The Helicoidal Oblique Bridge at Seventh Street in St Paul Minnesota

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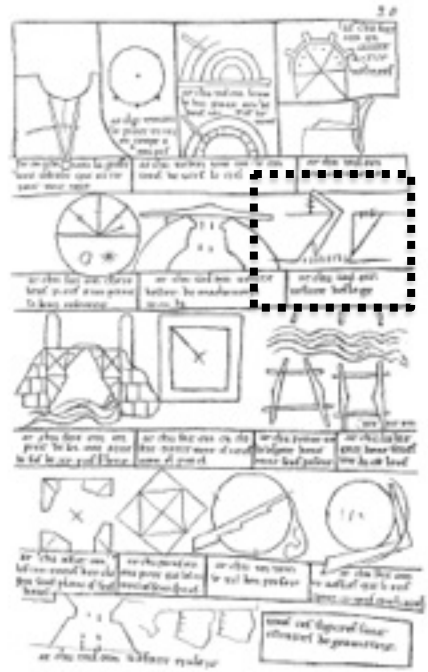
Introduction

Oblique bridges were necessary when railways, roads, or rivers intersected at a slanting angle. This condition became typical after the industrial revolution when motorized vehicles became ordinary means of transportation. By the end of the 1800s the use of masonry structures was common to construct the infrastructure of cities and the engineering solution to this type of road crossing was challenging, especially when working with stone arches and vaults. Different methods to solve these oblique bridges such as the *ribbed arches method,* the *logarithmical method,* and the *helicoidal method* emerged providing yet further constructive challenges to engineers, contractors, and masons. This paper examines a National Engineering Landmark located within the city of Saint Paul, the Capitol of Minnesota. The Seventh Street Improvement Arches form a double-arched stone bridge at the crossing of 7th Street and the Duluth Railway which was part of a public works project funded by the city in 1883. The arches were designed to resolve the oblique relationship between the street over the railway lines and the two transportation paths intersecting at a 60 degree angle. However, due to the rarity of this situation in the United States, and its complete non-existence in the State of Minnesota, this bridge became the most challenging component of the large-scale project. The City of St Paul Engineer's Office assigned the engineering of this bridge to William A. Truesdell. In order to provide a solution Truesdell evaluated every alternative possible, which was necessary to understand the processes involved in each method. His ultimate selection of the helicoidal method was chosen regardless of its stereotomic complexity. This study focuses on the implications of the solution selected by Truesdell.

Skew masonry arches; an old stonecutting challenge

The role of stereotomy in stone construction consists of defining the shape of stones in addition to providing the rules for a correct assembly and structural stability of the pieces involved in the construction of building elements. The proper structural work of a spanning element such as an arch is determined by its geometry creating an interdependence between the form and structural stability. Curiously, even when this connection between form and structure is crucial, the structural component of spanning elements described in most treatises of the sixteenth and seventeenth centuries do not occupy a primary object of discussion. Several descriptions related to structural work are based on vague arguments of intuitive nature; the content found in these documents prioritizes stonecutting methods and issues related to the assembly processes. One can assume that structural criteria was not decisive or was even inexistent, thus the discussion revolves more about the proper solution based on geometric and/or historic arguments. The models of the arches found in the well-known treatises show that the authors focused their interest on the conception of a shaped volume and the over all form. These authors gave importance to drawings and how lines can be used to depict volume.

From the structural perspective we know that an arch or barrel vault crossing through a wall discharges the thrust forces and dead-loads on the abutments. The skew arch, found commonly as a stereotomy problem in treatises, changes this simple structural convention. The tilted axes of the arch's barrel implies that the thrust is not perpendicular to the wall and therefore the forces involved push toward the "void", without a reaction maintaining the equilibrium of the structure. This conundrum of forces applied with no reaction to maintain equilibrium has been known commonly as *"thrust to the void."* The term is contradictory in itself because thrust, as a force, should be applied to a solid. Nevertheless, the notion of this form of structural load was conceived from the assumption that all forces traveling through the arch are better handled when the bed joint is normal to that force.



