Structural Analysis of Historical Constructions – Jerzy Jasieńko (ed)
© 2012 DWE, Wrocław, Poland, ISSN 0860-2395, ISBN 978-83-7125-216-7

CHARLES MARCELLIS AND ARTHUR VIERENDEEL: A CENTURY OF BELGIAN BRIDGE BUILDING (1835-1940)

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ABSTRACT

The Belgian bridge builders Charles Marcellis (1798-1864) and Arthur Vierendeel (1852-1940) were jack-of-all-trades in the 19th century, but both were mostly known as bridge designers, trying to have a grip on new structural possibilities. Though the mechanical behaviour of their bridges is very different, Tom Peters already noticed the visual resemblances between Marcellis' girder and box bridges made out of pierced cast-iron plates (1835-1860) and Vierendeel's development of the bridge type named after him (1890-1940).
The non-simultaneous yet very similar evolution of these two characters is a duet with consonants and dissonances. Marcellis was an industrialist whereas Vierendeel was an engineer, professor and self-made art critic. Marcellis had imported the idea of cast-iron girder and box bridges from England (e.g. from Fairbairn and Stephenson) and he did not shrink from calling this a Belgian system to erect bridges. Vierendeel on the other hand, after having seen bridge collapses where the diagonals were hardly deformed, developed a simplified arithmetic method to calculate a beam that consists only of a series of rectangular frames, a system that still finds use in design problems today.
This recurring pattern of engineering feats is the connecting thread between Marcellis and Vierendeel in this paper. Within a time frame of 100 years both men stood in a fascinating period on new materials (transition from cast iron to steel) and new calculation methods (transition from elementary formulas and trial-and-error testing to full understanding of secondary stresses and mechanical behaviour of materials).

Keywords: *Cast-iron girder bridges, Vierendeel bridges, Structural analysis, Trial-and-error*

1. INTRODUCTION

1.1. Intentions and context of this research

Industrialist Charles Marcellis (1798-1864) and engineer Arthur Vierendeel (1852-1940) were both avid supporters of the then new bridge typologies in respectively the second quarter of the 19th century and at the beginning of the 20th century. The first developed cast-iron (whether or not pierced plate) girder bridges, whereas the latter 'invented' the Vierendeel bridge – as shown in previous research of the authors this designation 'invention' has to be put into the right perspective [1]. Though visually similar,

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these bridges are structurally different, not in the least due to the different material characteristics of cast iron and steel.
Marcellis and Vierendeel worked in different eras – Marcellis before the second industrial revolution and before knowledge on calculation and mechanics of materials got widely spread, whereas Vierendeel himself took part in the transition from testing to calculating, especially when it came to secondary stresses in hyperstatic constructions. This makes it interesting to examine their respective approaches towards innovation in bridge building.
This research is part of a broader investigation on the iron and steel industry in Belgium in the 19th century. Its history is not examined from a standard architectural historical point of view, but by studying ironworks, engineers and contractors: in this paper the cast-iron girder bridges developed by Marcellis' workshop in Liège between 1835 and 1860, and Vierendeel's bridges developed between 1890 and 1940.

1.2. Historiographical reflections

In canonical history of architecture and construction, scholars are familiar with Marcellis [2-5] and Vierendeel [1, 6- 8]. Both are however mostly known for their bridges without any comparison to their other realizations. The research presented in this paper tries to achieve a more in-depth analysis, by digging into previously less well known archive material, and by combining the results of these two researches.

