A graphical analysis of a skewed arched-masonry bridge along the Circumetnea railway track

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Abstract

The objective of this essay is the geometrical study of a vaulted system belonging to a railway masonry arched bridge along to the Circumetnea route, a regional railway line built at the end of 19th century. Through the investigative tools of digital representation and surveying, the research is aimed at finding the geometrical rules underlying the design and construction of the identified helical apparatus, to understand if it was realized according "rule of the art". The answer to this question opens new research avenues related to the understanding of a technological solution, no longer in use in construction practice but still of highest quality in terms of statics and construction technique. Indeed, its knowledge could become of fundamental importance when it is necessary to undertake consolidation and conservation interventions.

Keywords
Masonry Bridges, Descriptive Geometry, Geometrical Studies, Digital Survey, 3D Modelling.

Dense point cloud reconstruction of the Maletto skewed masonry bridge (Catania) with the related graphical analysis, aiming at finding the geometrical rules underlying the design of the identified helical apparatus.

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Introduction

The design and construction of bridges had a great impulse in the 19th century with the advent of railways, which did not allow large slopes and small radii of curvature, needed in difficult morphological conditions to overcome large spans.
Even though the construction of railway bridges is located in a rather limited time (100 years, approximately from 1840 to 1930), they have some common structural solutions, with technical choices and executive details that vary according to the time of construction, the geographical area, and the designer. The geometry of a bridge is strongly influenced by the orography of the site to be crossed; wide and generally deep valleys are crossed by multi-span bridges on high piers, while shallow wide valleys require multi-span bridges but on low piers.
Skew masonry arched bridges represent a very common solution in the rail infrastructure since they allow to cross a watercourse, a valley or a road along a route that is not orthogonal to the train tracks. From both a technological and a constructive point of view, this kind of bridges testify the ability of the workers in the stereometric cut of stones and the installation of ashlars. The geometrical study of a skewed-arched masonry bridge by means of digital representation and surveying enables a critical view on the effectiveness of digital tools to reconnect and better understand the present and the past.
The adopted methodology starts from the study of treatises to identify the tracing and constructive rules, moves to the survey and documentation of the analysed bridge and, lastly it continues with the verification, through a process of reverse modelling, of the geometric construction rules of the intrados to verify the consistency of the bridge with the "rule of art". As case study, we chose a masonry arched bridge which is part of the Circumetnea railway, a narrow-gauge regional railway line in Sicily built at the end of 19th Century that makes the tour of Mount Etna, connecting Catania with Riposto passing through several towns in the foothills of Etna.

Methodological premises

Considering the goals of this research, the methodology developed is aimed at the rigorous verification of the geometry of the bridge using the investigation tools of the disciplines of surveying and representation as a system of interpretation and knowledge, from the real object to the designed shape [Santagati 2005; Cipriani et al. 2017; Vitali 2017; Spallone et al. 2019].
In this specific case, the study of the geometry and equipment of the vaults of oblique masonry bridges is a question linked to stereotomic tracing rules, solving a problem that in the past was treated bidimensionally by means of 3D modelling. Digital technologies facilitate the description of lines, surfaces, and volumes directly in space, continuously, and with high levels of precision [Salvatore 2009; Fallavolita, Salvatore 2012]. Hence, a first phase of study of stereotomic and skew bridges construction treatises has been carried out to focus the research outlines and the main features of skew vaults, particularly the English or helicoidal methods. Subsequently, it has been carried out an integrated digital survey of the identified case study by using low-cost photogrammetric techniques. The numerical model obtained forms the basis for the subsequent study which involved the following steps: the unroll of the surface; the test of the net to verify the geometric rules behind the tracing of helicoidal equipment; construction of the ideal mathematical model starting from the geometric characteristics extracted from the surveyed surface; development of the subsequent mathematical surface; the comparison between the two models.

Semi-circular skewed masonry arch bridges

An oblique bridge (or *ponts biais* or skewed arched bridge) is characterized by a skew arch, that stands out for the non-right angle from the horizontal projection of the intrados surface generatrixes to the face plane trace. Hence, it is a method of construction that enables an arch bridge to cross a non-straight obstacle. The deviation from perpendicularity is known as the skew angle or the "obliquity" of the arch.

