DEVELOPMENT OF THE VIERENDEEL: CALCULATION, AESTHETICS, WELDING, CONCRETE

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Abstract The Vierendeel is a frame with rigid joints patented in 1896 by Belgian engineer Arthur Vierendeel (1852-1940). 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 then discussion on secondary stresses. After designing a church tower and testing a full-scale bridge model during the 1897 Brussels World Fair, many bridges 'système Vierendeel' were erected the following decades in his homeland, as well as a few dozens around the globe. At times the discussion on the Vierendeel got heated in trade journals and amongst people, mainly due to a lack of 'visual' safety and theoretical uncertainties concerning calculation, safety factors and welding techniques. Nowadays the Vierendeel principle is still topical and many (structural) designers apply his formal ideas. This led to a broader meaning of the word Vierendeel varying from aesthetic to strictly structural.

Keywords Vierendeel, structural mechanics, construction history, Belgium, 19th and 20th century, iron, steel, welding, concrete

1 INTRODUCTION

Historically, a Vierendeel is a series of rectangular frames "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." (Vierendeel [26]) It is named after its inventor, Belgian engineer Arthur Vierendeel, who patented it for the first time in 1896. 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.

On reflection it is not easy to determine the characteristic traits of a Vierendeel. The meaning may be obvious to all those engaged in civil engineering, the actual denotation has meandered between different senses up until today. Moreover, even before Vierendeel's patents, engineers were looking for a better grasp of the distinctions between pin-jointed and rigid connections.

This paper will examine the origin of Vierendeel's rigid framework within the scope of the general history of iron and steel frameworks, a history that covers more than 150 years of contemplation for all the metalworkers, engineers and architects involved. Their discourses had various assumptions, from purely architectural to purely structural. As a result the Vierendeel tells a history of many disciplines: initially starting out as a solely engineer's invention, it gradually became a tool to solve aesthetic, technical and structural issues in architecture.

2 ARTHUR VIERENDEEL AND 19TH CENTURY FRAMEWORK CONSTRUCTION

2.1 Life and work of Arthur Vierendeel

In 1874 Belgian Jules Arthur Vierendeel (1852-1940) 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 the Ateliers merged 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. After the First

World War, which had been extremely destructive for the coastal province, he played an important role in the reconstruction of the heavily devastated front.

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 civil works. 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.

2.2 Theories on pin-jointed and rigid frames at the end of the 19th century

The year 1851 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 - one that heralded the beginning of the discussion on pin-jointed and rigid frames - was the introduction of the term 'trussed framework' by German structural 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 by extension the carpenter were replaced by the iron framework and the metalworker. (Kurrer [5])

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 century 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.

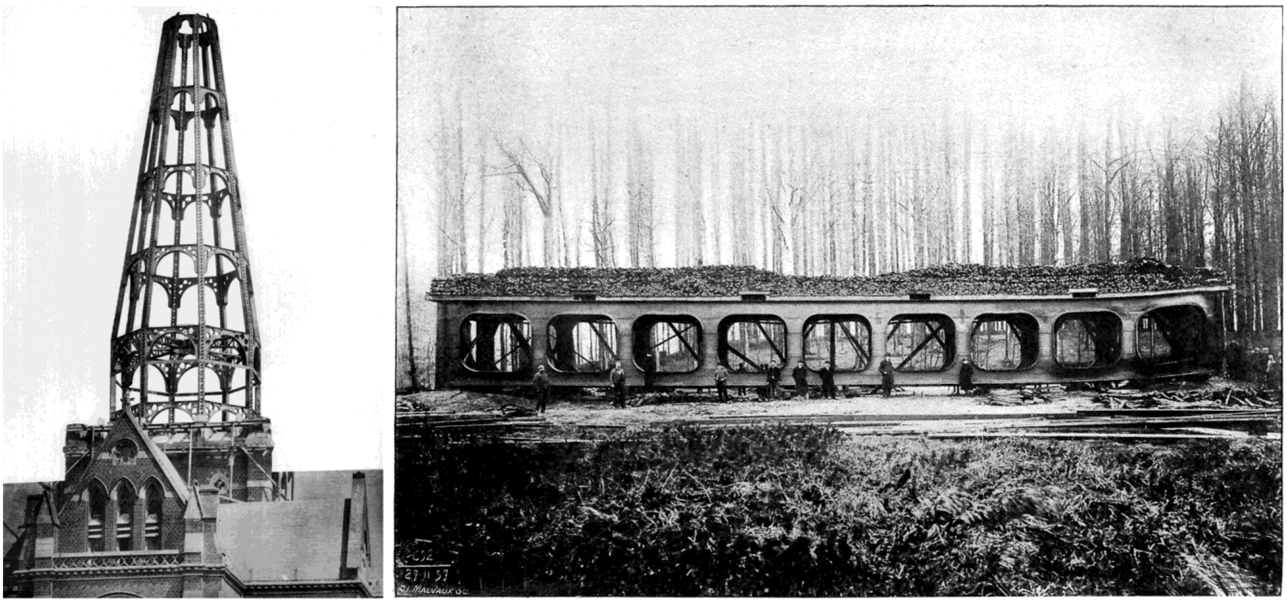

Figure 1. Framework of the crossing tower of the Dadizele church (Vierendeel [27], pl. 94) and Vierendeel's experiment of Tervuren in 1897 (Lambin, Christophe [6]).