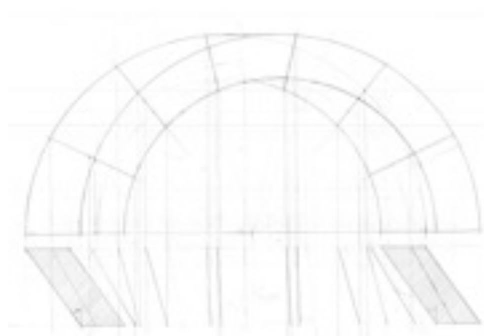
Skew arch drawing in the manuscript of Villard of Honnecourt

The structural problem poses two layers of complexity for skew arches and oblique vaults; one related to the structural stability and the second related to the stereotomy of the pieces. The solution for stereotomy has been addressed throughout the history of building construction. The complex nature of this type of arch and its recurrent appearance in buildings awoke the curiosity of many of the treatises authors. Villard of Honnecourt, a master builder from the thirteenth century, illustrated this constructive problem suggesting the knotty tasks involved in the conceptual and fabrication process. Villard certainly includes his drawing referring to skew arches because this oblique intersection between arches and walls was a common challenge for masons. The conditions generating the need for a skew arch were sometimes related to new additions, centering doors within the rooms, corner thresholds, and slanted configuration of spaces. Since Villard does not provide a specific solution in his treatise, one may think that he recognized the intricacies inherited in this type of spanning element, but his ability to depict each graphically were very limited. We should remember that descriptive geometry, the foundation of modern stereotomy, became a well-known depiction method until the end of the eighteenth century.

Model of skew arch with semicircular heads made by students at the University of Minnesota

The graphic media used to represent geometric problems of building elements was solidly established by the second half of the sixteenth century. The methods and solutions found in manuscripts suggest that architects and master builders were able to preconceive shapes and achieve constructive solutions in buildings. This mode of practice was a natural evolution of techniques used in Gothic construction where building form was a consequence of the construction process itself. Alonso de Vandelvira, a Spanish master mason of the sixteenth century, also includes in his treatise the solutions for these skew arches. Enrique Rabasa shows how Vandelvira, being a master builder of the renaissance, did consider the overall geometry but disregarded the mechanical behavior and even some of the carving complications of his proposed solutions.[1] These complications emerge from his two proposed solutions; the first being an intrados generated by a cylinder of circular directrix where the heads of the arch, on the walls' surfaces, are by consequence elliptical. The second solution proposes circular directrix for the arch's heads on the walls; the result is an intrados defined by an oblique cylinder of elliptical section. These elliptical forms, either on the intrados or the wall's surface, would be more evident as obliquity of the intrados surface increases, thus becoming insignificant as if the wall were thin and the angle of the intrados generatrices was nearly 90 degrees with respect to the wall's surface. Because the cylinders generatrices of Vandelvira's methods run parallel to the threshold planes, they do not offer a solution for the *thrust to the void*, in other words, the resultant forces in these arches do not apply parallel to the long axis of the wall and therefore posing a potential structural problem.

As explained by Rabasa, the solutions to skew aches found in the treatises of Gines Martinez Aranda and Philibert de l'Orme, both from the sixteenth century, propose an ingenious solution known as *biais passé* in the French tradition. The *biais passé* on one hand addresses the thrust to the void but on the other, does not develop a perfect cylinder in the intrados surface, but is instead a warped ruled surface. This solution, was named in Latin by Millet Dechalles *"Arcus oblicous perfectus"* (perfect skew arch) in his manuscript of 1674. When looking closer to this solution one may notice that it draws slightly curved lines for the bed joints in the intrados of the arch, which, in fact, are not perceptible to superficial observation in regular thickness arches.[2] This solution is achieved by simply drawing the two intrados overlapping arcs on a plane parallel to the surface of the wall (pretending the wall is transparent) and slicing both arcs with converging lines as if it was a single arch. These converging lines will intersect at the cross-point between the spring line and the vertical line drawn form the point where both arcs intersect each other. The lines drawn define the bedjoints on the vertical projection. On the horizontal projection one can notice that the bedjoints "rotate" to reach the inclination of the abutment.