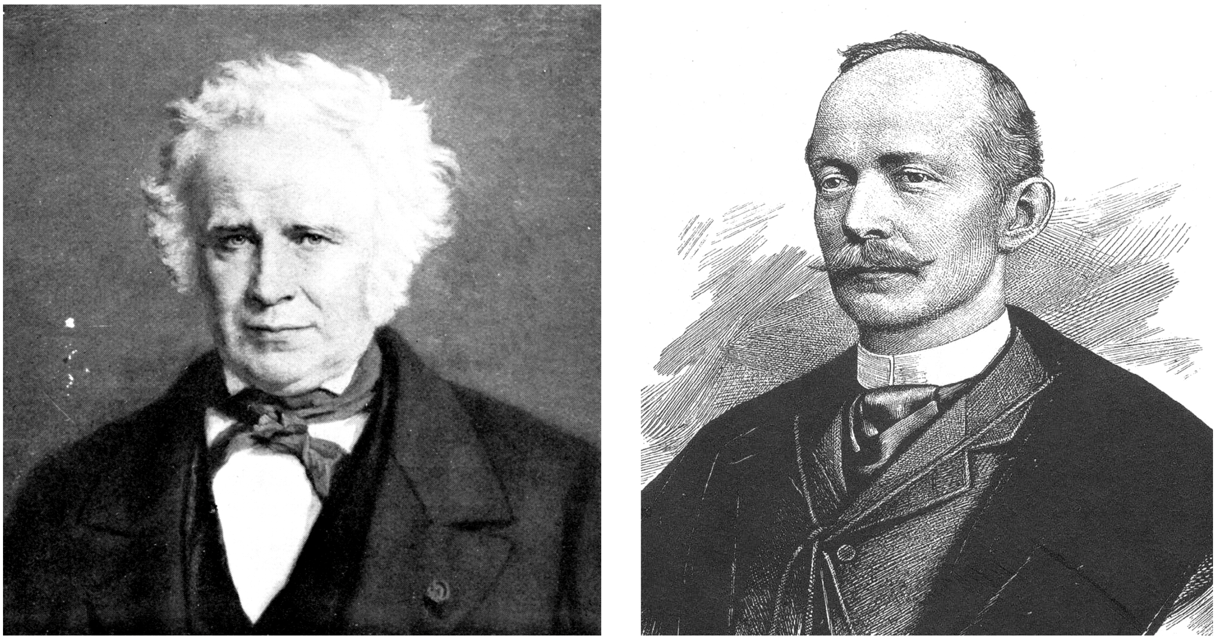

Fig. 1 Industrialist Charles Marcellis (left) [9] and engineer Arthur Vierendeel (right) [8]

1.3. Structure of the paper

This paper starts with a short biographic notice on Marcellis and Vierendeel, and their respective professional backgrounds. Then a short introduction on bridge building in the 19th century is followed by the study of one case study of each builder: Marcellis' bridge over the Scheldt in Ghent, and Vierendeel's first test on his structural system. Finally and before concluding the structural tests on the bridges are clarified and the discussions in the professional world are explained.

2. BIOGRAPHIES OF TWO MEN AT WORK

2.1. Charles Marcellis and the *Fonderies et Ateliers de Construction de Machines*

In 1835, Belgian lawyer Charles Marcellis bought a foundry in the city of Liège and suspended his earlier writing and political activities. From then on he became a determined defender of cast-iron architecture, mostly to support his own workshop and the Belgian metallurgical industry [2, 3].
In only a few years time Marcellis was able to transform himself into an important industrialist. He closely collaborated with V. Duval, a person of whom little is known. Most works refer to Duval as a French (mining) engineer [10], though there is no real evidence for this and his name is only

mentioned as a co-author of some of Marcellis' books. While Marcellis was the representative and the one who had contacts from his political career, Duval looked after the technical aspects. Throughout the course of 30 years the firm erected among other things a cast-iron bridge in Ghent in 1844, the span over of the Antwerp Stock Exchange in 1854 and numerous heating systems and pumps.

Marcellis also wrote extensively which makes him a worthy case to examine middle 19th century cast-iron architecture and engineering. His written work obviously calls for critical evaluation, since he hardly ever came up with quantitative data to support his designs.

2.2. Arthur Vierendeel as an engineer, professor and writer

In 1874 Belgian Jules Arthur Vierendeel obtained with great distinction the degree of *Ingénieur des arts, des manufactures, du génie civil et des mines* at the Ecoles Spéciales of the Catholic University of Leuven. Two years later he started his career in the building industry as a commissioner of the *Ateliers Nicaise et Delcuve* in La Louvière where he worked until 1885 (in 1913 these Ateliers would merge with *La Brugeoise* and they constructed many Vierendeel bridges in Belgium). In La Louvière, Vierendeel took charge for the construction of the Royal Circus in Brussels, one of the first large iron frameworks in Belgium. This building did not arise without a struggle though. The owners and the press were convinced that the light structure would never be sufficiently supportive. Only after an ultimate test with a regiment of grenadiers ordered by the minister, animadversion came to an end.

