The Vierendeel Bridge at its Heyday: Rational Design, Experiments and Brittle Failure

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The beginnings

In 1896, the Belgian engineer Arthur Vierendeel [1852-1940], Professor at the University of Leuven, proposed a new bridge type (Vierendeel 1896). This steel girder consists of two chords [upper and lower] and vertical posts connected to the chords by rigid nodes. The cross section of all elements from chords and posts is I-shaped. The salient feature of this girder is the absence of diagonals, which are characteristic of trussed type steel bridge girders. This girder will be known under several names: "*poutre à arcades,*" "*poutre échelle,*" girder without diagonals, framed type girder or simply and rapidly under the name of its inventor. It must be immediately emphasized that the Vierendeel girder is in fact a highly statically indeterminate system rather than a beam.

The main reason advocated by Vierendeel in his memoir of 1896 in order to promote his girder is of rational nature. The structural analysis model used then by the engineers to design truss girders assumes pin jointed connections at the nodes where the diagonals and posts meet the chords, which allows a simple determination of the stress distribution in the structure solely based on the equilibrium equations. The so-called secondary stresses induced by the technical realization of the nodes with riveted gussets are completely ignored in the design process. But at that time, it was well known either from more sophisticated structural analyses or from strain measurements on actual truss bridges that the magnitude of these "secondary" [bending] stresses was far from being negligible with respect to the "primary" stresses. Since the design criterion used at the time was to limit the working stress in the steel to a fraction of the yield strength, and that a significant portion of the total working stress was omitted in the computations, Vierendeel argued that the actual safety of the trussed type girders was unknown. But for his girder, Vierendeel proposed an approximate method of structural analysis that fully accounted for the bending induced in the elements by the stiffness of the nodes and connections. In a philosophical sense, the girder without diagonals was supposed to be more "true" than the truss girder with diagonals. Other advantages put forward were of economic, technological and aesthetical nature. In 1897, Vierendeel published his general method of structural analysis of his system. The same year, he also conceived a full-scale experiment on a 31.5m. span prototype bridge built, reputedly at his own expenses (Radelet de Grave 2002), at Tervueren during the International Exhibition that was held in Brussels that year. This test is exceptional by its sheer size and the fact that the loading [by iron dead weights] was increased up to failure. It was witnessed by two civil engineers from the Department of Bridges and Roads, Albert Lambin and Paul Christophe [1870-1957], who had been commissioned by their minister to record officially this experiment. Their report was published the next year (Lambin and Christophe 1898). The authors, who do not reject the new system, analyse critically all the arguments advanced by Vierendeel. This prompted an immediate reply by Vierendeel in defence of his girder (Vierendeel 1898).

The debate goes international

In July 1900, Vierendeel is invited to present his system at a meeting of the prestigious Society of the Civil Engineers of France in Paris held during the International Exhibition (Vierendeel 1900). The record of the discussions of his paper already reveals scepticism about the so-called advantages of the girder without diagonals. In fact, this girder was never largely used in France. This is probably due to the negative opinion expressed early by the leading French engineer Jean Résal [1854-1919] in his authoritative treaty on steel bridges (Résal 1908, 117; Marrey 1995, 93). In German speaking countries, the Vierendeel girder also gave rise to a fierce debate, with numerous papers published in the scientific and technical literature, even by Vierendeel himself who never missed an opportunity to reply and attack virulently his critics or praise his supporters. References to this debate may be found in (Vierendeel 1920; Kriso [1922] 1926) and more recently in (Kurrer 2008). The debate focused mainly on the issue of the "best" method of structural analysis of the Vierendeel girder. At that time, structural engineers could only use force methods to analyse statically indeterminate systems. But force methods lent themselves to a large variety of choices for the set of statically inderminate unknowns. Some sets lead to systems of compatibility equations that are easier to solve than others for obtaining the unknowns. And some additional hypotheses may be useful to reduce the size of the system of simultaneous equations. In 1914, the professor at Ghent University François Keelhoff [1863-1952] proposes an interesting contribution to the question of the position of the points of contra flexure in the posts, which is a key issue for justifying the simplification of the general method of structural analysis (Keelhoff 1914).