History of construction shows that both types of skew arches, the *biais passé* and the cylinder, were commonly used in various circumstances. From their applications in different situations we learn that they were utilized indistinctly regardless of the conditions presented by abutments and supports. As Rabasa points out, an example of this is found in the Plaza Mayor de Madrid, where several arches with similar geometry, span, and supporting members were solved using both methods. The difference might be alluded to different masons hired to construct the arches. We can conclude that the solution depended on the ability of the master mason in charge. The scale of the arches does not influence the solution and therefore the structural differences between the methods were not worth consideration in terms of efficiency and/or safety.

Model of skew arch *biais passé* made by students at the University of Minnesota

The skew arch is the historic precedent of the oblique bridge. Nevertheless, the structural and geometric implications of skew arches are different when translated to structures where the arch's length extends to the point where it is no longer an arch, but a vault. From the geometry point of view, the extension of the intrados surface does increases the length of the directrices of the warped ruled surface creating several inconstancies, difficult to be solved when defining the intrados surface and the voussoirs forming the vaults. Fo example, if one simply tries to extrude the *biais passé* intrados to form a vault, the consequence is lack of feasibility to concretize the construction. On the other hand, we should consider that from the structural point of view, vaults are needed when building larger structures such as bridges and other pieces of infrastructure, these infrastructure pieces are considerably larger, the loads to handle, such as trains and cars, were more substantial. In addition, these large structures stand alone and are not embedded within a building that supports them, therefore their stability lies in the structure itself.

The Oblique Bridge

Ledbury & Gloucester Railway, Ribbed Arch, Hereford Road Bridge, Ledbury

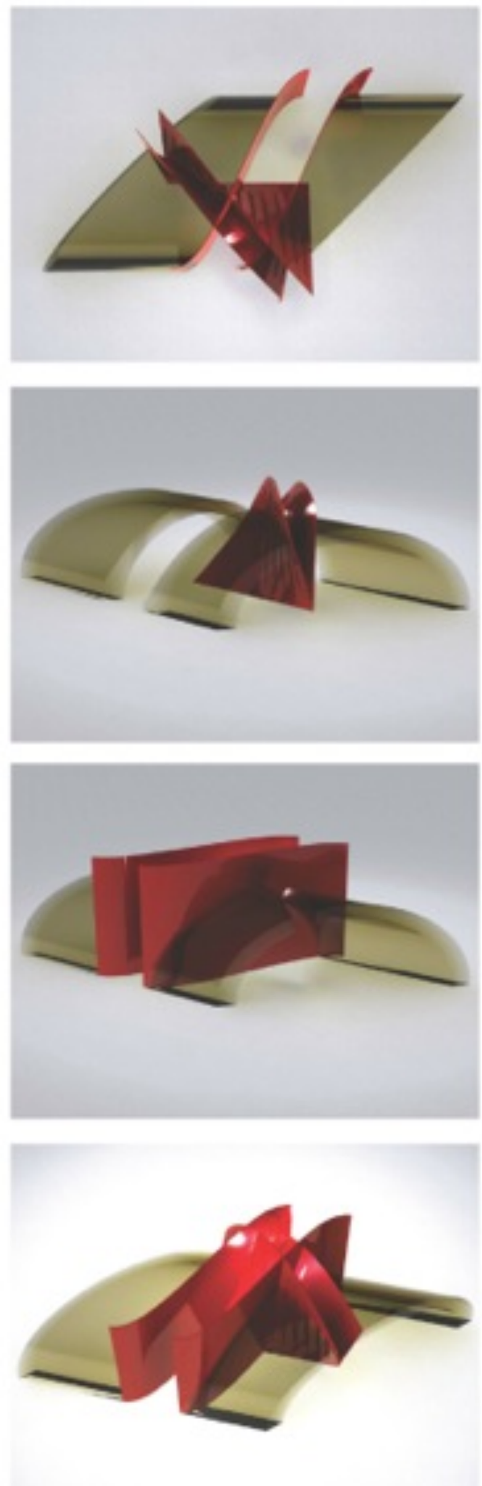
Peter Robinson, Logarithmic Skew Arch, Bridge 74A, Leeds and Liverpool Canal

