were unpretentious, varying overtones of rustic log cabins, Swiss chalets, and half-timber cottages (Fig. 4). Groceries came by wagon or, during one period, by scow on which quarters had been built for a grocery store. Trips to Seattle were usually by boat, the commuters landing on Seattle's Lake Washington shore to continue their trip into the city by cable car. Doctors in emergencies were brought over from Seattle by speedboat. Otherwise babies were born and the sick cared for in the city.[13]

But the innovative hopes of the founders for a colony of artists, removed in their own setting from the routines and rituals of conventional society and released for creativity, were never realized. The Village was both too expensive and bourgeois, unlikely in either case to attract a membership of artists. A brief episode of notoriety, when a yoga-practicing resident couple was discovered to be unmarried and ordered out of the Village (they were renters, not members), confirms that conventionality remained the community standard. The facilities of the art center—studios and workshops—were never built, and in 1925 Atelier Square was sold for $3,000 to a resident who planned initially on fencing it in for quail and deer; it has since been subdivided and built on. In 1954 the Village incorporated as a town, its residents composed of "lawyers, judges, businessmen, architects, engineers, and a few artists."[14]

Thus Beaux Arts Village backed into its present-day status as another residential suburban community. Yet it still retains hints of its founders' dreams, signs of lingering individuality: the narrowness of its streets, a mix of architectural reminiscences, its communal beach, and the generous presence of mature trees—an enclave of picturesque nostalgia in what has otherwise become a vast mileage of almost unrelieved postwar suburbia.

13. Vogel, pp. 1, 9.

14. Vogel, p. 1.

The Vierendeel

DAVID J. WICKERSHEIMER

Department of Architecture, University of Illinois, Urbana-Champaign

Why the Vierendeel?

THE VIERENDEEL FRAME, or truss as it is more popularly but inappropriately called, is a series of rectangular frames which achieves stability by the rigid connection of the vertical web members to the top and bottom chord. Contrary to the typical pin-connected truss in which all members are axially loaded and shear is transferred axially through diagonals, the Vierendeel transfers shear from the chords by bending moments at the joints and finally by bending moments in the vertical webs. As a result, all members are combined stress members in which axial, shear, and bending stresses exist (Fig. 1).

At first little appears to be gained by this system. The Vierendeel frame will be heavier than an equivalently loaded truss. Even though the diagonals are eliminated, bending in all members results in chord sizes and vertical webs significantly larger in cross-sectional area. Shop fabrication of the gussets is usually complicated without again increasing member sizes, or the system's depth.

The Vierendeel's popularity today is not attributable to engineering assets, but to the architectural and mechanical integration possible. Where expression requires a rectangular grid of openings, be it for doors, windows, or corridors, the Vierendeel is preferred. Where large open spaces occur below such rectangular grids, the Vierendeel excells again. The height can be as small as the structural depth between the ceiling of the story below to the floor of the story above, and therefore invisible to the layman's eye. Such a floor system resembles a castellated beam, but with much larger web openings. Wherever mechanical requirements are extensive and require room to accommodate large duct work or elbow room to change directions, the Vierendeel appears highly advantageous.

As in most structural systems, the Vierendeel gains tremendous rigidity with increased depth. In addition, several stories of a Vierendeel grid linked together can open extremely large areas of space below the framework and still permit rectangular openings through the system. These unique architectural opportunities have kept the Vierendeel current.

Early Development

Despite the structural disadvantages surrounding the Vierendeel, it was in the area of civil engineering rather than architecture that it was first utilized—specifically for short-span bridges. The Vierendeel's origin dates to 1896. The Belgian engineer Arthur Vierendeel, then professor at the University of Louvain, unveiled the concept in his book *Longerons en Treillis et Longerons à Arcades*. At that time steel trusses required extremely large gusset plates to accommodate rivet groups; members were generally oversized and rarely did the center lines of all joined members intersect. Therefore, the pin-jointed theory which ignored moments, due to these eccentricities, led to errors on the critical side, approaching fifteen percent when office calculations were compared to field measurements. These discrepancies between simplified analytical methods and reality are what led Professor Vierendeel to propose the rectangular rigid-jointed system where these eccentricities could be eliminated and accuracy between analysis and reality kept in close accord. A smaller factor of safety could be used, due to this improved accuracy, so that in the early 1900s Vierendeel bridges did weigh less than alternative truss solutions.

