

Islamic domes of crossed-arches: Origin, geometry and structural behavior

P. Fuentes and S. Huerta

Polytechnic University of Madrid, Spain

ABSTRACT: Crossed-arch domes are one of the earliest types of ribbed vaults. In them the ribs are intertwined forming polygons. The earliest known vaults of this type are found in the Great Mosque of Córdoba in Spain built in the mid 10th century, though the type appeared later in places as far as Armenia or Persia. This has generated a debate on their possible origin; a historical outline is given and the different hypotheses are discussed. Geometry is a fundamental part and the different patterns are examined. Though geometry has been thoroughly studied in Hispanic-Muslim decoration, the geometry of domes has very rarely been considered. The geometrical patterns in plan will be examined and afterwards, the geometric problems of passing from the plan to the three-dimensional space will be considered. Finally, a discussion about the possible structural behaviour of these domes is sketched.

Crossed-arch domes are a singular type of ribbed vaults. Their characteristic feature is that the ribs that form the vault are intertwined, forming polygons or stars, leaving an empty space in the centre. The fact that the earliest known vaults of this type are found in the Great Mosque of Córdoba, built in the mid 10th century, has generated a debate on their possible origin. The thesis that appears to have most support is that of the eastern origin. This article describes the different hypothesis, to then proceed with a discussion of the geometry. Geometry is a topic that has been thoroughly studied in Hispanic-Muslim decoration; however, the geometry of domes has very rarely been considered. Also, the function of the ribs has never been discussed, in contrast with the abundant literature on gothic ribs. In what follows, we will give first a historical overview of the evolution of this structural type. Then the geometrical patterns in plan will be examined. Afterwards, the geometric problems of passing from the plan to the three-dimensional space will be considered. Finally, a discussion about the possible structural behavior of these domes will be given.

1 HISTORICAL DEVELOPMENT

The first examples known appear in Al-hakam II's extension of the Great Mosque of Córdoba, between the years 961 and 965. Four domes were constructed during these years (Fig.1.a); three of them close to the mihrab, while the fourth was built in the place where the old mihrab of Abd al-Rahman II's mosque used to be.

The mosque of Bib al-Mardum or Cristo de la Luz, in Toledo, appears ca. 50 years later. A full catalogue of possible solutions for crossed-arch domes is offered in this building (Fig.1.b). Each of the nine bays has a different layout, some repeating what had already been seen in Córdoba, while others will have an influence in later buildings, as we will see.

Throughout the 11th century, other crossed-arch domes are built, such as the one in the Tornerías Mosque, or that in the Belén Chapel, in the convent of Santa Fe, both in Toledo. Another example is the small dome covering the niche located over the central column of the church of San Baudelio de Berlanga, in the province of Soria.

From the end of the 10th century, ribbed domes appear in Armenia and Persia, featuring, however, important differences between them. Muslim architecture employs a network of thin ribs, made of brick, and multiplies intertwining between them, creating polygons or stars. Geometry acquires a key role in these domes. In Armenia, nonetheless, large arches are built in good quality stone voussoirs. Armenian builders divide the vault in parts, while Arab builders

make use of the ribs to organize the decorative brick bond in the webs, but always constructing a homogeneous intrados. The scale is also different: in Armenia, these vaults are elements applied to the whole of the building, while in Muslim architecture the vault only covers part of the room (Baltrusaitis J., 1939).

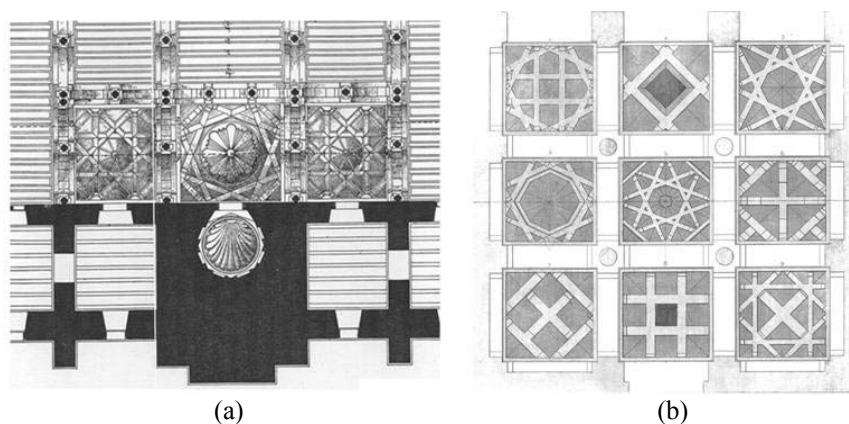


Figure 1 : (a) Plan of the domes of the maqsura in the Great Mosque of Córdoba, (b) Domes of Cristo de la Luz

Towards the end of the 12th century, two types of vaults can be distinguished. On one hand, in Christian architecture, the vaults feature thick ribs, usually creating drawings based on the square or the octagon. Various examples can be found in Spain and the South of France. In Islamic architecture, on the contrary, the number of ribs increases while their thickness is reduced, and the domes often feature stalactite ornament and fretwork webs. Some of the most important Christian examples are the churches of Torres del Río (Fig.2.a) and San Miguel de Almazán in Spain, and Santa Cruz de Olorón and San Blas Hospital in France (Fig.2.b). As far as the Islamic type is concerned, various examples are found in Spain and the North of Africa. It is worth mentioning those of the Toro-Buiza house, in the Alcazar of Seville, the vaults in the Torre del Homenaje of the Villena Castle in Alicante and the vault covering the San Sebastian Chapel in Granada. Further examples can be seen in the North of Africa, such as the vault over the top floor of the Koutoubiya minaret. Also worthy of mention are the tracery vaults of Tremecen, Taza and Fez (Fig.2.c).

At the beginning of the 16th century, this type of vault is revived in Spain to be used in some of the most important ciboria, such as the ones in Zaragoza, Teruel and Tarazona (Fig.3). The vaults of these ciboria reproduce one of the designs found in Córdoba, combining the Hispanic-Muslim influences with the contemporary Gothic style. On the outside, these constructions feature a superposition of prismatic elements.

