, numerous metal roof trusses, varying from simple industrial *Polonceau* trusses to richly decorated *de Dion* trusses, span the 9 to 15 m wide central hall. Invented in 1837, the *Polonceau* truss had already established a solid reputation, and calculation methods were known and generally accepted at the time of the model schools. However, the structural functioning of the *de Dion* truss was completely new at that time. A study of the records and literature study did not reveal any kind of calculation notes for this truss typology. As a consequence, the extremely slender examples of this kind of truss raise questions on their real structural functioning, load-bearing capacities and capability to comply with modern standards without harming the subtle original structure.

By means of historic documents, on-site surveys and finite elements calculations, this article goes deeper into the load-bearing capacity and stability of two *de Dion* roof trusses. Contemporary structural problems are stated, and the current conditions and safety level of these two trusses are discussed.

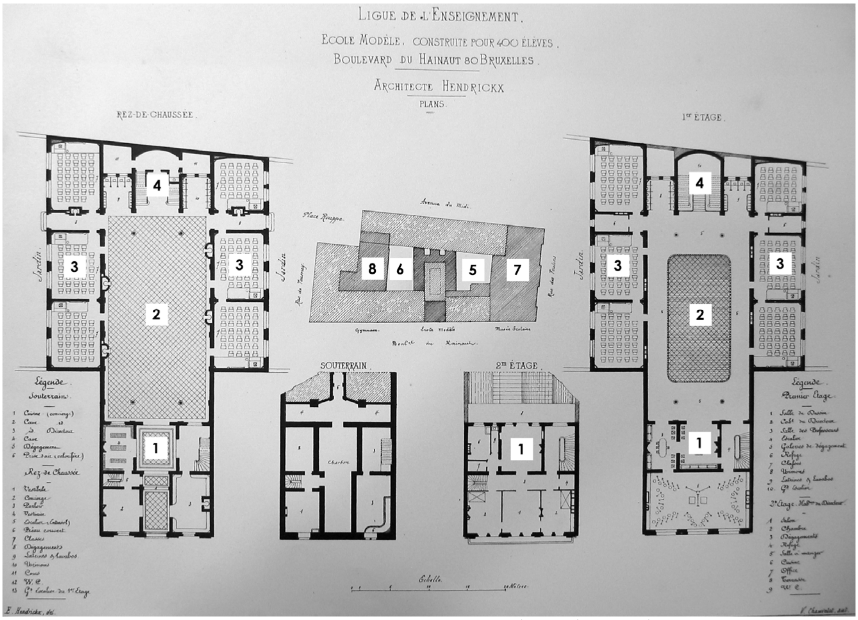
Keywords: metal roof truss, de Dion, École Modèle, model school, Brussels, iron, steel, structural assessment, typologies, finite elements calculation.

WIT Transactions on The Built Environment, Vol 109, © 2009 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/STR090111

1 Introduction

Today, education is a civil right for everyone in Belgium and the city centre of Brussels houses over 250 teaching establishments with appropriate accommodations. However, this casualness was not the case during the nineteenth and twentieth century. During those centuries a rapid and interesting evolution took place in the Low Countries, which were split up into the Netherlands and Belgium in 1830. Between 1875 and 1920 the Belgian teaching establishment even acted as an international pioneer on school architecture and pedagogy [1].

With the support of the Brussels mayor Karel Buls and the *Ligue de l'Enseignement*, the young architect Ernest Hendrickx (1844-92) starts to develop his plans for the *École Modèle* (Figure 1) in 1872. His prototype was a kind of pedagogical laboratory that would incorporate all contemporary ideologies on pedagogy, quality of education, functionality, health, hygiene, ergonomic furniture, airy rooms, etc. Once enough funds were raised and a suited setting was found (viz, at the Maurice Lemonnierlaan 110), the erection of the *École Modèle* starts and the school opens her doors on the 17th of October 1875. The implementation of new pedagogical and architectural ideas, technical developments on hygiene, heating, lightning, ventilation and organization soon gained (inter)national interests.



1 administrative offices, waiting room, janitor's home, reception rooms and principal's office
2 central covered courtyard
3 classrooms
4 staircase
5 boys' playground
6 girls' playground
7 museum of education
8 gymnasium for studying and practising physical exercises

Figure 1: Plans of the *École Modèle* by E. Hendrickx, Brussels, 1875 [2].

www.witpress.com, ISSN 1743-3509 (on-line)

During 1875 and 1920 famous architects such as H. van de Velde, H. Jacobs, E. Quétin and V. Horta built over 55 schools in Brussels with a setting according to Hendrickx' model (Figure 1): the street side was composed by a small façade, merely the size of a private house. Behind this façade an impressive school building (mostly not visible from the street) unfolds itself. The 9 to 15 m wide central covered courtyard (no.2 on Figure 1) – or so-called *préau* – became a standard space that would form the core of every school built according to this prototype [1].