The first Vierendeel bridge was experimental. It spanned 96 feet and was tested in 1897 at Tervueren with an assimilated railway loading pattern. The riveted framework responded by carrying 2.73 times the design live load and prompted the Belgian Bridge and Highway Department to state in their official report that, "In the present state of the question, the portal frame truss is, generally speaking, a system nearly equivalent to the triangulated truss."[1] The first actual usage of a Vierendeel bridge occurred in 1901 with a 128-foot span of riveted construction at Avelghem, Belgium, followed by the 136-foot span at Ousselghem in 1910, also riveted. The last revealed the complex buildup of shapes occasioned by riveting and the need of a curved gusset to handle large stress concentrations at the member inter-

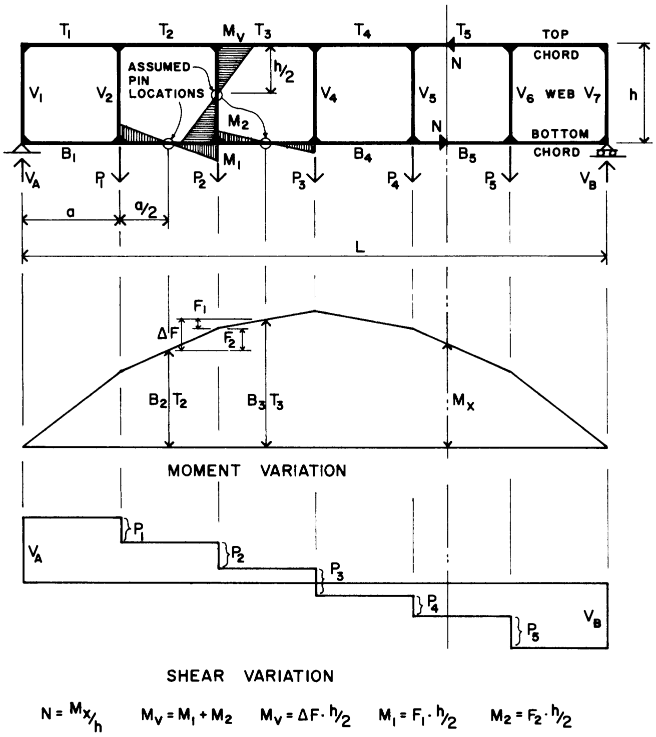

Fig. 1. Vierendeel analysis (author).