Spanish 16th Century ciboria are not the last examples of this type of domes. In the Italian Baroque, Guarino Guarini designed several churches inspired in the earlier examples and built the dome of San Lorenzo in Turin using crossed-arches. Again in Italy, in the 18th century Vittone included these vaults in some of his buildings, such as the Chapel of San Luigi Gonzaga. Even in the 20th century some examples of crossed-arch vaults have been produced. In Spain, Luis Moya roofs some of the most important constructions of his architectural production with these domes, including the Chapel of the Universidad Laboral in Zamora or the parish church of Torrelavega, in Cantabria.

2 ORIGIN

The theories on the origin of these domes are diverse. The first known domes are those of the Great Mosque of Cordoba, but the level of complexity and perfection achieved in these domes is sufficient to consider that earlier examples must have existed.

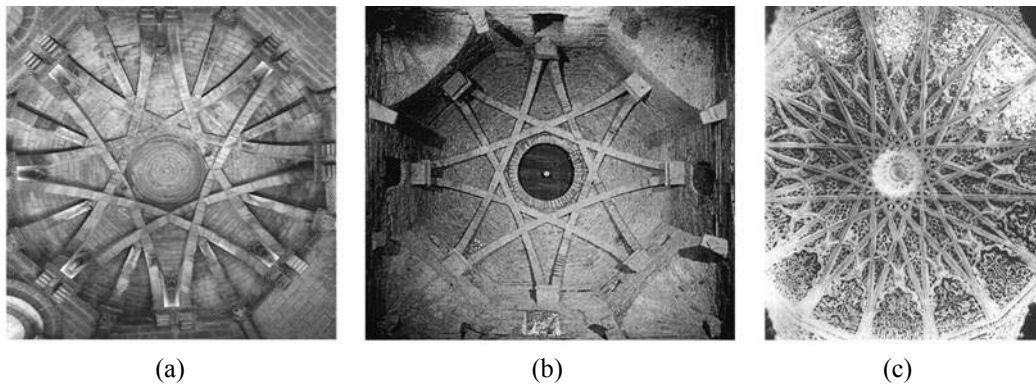


Figure 2: (a) Torres del Río, (b) Santa Cruz de Olorón, (c) Mosque of Taza (Terrasse 1943)

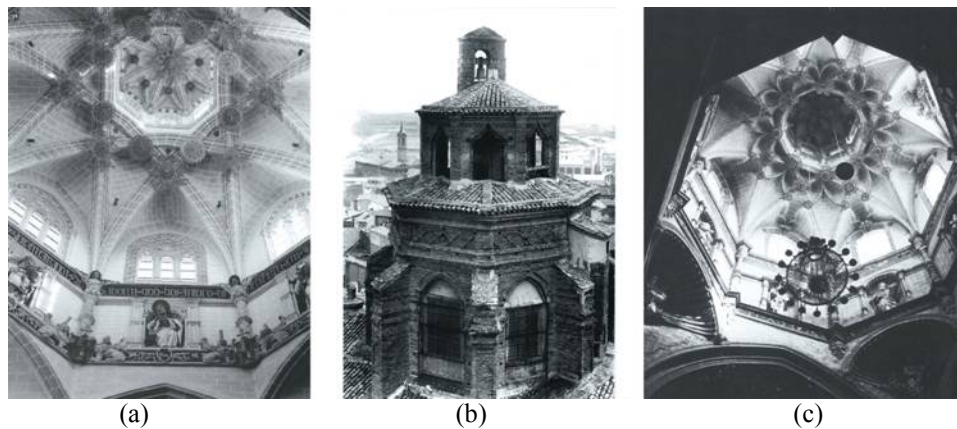


Figure 3 : Spanish ciboria: (a) and (b) Zaragoza interior and exterior views, (c) Tarazona

The ‘official’ theory maintains that crossed-arch domes are of Eastern origin. However, this theory has not yet been proved. Marçais suggests the possibility that earlier plane crossed arch examples may have resulted in the use of crossed arches in domes: “Le même architecte était, à la rigueur, capable d’imaginer ces deux applications si curieuses du même principe”. However, in the Spanish edition of 1983 he supports the theory that these vaults come from Persia. Velázquez Bosco (1894) suggests the possibility that these domes are the masonry interpretation of timber domes constructed in some parts of Asia Minor, which features a hole in the centre for fume extraction. Lampérez supports the theory of Velázquez Bosco. Terrasse is of the opinion that the origin is in the arches that originally framed the squinches and believes that these vaults must have originated in Mesopotamia or Persia. After Godard’s work, Terrasse supports the theory of the Persian origin. Baltrusaitis, in *Le problème de l’ogive et l’Arménie*, presents the differences and similarities between Armenian and Arab domes. He believes that ribs only carry a structural function in Armenian domes, while in those of Arab origin, ribs are merely decorative. He compares these ribs with the geometric patterns that appear in ornaments. Despite the oldest examples of this ribbed system are found in the west, he believes that it did not originate in the west, but in the east. He rules out the hypothesis of eastern examples originating from the western ones, and considers them to be two independent events developed in parallel: “Les ogives arméniennes et les coupôles d’Islam seraient deux formations indépendantes et parallèles inspirées par un modèle unique, l’une interprétée par des géomètres, l’autre par des architectes” (Baltrusaitis J., 1936). Lambert points at the domes of the great mosques of Kairouan (836) and Tunis (864) as possible precedents of the domes in Cordoba, for they are chronologically located between the extension of the mosque by Abd ar-Rahman III and Al-Hakam II. He emphasizes the evolution between the pumpkin dome of Kairouan, and the dome of Tunis, featuring arches with rectangular section between the domes webs. Gómez-Moreno proposes a possible Mesopotamian origin (Gómez Moreno M., 1951). Galdieri supports this theory. Pavón Maldonado writes about a possible origin in Roman antiquity. The

last book on the subject by Giese-Vogeli doesn't give new evidence or theories. It appears that the matter is still not settled.

3 GEOMETRY

Geometry is a key feature of crossed-arch vaults. There is an enormous range of possibilities for the design of the plan projection of these vaults. However, spatial geometry must be simultaneously considered, as some designs might present incompatibilities in their geometry when implemented in three dimensions. Different layouts are used that adapt to the requirements of each particular case. As we have seen, three different layouts can be found in the four domes of Córdoba. Fifty years later, with the construction of the nine domes of Cristo de la Luz, almost all the possible layouts are finally defined, and most of what was built afterwards was based in these designs.

The octagon is possibly the most used figure in the layout design of these vaults. Octagons can be obtained in different ways. One of the most common methods consists in dividing the sides of a square in three parts, and placing eight ribs spanning between the internal divisions, so that two ribs arrive at each point, one rib parallel to the side of the square, and the other in the diagonal direction. According to the ratio between the divisions, the design in plan is different.