Nowadays, after 125 years, these buildings and their *préau* are still well appreciated and desired school buildings. Due to the functional layout, the spatial classes and the polyvalent hall they exert easily their original function creating a stimulating surrounding for children.

2 Metal roof trusses in Brussels Model Schools

To span the *préau* architects used a solid (concrete or brick barrel vault) roof structure or metal roof trusses. Within the latter category, the trusses could be hidden or visible. It is remarkable that the hidden metal roof trusses always consist of duopitch industrial bar roof trusses (*Howe*, *Pratt*, *Belgian type*, etc.). These were not considered aesthetically beautiful and as a consequence they were always concealed from sight by a false ceiling. With regard to the visible metal roof trusses, one finds two imports: the plain and straightforward *Polonceau* truss versus the decorated and smooth *de Dion* truss [1]. Corresponding parallels can be drawn to the geometrical and pure *Art Nouveau* trend (e.g. P. Hankar, H. Jacobs, P. Hamesse) versus the natural and organic one (e.g. V. Horta, G. Strauven, E. Blérot) respectively.

Within Belgium, both the *Polonceau* and the *de Dion* trusses occupied a prominent position in the course of the considered period. Yet, even though Paul Combaz and Arthur Vierendeel – two important engineers and professors of Belgium at that time – praise the elegance, ease of calculation and very low self-weight of the *Polonceau* trusses, they criticize the considerable involved costs to forge the difficult joints (forks, eye-rods, etc.), and the loss of stiffness and equilibrium when the truss is not completely in one vertical plane. They both state that the *Polonceau* system would therefore be substituted more and more frequently by rigid (*de Dion*) trusses that are unified by the use of riveted gusset plates at their extremities [3, 7]. This tendency is confirmed within the model schools, which reflect well the history and evolution of metal roof trusses in Belgium over a period of 45 years [1].

3 Structural analysis of two oblate *de Dion* roof trusses

The French engineer and count Henri de Dion invented the *de Dion* truss in 1878 when he designed the *Gallerie des Machines* of the Universal Exposition of Paris. He connected the principal rafters of the duopitch roof to the vertical support posts by means of an underlying circular connection arch in a way they would collaborate as one single entity. This invention allowed dropping the inconvenient tension ties, so as to create a greater usable interior volume [3, 4].

Within the category of the *de Dion* roof trusses we can distinguish two types: the semi-circular truss (Figure 2, left) and the oblate truss (Figure 2, right). Focussing on the connections (at the top, at the corners and at the intersection points), we can distinguish four periods [1]. At the beginning (1880-1895) one flat-iron connection strip was used at each corner and at the top. Thereafter (1895-1905), these strips were replaced by several flat-iron truss members at the top and corners, and long iron plates at the intersection points. During the third period (1905-1915), the rafters, vertical posts and underlying arch were connected by the use of section irons with several intermediate gusset plates. Finally, between 1915 and 1920, industrial looking bar-trussed roof structures were used.

This paper deals with the structural analysis of two oblate metal *de Dion* roof trusses. To pinpoint the evolutions in building techniques the 1883 *Des Étangs* school truss (Figure 3, left) from the first period will be compared to one of the third period, namely the 1910 *Dachsbeck* school truss (Figure 3, right). By means of the finite elements software package *SCIA Engineer* [9], we successively go deeper into the trusses' efficiency, reaction and thrust forces, member stresses, deformations, and, finally, the buckling and section checks.

The applied loads are in accordance with the *Eurocodes* (EC) [10–13] and corresponding national annexes. The applied loads consist of the self-weight, the imposed loads on roofs (category H), and symmetrical and asymmetrical snow loads. At this stage of the research no wind loads are considered. The self-weight consists for both trusses of the structural metal bars and plates of the truss itself, and a zinc sheet covering (no.14 – 0.82 mm) on double wooden roof boards (European Douglas 30 mm and Californian Redwood 20 mm), which was the typical arrangement for these roofs according to study of the records and on-site surveys.