1. Leon G. Rucquoi, "Vierendeel Truss Bridges Popular in Belgium," *Engineering News Record* (25 July 1935), p. 116.

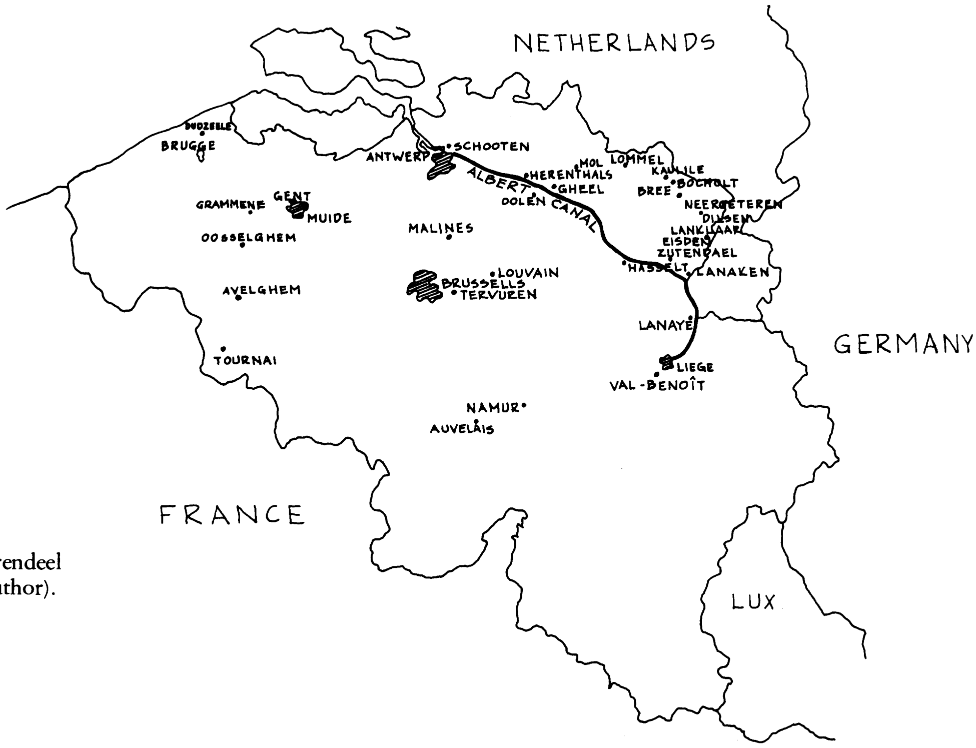

Fig. 2. Belgium, Vierendeel locations to 1939 (author).

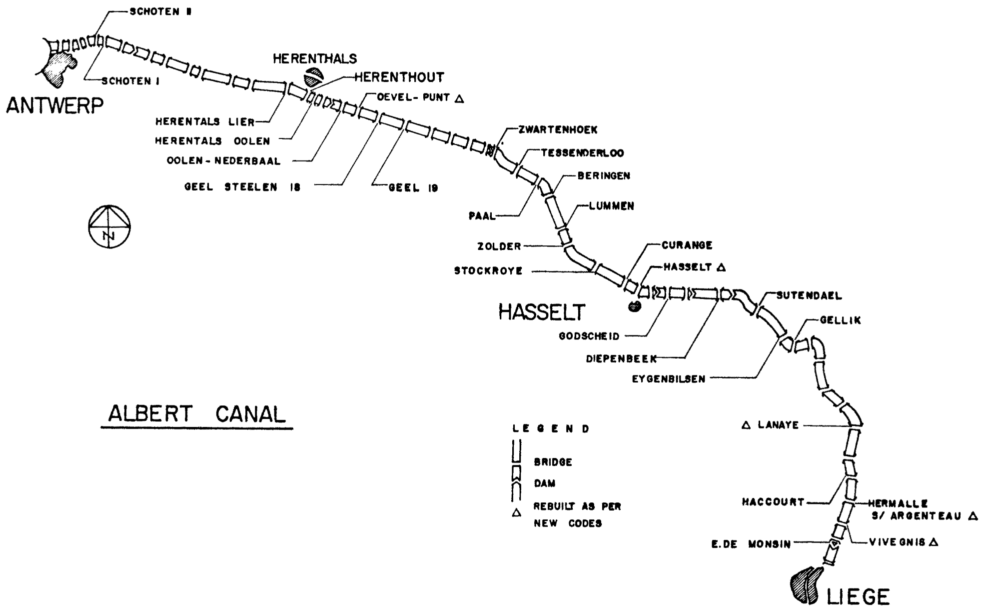

Fig. 3. Vierendeel bridge locations on the Albert Canal (author).

sections. This curve was a characteristic feature of all the early Vierendeels, which by 1930 numbered over thirty railway and highway bridges in Belgium, and twenty-three railway bridges in the Belgian Congo. (Figure 2 locates many of the Vierendeel bridges built before World War II.) The relatively short span (100–300 feet) of the bridge type limited its appeal. Although the Germans and Czechoslovakians were intrigued by its appearance and commented on its analytical solution, few such bridges were built outside Belgium.