3 THE 'POUTRE À ARCADES' OR VIERENDEEL

3.1 The iron tower of the Our Lady church in Dadizele

The Our Lady church in Dadizele, 50 km south of Vierendeel's hometown Bruges, Belgium, illustrated his first use of rigid joints. The church, designed by Edward Welby Pugin (1834-1875), was erected between 1859 and 1880.

Nevertheless there was no crossing tower by the time of the inauguration in 1880 and Vierendeel and architect Van Assche came up with a brand-new structural design: an iron construction that respected Pugin's formal design. This tower wasn't erected until 1893. Vierendeel described the structural design as particularly interesting since the dead weight of the tower, which was to be supported by four slender brick columns, could hardly be increased.

The reason for using gussets composed of sheet iron instead of diagonal braces was only described very vaguely and didn't seem to be inspired by the aforementioned problems: “Nous avons remplacé ces éléments multiples et compliqués par une seule espèce de membrures (des arcatures) jouant simultanément le rôle d'enrayures horizontales et de treillis verticaux, c'est l'emploi et le calcul de ces arcatures qui constituent la nouveauté de notre système de construction; elles ont pour avantage de donner une construction plus simple et plus claire, en un mot, plus architecturale.” (Vierendeel [27]) Furthermore, there seemed to be no technical nor formal grounds to avoid braces, as there were no windows or other openings. Vierendeel clearly designated the novelty of *his* construction system.

3.2 Testing and patenting his invention during the 1890s

A few years later, 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*. 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.” (Vierendeel [24])

While Vierendeel's patents describe vaguely the calculations without explaining the trailing theories, his book goes into detail on how to calculate the particular case of a symmetric bridge with parallel flanges and the general case of an asymmetric bridge with non-parallel flanges.

Vierendeel's main criticism on contemporary calculation was a discrepancy between analytical structural theory and actual building practice. Calculation assumed pin-jointed connections whereas the execution with rivets tended to be more rigid. After Schwedler and Winkler, German scientific assistant Heinrich Manderla (1853-1889) had described a calculation method in 1880 to determine the additional secondary stresses. He assumed that angular rotations were not possible in a framework. However Vierendeel still thought this method to be incorrect, primarily because the rigid joint was also far from perfect: the truth balanced between a rigid joint and a pin-joint. (Vierendeel [24])

Dutch engineer J. Schroeder van der Kolk summarized in the *Tijdschrift van het Koninklijk Instituut van Ingenieurs* (edition 1889-1890) the results of an experiment that listed the secondary stresses of a truss bridge in relation to the primary stresses. It was striking that those secondary stresses could not be ignored, as they amounted up to 60 % of the primary stresses. Secondly, Vierendeel indicated that in the diagonals the secondary stresses were limited (ranging from 6 to 16 % of the primary stresses). In other experiments he had noted that deformations in the diagonals were nearly negligible.

Vierendeel also referred to Winkler who tried to lower these stresses by using St. Andreas crosses, i.e. doubling the diagonals. It had already been applied in the Netherlands on some railway bridges between Rotterdam and Amsterdam. German civil engineer Otto Mohr's method was used to calculate the basic structure, along with Manderla's equations. However according to Vierendeel it didn't reduce the secondary stresses. After tests in France in 1893 ordered by the state, engineers tried to turn truss bridges into girder bridges by using a lattice-work. Though Vierendeel acknowledged some of the advantages, he still argued that “la vraie solution se trouvera, non pas en compliquant le treillis, mais en la simplifiant encore, c'est-à-dire en supprimant la diagonale dans le canevas triangulaire.” (Vierendeel [24])

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, 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.

3.3 The Vierendeel as an aesthetic concept

Though Vierendeel focused mainly on the structural aspect of his invention, other publications of his pointed out that the Vierendeel was more than just a part of a technical or structural development, as it was an important part of his own aesthetic discourse described in his opus magnum *L'Architecture en fonte, fer et acier*. He criticized the Eiffel Tower and the Galérie des Machines, since they relied on superseded architectural theories and 19th century neo-styles. He stated that, due to the slender form of its composing elements (mainly in the lattice-work), light can easily deform them, creating a structure with an awkward look. In the end Vierendeel tried to refute the argument of iron being a massless material by building up structures using as few slender lines as possible.

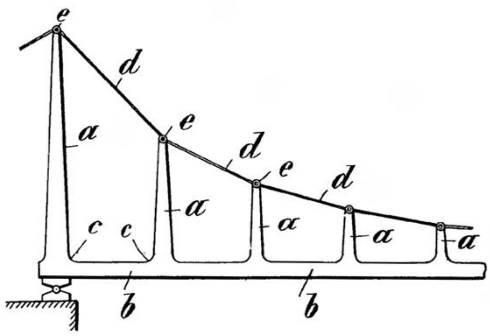

Figure 2. Vierendeel’s first large bridge in Avelgem built in 1904 (contractor’s catalogue); A concrete suspension bridge (Vierendeel [29]); A 287 m high radio pylon in Ruiselede (Jadot [4]).