Masonry arch bridges have existed since ancient Roman times, initially constructed to cross over natural and man-made watercourses at right or nearly right angles. However, as time has passed, certain cases have arisen that have not allowed for such "grid-like" and perpendicular crossings – especially those that have correlated with the growth and expansion of the European and American railway systems.[3] The oblique bridges emerged during the nineteenth century when the course of stereotomy, as we currently know it, was well developed. In fact, stereotomy was almost looking at the dusk of its existence during this period of time. The needs of bridges resuscitated discussions related to the historic topic of the *thrust to the void* , especially when the oblique bridges became a common task to engineers. A characteristic of the nineteenth century is the creation of railroads. Historically previous paths, if approaching one another irregularly, were easily corrected, but, in many cases involving the developing railway lines, "the speed of the locomotive engine rendered this arrangement [to be] quite inadmissible."[4]

Though the oblique bridge would become its own specific structural type, it did not emerge into existence by means of one singular method of construction. Instead, it would gain its significance by means of the employment of a variety of schemes. The objective of masons and engineers was to minimize complications in the construction process while addressing the structural needs of bridges. The notion of *thrust to the void* was as important as it was to achieve geometric clarity. Several years of building tradition stipulated that all forces traveling through the arch are better handled when the bed joint is normal to those forces. This condition can only be accomplished if the voussoirs bed joints are perpendicular to the surface of the wall, a condition that is difficult to maintain throughout the entire surface of a vault without avoiding complications and deformations. The ribbed, logarithmic, and helicoidal methods served as the three primary techniques to construct an oblique bridge.

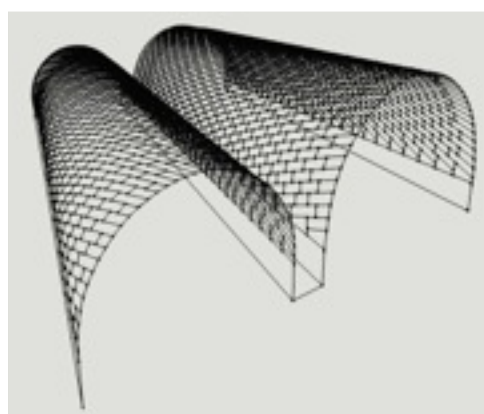
Out of the three schemes, the ribbed arch method tackled the issue of obliquity with the simplest approach requiring oblique bridges to be constructed by placing a number of short right arches or ribs in contact with one another, with each successive rib being placed a "little to one side of its neighbor".[5] This approach proved to be beneficial for brick masons as the brick would be able to form regular arches leaning against each other. Stone masons and cutters that were inexperienced with this type of construction were also attracted to this method, as it required the least amount of skill compared to other existing methods. However, the ribbed arch method's easy solution to the problem brought with it a set of disadvantages. Many viewed the method as not only being "wasteful of material on account of the ribs," but also of creating a bridge with a rather questionable amount of strength.[6] Perhaps the lack of binding among the ribs was a source of concern for builders. Form the point of view of stereotomy, this method avoided the analysis of the geometric implications inherent in this constructive challenge. In addition, once built, the method was criticized for matters of public opinion, including through the argument that the gradual offsetting of the ribs produced a structure with a "rough" and "very ugly appearance."[7] However, while this method struggled to gain strong acceptance in most European countries, its minimal requirement of skill and experience allowed it to find occasional support within the United States.[8]

By far, the most complex and challenging approach to the problem was that which was based on the logarithmic tables of Scottish mathematician Edward Sang. The method finds its origins in the orthogonal or French method that aims to avoid any possible *thrust to the void.* The method used by French builders finds its origins in the skew arches mentioned above. The solution is obtained by unfolding the cylinder onto a plane. The result is a surface defined by two parallel sinusoids. These sinusoid lines are divided in equal parts (same procedure for both heads of the vault) allowing to draw the necessary voussoirs in the intrados. As the *thrust to the void* should be avoided, the lines defining the voussoirs are perpendicular to the sinusoid's tangent found right at the crosspoint with the voussoir line. Each line responds to the curvature of the sinusoid being the last one parallel to the abutments and therefore, achieving bed joints that are normal to the forces. Although this solution seems to handle the structural problem efficiently, the differences in vousssoirs' sizes and coursing thickness made the construction rather difficult and imprecise. While this method rudimentarily applied was heavily depended upon the strength of the mortar for structural stability, Sang's method depended upon