In spite of local acceptance, engineering offices rebelled. The highly indeterminate nature of the system required strenuous calculations, and its feasibility in practice was at that time questionable. These feelings were later to be dispelled by academic proponents, such as Professors Keelhoof of Ghent, Campus of Liege, and Baes of Brussels, who vastly expanded the knowledge available on the Vierendeel by laboratory testing various joint details, running photoelasticity model studies, and developing simplified analysis methods. Finally, Professor Magnel of Ghent University published influence line charts which graphically depicted the stress patterns as a unit load (one kip) moved across the frame. Concurrently, Vierendeel published his important treatise entitled *Cour de Stabilité des Constructions* (1920) which completely described design, analysis, and construction.

Two events occurred in 1929 to increase the Vierendeel's popularity in Belgium: the initiation of a vast civil engineering program to create a 130-kilometer canal system between Antwerp and Liege, and the introduction of electric arc welding. The Albert Canal required sixty-five bridges—almost one every two kilometers—and almost half took the Vierendeel form (Fig. 3). Yet the canal merely created the need; electric arc welding established the means to simplify fabrication and improve upon the aesthetic objections raised by the patchwork of rivets in the earlier frames. Refinement of detail and form resulted in most of the bridges over the canal having a parabolic top chord, which reflected the moment variation across its length. Typical of this form, and of primary significance, is the bridge at Lanaye built in 1933 (Fig. 4). It was the first all-welded (except for field splices) bridge in Belgium, and then the world's largest welded bridge, spanning 208 feet. By 1935 the Belgians had built the largest Vierendeel span of 295 feet at Herenthal.

Decline

Mishaps (cracks and dislocations), primarily due to insufficient knowledge of the ramifications of welding procedures, poor workmanship, and low steel quality, resulted in increasing skepticism about the Vierendeel system. The col-

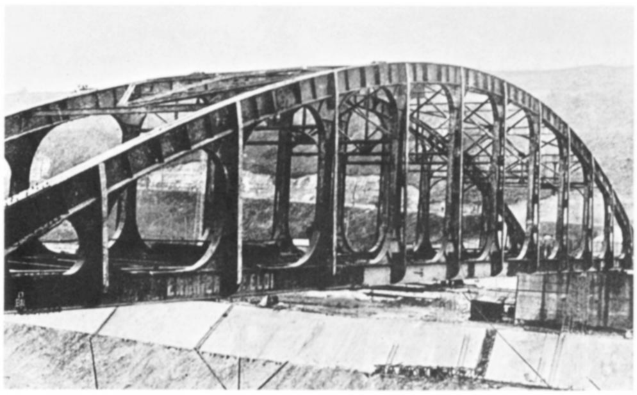

Fig. 4. Lanaye, A. Vierendeel, 1933. First bridge on the Albert Canal (photo: *L'Ossature Metallique*, 1933).

lapse of a 245-foot-span bridge at Hasselt in 1938 was the most total and dramatic. A Belgian committee assigned to investigate the collapse, together with outside consultants, concluded that the welded Vierendeel system, although considered to be adequately designed, was sensitive to external influences, such as cooling, heating, vibration, or impact. By reason of its inherent joint rigidity, the system also attracted internal residual stresses and demanded an extensive knowledge of the art of welding. Similar problems with welded plate girder bridges were occurring in other countries of Europe. It was apparent that welding technology needed to catch up with welding demand. G. Willems, engineer for the Belgian state, reflected in *Acier-Stahl-Steel* in 1957 that "Welding afforded so many advantages—of an economic, technical, and aesthetic nature—that any suggestion of abandoning it for good was quite unthinkable."[2] Germany, for example, continued to build all-welded bridges while applying their construction experiences toward developing specific recommendations on welding procedures.

Unfortunately, the vast majority of Belgium's Vierendeel bridges enjoyed a brief existence, due to the German invasion and occupation in 1939. Those that were rebuilt were again destroyed during the bombing and battles that followed the D-Day invasion in 1944.

After the war, the rôle of the Vierendeel frame in Belgium's bridge reconstruction was minimal. The landscape was now redefined with more slender bowstring arches, as well as unobtrusive plate and box girder bridges. The larger spans required in other countries were gracefully handled by suspension systems and the newly developed cable stayed system found in Germany. Meanwhile, France was preoccupied with its own intriguing invention, prestressed concrete.