Vierendeel bridges in Belgium and Congo before 1930

Even in Belgium, Vierendeel meets resistance to have his girder adopted for bridge projects issued by the state administrations. One cannot help thinking that this may partly be due to the question of the patent fees to be paid to the inventor for each bridge constructed, an issue which was only settled in 1933 (Lederer 1970). Before 1914, only six Vierendeel steel bridges – with span up to 44m. – had been constructed in Belgium (Baes 1937). The first reinforced concrete Vierendeel girder in Belgium is an elegant footbridge with parabolic upper chord and spanning 56m. built in 1913 at La Louvière (Vierendeel 1921). The first Vierendeel railway bridge is the single-track bridge of Grammene with 56.16m. span built in 1923 (Vierendeel 1925). Around 1922 seems to appear the Vierendeel road bridge in reinforced concrete with parabolic upper chord; half a dozen of such bridges with spans between 40m. and 50m. have been built over the Scheldt River (Balis 1934). At the end of the 1920s, Keelhoff (1930) gives the following figures for the number of Vierendeel bridges erected or under construction since 1902: 14 in Belgium for the state administrations [either road or railway] and about 24 single-track railway bridges in Congo, with spans up to 72m. The same figures are given by Baes (1937). In 1930, the total number of Vierendeel girders built in Belgium or in Congo are therefore less than 40 with the majority located in Congo. Most of them were steel girders with the connections between the elements by means of hot riveting.

Research interests in structural engineering at the Belgian universities 1920-1940

Structural analysis

The question of deriving a tractable method of structural analysis for girders without diagonals – whose lack had been one of the reasons that had hampered the diffusion of the Vierendeel bridge – had made a significant advance with the thesis of Kriso (Kriso [1922] 1926) but remained an important theme of research in all chairs of structural engineering in the Belgian universities during the years 1920-1940. At Liège University, Professor Ferdinand Campus [1894-1983] publishes a paper on the position of the points of contra flexure in 1929 (Campus

1929). At Ghent University, Professor Gustave Magnel [1889-1955], better known for his later contribution to the development of prestressed concrete, publishes in 1933 a book dealing exclusively with the practical analysis of Vierendeel girders (Magnel 1933). Finally, at the University of Brussels, Professor Louis Baes [1883-1961] performs photoelastic stress analyses (Fig. 1) that allow him to deduce the definitive formulae for locating the position of the points of contra flexure in the posts. His results are presented in four memoirs published in the Belgian periodical *L'Ossature Métallique* after a series of lectures presented at meetings of the Belgian Association for the Testing of Materials [ABEM] from July 1, 1936 (Baes 1936). These memoirs were reprinted with little modification in the French journal *Travaux* in 1937 (Baes 1937) and even summarized in English (Baes 1941). After the first lecture delivered by Baes, Vierendeel, who attended the lecture, write a testament-like paper in which he considers that after 40 years since 1896 all leading Belgian structural engineering professors have now acknowledged the virtues of his girder and reaffirms for the last time his solemn condemnation of the truss girder (Vierendeel 1936).

Still in the field of structural analysis, we should mention the derivation of a method for estimating the buckling strength of the upper chord of parabolic Vierendeel girders by Raoul Desprets [1884-1963], Professor at the University of Brussels, but also Chief Engineer at the Belgian State Railways where he had to design in the 1930s the large Vierendeel railway bridges at Mechelen [double track, 80m. span], Herenthals [double track, 80m. span] and Gellick [single track, 113m. span] (Desprets 1935).

Electric arc welding and rational form of connection nodes

At the University of Brussels, a laboratory for testing of materials, fully equipped with the best testing machines, had been set up since 1924 by Professor Henri Dustin [1882-1935] who dedicated his research to electric arc welding, which was then a very original research theme. He was assisted by Daniel Rosenthal [1900-1989]. Their research was performed in collaboration with the company *La Soudure Electrique Autogène ARCOS*. Dustin and Rosenthal presented papers at international congresses and rapidly gained international recognition for their innovative research on welding connection. Dustin received in 1929 the Lincoln prize awarded by the ASME for his work on electric arc welding. The stress distribution in welded nodes of Vierendeel girders was one of the research subjects of Rosenthal by 1932 (Rosenthal 1932). Another Professor at the University of Brussels, Lucien J. Vandeperre [1895-1967], carried also research from the beginning of the 1930s on the application of electric arc welding to steelwork (Vandeperre 1931). He collaborated with the company *La Construction Soudée* (Vandeperre and Joukoff 1939).