In 1885 Vierendeel was named head-engineer-director of the technical services of the province of West-Flanders, making him among other things responsible for 2271 km of road construction. Four years after Vierendeel started working in West-Flanders, Louis Cousin asked him to be his successor for the course on structural mechanics at the Catholic University of Leuven. When Vierendeel began teaching, his architectural work that had included the covering of the railway station of Kortrijk and the tower of the church of Dadizele came to a standstill. From then on he would only construct bridges, pylons and other works of civil nature, and more importantly become the so-called inventor of the Vierendeel bridge. As a jack-of-all-trades Vierendeel also wrote on soil mechanics, electromagnetism and aircraft building (never published) and he derived a general formula to explain buckling failure [6].

In contrast to Marcellis, Vierendeel did provide an enormous amount of quantitative data and calculations in his extensive writings in books and journals.

3. BRIDGES IN THE 19th CENTURY: NEW MATERIALS AND STRUCTURAL INNOVATIONS

The industrial revolution marked a new era when it came to bridge building, mainly shifting from wooden and stone bridges to iron bridges. One of the first ones, the Iron Bridge near Coalbrookdale in England is probably the best-known cast-iron bridge worldwide. Built in 1779 by Abraham Darby III this arch construction had no precedent and thus was the method to erect and connect the structure based on carpentry. This particular bridge has been the subject of much investigation, but so far we know little on the history of the development from the first cast-iron bridges (such as Marcellis' bridges) in its different forms (arch and girder) towards suspension bridges or more complex box girder bridges or later truss bridges (such as Vierendeel's bridges). When it comes to cast-iron girder bridges, some aspects have been studied, but an exhaustive approach of its development doesn't exist. Overall these bridges were rare as uncertainties on stability had worried clients, especially after some serious disasters in England. From the 1860s onwards cast-iron (box) girder bridges were demolished and cast-iron was replaced with wrought-iron (and later steel) composite beams formed by riveting sheets together, and then steel rolled beams, materials with higher values for both tensile strength and ductility, materials and elements Vierendeel used [11].

4. A QUEST FOR INNOVATION: MARCELLIS' AND VIERENDEEL'S BRIDGES

4.1. The example of the Marcellis bridge in Ghent (Belgium)

In February 1840, only five years after Marcellis had become active in the metal industry, Marcellis and Duval published their *Notice sur un nouveau système de ponts en fonte*, the first of a pair of notices on their so-called 'new' system to erect cast-iron bridges [13]. Marcellis regretted that the city of Liège had decided to reconstruct the recently demolished stone Boverie Bridge over the Meuse by another stone bridge. Marcellis illustrated his system by redesigning this Boverie Bridge, but his proposition would remain unrealized and the bridge was eventually re-erected in stone.