A bridge with a skew angle less than or equal to 20 degrees has a small obliquity, while an angle greater than 20 degrees has a large obliquity.
The construction of *ponts biais* was necessary in some situations, such as a railway bridge crossing a waterway. Its construction was much more difficult and expensive than a straight bridge, mainly because of the need for high skilled masons, since the precise stone cutting and their complex assembly. For this reason, the subject of the stone oblique vaults is retained one the most refined theoretical speculation of the stereotomic lesson [De Paola 2011]. In the early 19th century, following a deep understanding of the behaviour of oblique vaults through theoretical and mathematical analysis, it became considerably easier and cheaper to build a skew arch using bricks.
The main well-known types of equipment suitable for bridges with a large obliquity (i.e., more than 30 degrees) commonly found are [Page 1993]:
I. False skew arch: in this method, the simplest one, the units (voussoir) are laid parallel to the abutment.
II. Helicoidal or English method: in this, the bedding joints were perpendicular to the spandrel walls. Since each voussoir is like all others, it is suitable for the use of bricks or small size stones.
III. Orthogonal or French method: is the most expensive one since it requires the use of different sized masonry blocks with almost every block in the barrel being a unique shape. For this reason, this does not apply to skewed brickwork arch bridges.
As mentioned in [Baggi 1926], in the English method the helicoidal pattern approximately realizes the theoretical conditions for the equilibrium of the vault, since the edge lies on a plane rather than on a helicoidal surface; these approximations decrease as the lowering of the arch increases. This is the reason why the skew bridges were almost exclusively made with depressed arches. The greatest advantage in the use of the English method is the considerable savings from the use of bricks or small size stones (fig. 01).

The helicoidal method in treatises

The oldest evidence about oblique arches dates to Villard de Honnecourt, which included in his notebook an illustration showing how these structures were already known in the Middle Ages. Between the 16th and 18th centuries century several examples could be found in French and Spanish stereotomy treatises: Philibert de l'Orme (1567), Alonso de Vandelvira (late 16th century), Ginés Martínes de Aranda (1598), Philippe de la Hire (1687), Jean-Baptiste de la Rue (1728), Amédée François Frézier (1737-39) (Armetta, 2012).
Notwithstanding the value of these treatises, the arches were limited to narrow passages. The case of a bridge is more complex because of the major size and the static effects to be considered. During the 18th, several scholars as well as engineer and technical experts,

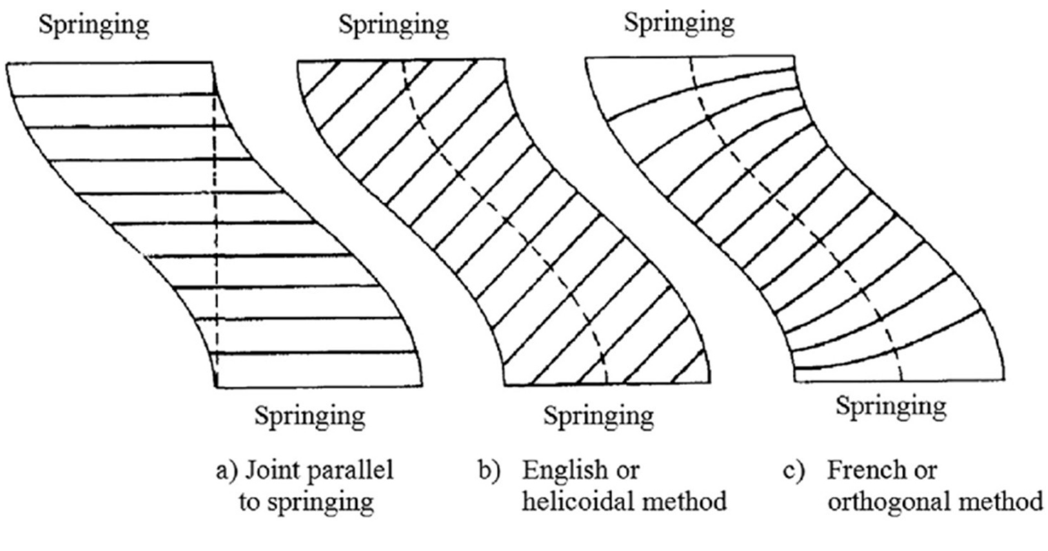
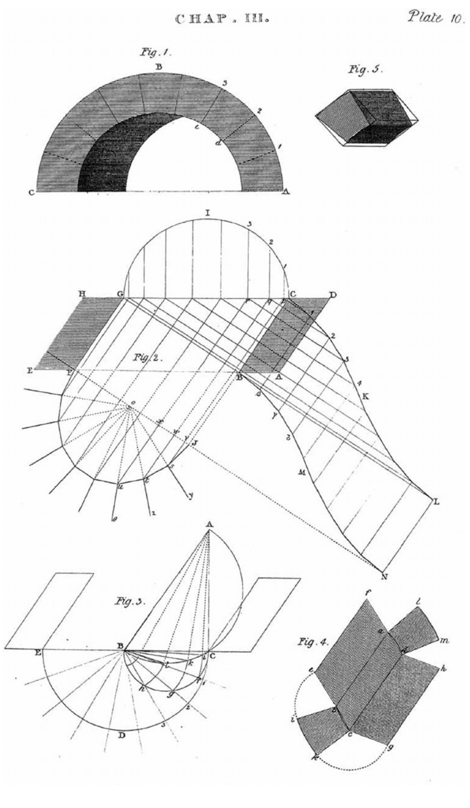