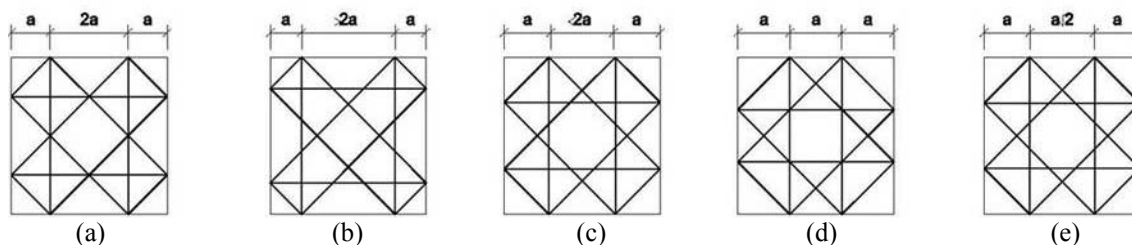


Figure 4 : Design variations obtained from the same initial diagram

Two squares are always present in the centre, rotated by 45° . When the side of the square is divided so that the middle section is smaller than twice the lateral sections (Figs.4.c and 4.e), an octagon is created in the middle. Furthermore, if the proportion of Fig.4.e is met, the octagons, both the external and the internal one, will be regular polygons, and all ribs will be equal, making construction a lot easier. The latter two are among the most common cases. They appear in the lateral domes of the maqsura in the Great Mosque of Cordoba, in the Belén Chapel and in the Spanish ciboria in Aragon. These designs can adapt to real plans, such as the ciboria of Zaragoza and Teruel; where the plans are not square, but the same scheme is adopted. These changes in plan have a large impact on the final spatial arrangement. While ribs for square layouts could be semi-circular, in the case of a rectangular layout they can't be so, for they would then not cross each other.

One other common layout, especially in the 12th and 13th centuries in Spain, is that found for the first time in the dome of Cristo de la Luz. From an octagonal layout, ribs spring in pairs from the middle points of each side, defining another octagon in the centre. All ribs are equal in this case. The octagon must be regular in order that the ribs meet in space. This pattern is also found in Torres del Río and Almazán in Spain; and Olorón and the Hospital of San Blas in the South of France. In San Miguel de Almazán the layout of the transept is a skew square, and thus the ribs cannot all be equal, but those that are parallel will be. Further ahead we will talk about what happens at a spatial level in these cases, Fig.5.

Another scheme found in Cristo de la Luz is the one shown in Fig.6.a. Starting from a square plan, ribs are drawn from the centre of the square to a corner. All ribs are equal in this case. The scheme can also be found at the Hospital of Santa Cruz in Toledo (Fig.6.b), where four additional ribs are added spanning from a corner of the square to a corner of the octagon, and at the Purificación chapel in the cathedral of Tarazona (Fig.6.c), where the scheme becomes more complex with the introduction of curved ribs.

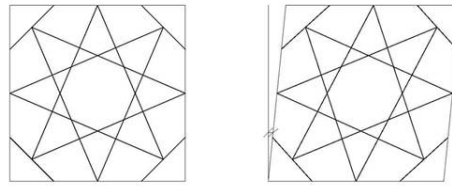


Figure 5 : Plans of Torres del Río (left) and Almazán (note the slight skew of the plan)

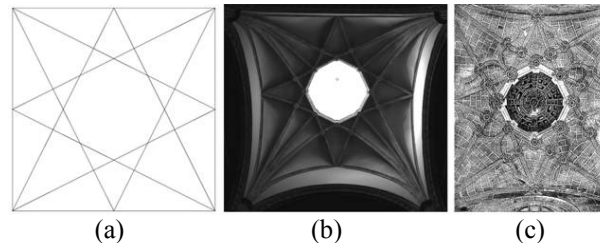


Figure 6 : (a) Schematic plan, (b) Hospital de la Santa Cruz, (c) Capilla de la Purificación

In the central dome of the Great Mosque of Cordoba we find a scheme originated from two squares rotated in plan, and inscribed inside a third square (Figs.7.a and 7.b). Thus, an octagon is again drawn both inside and outside. In order that these two octagons are regular, the relationships given in Fig.7 must be met, or, equivalently, the initial two squares must be rotated by a 22.5° angle with respect to the external square. This scheme is also found at the Almoravid quba in Marrakech (Fig.7.c)

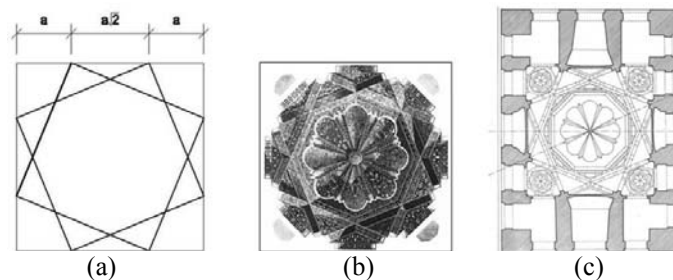


Figure 7 : (a) Schematic plan, (b) Central dome in the maqsura of the mosque of Córdoba, (c) Quba of Marrakech (Meunié and Terrasse 1957).

In all the designs described above, the ribs spring in pairs. However, there are other domes in which ribs spring individually; Torres Balbás attributes these constructions to the Almohads or their influences. There are various examples of this kind of vaults: the vault in the tower at the prison of Alcalá la Real, the chapel of la Asunción in the monastery of las Huelgas, or the vault over the first floor of the Tower of the Homenaje at the castle of Villena (Fig.8). Similar to these three, but incorporating some particularities, is the Chapel of Talavera in the old cathedral of Salamanca (Fig.9, left). In this case, each rib spans from a corner of the octagon to the mid-point of a side, skipping four corners. Eight equal ribs thus appear, each one parallel to another one, but not parallel to the sides of the octagon.

A further singular design is found at the Chapel of Villaviciosa Fig.9, right), in the Great Mosque of Cordoba. The plan is rectangular, measuring 7.35 x 8.35 m (Gómez Moreno, 1951). Four arches, parallel to the sides of the rectangle, cross forming a square. A further four arches form a diamond inscribed in the plan. The latter four arches cross the earlier four at the corners of the square, so that three arches cross at one point.