In 1929, Professor Campus at Liège University was involved in the design of the new Institute of Chemistry and Metallurgy. The structure was a riveted steel frame with stiff nodes. He studied deeply the best form for the nodes through tests on models in 1930 with his assistant Alex Spoliansky. The second university building designed by Campus was the Institute of Civil Engineering and this time, the nodes of the steel frame structure would be realized by using the welding technique. The tests on models of welded nodes for this Institute were performed early in 1933 (Campus 1936b). Research on the optimi-

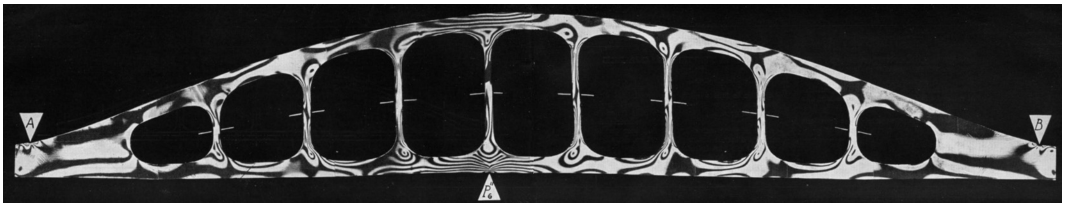

Fig. 1: Photoelastic stress analysis of a Vierendeel girder performed at the *Université Libre de Bruxelles* by Baes (1937).

sation of the form of the nodes of Vierendeel and framed type welded steel structures continued in Belgium after 1935 with contributions from several engineers.

It should be underlined here that arc welding applications and design rules were keynote topics for the first [Paris, 1932] and second [Berlin-Munich, 1936] congresses of the International Association for Bridge and Structural Engineering [IABSE].

The Vierendeel Bridges over the Albert Canal

The digging of the Albert Canal was the largest public works enterprise in Belgium in the 1930s. This canal, 129km long from Liège to Antwerp, established a link between the river Maas and the river Scheldt. It needed the construction of 66 bridges. The projects were initially prepared for the adjudication by a specialized division of the Ministry of Public Works that had been set up in 1919 and directed by engineer Georges De Cuyper [1891-1951] since 1928. Given the site constraints, the span lengths and the economic conditions, it appeared rapidly that steel bridges were more economical than concrete bridges, which explains why 54 out of the 66 bridges are in steel. To this figure should be added also a significant number of smaller bridges to be built at the same time for the Campine Canals. The invitations to tender for building bridges began in 1929. The first projects were V-type [Neville] riveted truss bridges (De Cuyper 1939).

In October 1930 or August 1931 [the dates given by Spoliansky and Santilman differ] was issued the invitation to tender for the Lanaye Bridge, a riveted Vierendeel road bridge with parabolic upper chord and 68m. span that had been designed by Vierendeel himself for the Ministry (Spoliansky 1935; Santilman 1933). The company *Société Métallurgique d'Enghien Saint-Eloi* won the adjudication to build that bridge and submitted an alternative design that mixed welded connections in the workshop and riveted connections on site. It had been conceived by its newly appointed chief engineer Alex Spoliansky who had previously been an assistant to Campus. This was the first time that welding was proposed in Belgium for the building of a bridge. It led to a significant saving in steel weight [20%] and was more economical than the fully riveted solution. It should however be mentioned that the first application of welding to a Vierendeel girder had taken place in Germany in 1931 (Editor 1932). The Administration, "thanks to the undertaking mind of Inspector General de Brabandère" (Moressée 1937) accepted the alternative submission under the conditions of full transfer of liabilities to the company *Enghien Saint-Eloi* and the successful testing of a welded node, which was performed in the workshops of the company in January 1932. After construction, the Lanaye Bridge was submitted to extensive load testing and strain measurements in February and April 1933 (Spoliansky 1935; Santilman 1933; Campus 1936b). Campus (1936b) clearly points that the alternative bidding by *Enghien Saint-Eloi* for the Lanaye Bridge with welded nodes evolves from his research with Spoliansky for the university buildings in Liège in 1930.