American Involvement

The United States' civil engineering development of the Vierendeel began in 1901. A series of towers, forming the Kinzua Viaduct for the Erie Railroad in McKean County, Pennsylvania, used vertical tapered Vierendeels up to 285 feet in height. This solution was a radical departure from conventional tower design. The selection of rigid joints by engineer C. R. Grimm eliminated the need for a complex diagonal bracing system, while providing a cleaner appearance. Continued use of vertical Vierendeels occurred in the towers for many suspension bridges, where lateral load and vibration resistance require substantial rigidity without objectionable diagonals. The first American example was the Waldo-Hancock suspension bridge of 1929 over the Penobscot River near Bucksport, Maine. Many similar bridges used the vertical Vierendeel tower technique, most notably the Golden Gate Bridge in San Francisco. The only Vierendeel used for a horizontal bridge span is to be found in Glendale, California, where nine, 95-foot-span bridges were erected by the Corps of Engineers to cross flood control channels. Designed in 1937 by engineer L. T. Evans, their voids satisfied the function of improved visibility for drivers and eliminated overhead bracing. The bridge design prompted Professor Vierendeel in 1937 (then eighty-four years old) to write to the *Engineering News Record*: "American engineers will not mind, I hope, my kindly telling them that they are not, in this field, up to the last progress. . . . In this long period [forty years since its invention] the system has been perfected both from the technical and the construction standpoint. . . . The type used at Los Angeles, of 95 foot span, is of rather heavy appearance and must be rather expensive."[3] The remainder of the letter cites lighter, cheaper, and more pleasingly proportioned Belgian Vierendeels used for similar spans, clearly expressing dissatisfaction with America's one and only attempt to utilize his system. As a bridge type, the Vierendeel's assets could not overcome the economic advantages of other spanning systems.

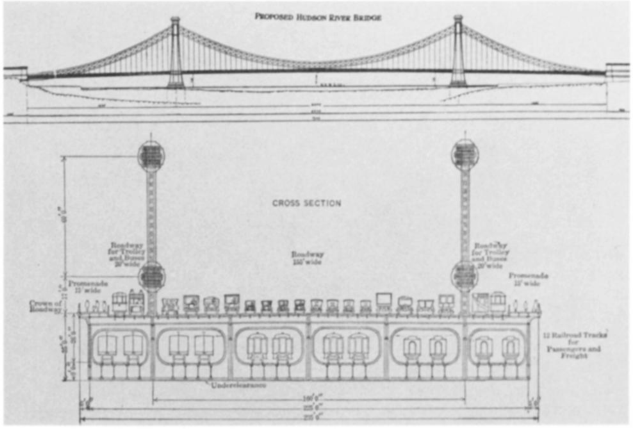

Fig. 5. Hudson River, proposed suspension bridge, G. Lindenthal, 1921. Elevation and section (Steinmann, *Suspension Bridges*, 1929).

An elaborate proposal for a suspension bridge over the Hudson River by G. Lindenthal in 1921 was intended to provide railway traffic through Vierendeel girders below a multilane roadway (Fig. 5). Although never realized, his vision suggested possibilities for the cubistic voids of the Vierendeel, later to be applied in architecture. These examples illustrate the very specialized occasions found appropriate for use of the Vierendeel system in America. By the 1930s, when the Vierendeel's civil engineering importance appeared to be waning, its architectural potential was be-

2. G. Willems and R. Fougnies, "The Evolution of Steel Bridges in Belgium in the Last Twenty-five Years," *Acier-Stahl-Steel*, CCII (June 1957), 244.