Figure 2: School *Les Maronniers* by L. E. S'Jonghers, Anderlecht, 1902 (left); school *Serge Cruz* by H. Nogent, Sint-Jans-Molenbeek, 1920 (right).

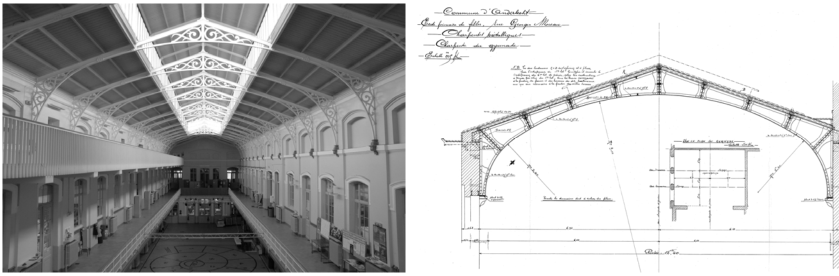


Figure 3: School *Des Étangs* by L. Delbove, Elsene, 1880-3 (left); detailed drawing of the *Dachsbeck* school truss, Anderlecht, 1910 (right) [8].

3.1 Efficiency

During the considered period, the cost of metal structures was merely determined by the amount of iron or steel to use, as labour costs were very low compared to material costs [14, 15]. As a consequence, engineers focussed on the weight-to-span ratio of different options to determine whether a structure such as a roof or bridge was efficient or not.

Analysing the *Polonceau* trusses in the model schools showed a mean weight-to-span ratio of about 0.37 kN/m (self-weight of the metal truss members only). The 1883 *de Dion* truss of the *Des Étangs* school (4.77 kN for 13 m span) and the 1910 *de Dion* truss of the *Dachsbeck* school (9.99 kN for 12.41 m span) showed ratios of 0.37 kN/m and 0.81 kN/m respectively. Two facts leap to the eye:

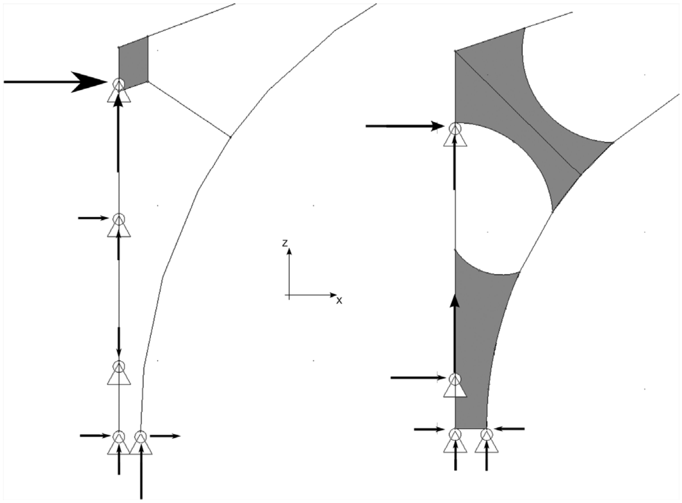
- the weight-to-span ratio of the 1883 *de Dion* truss is the same as the mean ratio of a *Polonceau* truss;
- the weight-to-span ratio of the more recent 1910 *de Dion* truss is more than double of the much older 1883 *de Dion* truss.

Both findings raise some questions. Firstly, a *Polonceau* truss uses each material and structural component in (almost) optimal conditions (compression only for the cast iron struts and tension only for the wrought iron or steel tension ties), whereas the *de Dion* truss does not. So how could it be evenly efficient? Secondly, how comes that the more recent truss would be that less efficient as one would believe engineers always searched to improve the efficiency?

In the next part of this paper we will discuss the results of an in-depth structural analysis of both trusses to evaluate their real structural behaviour, structural efficiency and, as a consequence, their safety level.

3.2 Reaction and thrust forces

Firstly, we analyse the reaction forces and corresponding resultants of both trusses to check whether these oblate trusses indeed eliminate the thrust forces as was the original intention by Henri de Dion.



(a) – 1883 (b) – 1910

Figure 4: Relative magnitudes of the reaction forces of the 1883 truss (a); relative magnitudes of the reaction forces of the 1910 truss (b).

Table 1: Numerical values of the reaction forces and the corresponding resultants (R) of the 1883 truss and the 1910 truss.