Then, the events accelerated at the rhythm of issuing the invitations for tender for the numerous steel bridges that had to be build. Each time, the rules of tender allowed submissions with solutions which were alternative to the projects designed by the Administration, which were initially always riveted. And each time, the Administration agreed on the mixed welded-riveted solutions, which were more economical than the fully riveted designs. The same mixed solution was accepted as alternative design for the Vierendeel type bridges at Schooten [bridges #39 and #40, with 63m. span], at Lanklaer and at Lanaeken-Smeermaes [both with 54.36m. span], all four built by the company *Ateliers Métallurgiques de Nivelles* in 1933 (Spoliansky 1933; Campus and Spoliansky 1936). Then was issued in 1933 the invitation to tender for two bridges at Herenthals: the Herenthals-C (Herenthals-Lier), a Vierendeel span of 57.5m whose riveted design had been provided by Vierendeel himself for the Administration (Spoliansky 1935; Moressée 1937), and the trussed bridge Herenthals-A. The company *Enghien Saint-Eloi* won the adjudication and Spoliansky submitted this time an all welded alternative design for both bridges, which was accepted. The Herenthals-C Bridge therefore became in 1934 the first steel bridge in Belgium to be fully realised by welding, with parts prefabricated in the workshop and finally assembly by welding on site. The savings obtained by this solution were so evident that all further invitations to tender issued by the Administration called immediately for all welded designs (Spoliansky 1935).

Between 1932 and 1937, no less than 50 typical Vierendeel road bridges with parabolic upper chord will be erected: 25 of them on the Albert Canal, 23 on the Campine canals, and two at Dudzeele [near Bruges]. As seen above, five of them were partly welded, and the rest of them were fully welded. The most imposing [90m span] and one of the last built was in 1937 the Haccourt Bridge (Santilman 1939). Moressée (1937) has published the detailed list of these Vierendeel bridges. The only riveted Vierendeel bridges built at the same time were railroad bridges. It is also worth underlining that out of the 54 steel bridges constructed for the Albert Canal, 29 were not of the Vierendeel type.

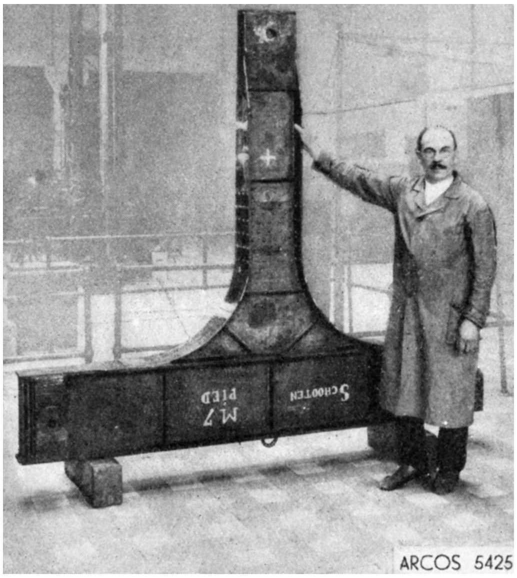

Fig. 2: Model of a node of the Schooten bridges for fatigue testing performed at the *Université Libre de Bruxelles* by Dustin (1935a).

The price paid for technical progress

The achievements of electric arc welding applied to structural steelwork in Belgium are amply presented in several papers at the second IABSE congress held in Berlin and Munich in 1936, where foreign experiences are also exposed. It clearly appears that this fast and massive application of welding to steel bridges was paved with serious problems, with notice – even in the workshops – of the appearance of severe deformations and even cracks arising from the restraint to shrinkage induced by welding (De Cuyper 1936; Spoliansky 1936; Campus 1936a; Moressée 1937; De Cuyper 1948; Louis 1950). Similar problems were encountered in Germany (Voormann, Pfeifer and Trautz 2006). The Belgian Administration, which had witnessed these problems from the very beginning of the introduction of welding, initiated research in the universities. Dustin (1935a; 1935b) at the University of Brussels received in 1933 a commission to study the fatigue resistance of welded nodes (Fig. 2). In 1936, the Administration commissioned Campus to prepare a research program to improve the application of welding to steelwork. This turned into a research program performed between 1937 and 1944, which mainly concentrated on the shrinkage induced by welding and the means to limit it (Campus 1946; Campus 1947).

Retrospectively, it is quite evident that this fast transition from riveted to all welded construction of Vierendeel bridges contained the ingredients of flaws that typically lead to disasters. This occurred in the early morning of 14 March 1938 when the all welded 74.5m. span Hasselt Bridge, which had been completed in 1936, failed and fell in to the Albert Canal [without casualties]. Immediately, a large number of engineers – even from abroad – visited the site and inspected the broken parts of the bridge. All were astonished by the apparently brittle aspects of the cracks without any manifestation of striction. This spectacular failure, without precedent at this scale, deeply shocked the community of engineers in Belgium and abroad. One of the very first to express his stupefaction was Eugène François [1870-1957], a respected Belgian consulting engineer, Professor at the University of Brussels, Vice President of the information centre of the steel industry and co-founder with Professor Magnel of the recently created SECO office to control the safety of constructions. In the weeks following the failure of the Hasselt bridge, he writes an extremely honest paper that simultaneously confesses the ignorance by the metallurgists and engineers of the causes for the failure and affirms his confidence that the technique of welding will continue to progress (François 1938). This paper is the first of more than 40 papers dealing with the failure of the Hasselt Bridge published within one year in the international engineering press or in scientific journals. Part of this list of references may be found in (Editor 1938) and in the report by Shank (1953) who gives the best summary account of the failure.