3. Arthur Vierendeel, "Vierendeel Truss Bridges," *Engineering News Record* (4 March 1937), p. 345.

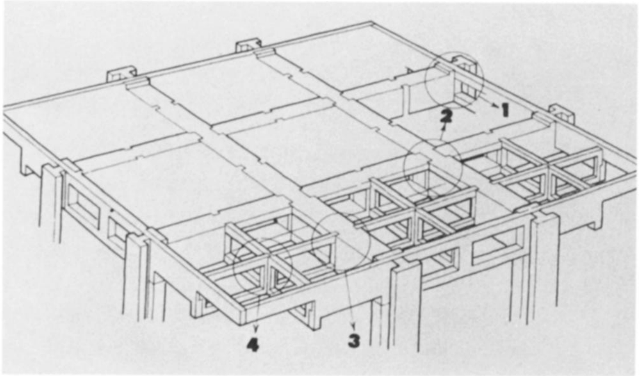

Fig. 6. Philadelphia, Medical Research Laboratory, University of Pennsylvania, L. Kahn, 1959. Structural framing (*Architectural Record*, September 1959).

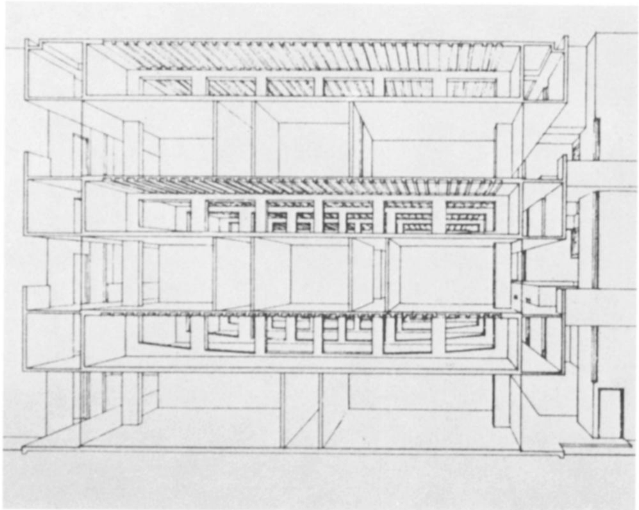

Fig. 7. San Diego, Salk Institute, L. Kahn, 1966. Section (*Zodiac*, 1967).

ginning to surface, both abroad and in the United States.

The cloud of doubt which had surrounded the Vierendeel because of welding problems began to disappear. Belgium and Germany had discovered that relieving the Vierendeel of the dynamic load requirements imposed in bridge design, and subjecting it to the static loads found in most buildings, virtually eliminated difficulties produced by welding.

Maturity

Current architectural advantages of the Vierendeel were stated at the beginning of this paper. The creative spirit of today's design philosophy has mustered a recurring need for the Vierendeel—it has become a means to an end. The Vierendeel is truly a structural compromise—less efficient than a truss in handling loads, but still in many cases superior for spatial penetration. Presumably for each instance discussed below, a more efficient structural solution was possible, but not without sacrificing space, function, circulation, light, and desired detail. The Vierendeel has proven to be a valuable contrivance. It is difficult to categorize its full range of applications, but a few major areas should be noted.

The need for integrating more and more complicated mechanical systems into building design has frequently necessitated Vierendeels. Building types such as hospitals, laboratories, or schools, which require total flexibility for their mechanical network of pipes, ducts, and conduit, have had short or full-story Vierendeels sandwiched between typical floors to permit service access from above or below. A unique example of this is a three-foot-deep open web grid system in two directions for the Medical Research Laboratory at the University of Pennsylvania (Fig. 6). Louis Kahn's design was intended to accommodate a vast network of mechanical services, while providing 47-foot clear spans for the laboratory spaces in between. Structural consultant August E. Komendant devised pre-cast concrete Vierendeel segments intricately joined by post-tensioning techniques which kept member sizes reasonable and provided continuity with the H-section columns. Another Kahn design, the Salk Institute in San Diego, California, employs full-story Vierendeels slotted between laboratory spaces, to achieve total mechanical flexibility for changing future needs (Fig. 7). Komendant was again the structural consultant. His solution incorporated enlarged web and chord members near the wall supports to stiffen the reinforced-concrete Vierendeels, reducing their deflection. Another means of improving the Vierendeel's structural efficiency is variable spacing of the vertical web members, which helps to stiffen the span ends and results in reduced beam deflections. Many structures around the world have employed Vierendeels for complex mechanical integration, and this trend assures the Vierendeel of promise for the future.