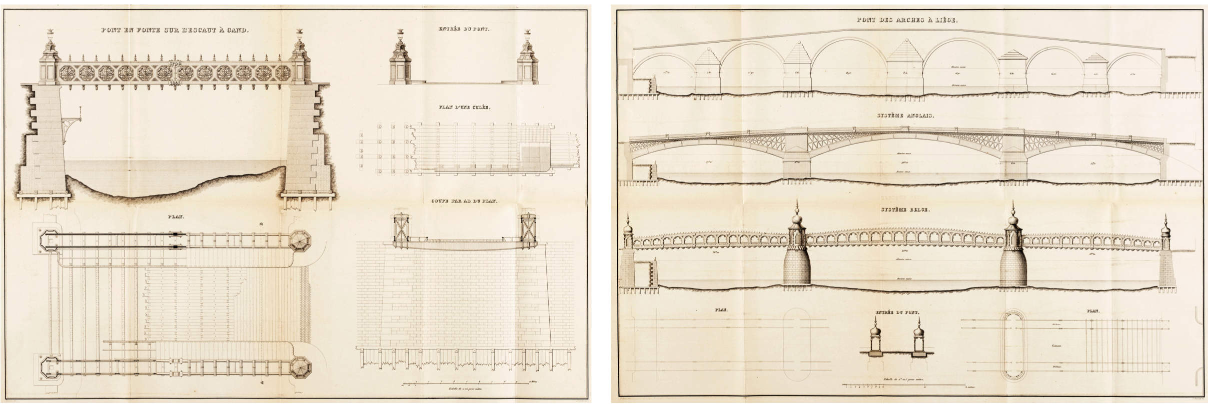

Fig. 2 Cast-iron Marcellis bridge in Ghent of 1843 (left) [12] and proposition for a cast-iron girder bridge (bottom) in Liège as opposed to a stone (top) or iron (middle) arch bridge (right) of 1840 [13]

Three years later, in 1843, Marcellis was able to build his ‘Belgian system’ as he started naming it from then on. He had convinced Charles Rogier (1800-1885), Belgian Minister of Public Works from 1840 till 1841, to grant him a subsidy to erect a cast-iron bridge over the Scheldt in Ghent. The Ghent council had agreed to build the bridge to link the new train station to the old Saint-Peter’s quarter. The bridge, which would soon be named after Marcellis, consisted of two pairs of cast-iron pierced plates of 20 m long, the members of each pair were combined by 6 struts, thus forming two box girders. Each of the plates was made out of 10 m long plates bolted in the middle by means of 8 smaller plates. Seventeen cast-iron crossbeams of 11,4 m were connected at the bottom of the box girders and carried the bridge deck made out of wood. The crossbeams were connected to the box girders by 3 bolts at each end, 2 of which were connected to the plates and one by a tie-rod connected to a small crossbeam that connected the pierced plates at the top. [12] The plans of the design (the bridge itself was demolished in 1865) highly correspond to designs by Fairbairn for a bridge over the Althorpe Street in London [14].

4.2. The Vierendeel

Historically, a ‘Vierendeel’ is a series of rectangular frames - which was patented for the first time in 1896 – and “in which the diagonals are removed and the vertical members rigidly connected to the booms by rounded pieces in such manner that the booms and vertical members form practically one piece.” [15] Contrary to the typical pin-jointed truss in which theoretically only axial stresses occur, the Vierendeel transfers shear from the chords by bending moments in the vertical webs. His invention came about after he noticed that experiments and calculation methods on iron and steel frameworks didn’t agree, making his invention a response in the contemporary discussion on secondary stresses.

4.3. Vierendeel’s answer on the discussion on secondary stresses

The year 1851 had marked a turning point in the use of iron and steel in construction, materials that Vierendeel would defend vividly from the moment he became a professor and his writings started to flourish. A milestone was the Crystal Palace, a cast-iron and glass structure erected in Hyde Park, London, to house the Great Exhibition (the first World Fair). Another event in 1851 that heralded the beginning of the discussion on pin-jointed and rigid frames, was the introduction of the term ‘trussed framework’ by German engineer Karl Culmann (1821-1881), a pioneer of graphical methods in engineering. He introduced this word in the first of his 2 travelogues – he had made a study tour to the United Kingdom and the United States from 1849 to 1851 – and it marks a new era where the timber framework and the carpenter were replaced by the iron framework and the metalworker [16].

Also in 1851 Berlin engineer Johann Wilhelm Schwedler (1823-1894) noted that the individual framework components can be assumed to be capable of rotation. When later riveted joints were preferred over bolted ones, this theory was less applicable and German engineer Emil Winkler (1835-1888) noted that the pin-jointed model contradicted with the as-built reality with riveted joints. This led to the theory of secondary stresses, as they were called at the time. Secondary stresses were due to the bending moments and shear forces that existed in the truss members, next to axial forces of tension and compression. Because of the statically indeterminacy of rigid-jointed structures, calculations were much more complex.