	1883 – *Des Étangs*						1910 – *Dachsbeck*				
Nodes	1	2	3	4	5	R	1	2	3	4	R
R_x [kN]	49.76	1.49	0	0.16	3.89	53.53	27.34	16.98	0.58	-1.28	42.43
R_z [kN]	20.48	0.96	-0.45	0.03	14.95	33.50	11.38	21.97	0.34	4.01	34.47
M_y [kNm]						68.96					35.96

Figure 4 and Table 1 clearly indicate the presence of thrust forces in both trusses, which contradicts the original aim of H. De Dion. Yet, they also demonstrate that with a similar resultant vertical component, the horizontal and momental components of the 1910 truss are much lower than those of the 1883 truss. This difference and improvement can be explained by the use of large gusset plates in the 1910 truss. These plates rigidify the joints and redistribute the internal forces more evenly over the different bearings as can be noticed in Figure 4 and Table 1.

3.3 Member stresses

For both trusses the maximum stresses occur under the ultimate limit state with asymmetric snow loads. The maximum equivalent stresses in the plates indicate in both cases stresses beneath 60 MPa, which was the lowest value of the recommended maximum design stress for plates and beams in Belgium at that time. Yet, for the beam member stresses, we notice a difference between both

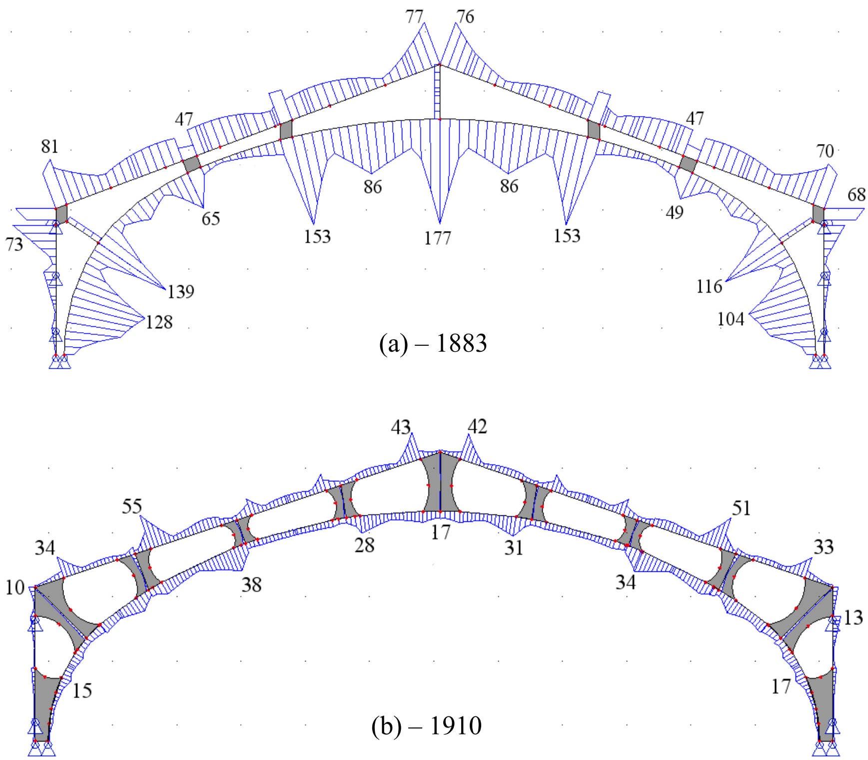


Figure 5: Member stresses [MPa] of the 1883 truss (a); member stresses [MPa] of the 1910 truss (b).

trusses. The Von Mises stresses of the 1910 truss stay indeed below 60 MPa (Figure 5(b)), whereas the ones of the 1883 truss rise up to 177 MPa (Figure 5(a)). These higher stresses could clarify the fact that the 1883 truss is more efficient than the 1910 truss according to the then efficiency definition.

The fact that the 1883 truss' design stress is about three times the then allowed design stress, does not seem to form any problem according to some recent test data carried out at the Department of Architectural Engineering of the Vrije Universiteit Brussel and the present-day knowledge on these historic materials ($\sigma_y \geq 210$ MPa, $\sigma_u \geq 350$ MPa) [16–18].

3.4 Deformations

The maximum deformation takes place for both trusses in the principal rafters under the serviceability limit state with asymmetric snow loads. With a calculated maximum vertical deflection of 4.8 mm for the 1883 truss and 1.0 mm for the 1910 truss, they both stay way below the tolerable maximum deflection of 17.5 mm and 16.5 mm respectively (L/400).