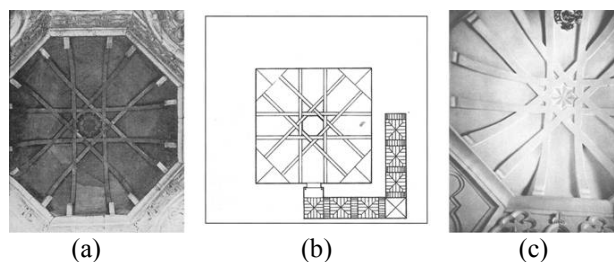


Figure 8 : (a) Minaret of the Koutoubitya (Basset and Terrase 1926), (b) Alcalá la Real (Pavón Maldonado, 2009), (c) Chapel of la Asunción (Torres Balbás, 1949).

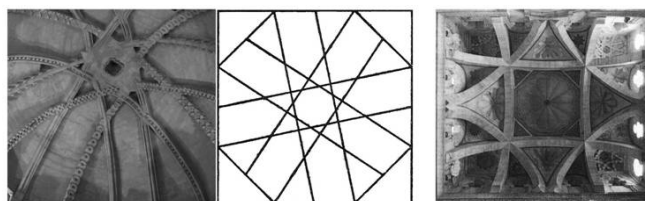


Figure 9 : Chapel of Talavera: Photo and plan layout (left) Chapel of Villaviciosa

When transferring these schemes on plan to three dimensional designs, we come across different cases. For the simplest one, ribs are contained in a spherical surface, as is the case of the Hospital of Santa Cruz, or the vaults of the maqsura of the Great Mosque of Cordoba. Furthermore, all arches can be equal. In the first case, the square layout is defined by four arches, so that the mid points of the square are higher than the corners. The ribs, therefore, are rampant arches (Fig. 10).

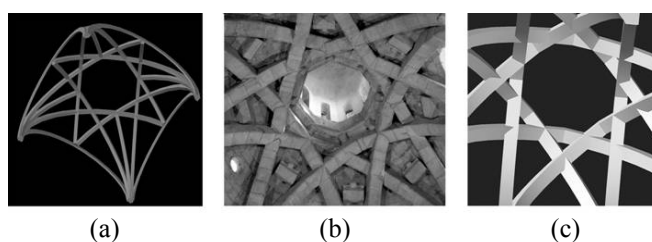


Figure 10 : Spatial layouts: (a) Hospital of Santa Cruz and (b), (c) San Miguel de Almazán (Martínez de Aguirre and Gil Cornet, 2004)

In the case of using pointed arches, as in Torres del Río, the arches cannot be contained in a sphere. Nonetheless, if the octagon is regular, all arches will be equal and will cross in space. Problems appear when the octagon is not regular, as is the case of San Miguel de Almazán. As seen above, the arches cannot all be equal and their axes don't cross. A possible solution would be not to consider this problem, making all arches instead with the same curvature and with a vertical springing. Accepting this hypothesis, if the distances between the axes of the arches are measured at the points where they would theoretically cross, these distances are found to lie between 11 and 91 mm, that is, between 0.2 and 1.5% of the total span of the vault. Carefully observing the intersections between ribs, it is indeed possible to see small differences in level between the crossing arches (Fig.10.b, 10.c). In any case, this is only a hypothesis and a detailed survey of the vault's geometry would be necessary to either corroborate or dismiss it.

4 STRUCTURAL BEHAVIOR

A crossed-arch dome is a ribbed vault. The question arises as to the actual function of the ribs in supporting the dome. This question has been debated for more than two centuries in relation to the gothic rib, but it has been rarely, if ever, posed in relation to crossed-arch domes (Frankl,

1960). One reason may be the emphasis on decoration of the studies on Muslim architecture. Ribs are considered mostly as decorative. However the size of the arches in the vaults of the Maqsura of Córdoba, in the Armenian domes and in the Spanish ciboria does not fit with this hypothesis. Besides, recent constructive studies (Galdieri, 1981) made on ribbed Persian domes has demonstrated that the thinness of the arches is only apparent, as the ribs project to the outside of the extrados, as may be easily seen in Fig.11.

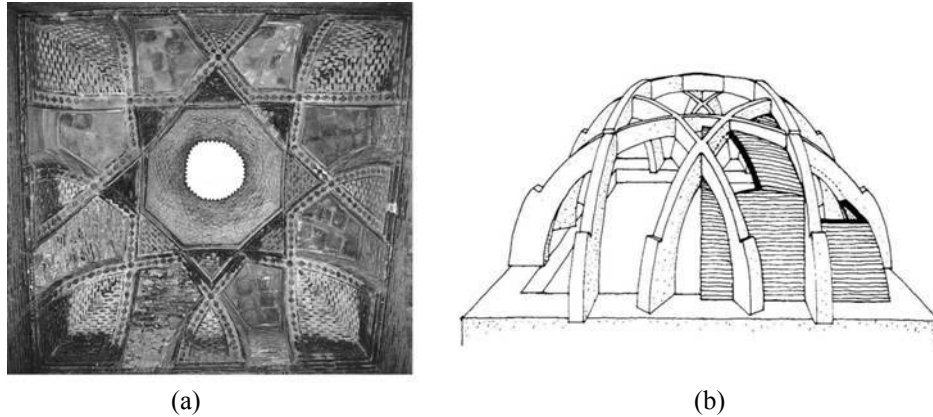


Figure 11 : Vault 60 of the mosque of Isfahan, ca. 1100. (Galdieri, 1981)

In Gothic architecture, there is wide agreement that the ribs serve to define the geometry of the vault and form a permanent centring during construction. Besides, they cover the groin hiding the difficult encounter of the masonry of the webs. What was at the heart of the debate was the structural function of the rib. Are the ribs the active structure and the webs only a passive load, or, on the contrary, the ribs have merely decorative? (The first theory corresponds to Viollet-le-Duc and Choisy and was considered right until the 1930's. The second originated in the work of V. Sabouret and, above all, P. Abraham (Huerta, 2009)). If this question is pertinent for gothic vaults it will be also pertinent in the case of the Muslim ribbed vaults and domes. However, the whole matter of the structural behavior of Islamic vaults and domes has been so far neglected. This is curious as some scholars have (Lambert, 1928, Torres Balbás, 1935, Pope, 1963) seen the very origin of the gothic rib in the earlier crossed-arch domes.