Helicoidal sections through the oblique barrel vault its highly detailed and systematic manner of construction controlled by his proposed logarithms. In this method, "voussoirs are custom cut in a variety of shapes to fit the configuration of the arch," and their organization efficiently allows the structure to support itself against the forces exerted upon it .[9] This method, needing a variety of patterns to produce the numerous voussoir shapes, required an extremely high level of skill from the workers. Despite its complications, the method created a structure with the reputation of being "the strongest oblique arch that could be built."[10] Most of the examples that were built followed a simpler and more handcrafted oriented solution, never satisfying the rigor and precision requested by the stereotomy of the nineteenth century.

The last approach, the helicoidal method, sought to take into greater consideration the unique condition of the oblique bridge, while providing a system of construction that was efficient and embodied individual elements that were easy to produce. In this method, "voussoirs are laid in spiral courses, parallel with each other, and are of one size and shape throughout the whole arch except the ring stones." [11] The spiraling lines are obtained again from the development of the cylinder (unfolding onto a plane), but this time the lines defining the voussoirs are not perpendicular to the sinusoids but perpendicular to a line that connects both end of the sinusoid creating two parallel lines running on both heads of the vault. These parallel lines are divided in equal parts connecting these segments with straight lines. These straight lines are folded back into the cylindrical surface forming helicoidal "trajectories" along the intrados surface of the vault. Once folded back into the cylinder, the contact area of bedjoints are ruled surfaces of helicoidal directrix as the lines forming this surface are always perpendicular to the cylindrical surface of the vault. Although this solution does not completely fulfill the required normal bedjoint to the force, the solution is very close, requiring only triangular adjustment pieces on the abutments. The benefits of this method is that one set of patterns answer for most of the voussoirs, and "when the stone-cutters are once taught to cut a stone no further difficulty is encountered."[12] The efficiency in this method came not only from the fact that the pieces (with the exception of the outer ring stones) were able to be produced from one set of patterns, but also from the ability to determine their shape, and the overall form of the structure, before construction even began. The helicoidal method was strongly supported by a man named Peter Nicholson, who, in *The Guide to Railway Masonry, Containing a Complete Treatise on the Oblique Arch*, illustrated and explained how the design and organization of the pieces could be determined from the development of the intrados, or the unrolled and flatted view of the interior face of the arch vault.[13] While this method only approximated the course angle needed to counter the thrust placed upon the entire organization, it still proved to be structurally sufficient and gained high acceptance

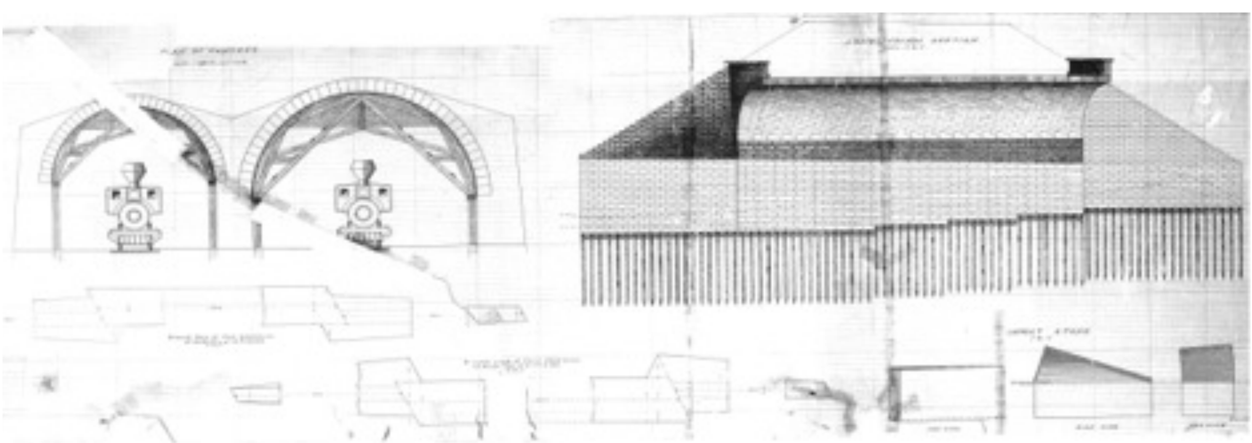


Wire perspective of the oblique barrel vaults at St Paul MN in such countries as England and Scotland finding such popularity in England that it also became known as the English method.