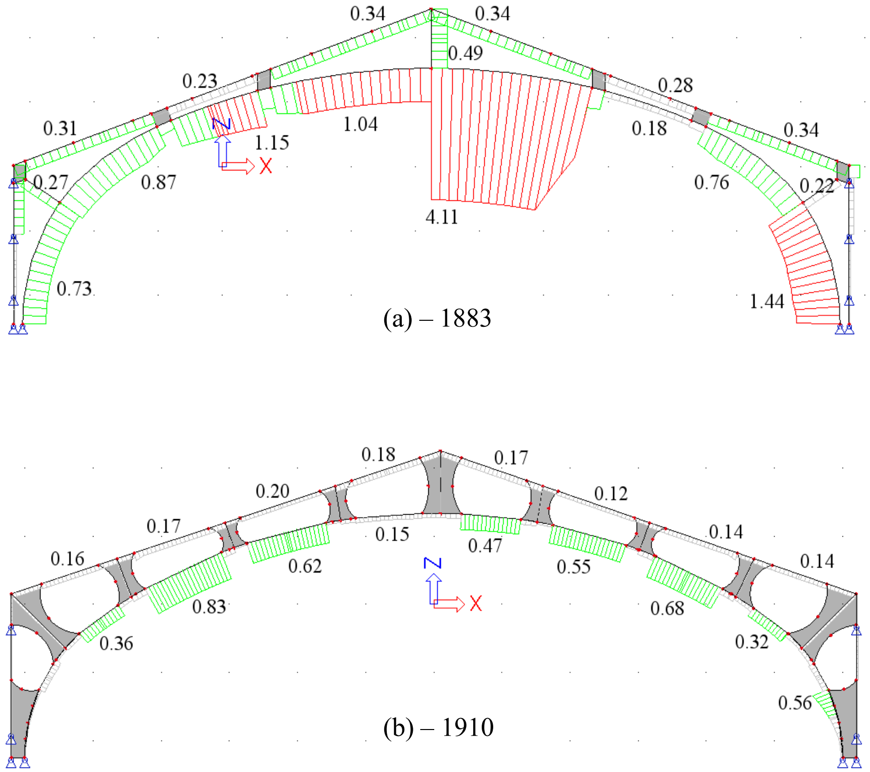


Figure 6: Stability check ratios of the 1883 (a) and 1910 truss (b).

3.5 Buckling and section checks

Because of a lack of proper material characteristics at this stage of the research and within mind the research results of Kühn [16], O'Sullivan [17] and de Bouw [18], we checked the sections and buckling of the 1883 and 1910 truss members by assuming a S235 steel grade, which should be a realistic supposition in first instance (see 3.3).

All members fulfil the section checks of the EC with ease. The 1910 truss also meets all of the stability checks, unlike the 1883 truss. Figure 6:-a clearly indicates the areas of the lower arch which would fail (up to a factor of 4!) due to buckling according to the EC (ratio >1). Remembering the extremely low weight-to-span ratio of this truss (see 3.1), this result is not surprising. However, in reality we did not notice any buckling. So, how could we explain this difference between the EC and reality?

First of all, we double-checked our calculation models. Yet, with different approaches, the hereby presented results and corresponding calculation models are far the most favourable (still realistic) suppositions. The intermediate decoration pieces of the 1883 truss do not reduce the buckling lengths of the lower arch, as these pieces would fail immediately due to buckling if they would take up some loads. Another possible explanation could be the supposed material characteristics. However, it is unlikely that the (possible) gains by sampling and material testing would be high enough to solve the problem. A third explanation would be that the extreme conditions supposed and proscribed by the EC did simply not occur yet.

Notwithstanding the fact that the truss stands for over 125 years, it still seems quite reasonable that buckling may occur in the 1883 truss as the calculations, the high buckling ratio, the very slender appearance and the extremely low weight-to-span ratio all point towards the same conclusion. Moreover, the fact that the (transverse) stability was indeed an issue is confirmed when analysing the evolution of *de Dion* truss composition in the model schools [1]. For each of the four periods, we can record a change in the connection methods, which strongly influence the stability results (e.g. the introduction of section irons, the shortening of system lengths, or the stiffening by the introduction of gusset plates). Next to this evolution, one can also observe the rise of an elaborate structural transverse truss, which connects the top junction of two successive *de Dion* trusses and hereby braces both the upper chords as well as the lower arches to ensure their out-of-plane stability [1].