The recent book by Giese-Vogeli tackles briefly the matter of the structural behavior of crossed-arch domes, mainly with reference to the gothic debate. Giese-Vogeli, after a brief review of modern literature, takes side with Abraham: "We know today that the ribs do not carry the vault shell". However, she doesn't seem consider the modern theory of Limit Analysis of Masonry Structures, developed mainly by Jacques Heyman since 1960's (Heyman, 1995). It is only within the correct frame of Limit Analysis, which leads to the approach of equilibrium, that masonry structures of any kind can be understood. The whole debate of the function of the rib has been obscured by the false supposition that there is an "actual" observable state of the structure (Heyman, 1968, Huerta, 2009). In fact, in a hyperstatic structure there are infinite possible states of equilibrium and the actual state cannot be find, depending mainly on small variations of the boundary conditions (Heyman, 2008). Then, depending on the specific situation the rib may or may not carry, the shell may be supported or not, or, perhaps, a certain indeterminate amount is supported by the ribs and the rest by the shell, and the proportion may vary with time.

REFERENCES

- Amador de los Ríos J., 1877. Mezquitas llamadas del Santo Cristo de la Luz y de las Tornerías, Monumentos arquitectónicos de España. Madrid: Fortanet y Calcografía Nacional.
- Baltrusaitis J., 1936. Le problème de l'ogive et l'Arménie. Paris.
- Baltrusaitis J., 1939. La croisée d'ogives dans l'architecture transcaucasienne. Recherche 1, p.73-92.
- Frankl P., 1960. The Gothic: Literary Sources and Interpretations Through Eight Centuries. Princeton: Princeton University Press.

- Galdieri E., 1981. Contributi alla conoscenza delle strutture a nervature incrociate. *Rivista degli studi orientale* 57, p.61-75.
- Giese-Vögeli F., 2007. *Das islamische Rippengewölbe. Ursprung, Form, Verbreitung*. Berlin: Geb.Mann.
- Godard A., 1949. Voûtes Iraniennes. *Athar-E-Iran, Ann. Service Archéologique de l'Iran* 4, p.187-345.
- Gómez Moreno M., 1951. El arte árabe español hasta los almohades. *Arte mozárabe*. Madrid: Plus Ultra.
- Heyman J., 1968. On the Rubber Vaults of the Middle Ages. *Gazette des Beaux-Arts* 71, p.177-188.
- Heyman J., 1995. *The Stone Skeleton. Structural Engineering of Masonry Architecture*. Cambridge: Cambridge University Press.
- Heyman J., 2008. *Basic Structural Theory*. Cambridge: Cambridge University Press.
- Huerta S., 2009. The Debate about the Structural Behaviour of Gothic Vaults: From Viollet-le-Duc to Heyman. *Proc. Third Int. Congress on Construction History, Cottbus*, p.837-844
- Ibáñez Fernández J., 2007. Los cimborrios aragoneses en el siglo XVI Tarazona (Zaragoza): Centro de Estudios Turiasonenses de la "Institución Fernando el Católico".
- Lambert E., 1928. Les voûtes nervées hispano-musulmanes et leur influence possible sur l'art chrétien.. *Hesperis* 8, p.147-175.
- Lambert E., 1939. La croisée d'ogives dans l'architecture islamique. *Recherche* 1, p.57-71.
- Lampérez V., 1899. Segovia, Toro y Burgos: observaciones sobre algunos de sus monumentos arquitectónicos de la Edad Media. Madrid: Hijos de M. G. Hernández.
- Marçais G., 1926. *Manuel d'art musulman. L'architecture Tunisie, Algérie, Maroc, Espagne et Sicilie*. 2 vols. Paris: Auguste Picard.
- Marçais G., 1983. *El arte musulmán*. Madrid: Cátedra.
- Martínez de Aguirre J. and Gil Cornet L., 2004. *Torres del Río. Iglesia del Santo Sepulcro*. Edited by D. d. C. y. t. Gobierno de Navarra and I. P. d. Viana.
- Meunié J. and Terrasse H., 1957. *Nouvelles recherches archéologiques à Marrakech* Edited by I. d. h. é. marocaines, Publications de l'Institut des hautes études marocaines. Paris.
- Nizet C., 1905. *La mosquée de Cordoue*. Paris: Libraire Générale de l'architecture et des travaux publics.
- Pavón Maldonado, B. 1975. La decoración geométrica hispanomusulmana y los cimborrios aragoneses de tradición islámica. *Actas del I Simposio Internacional de Mudejarismo (Teruel)*.
- Pavón Maldonado B., 2009. *Tratado de arquitectura hispanomusulmana*. 4 vols. Madrid: Consejo Superior de Investigaciones Científicas.
- Pope A.U., 1963. Possible Iranian contributions to the beginning of gothic architecture. In: *Beiträge zur Kunstgeschichte Asiens*. In Memoriam Ernst Diez, ed. by O. Aslanapa. Istanbul, p.1-29
- Terrasse H., 1932. *L'art hispano-mauresque des origines au XIII siècle*. Paris: G. Van Oest.
- Terrasse H., 1943. *La grande mosquée de Taza*. Paris: Les Éditions d'Art et d'Histoire.
- Torres Balbás L., 1935. La progenie hispano-musulmana de las primeras bóvedas nervadas francesas y los orígenes de las ojivas. *Al-Andalus* 3, p.398-410.
- Torres Balbás L., 1940. La bóveda gótico-morisca de la capilla de Talavera de la Catedral Vieja de Salamanca. *Al-Andalus* 5:1 (Crónicas Arqueológicas de la España musulmana, VI), p.174-178.
- Torres Balbás L., 1949. *Arte almohade, arte nazarí, arte mudéjar*. Madrid: Plus Ultra.
- Velázquez Bosco R., 1894. *Discurso de recepción del Excmo. D. Ricardo Velázquez Bosco en la Real Academia de Bellas Artes de San Fernando*

ARCH'10

6th International Conference on Arch Bridges

Proceedings of the

6th International Conference on Arch Bridges

October 11-13 2010

Edited by:

Baochun Chen, Jiangang Wei

College of Civil Engineering, Fuzhou University, Fuzhou, China

Copyright 2010, College of Civil Engineering, Fuzhou University, Fuzhou, China

All rights reserved. No part of the contents of this publication may be reproduced or transmitted in any form or by any means without the written permission of the publisher.