Though the last two methods, as well as other more intricate schemes, found great acceptance and use in oblique cases throughout Europe, their application in the United States was far less common. This was not only due to the fact that the United States was younger and lacking a similar history with the methods, but also because it was a country that continually sought new and emerging technologies and strategies. As has been noted by local historians, stone construction in general "was of little interest to the American engineering profession, which heaped acclaim upon the newest, the biggest, and most innovative of whatever technology it paused to observe."[14] However, of the few oblique cases that snuck into existence within this country, these methods were able to leave a sense of pride and personal achievement on areas that incorporated them.

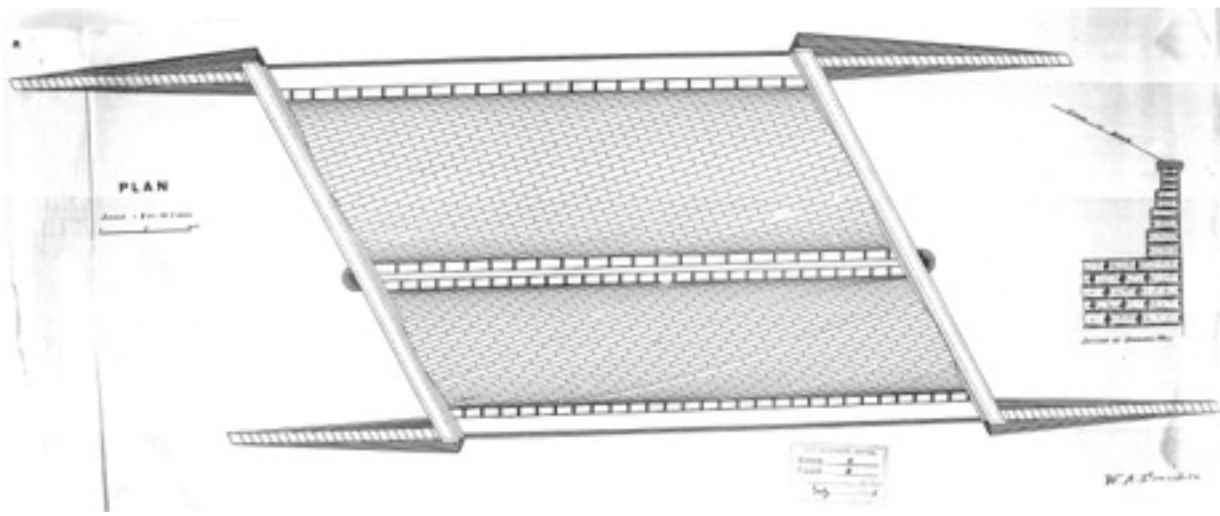
The Seventh Street Improvement Arches in St. Paul Minnesota

The Seventh Street Improvement Arches are located within the city of St. Paul, the capital of Minnesota. This double-arch stone bridge at the crossing of the St. Paul and Duluth Railway was part of a larger public works project being funded by the city in 1883; however, the structure instantly became "the most interesting part" of the large-scale project.[15] This is because it was not composed of just any set of regular double arches, for together, the arches solved the problem of the oblique crossing of East Seventh Street over the railway lines. With the two transportation paths having an angle of intersection of 63°28", it had become clear early on that an oblique arch method would need to be used.[16] However, due to the rarity of the situation in the United States, and complete inexistence in the state of Minnesota, the answer as to how to produce such a structure was yet to be determined.[17]