Fig. 01. The main well-known types of equipment suitable for bridges. Camilla Torre - Ponti in muratura. Dizionario storico-tecnologico. Alinea Editrice. Firenze, 2003

have been involved in the study of skew bridges. The input was the significant increase of rail networks at the beginning of the century. Particularly, the English and French studies of 19th century focussed on skew bridges, led to the main well-known types of equipment: the helicoidal and perpendicular methods.
Even if the knowledge about stone-cutting and related projective techniques already existed and was practised, Peter Nicholson (1765-1844) found a proper interpretation of Monge's system to the practical needs of nineteenth century [Gregory 2011]. In 1828 Nicholson wrote the "Popular and practical treatise on masonry and stone-cutting" dealing mainly on the oblique helical method (fig. 02). Performing his calculations, Nicholson considered the arch barrel as a thin-thickness surface and, therefore, he developed only the intrados in his graphical construction. Charles Fox (1810-1874) developed the concept of Nicholson, defining the rules behind the English or helicoidal method of constructing brick skew arches (fig. 03). Considering the barrel intrados and the extrados as separate surfaces by drawing a separate development for each, it could be possible to develop an arbitrary number of concentric intermediate surfaces to plan the courses in multi-ring skew arch barrels, allowing them to be constructed in bricks. George Watson Buck (1789–1854), one of the greatest experts on skew arches, wrote *A practical and theoretical essay on skew arched bridges* in 1830, which is considered the definitive work about the helicoidal skew arch.
In 1855 Francis Bashforth (1819-1912) wrote a treatise on the construction of oblique bridges, with a chapter dedicated to the helicoidal method. Despite expressing several objections on helical spiral courses, he shows that it was the best method. He used an easy language for masons who should have to build bridges in practice. During all the 19th century, several scholars from different backgrounds continued to debate about the rules to properly build an oblique bridge.
In 1851 Jules Maillard de La Gournerie (1814-1883) wrote a *memoir* to explain the advantages of orthogonal joints, the best shapes of the arches and the relationship between oblique degree and stability. Francesco Colombani (1813-1864) introduced the helicoidal method in Italy. While in 1875 Giovanni Curioni (1831-1887) paid high attention to this construction method, and was quickly dismissive of others, given that, on his own admission, this was the



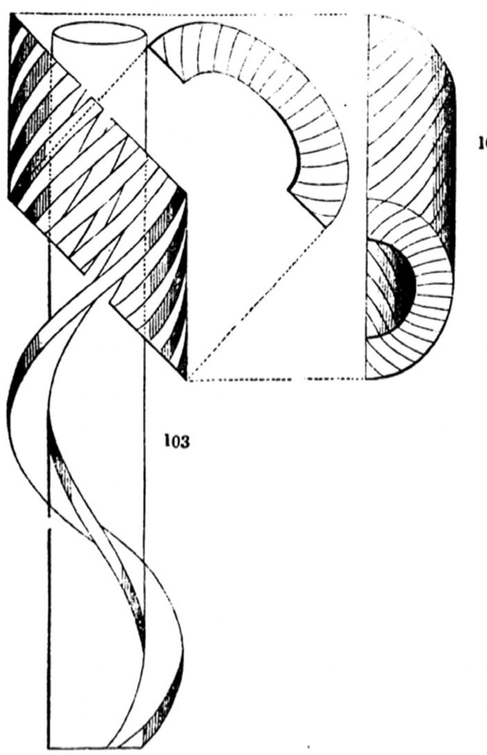


Fig. 02. Peter Nicholson, 'A Practical Treatise on the Art of Masonry and Stone Cutting' (M. Taylor, 1839): Chapter III, 'On Oblique Arches', Plate 10.