Fax: +86 591 2286 5355

e-mail: arch10@arch-bridges.cn

baochunchen@fzu.edu.cn

Printed in China

International Scientific Committee

| | |
|----------------------------------|-------------------------------|
| Clive Melbourne (UK) | Anna Sinopoli (Italy) |
| Charles Abdunur (France) | Pere Roca (Spain) |
| Paulo Lourenco (Portugal) | Enzo Siviero (Italy) |
| Jure Radic (Croatia) | Dongzhou Huang (USA) |
| Jiri Strasky (Czech) | Baochun Chen (China) |
| Yuanpei Lin (China) | Yonglin Pi(Australia) |
| Lichu Fan (China) | Jielian Zheng (China) |
| Maorun Feng (China) | Iroshi Hikosaka (Japan) |
| Kazuo Takahashi (Japan) | Bijaya Jaishi (Nepal) |
| Robert D. Turton (USA) | Jan Bien (Poland) |
| Carlos Fernandez Troyano (Spain) | Sunggul Hong (Korea) |
| Andrzej S. Nowak(USA) | Tonlo Wang (USA) |
| Carlos Fernandez Troyano (Spain) | Christian Kohlmeyer (Germany) |

Organising Committee:

Baochun Chen (Fuzhou University), President

Bruno Briseghella (Fuzhou University)

Jiangang Wei (Fuzhou University)

Qingxiong Wu (Fuzhou University)

Organizer



Sponsors



Publisher: SECON-HDGK

Print & Bound: New Art Color-Plate & Printing Co., LTD., Fujian, China

ISBN: 978-953-7621-10-0

A CIP catalogue record for this book is available from the National and University Library in Zagreb under 743538.

This book contains 117 papers that were presented during the 6th International Conference on Arch Bridges, which was held in Fuzhou, China from October 11-13, 2010.

Proclaim:

The papers are published in the form submitted by the authors and revised by the Scientific Committee. The Editors cannot take any responsibility for possible errors or discrepancies.

Contents

Invited lectures

| | |
|--|-----------|
| The new Mike O’Callaghan Pat Tillman Memorial Bridge at Hoover Dam..... | 1 |
| <i>David Goodyear and Robert Turton</i> | |
| Recent development of arch bridges in China..... | 9 |
| <i>Maorun Feng</i> | |
| Dynamic monitoring of the Paderno iron arch bridge (1889)..... | 22 |
| <i>Carmelo Gentile and Antonella Saisi</i> | |
| Stress ribbon & arch pedestrian bridges..... | 38 |
| <i>Jiri Strasky</i> | |

Special session I: new arch bridges and future trends

| | |
|--|------------|
| Concept and construction methods of arch bridges in Italy..... | 49 |
| <i>S. Palaoro, E. Siviero, B. Briseghella and T. Zordan</i> | |
| Engineering innovation in arch design..... | 58 |
| <i>M. Kasi and I. Darwish</i> | |
| Aesthetics conceivability and structural characteristics of Dagu Bridge..... | 67 |
| <i>Zhendong Ma</i> | |
| A new multi-span arch bridge over the Piave River in Venice: conceptual design and structural optimization..... | 74 |
| <i>B. Briseghella, L. Fenu, C. Lan, E. Mazzarolo, E. Siviero and T. Zordan</i> | |
| Steel arch bridges in Croatia-past and present..... | 83 |
| <i>Z. Savor, J. Radic and G. Hrelja</i> | |
| New Bridge over Llobregat River..... | 91 |
| <i>Marcos J. Pantaleón, Roberto Revilla and Patricia Olazábal</i> | |
| State-of-the-art of steel arch bridges in China..... | 98 |
| <i>Kangming Chen, Qiu Zhao, Shozo Nakamura and Baochun Chen</i> | |
| Design & technology characteristics of main bridge of Chaotianmen Yangtze River Bridge..... | 107 |
| <i>Xuwei Duan, Xiaoyan Xiao and Wei Xu</i> | |
| Scheme design of a 530m CFST arch bridge--the First Yangtze River Bridge in Hejiang, Sichuan, China..... | 113 |
| <i>Tingmin Mou, Bikun Fan, Bo Tian and Qiyu Tao</i> | |
| Trial design of tied CFST arch bridge with steel web PC tied beam..... | 120 |
| <i>Chao Sun, Fan Zhang and Baochun Chen</i> | |
| Trial design of a reactive powder concrete (RPC) arch bridge with a span of 420m..... | 126 |
| <i>Renyuan Du, Jian Yu and Baochun Chen</i> | |

| | |
|---|-----|
| Analysis of a flexible concrete arch | 133 |
| <i>John Bourke, Su Taylor, D Robinson and Ae Long</i> | |

Modern arch bridges

| | |
|--|-----|
| Los Tilos arch on La Palma Island | 143 |
| <i>Santiago Pérez-Fadón, José Emilio Herrero and Juan José Sánchez</i> | |

| | |
|---|-----|
| The arch bridge over the Serchio (LU), Italy | 151 |
| <i>Massimo Viviani</i> | |

| | |
|--|-----|
| Design of 400m net span deck-type steel truss arch bridge over Chongqing Daning River | 157 |
| <i>Yuancheng Peng, Gujian Huang, Wenjun Wang and Meijun Fan</i> | |

| | |
|--|-----|
| Long-span deck-type CFST arch bridge combined with diagonal cable | 163 |
| <i>Y. Liu, X. ShangGuan and J. Liu</i> | |

| | |
|--|-----|
| Design of Hubei Zhijing River Bridge | 167 |
| <i>Yuancheng Peng, Yiqian Li and Xiaohong Long</i> | |

| | |
|---|-----|
| A twin diverging arches bridge in Milan Portello | 172 |
| <i>Pier Giorgio Malerba, Paolo Galli and Marco di Domizio</i> | |

| | |
|---|-----|
| Design and construction of the balanced arch bridge on the deep foundation | 180 |
| <i>Jae-Ho Jung, Jae-Hong Kim, Hyo-Chang Yoon and Woo-Jong Kim</i> | |

| | |
|--|-----|
| Design and construction techniques of Daning River Bridge | 188 |
| <i>Shuixing Zhou, Xiaoping Du, Dan Li and Yongsheng Duan</i> | |

| | |
|---|-----|
| Design and research of composite-arch-rib bridge | 194 |
| <i>Ying Li, Xiangyu Feng and Huxiang Tang</i> | |