William A. Truesdell, Original Drawings of Elevations and Sections

The City of St. Paul's Engineering Office hired a man named William A. Truesdell to supervise the entire project – including the future Seventh Street Improvement Arches themselves. Truesdell had been working since 1880 on the engineering staff of the St. Paul, Minneapolis, and Manitoba Railway, and while "he was involved with all kinds of construction" in his position, he had never before personally faced the challenge of constructing an oblique arch.[18] However, despite his lack of personal experience, he was familiar with the various schemes employed, because in the July 1886 volume of the *Journal of the Association of Engineering Societies*, he not only noted how "every known method of constructing such a bridge was duly considered," but he also documented his evaluation of the three primary methods.[19]



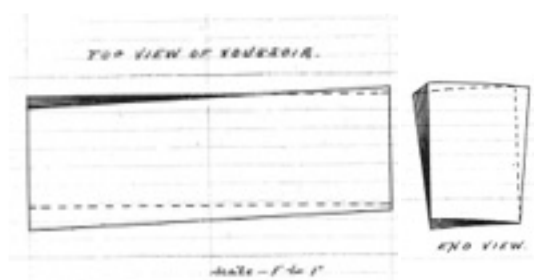
William A. Truesdell, Original Drawings Plan

The first method that Truesdell had considered but immediately rejected was the ribbed arch approach. Though this approach had been the "American" answer to the skew arch problem, Truesdell did not trust that it was sufficient or appropriate to be used in this case.[20] He stated that the method would produce a structure "unstable for this locality," both due to the "great weight of earth [that] the arches would have to sustain" and the inability of each rib's stones to bond with the next.[21] Also, "nothing, probably, would have been saved in the stone-cutting" – even further providing no real advantage in the long run.[22] Therefore, not willing to take the easiest approach to the problem, Truesdell passed upon this method and continued onto the next.

Helicoidal Oblique Arch, Seventh Street Improvement Arches, St. Paul, MN

Truesdell then turned to the logarithmic method, because he was aware that it offered the highest level of internal strength and stability against imposing forces.[23] However, even though this method fully satisfied one of his goals to achieve, he knew that its intricate requirements were far beyond the capability of the locality. The variety of voussoirs that it required would have been far too difficult for the local masons and stonecutters to cut and shape, and the cost to produce the entire project would have been an expense "beyond all consideration."[24] Therefore, while this method carried with it very desirable qualities, it was just too unrealistic in terms of skill level and construction cost.

After deciding that neither of the previous approaches would be appropriate for the situation, Truesdell finally turned to the possibility of incorporating the helicoidal method. While Truesdell saw the previous two methods as being too inadequate or out of reach for the project, he saw the helicoidal method as offering a much greater sense of possibility. He felt that "although the initial calculation and



Voussoir detail at the impost of the oblique barrel vault at St. Paul MN cutting [of] the curves" to generate the voussoir shape would prove to be a challenge, this method had the "overriding advantage" of being able to repeat the pattern across the entire arch interior.[25] Not only would the efficiency of this method still produce a structure of great strength, but it also seemed to be the cheapest to construct "of any of the known methods."[26] Therefore, in satisfying both of Truesdell's goals, the helicoidal method was eventually adopted.

In the summer of 1883, plans were prepared and specifications were drawn up detailing how the bridge was to be constructed.[27] As the drawings displayed, the two arches previously mentioned were planned to divide up the Duluth Road's 70 foot width with direct spans of 27 and 37 feet, and oblique spans of 30 feet and 1 inch and 41 feet and 3½ inches.[28] While the oblique angle of the original path crossing was 63º28", the oblique angles that were to be designed for the arches were 63º49' and 63º40'.[29] Truesdell further noted that "each arch was to be 124 feet and 7 inches in length, both of them full centre arches, [and with] the springing line of the small one 3 feet and 4 inches above that of the larger one."[30] The two arches would allow five tracks to run within them, "two passenger tracks through the small arch, and three for freight traffic through the larger arch".[31] While the spring lines would stay horizontal as they continued through the arches, as the railroad tracks passed through, they would descend with a grade of 2 feet per one hundred.[32] Between the two arches, a central pier was to support the structure with a 6 foot direct span, while their east and west sides were to receive their support through abutments and adjacent wing walls stretching north and south from them.[33] Four feet above the crown of each arch (36 feet above the railway track) a parapet was to be built, while a coping stone would top the structure following grade of East Seventh Street (rising 4 feet and 10 inches per one hundred feet).[34]