3.4 Rise and fall of the Vierendeel in bridge construction

It comes as no surprise that the first large Vierendeel bridge was erected in the province where Vierendeel was head-engineer-director. In 1904 he could prove in Avelgem that his poutre à arcades could provide enough strength and stability (Fig. 2a). Even after the Tervuren experiment the dogma of the triangle was not yet overcome and his opponents outnumbered his followers, with e.g. quite a number of his workmen being suspicious - a flashback to the problems he had to deal with during the construction of the Brussels Royal Circus. And so during a final structural test the worker who had to drive the fully-loaded coach to measure the deformation demanded that Vierendeel would be standing in the middle of the bridge during this trial.

After this first bridge many more Vierendeel bridges were erected. The railway bridge in Grammene, 30 km southwest of Ghent, was ordered by the Belgian State Railways and was to be compared with a typical truss bridge.

The Vierendeel's popularity increased after two events in 1929. The creation of the 130 km long Albert Canal connecting Antwerp and Liège, and the spread of welding. The canal required 65 bridges and almost half took the Vierendeel form. By 1930 there were over 30 Vierendeel bridges in Belgium and 23 in the Belgian Congo.

As electric arc welding was a new technique during the interwar period, it did provide opportunities, but there was a downside when insufficient knowledge of welding techniques led to a series of serious bridge collapses. Though he was not to be blamed, they got often attributed to the notion of the Vierendeel.

After Second World War, the role of the Vierendeel in bridge (re)construction was minimal. The landscape was now redefined with slender arches, as well as unpretentious girder bridges. Larger spans, as required in other countries, were handled by suspension bridges, whereas France was preoccupied with its own invention, prestressed concrete. (Wickersheimer [32]).

3.5 Less-known Vierendeels: pylons and concrete suspension bridges

Vierendeel applied his construction not only to spans, but also to erect masts, like the 8 radio pylons of 287 m high for the Télégraphie Sans Fil in Ruiselede, close to Dadizele, in 1927 (Fig. 2c). These masts were meant to provide communication with the Belgian Congo, but due to atmospheric interferences this was impossible. Until 1940 they were used to communicate with ships crossing the Atlantic. A few years earlier Vierendeel had patented another unlike Vierendeel application: a concrete suspension bridge of which the lower part was a Vierendeel, and the upper part were steel cables (Fig. 2b). Applications of concrete Vierendeel bridges still exist in Belgium and abroad, though the suspended version has not been known to exist.

4 THE POST-VIERENDEEL ERA

4.1 Semantics of the notion Vierendeel

The Vierendeel is a structural element still in use. It is moreover the abundant occurrence of the man's name in patents, books, research papers, architectural monographs and articles that prove that the name - or the word, since the link with the person is sometimes lost - has considerably adopted the idea of a rigid frame. At the same time 'Vierendeel' is not a narrow definition. It has a cloud of meanings around it. The word Vierendeel obviously refers to the engineer; to a (simplified) calculation method for rigid frames - the true original meaning; a structure with rigid connections instead of pin-joints; a global step in the process of determining (secondary) stresses in metal frameworks at the end of the 19th century; or any structure using rigid connections, not necessarily in the form of a rectangular frame. It is mainly this latter definition that is suitable for most of the current Vierendeels.

5 CONCLUSIONS

Challenging the dogma of the triangle was one of his objectives, Vierendeel said. Nevertheless this dogma was merely a rhetorical cover. Vierendeel was an engineer who believed in the prospects of iron and steel in architecture and who had thoroughly examined frameworks and its structural and mechanical behaviour.

Blindly following the tradition of trusses with improper calculation would not drive mankind to progress. So when Vierendeel delved into the 19th century issue on secondary stresses, he seized his chance to solve this, by working out approximate methods to determine stresses in frameworks without diagonals. He had seen that during experimental loading, the diagonals were hardly charged and their secondary stresses were limited. He found an analytical theory that matched the as-built reality.

After his first experiments and overcoming some resistance, Vierendeel convinced state principals to order dozens of Vierendeel bridges in Belgium and its African colony during the next decades. The 'poutre à arcades' as he had called it initially, was also applied in some other structures as pylons and concrete spans.

The Vierendeel is a crossbreed, a structural compromise. It is not as rational as a truss when it comes to loadbearing capacities, but it remains superior when it comes to spatial qualities. In retrospect we can say that the concept of the Vierendeel has shifted. Vierendeel's definition as described in his 1899 USA patent is a beam 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." Nowadays calculation uses different methods and since the breakthrough of digital calculation more complex algorithms are possible. His name is however still connected to the concept of rigid frames that gain stiffness through these rigid corners. The connotation with the inventor is sometimes lost, but the multifunctional aspects to obtain aesthetic, formal, mechanical or structural plus-points will remain its ace of trumps.

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