| | |
|---|-----|
| Footbridge Ronda Bahía, Santander (Spain) | 202 |
| <i>Marcos J. Pantaleón, Roberto Revilla and Patricia Olazábal</i> | |

| | |
|--|-----|
| A steel suspended deck arch bridge over “Torrente Gravina” | 210 |
| <i>A. De Luca, A. De Martino, F. Leccisi, G. Lucibello, F. Ricciardelli, G. Mautone, C. Briatico, V. Caputo, A. Medici and G. Napoli</i> | |

| | |
|--|-----|
| A newly developed technique for the design of the Jialing River Bridge in Guangyuan (China) | 218 |
| <i>Jian Liang, Tingmin Mou, Yu Xiao and Qiyu Tao</i> | |

| | |
|--|-----|
| Cycle-pedestrian bridge to connect Via Isonzo and Via Vittorio Veneto next to “Rari Nantes” sports facilities | 225 |
| <i>Enzo Siviero and Lorenzo Attolico</i> | |

| | |
|---|-----|
| Design of Shenyang Sanhao Bridge (China) | 229 |
| <i>Guoxiang Liu and Zhendong Ma</i> | |

| | |
|--|-----|
| The heritage and development of the stone arch bridges in China | 234 |
| <i>B. Wang, S. Tang and X. ShangGuan</i> | |

| | |
|---|-----|
| Sustainable bridge constructions–elegant arches–filigree structures–cost effective design | 243 |
| <i>O. Josat</i> | |
| Research and application of concrete filled steel tube arch bridge | 255 |
| <i>Zhongfu Xiang and Anbang Gu</i> | |
| A new way to design suspenders for through and half-through arch bridges | 262 |
| <i>R.J. Jiang, Y.Y. Chen, Q.M. Wu, W.M. Gai and D.M. Peng</i> | |
| Optimal network arches for road and rail bridges | 271 |
| <i>Per Tveit</i> | |
| A large span roof made of cable stayed arches | 279 |
| <i>Pier Giorgio Malerba, Paolo Galli, Marco di Domizio and Giacomo Comaita</i> | |
| Tensegrity footbridges with arch deck: static and dynamic behaviour | 287 |
| <i>Bruno Briseghella, Luigi Fenu, Wenjin Huang and Tobia Zordan</i> | |
| Historical arch bridges | |
| Corbelling domes and bridges in Spain and Portugal: a comparative study | 297 |
| <i>Fernando Vegas- López Manzanares, Camilla Mileto and Valentina Cristini</i> | |
| The Hannibal Bridge: history and structural behaviour | 304 |
| <i>M. Lippiello, L. Bove and L. Dodaro</i> | |
| S. Teresa’s Bridge along Lama Balice in Bitonto (Italy) | 312 |
| <i>Tommaso Maria Massarelli</i> | |
| Construction techniques of Roman vaults and opus caementicium: The cases of Lupo and St. Gregory’s Bridges | 319 |
| <i>Sinopoli A., Basili M. and Esposito D.</i> | |
| Force flows in the oldest observatory of stone masonry in Korea | 326 |
| <i>Sung-Gul Hong, Namhee Kim Hong and Byung-Sun Bae</i> | |
| Line of thrust and theoretical load of masonry arch bridge | 332 |
| <i>Mitsuo Tsutsui, Yoji Mizuta and Tsutomu Sakata</i> | |
| Arches in masonry structures: Viollet-le-Duc’s rationalist theories | 338 |
| <i>I. Tarrío</i> | |
| Islamic domes of crossed-arches: Origin, geometry and structural behavior | 346 |
| <i>P. Fuentes and S. Huerta</i> | |
| Coulomb’s theory of arches in Spain ca. 1800: the manuscript of Joaquín Monasterio | 354 |
| <i>A. Albuerne and S. Huerta</i> | |
| Load rating of existing masonry arch bridges in USA | 363 |
| <i>Xuezeng Wu</i> | |

| | |
|--|------------|
| Development of static analytical method for mechanical behavior of stone arch bridges..... | 370 |
| <i>Toshitaka Yamao, Kenjiro Yamamoto, Teruhiko Kudo, Kazuya Ogami and Hideki Nakamura</i> | |
| Numerical simulation of stone masonry arch bridges behaviour under road traffic moving loads..... | 379 |
| <i>C. Costa, A. Arêde and A. Costa</i> | |
| The theory and application of plane-hinged arch in the stone arch bridges..... | 387 |
| <i>Y. Yan, H. Xu, X. ShangGuan and Y. Liu</i> | |
| Geometric analysis and load capacity of masonry arch bridges: a case study from Northwest Iberian Peninsula..... | 391 |
| <i>Daniel V. Oliveira , Cláudia Lemos and Paulo B. Lourenço</i> | |
| Historical stone arch bridges under horizontal debris flow impact..... | 399 |
| <i>Klaudia Ratzinger and Dirk Proske</i> | |
| Investigation of the historical Osobowicki Bridge in Wroclaw..... | 405 |
| <i>Tomasz Kamiński, Jan Bieñ, Mieszko Kuźawa and Józef Rabiega</i> | |
| Removed, rebuilt and new timber arch bridges in China..... | 413 |
| <i>Yan Yang and Baochun Chen</i> | |
| Investigation of mechanical behavior of the Japanese historical timber arch bridge: Kintaikyo Bridge..... | 419 |
| <i>Teruhiko Yoda</i> | |
| Study on the wooden arch structure of Gansu Weiyuan Baling Gallery Bridge..... | 427 |
| <i>Enyong Wang, Jie Liu, Yuxia Hu, Yurong Hao and Xingjia Chong</i> | |
| Chinese craftsmen of wooden arched bridge..... | 431 |
| <i>Difa Gong</i> | |
| Don Bosco Bridge at Arenaccia: the architecture white as light..... | 438 |
| <i>A. De Luca, G. Lucibello, A. De Martino and G. Mautone</i> | |
| Inspection, assessment and management of arch bridges | |
| Numerical analysis of masonry arch bridges: benefits and limits of damage mechanics..... | 449 |
| <i>N. Domède and A. Sellier</i> | |
| Structural analysis and strengthening intervention of the multispans stone masonry bridge of Ribellasca, between Italy and Switzerland..... | 457 |
| <i>A. Cappini, G. Stagnitto, A. Pederzani, C. Rossi and P.P. Rossi</i> | |
| Application of limit analysis to stone arch bridges..... | 465 |
| <i>P. Clemente, G. Buffarini and D. Rinaldis</i> | |
| Limit analysis of masonry arches under vertical loads applied out middle plane..... | 473 |
| <i>C. Anselmi, E. De Rosa and F. Galizia</i> | |
| Ten stone masonry arch bridges and five different assessment approaches..... | 482 |