The second half of the 19th was a breeding ground for this discussion on pin-jointed and rigid-jointed frames, a discussion that Vierendeel joined in the beginning of the 1890s when he designed the supporting structure for the tower of the Dadizele church, which was left without a crossing tower by the time of the inauguration in 1880. Vierendeel and architect Van Assche came up with a brand-new structural design which lacked triangulized shapes but was based on a hyperstatic structure of rigid frames.

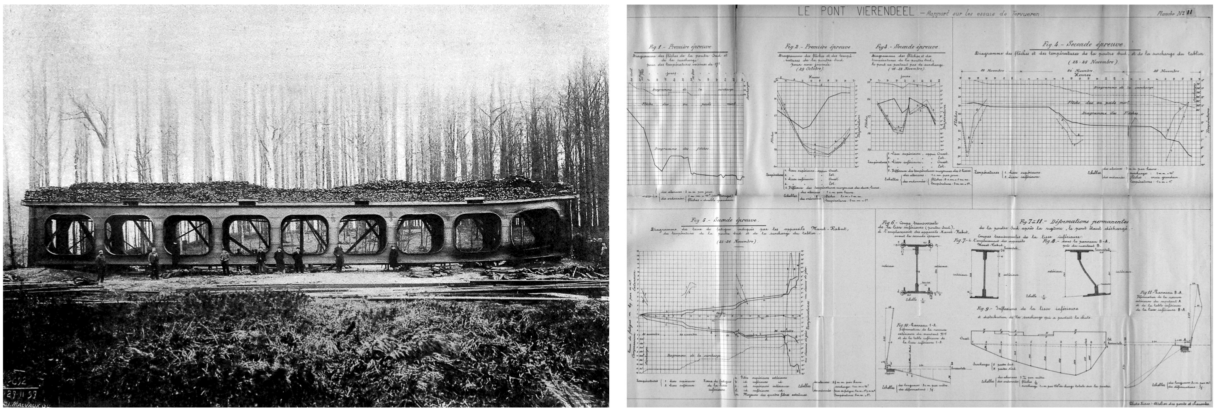

Fig. 3 Vierendeel's experiment of Tervuren in 1897 (left) [17] and results of the experiment of Tervuren (right)

5. TESTING AND DISCUSSING THE BRIDGES

5.1. Calculating and testing both bridges

5.1.1. Marcellis' tests in his workshop and on site

Uncertainty about cast-iron girder bridges remained in Belgium, as well as in England. When on 13th June 1842 the contract between the city of Ghent and Charles Marcellis was signed, it clearly stated that before construction in Ghent the bridge had to be tested in the workshops of the contractor. The official report of these tests was only described by Marcellis and Duval [12]. The bridge having a length of 19 m and a width of 9,2 m was charged with a load of 400 kg/m^2, which amounts up to a total load of 70 tons. Deflections measured at the large pierced girders were only 3 mm on the day of testing, and 4,5 mm after 24 hours. One can only conclude that the stiffness of the bridge is very firm with a relative deflection of less than L/4000.

An extra test to determine the load-bearing capacity was carried out on site when a loaded coach with a weight of 14 500 kg was placed in the middle of the bridge. A rope that had been stretched at the extremities of the bridge, and showed a natural deflection of 93 mm compared to a fixed point of the bridge, did not show a deflection of more than 1 mm when the weight was put on.

Comparing the height/length ratio of Marcellis's successive bridge designs we can however notice a clear raise of the height whereas at the same the length of the bridges decrease. Marcellis was probably aware of structural as well as technical issues (quality of the castings, etc.) on these bridges which caused him to oversize the bridge elements when he finally was able to build a girder bridge.