The second major usage of Vierendeel frames is to span large open spaces, while utilizing its rectangular openings for circulation or fenestration. One of the earliest examples is the Royal Institute of British Architect's Building in London (1934). The bottom chord of the Vierendeel supports a heavy floor load, and the top chord carries a roof terrace. Four years later, in 1938, a Vierendeel was employed in a building in the United States, the International Agricultural Corporation in Chicago Heights (Fig. 8). A network of conveyors and walkways weave through the Vierendeel's voids, leaving large portions of the floor below column free. Several downtown redevelopments for major American cities work with elevated pedestrian passageways. The Vierendeel has been a frequent choice for providing maximum visibility and minimizing obstruction of outdoor space. Minneapolis–St. Paul, Cleveland, and Spokane have such interconnected concourses.

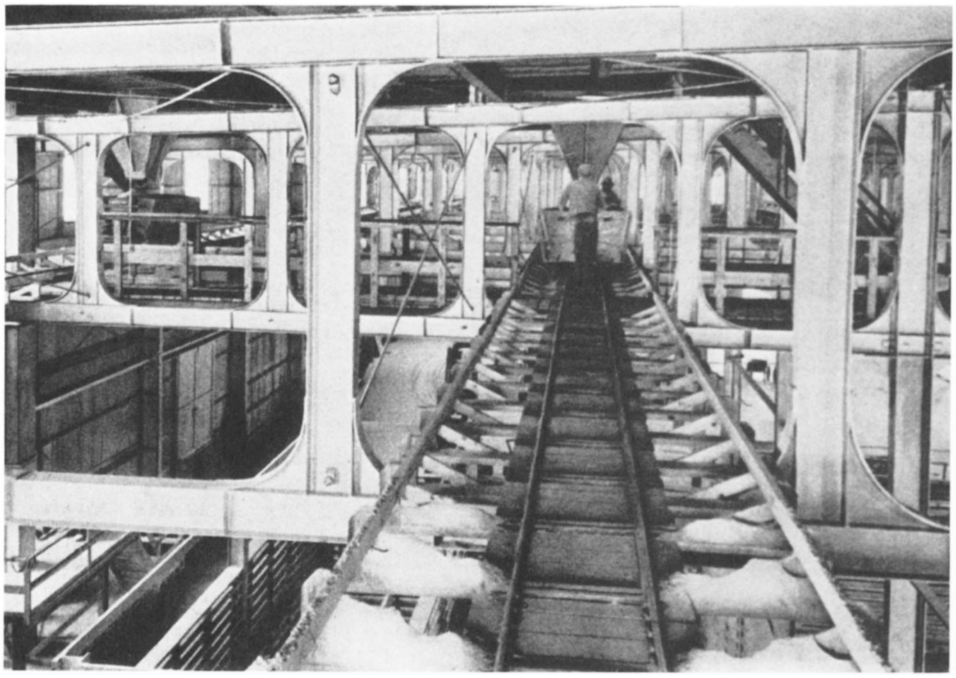

Fig. 8. Chicago Heights, International Agricultural Corporation, Austin Company, 1938. Interior (photo: *L'Ossature Metallique*, September 1938).

A third potential for Vierendeels in architecture remains concealed in the foundation. If a low bearing capacity and highly compressible soil condition exists, along with a need to eliminate differential settlements, an extremely rigid support system is required. A Vierendeel, formed by using a concrete mat for the lower chord and a concrete floor slab for the top chord, provides a deep rigid framework, tied together by columns or bearing walls as web elements. Although a solid egg-crate foundation would improve the stiffness even more, the Vierendeel's advantage is that it leaves usable space within its depth. Such a solution was attempted in 1929 for Building B of the Bell Telephone Company in Albany, New York (Fig. 9). This involved a two-level Vierendeel resting on highly sensitive clay which had to support heavy telephone exchange equipment. The delicate mechanisms required the elimination of differential movement. The foundation's performance to date has been problem free.