Helicoid coursing in the oblique barrel vault at St. Paul MN

As further displayed by the drawings, the ring stones of the structure would be cut "to simulate the appearance of semicircular right arches," however, once one entered the arch vaults they could quickly view the helicoidal design of the voussoirs and their courses.[35] The voussoir courses, resting parallel to one another, would spiral as they would proceed through the vault (creating a helix), in order to allow the voussoir beds to continually maintain an approximate right angle with the line of thrust.[36] Because the courses would be "generated by a straight line which intersects the axis of the arch," the four voussoir faces that meet the bed and head joints would become the ruled surfaces of helicoidal directrix mentioned above.[37] In terms of voussoir size, the dimensions needed to differ between the arches. While the interior voussoirs of the smaller arch required the dimensions of 5 feet 8½ inches in length and 2 feet deep, the dimensions of those for the larger arch would be the 4 feet 11 inches long and 2 feet 4 inches deep.[38]

Truesdell used his various drawings to not only understand and illustrate how the arches were to be built, but also to allow the individual voussoir pieces to be created before the construction on the arches even began. His drawings of the voussoirs were taken by the American Manufacturing Company in St. Paul, who turned them into templates and bevels to be used by the stonecutters. The materiality of the template and bevels depended upon their use, being made of iron and wood, and those that were to be used only "once or twice" being made of simple paper.[39] Those that were to be used most often were for the voussoirs of the interior of each arch, and were also duplicated "so that from 25 to 30 workmen could be kept at work continuously in the quarry."[40] Those that were to be used less frequently were primarily for the ring stones of the arch, which required individual attention as many of their lengths varied.[41]

In September of 1883, following the completion of the drawings and the other preliminary work, the construction was finally able to be initiated on the East Seventh Street site itself. The work began with the excavation, foundations, and abutments of the structure, with a St. Paul native, Michael O'Brien, serving as the general contractor for this early portion.[42] When his portion "up to the spring lines of the arches" was completed in June, 1884, "the project passed to [the] McArthur Brothers of Chicago" to lead the completion of the work.[43] After ensuring that the centering was properly put into place, the McArthur Brothers supervised the construction of the arches themselves - watching them go up in horizontal rows as opposed to their common lay by courses.[44] On October 14th, 1884, the workers finished the arches and began working on the rest of the masonry work, and that following December, on the 18th of the month, they were able to open Seventh Street to traffic.[45]

It is important to note that while the traffic on the St. Paul and Duluth Railroad was minimally disrupted during the initial period of work (to relocate existing tracks), during the construction that occurred under the McArthur Brothers, the traffic "was not in any way obstructed."[46] This was because the centering built for the arches was constructed in what is known as a "cocket," or raised, style, allowing enough room underneath for the trains and switch engines to freely pass through.[47] It is also important to note that although the Seventh Street Improvement Arches followed a European method of construction, the primary materials chosen for the structure's assembly were all locally sourced within the state. The portions of the structure up to the spring lines of the arches, as well as the supporting wing walls, were built of a gray limestone that was quarried within St. Paul, while the voussoirs, ring stones, coping and spandrel walls were constructed of a "finer-grained, buff-colored" limestone hailing from the city of Kasota, Minnesota.[48]

Voussoir detail in the oblique barrel vault at St. Paul MN

Acknowledgments

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Notes

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[20] "Minnesota's Historic Bridges," *Minnesota History Society*.

[21] Truesdell, William A., "The Seventh Street Improvement Arches," 318.

[22] Ibid.

[23] Ibid.

[24] Ibid.

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[26] Truesdell, William A., "The Seventh Street Improvement Arches," 318.

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[28] Ibid., 319.

[29] Ibid.

[30] Ibid.

[31] Ibid., 317.

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[38] Ibid., 323-324.

[39] Ibid., 321.

[40] Ibid.

[41] Ibid.

[42] "Minnesota's Historic Bridges," *Minnesota History Society*.

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[44] Truesdell, William A., "The Seventh Street Improvement Arches," 323.

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[46] Truesdell, William A., "The Seventh Street Improvement Arches," 323.

[47] Ibid.

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