Fig. 03. Charles Fox - The Architectural Magazine, Vol III (ed. Laudon): Plate from Fox's article, "On the Construction of Skew Arches".

only that could be conveniently used. His manual is rich in suggestions for problem-solving in specific instances (fig. 04). The international debate about the skew bridges construction methods seemed to be concluded with the agreement that the orthogonal equipment was better able to give stability, but the helicoidal one was easier to build [De Paola 2009].

Case study

The proposed case study is a skew masonry bridge located in Linguaglossa, about 40 kilometres far from Catania. The bridge is located along the narrow-gauge regional railway Circumetnea, constructed between 1889 and 1895. It is one of the numerous works of art built in an extraordinarily short time, considering the technology and the availability of the equipment of the time, in support of the railway line [Garozzo, Santagati 2021]. The construction of the Circumetnea gave considerable impulse to the commercial activity in the Catania hinterland, which had to attract foreign investors increasingly interested in Sicilian sulphur. The construction was entrusted to the well-known English constructor and engineer Robert

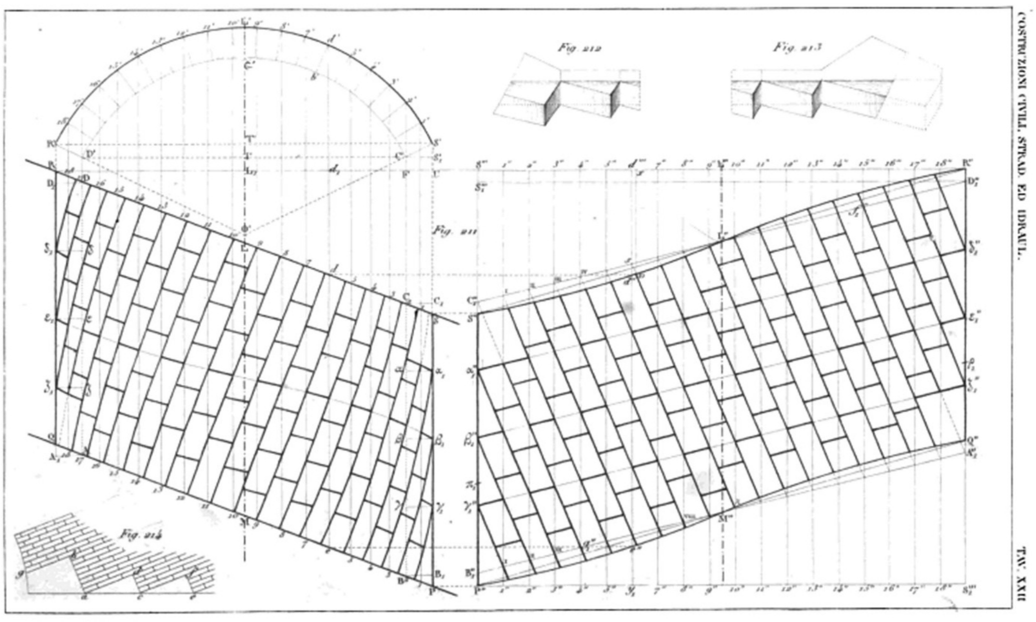


Fig. 04. Giovanni Curioni - L'arte di fabbricare: Costruzioni civili, stradali ed idrauliche (1872).

Trewhella [Sergi 1993].
The brickwork of the bridge was set out using the helicoidal method previously described. Therefore, it is possible to assume an English style influence in the design of the bridge, because this is a very unusual type of brickwork configuration in the Sicilian case.
The bridge analysed (fig. 05a) consists of a depressed-arched barrel vault lowered with an arrow equal to 0,97 m. The oblique span is 4,28 meters, the straight span is 4 meters. The width of the barrel, measured parallel to abutments, is about 3,7 m. The thickness of the brick vault is about 0,67 m, with a Flemish bonds bricklaying. The spandrel walls are in lava stone masonry as well as the abutments. The state of preservation is rather good.
Some traces of efflorescence have been found along the arch and the abutments. The low elevation of the bridge led, in time, the damaging of the intrados due to trucks that often undercross the bridge (fig. 05b).