5.1.2. Vierendeel's experiment of Tervuren

In April 1897, Vierendeel published the structural theory of his 'poutre à arcades' as he used to call his invention initially in his book *Longerons en Treillis et Longerons à Arcades* [X]. Examples of structures with fully rigid joints were very uncommon at the time. He could only refer to the Dadizele church tower. Vierendeel mentions his system for the first time in public at the *Congrès International des Architectes* in August 1897 in Brussels. There he also revealed his upcoming test on a 31,5 m span bridge he was going to build at his own expense within the scope of the Brussels World Fair in Tervuren. It would be loaded to failure to verify the agreement between calculations and measurement. "Et maintenant le treillis: grande sujétion dans l'emploi artistique du fer, car le treillis avec ses formes raides, droites, sans variété, sans elasticité, est un dispositif constructif qui n'est rien moins qu'esthétique; mais, heureusement, du treillis nous sommes delivrés; voici, un pont dont les fermes en fer sont realisées sans intervention d'aucune diagonale, d'aucun treillis, et cette réalisation est obtenue en faisant une économie de matière et sans rien sacrifier de la solidité, ainsi que le prouvent les expériences, actuellement en cours, à Tervueren, sur un pont analogue de 32 mètres de portée." [18].

5.2. Discussions on the bridges

When it comes to Marcellis' bridge we do not find as much heated discussions as on the Vierendeel. In his history of wooden, iron and steel bridges by French engineer J. Chaix we read that "Malgré les bons résultats obtenus, les ponts de ce système n'ont pas été reproduits, et nous croyons que c'est à cause des évidements pratiqués dans les parois, lesquels sont aussi peu favorables pour l'homogénéité de la fonte, que pour la transmission des efforts verticaux aux semelles" [14]. Chaix specifically referred to the pierced plate girder, illustrating it with the 'bridge of Ghent', instead of normal girders of previous types of these bridges. According to Chaix bridges with horizontal beams were mainly used for railways and to span roads or smaller streams (2 to 7 m). In Armand Demanet (1808-1865) [3] we read that "Les ponts de ce système n'ont reçu qu'un fort petit nombre d'applications. Une entre autre a été faite à Gand sur un bras de l'Escaut".

In more recent research by Tom Peters we read that "Pierced plate members were otherwise unknown until a small girder bridge built in Ghent around 1844 by the Belgians Ch. Marcellis and V. Duval, and another design by the Swiss Nikolaus Riggenbach in 1857. And they were only to be popularized by the Belgian Vierendeel at the beginning of the twentieth century." [19] Though this comparison isn't completely sound as the bridges are structurally so different, Peters does call for a visual resemblance from an aesthetic point of view.

Discussion on the Vierendeel got heated in trade journals and amongst engineers, mainly due to a lack of 'visual' safety and theoretical uncertainties concerning calculation, safety factors and later also welding techniques. At first there seemed to be no advantages by eliminating the diagonals, since then all members were combined stress members and greater dimensions were required, not saving on material nor cost. At the time however, when steel trusses were riveted, large gussets were necessary, not providing isostaticity either. The exacter calculation Vierendeel provided, could enhance the safety, and thus indeed save material. His theory, embedded in the discussion on secondary stresses as examined before, was new, so his articles and projects were not instantly reliable, but all the more interesting to his contemporary colleagues. These discussions were held in trade journals like *Annales des Travaux Publics de Belgique* and *Ossature Métallique* in Belgium and *Der Eisenbau* in Germany.

6. CONCLUSIONS: THE FOUNDRY VS. THE ENGINEER

The scientification of mechanics of materials was a process that had gradually developed throughout the entire 19th century. Not only did it include the development of new materials (from cast-iron and wrought-iron to steel and even the first steps towards reinforced concrete), but it also led to a better understanding and analytical comprehension of material behaviour. Over the course of decades trial-and-error testing was gradually replaced by graphostatics and later (manual) calculation based on the formulas for normal and shear stresses.

Charles Marcellis and Arthur Vierendeel are two examples of 'builders' that were part of this development, acting in the same building typology, namely bridges, and working within the same environment, namely Belgium. Involving different kinds of sources, such as course books, building files, trade journals, and writings of the builders, this research has opened new research perspectives to enhance the structural analysis of historic constructions.

Generally we can conclude that at foundries, especially in the early years, but also well into the second half of the 19th century all work was executed by men working there, from simple calculation towards the execution of the job. During Vierendeel's era, the large number of small ironworks in Belgium had evolved to a small number of large companies, who were mostly responsible for the production of elements and assembling them. The iron- or steelworks itself no longer necessarily did calculation.

ACKNOWLEDGEMENTS

This research is funded by FWO-Vlaanderen (Research Fund Flanders).

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