4 Conclusions

During 1875-1920 a rapid and interesting evolution took place in Belgium and Brussels with regard to the educational philosophy and architecture. To span the *préau* of the schools built according to the 1875 *École Modèle*, numerous *Polonceau* en *de Dion* trusses were used. The *de Dion* truss being a new roof truss typology, this paper compares the structural efficiency of the 1883 *Des Étangs* truss to the 1910 *Dachsbeck* truss.

According to the then definition of efficiency, the 1883 truss was as efficient as a *Polonceau* truss, whereas the 1910 truss was merely half as efficient. Yet, modern structural finite elements analysis reveals the opposite: the reaction forces of the 1910 truss are better redistributed, and the member stresses, deflections and buckling ratios are much lower. Calculation models even indicate a real risk of buckling within the 1883 truss. Notwithstanding the fact that this truss stands for over 125 years, the analysis of the *de Dion* roof truss' building techniques within the model schools confirms that buckling was indeed an issue back then: research revealed the decrease of truss member system lengths and the introduction of transverse trusses, ensuring the out-of-plane bracing of both the upper chord as well as the underlying arch, to solve this problem.

Acknowledgement

This research is funded by the Research Foundation – Flanders (FWO).

References

[1] de Bouw, M., Wouters, I., Lauriks, L., Forty Years of de Dion Trusses in Nineteenth Century Brussels Model Schools, *Proc. of the 3rd Int. Conf. on Construction History*, eds. W. Lorenz, Cottbus, 8 p., May 2009.

[2] *L'émulation*, 1879, 5ième année. Bruxelles: Société Centrale d'Architecture de Belgique (SCAB).

[3] Vierendeel, A., *L'architecture métallique au XIXe siècle et l'Exposition de 1889, à Paris*, E. Ramlot: Bruxelles. 1890.

[4] Lemoine, B., *L'architecture du fer – France: XIXe siècle*, Champ Vallon: Seyssel, 322p, 1986.

[5] Schädlich, C., Der Baustoff Eisen als Grundlage für die Herausbildung qualitativ neuer Baukonstruktionen im 19. Jahrhundert. *Zur Geschichte des Konstruierens*, ed. P. Graefe et al, Stuttgart, pp. 138-151, 1989.

[6] Schulitz, H.; Shobek, W.; Habermann, K., *Steel Construction Manual*, Birkhäuser: Basel, 404p, 2000.

[7] Combaz, P., *La construction: principes et applications*. J.-G. Pieper: Bruxelles-Liège-Paris, Vol.3-Part 7, 290p, 1897.

[8] Municipal archives of Anderlecht, 2007.

[9] SCIA Engineer, release 2009.0, SCIA Group nv: Herk-de-Stad, 2009.

[10] *EN 1990, Eurocode 0: Basis of structural design*, April 2002.

[11] *EN 1991-1-1, Eurocode 1: Actions on structures – Part 1-1: General actions – Densities, self-weight, imposed loads for buildings*, April 2002.

[12] *EN 1991-1-3, Eurocode 1: Actions on structures – Part 1-3: General actions – Snow loads*, July 2003.

[13] *EN 1993-1-1, Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings*, May 2005.

[14] Dechamps, H., *Les principes de la construction de charpentes métalliques*. Imprimerie H. Vaillant-Carmanne: Liège, 390p, 1888.

[15] Vierendeel, A., *La construction architecturale en fonte, fer et acier*, A. Uystpruyst: Bruxelles, 1902.

[16] Kühn, B., Lukić, M., et al., *Assessment of Existing Steel Structures: Recommendations for Estimation of Remaining Fatigue Life (Background documents in support to the implementation, harmonization and further development of the Eurocodes)*, JRC Scientific and Technical reports, Joint Report Prepared under the JRC – ECCS cooperation agreement for the evolution of Eurocode 3 (programme of CEN / TC 250), First Edition, February 2008, EUR 23252 EN, ISSN 1018-5593, JRC 43401.

[17] O'Sullivan, M., Swailes, T., A study of historical test data for better informed assessment of wrought-iron structures, *Proc. of the 6th Int. Conf. On Structural Analysis of Historic Construction*, eds. D. D'Ayala, E. Fodde, Bath, pp.207-215, July 2008.

[18] de Bouw, M., Wouters, I., Vereecken, J., Lauriks, L., Iron and steel varieties in building industry between 1860 and 1914 - A complex and confusing situation resolved. *Construction and Building Materials*, 13p, http://dx.doi.org/10.1016/j.conbuildmat.2009.03.009, 2009.