Digital surveying

Considering the moderate height of the bridge and the easy-to-reach and reduced-traffic street where it is located, the multi-image photogrammetry data acquisition has been chosen to carry out the digital survey.
This method was also chosen for its well-known expeditious and low-cost characteristics. The shooting was conducted using a Nikon D5300, focal length of 18 mm, with a resolution of 24 MP, for a total of 296 images, taken from the ground. The GDS (ground sampling distance) is 2.9 mm/pix.
The photographic dataset was automatically processed with Agisoft Metashape. A first stage of cameras alignment was followed by a sparse and then a dense point cloud reconstruction (40.177.863 points) (fig. 06).

Fig. 05. a) The case study; b) The damages of the vault. Authors images.

Fig. 06. The dense point cloud reconstruction of the bridge. Authors elaborations.

Reverse modelling and geometrical analysis

The 3D acquisition and processing phase were followed by a graphical analysis, aiming at finding the geometrical rules underlying the design of the identified helical apparatus, to understand if it was realized according "rule of the art".
Construction and development of the real model
The point cloud has been manually segmented to extrapolate the vault. Therefore, the cloud portion was imported in CloudCompare for developing the surface. First, the Ransac Shape Detection plugin was used to estimate the best-fit cylinder. Thanks to this, it was possible to align the cloud according to the y axis and get the required information for the cylindrical unrolling (x and z coordinates), using the Unroll command. The results are the net surface of the intrados and the relating deviation map with the histogram showing the deviation distribution (fig. 07), based on which it was possible to choose the best result after several attempts. Then the unrolled point cloud, converted in a .rcp format, was imported in AutoCAD together with the other converted one to carry out the geometrical analysis aimed at the verification of the consistency "rule of art" in the helicoidal method. First, the generatrixes of the cylinder were drawn on the top and front orthographic projections and on the net surface of the intrados (fig. 08a). Then, the longitudinal helices have been traced, based on the obtained point clouds (fig. 08b).
Construction and development of the "rule of the art" model
The theoretical model has been modelled in Rhinoceros using measurements deduced from the point cloud. The constructed cylinder was sectioned by two planes inclined with a degree equal to 22. Once the surface was obtained, it was unrolled using the Unroll Surface command. Then, the result was imported in AutoCAD for the graphical analysis.
Firstly, considering the number of voussoirs on the crown, 69 generatrixes have been drawn on the intrados net and then projected both on the top and on the front. The longitudinal helices, whose direction was established by tracing a perpendicular line from the point A to the point B as a guide, according to the Curioni's method [Curioni 1875], were drawn and projected in the other orthographic view (fig. 09).

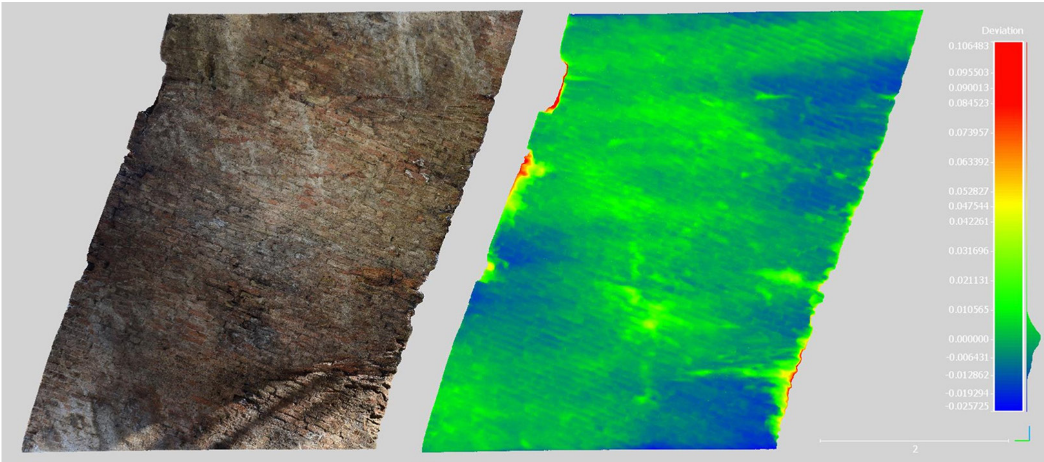
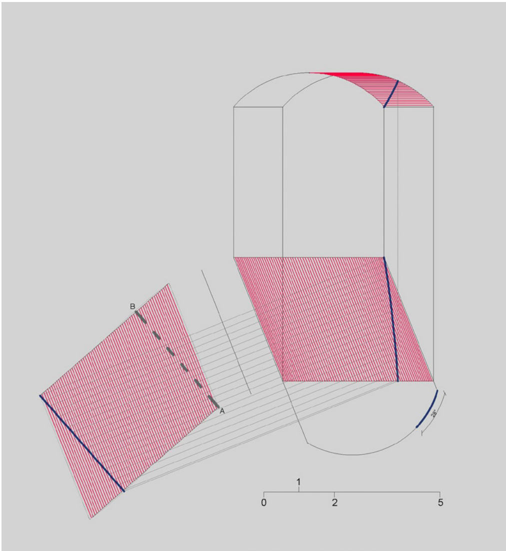