After Hasselt

As if the Hasselt failure was not enough, two other Vierendeel bridges suffered from sudden and extensive cracking in January 1940: the bridge at Herenthals-Oolen [61m. span on the Albert Canal, built in 1935-1936] and the bridge at Kaullile [48m. span on a Campine canal, built in 1934-1935] (Editor 1940). De Cuyper in his 1948 report mentions without naming it a third Vierendeel bridge badly cracked during the winter 1939-1940 (De Cuyper 1948). It may be inferred from a picture published by Nihoul (1948) that this third bridge could be the bridge at Hermalle, a 90m. span built in 1936. The best synthesis of the observations made at Herenthals-Oolen and at Kaullile may also be found in the landmark report by Shank (1953). On 8 May 1940, Belgium is invaded by German troops and most – if not all – bridges of the Albert Canal are destroyed. German engineers seize fragments from the Herenthals-Oolen Bridge on site (Busch and Reuleke 1946) and from the Hasselt Bridge that were kept by Campus (Campus 1947), in order to analyse them in Germany. This testifies, if necessary, of the importance for the international engineering community to understand the causes of these brittle failures.

The Hasselt Bridge failure is often considered as the first event in the long "Brittle failure story" although Shank (1953) has demonstrated that this is historically not correct. It is however correct to say that the Hasselt Bridge failure was the first brittle failure that received such a large attention and which is rather well documented. The second chapter in the brittle failure story is the series of damages that occurred to the "liberty ships" that were mass produced in the United States during the Second World War and which prompted in 1943 the setting up of the Ship Structure Committee to investigate these brittle failures. It was necessary to wait for the development of fracture mechanics theories from the 1960s onwards in order to be able to set a framework for a probable explanation why the welded Vierendeel bridges built in Belgium 1932-1937 suffered cracking and eventually failed under no other loading than their own weight. Quite curiously, it is only recently that an author first ventured to explain the failure of the Hasselt Bridge with the modern concepts of fracture mechanics (Åkesson 2008, 79-88). It should also be emphasised that the failure of the Vierendeel welded bridges did not deter the Belgian engineers to use welding for structural steelwork nor to build Vierendeel bridges again. However, the Vierendeel bridge was typical from its time. When the Albert Canal began to be widened in the 1970s, the typical bridge that was adopted then, even with a somewhat larger span, is the much lighter bowstring bridge.

Today, the Vierendeel girder is mostly – and rather positively – associated with structures in the field of architecture (Wieckersheimer 1976). In the field of bridge engineering, the name Vierendeel is unfortunately associated with a series of incidents that occurred in Belgium in the 1930s. It would be too easy to infer that they condemned this type of bridge. First, it should be recalled that, for instance, the Belgian railways did not stop designing and building Vierendeel railway bridges. A common characteristic of all Vierendeel bridges that cracked and even failed is that they were welded. It is fair to say that cracks and failures were observed at the same time on other types of bridges and steel constructions, in Belgium and abroad. But it would be incorrect to sustain, in contradiction with the statistical evidence, that the particularly stiff structure of the Vierendeel girder and given the state of the art of welding technology at the beginning of the 1930s, was not partly responsible for high welding stresses, which favoured the formation of cracks. But this was unknown at the time. If we consider that four out of 50 Vierendeel welded bridges were severely cracked and unable to carry their own weight, it is quite obvious that the safety of all bridges in this series was quite variable… which is sadly piquant if we remember that the main argument advocated by Vierendeel in 1896 was the better control of safety with his girder than with trussed girders! It should also be added that Vierendeel himself was not involved in the application of welding to the bridges. He just acknowledged that it led to important savings (Vierendeel 1936).

Fundamentally, the "rise and fall" of the welded Vierendeel bridge is a typical illustration of a recurrent phenomenon in the history of construction, and history of bridge building in particular: it is an example of bold innovation in structural design and construction technique that proceeds faster than the establishment of scientific knowledge, which lags at the decisive moment behind practice. This leads to accidents, but it is the price to pay to the technological progress.

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