A recent development in multi-story construction, referred to as a cantilevered tube, is in essence a fourth category of Vierendeel usage. The building's periphery consists of a fine mesh of rectangular openings between closely spaced columns with deep spandrel girders. Acting as an extremely rigid frame, it is called upon to carry lateral as well as gravity loads. The world's tallest buildings—the Sears Tower in Chicago, the World Trade Center in New York, and the Standard Oil Building, also in Chicago—each in some way uses this system. The most structurally efficient form would be a solid tube, but since light is necessary, the Vierendeel mesh offers a reasonable compromise. Horizon-

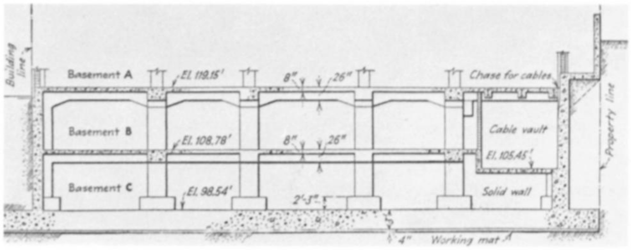

Fig. 9. Albany, Bell Telephone Building, Voorhees, Gmelin, and Walker, Architects, 1929. Foundation section (*Engineering News Record*, 27 November 1930).

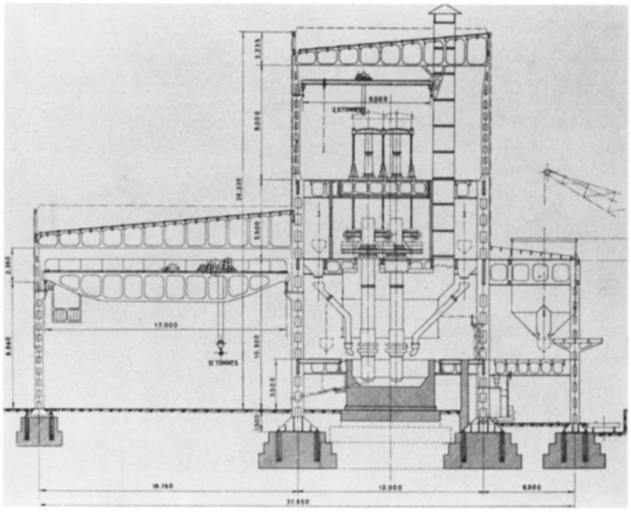

Fig. 10. Savone, new ILVA Steelworks, A. Bozzarelli, 1939. Transverse building section (*L'Ossature Metallique*, March 1940).

tally, multi-layered Vierendeels are employed to take advantage of the rigidity gained by the increased depth of the system. This technique permits spanning large spaces, while still expressing a rectangular grid. Yale's Beinecke Rare Book and Manuscript Library by Skidmore, Owings, and Merrill is actually a Vierendeel-framed prism five stories high, supported on four pedestals. The ground level thus becomes open space, 130 feet by 86 feet. A similar strategy is found at Cornell's Social Sciences Building, with the added advantages gained by cantilevering the ends.

The fifth category of Vierendeel application involves pure infatuation with its cubistic voids, buildings where aesthetic appeal is the only motivation for its application. Italy's ILVA Steelworks plant at Savone (1940) is probably the best example (Fig. 10). Horizontal, vertical, and sloping Vierendeels create a honeycomb interior merely to express a modern image for their product, specialty steels. Even at the sacrifice of economy and efficiency, aesthetic considerations dominated. The Boston City Hall and the Santa Cruz County Government Center in California also display Vierendeels for aesthetic purposes.

There exist a myriad of modified or partial Vierendeel applications, such as the staggered truss system, developed at M.I.T. in 1966, which maintains a pratt truss configuration for all but one rigid panel, this intended as a corridor. The idea has been effectively used in apartment buildings and hospitals to gain structural efficiency and greater rigidity, while still taking advantage of the Vierendeel's assets.

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