Fig. 07. The net surface of the intrados and the relating deviation map. Authors elaborations

Fig. 08. a) Generatrices of the cylinder; b) Trace plane of the longitudinal helices. Authors elaborations

Results

The comparison between the ideal and the real models was made through overlapping. From the aforementioned, no substantial differences arise. Considering the deformations due to time and the already quantified error of the point cloud, the bridge seems to be built according to the "rule of art" (fig. 10). Particularly it seems that the reference for the design of the bridge could be the Curioni Manual that is, as previously said, a collection of studies with updates, theoretical and experimental insights always careful to "art progress".



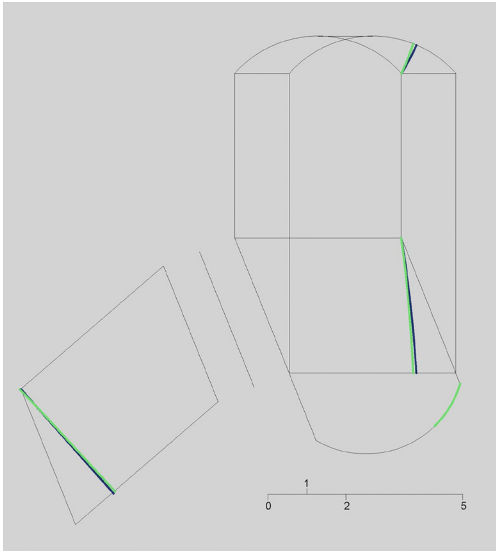


Fig. 09. The longitudinal helices construction. Authors elaboration.

Fig. 10. Comparison between the helices construction in the real and ideal model. Authors elaboration.

Conclusions

The research carried out on one of the oblique bridges of the Circumetnea railroad route showed that the construction of the vault was carried out in a workmanlike manner.Through the tools of surveying and digital representation, it was possible to investigate in depth the geometrical rules underlying the design and construction of the helical apparatus identified.Another relevant result is related to the verification of the development procedure of the numerical model, directly carried out on the point cloud starting from the geometric information measured (radius of the arc, arrow, angle of obliquity), through the evaluation of the deviation from an automatic algorithm of best fitting of the cylindrical surface.Given that the helicoidal equipment is closely related to the statics of the bridge, the subsequent stages of research will be directed to the assessment of the vulnerability of the arch to understand how much this equipment, no longer in use in construction practice, is still a technological solution of highest quality, whose knowledge can become of fundamental importance when it is necessary to undertake responsible and sustainable interventions of consolidation and conservation. Finally, another interesting research perspective can be found in the deepening of the figure of the engineer Trewhella, to understand his active contribution in the construction of this type of bridge in relation to his British cultural background.

Authors'contribution

Raissa Garozzo contributed to sections "Semi-circular skewed masonry arch bridges", "The helicoidal method in treatises", "Case study", "Digital surveying", "Reverse modelling and geometrical análisis" and "Results". Cettina Santagati contributed to sections "Introduction", "Methodological premises", "Results" and "Conclusions".

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