Niamh Gibbons and Paul J. Fanning

Development of Pippard's elastic method for the assessment of short span masonry arch bridges.....490

Jinyan Wang, Clive Melbourne and Adrienn Tomor

A new serviceability approach to masonry arch bridge assessment.....498

Tim Hughes and Lufang Wu

Castigliano based analysis of single span masonry arch bridges using a spreadsheet.....506

Lufang Wu and Tim Hughes

An identification method for short hanger tension of arch bridges.....514

Pei Yuan, Liangfeng Sun and Xu Xie

Impact factor characteristics of double parabolic arch ribs in a CFST arch bridge due to vehicle loads.....520

Dongyan Wu, Xu Xie and Guan Lin

Bridge management system for large reinforced concrete arches on Croatian Coast.....528

Jure Radić, Marija Kušter and Jelena Bleiziffer

Correlation analysis of structural stress responses and temperature of a tied arch bridge using long-term health monitoring data.....536

Yuanfeng Duan, Yi Li, Yiqiang Xiang and Bin Chen

Nonlinear calculation and evaluation method for load bearing capacity of stone arch bridge with cracking in crown and springer.....544

Jinquan Zhang, Wanheng Li and Jun Xie

Fracture development process for masonry under static and fatigue loading.....550

Adrienn Tomor and Jinyan Wang

Structural analysis and experimental studies

The polygonal arch bridge.....561

J. Radić and A. Kindij

Study of high-cycle fatigue behaviour of brick masonry.....568

Jinyan Wang, Adrienn Tomor and Clive Melbourne

Finite-element nonlinear geometric analysis for a proposal steel arch bridge over the Llobregat River in Barcelona.....576

Matías A. Valenzuela, Franco R. Rojas and Ángel C. Aparicio

Simplified design method of long- span railway soil-metal bridges.....584

Jabbar Ali Zakeri, Morteza Esmaili and Parisa Haji Abdulrazagh

Vehicle-induced vibration of steel deck arch bridges.....593

Dongzhou Huang

Testing and analysis of masonry arches subjected to impact loads.....603

Paulo B. Lourenço, Tibebe Hunegn, Pedro Medeiros and Nuno Peixinho

Tests of a composite box arch having steel truss web and concrete flange under

| | |
|--|-----|
| unsymmetrical in-plane loads | 611 |
| <i>Jiangang Wei, Yue Feng, Baochun Chen and Qingxiong Wu</i> | |
| Experimental study on the out-of-plane stability of a dumbbell-shaped CFST arch under spatial loads | 616 |
| <i>Xiaohui Li, Baochun Chen and Jiangang Wei</i> | |
| Experimental study on a steel arch rib segment with convex sections | 623 |
| <i>Kangming Chen, Qingxiong Wu, Baochun Chen and Shozo Nakamura</i> | |
| Numerical analysis of the influence of debonding on CFST single tube arch | 632 |
| <i>Junqing Xue, Baochun Chen and Bruno Briseghella</i> | |
| Effect of site condition on the seismic response of a fixed-end deck steel arch bridge and the feasibility of the pushover method | 641 |
| <i>Chengyu Liang and Airon Chen</i> | |
| Effect of hangers on structural behaviour of a concrete-filled steel tubular arch bridge .. | 651 |
| <i>Jingbin Li, Huai Chen, Sujuan Ge and Hui Qian</i> | |
| A study on the thermal field test of a concrete filled steel tubular truss arch | 656 |
| <i>Zhenyu Liu and Baochun Chen</i> | |
| Span-to-rise ratios in concrete arches: threshold values for efficient behaviour | 665 |
| <i>Jason Salonga and Paul Gauvreau</i> | |
| Optimal design of masonry arch bridges | 674 |
| <i>D. M. Peng, Y. Y. Chen, R. J. Jiang and C. A. Fairfield</i> | |
| Analysis of influencing factors on concrete creep deformation in tied arch bridge of Nilsson system in high-speed railway | 683 |
| <i>Zhongchu Tian, Yan Ding and Tianyong Jiang</i> | |
| In-plane strength of concrete-filled steel tubular circular arches | 694 |
| <i>Yonglin Pi, Mark Andrew Bradford, Changyong Liu and Yuying Wang</i> | |
| Self-prestress design of concrete-filled steel tube arch rib under sunshine-induced temperature | 703 |
| <i>Mingquan Zhong, Qinzong Chen and Xiaochun Zhai</i> | |
| A new practice in the design of arch axis | 709 |
| <i>C. Hu, Y. Wan and X. ShangGuan</i> | |
| Global stability analysis of an asymmetrical long-span concrete-filled steel tube arch bridge | 716 |
| <i>Shengyong Li, Christian Kohlmeyer, Frank Müller and Baochun Chen</i> | |
| Experimental study on in-plane mechanical behaviour of CFST-CSW arch | 723 |
| <i>Jing Gao, Jiazhan Su and Baochun Chen</i> | |
| Creep analysis of CFST arch bridges | 732 |
| <i>Krishna Man Shrestha and Baochun Chen</i> | |
| Health monitoring and parameter identification of a tied arch bridge under excitation of Wenchuan Earthquake | 740 |
| <i>Yiqiang Xiang, Yi Li, Yuanfeng Duan and Hui Fang</i> | |

Construction Techniques

- Performance analysis of a cable-hoisting erection system in Nanning Yonghe Bridge**.....753
Chaoyang Zhao, Chuanxi Li, Minghua Zeng, Wenshuang Yang and Lixin Tan
- Bridge over the river Tagus at Alcántara Reservoir**.....761
Jose Antonio Llombart and Jordi Revoltos
- Application of double spherical aseismic bearing in concrete-filled steel tubular arch bridge**.....775
Hua Zhang, Jianzhong Li and Tianbo Peng
- Construction of the main spans of the Chongqing Caiyuanba Yangtze River Bridge**.....782
Xueshan Liu, Anshuang Liu, Shanping Wei and Zhong Yang
- The construction technology of Chongqing Chaotianmen Bridge**.....788
Zhongfu Xiang, Wei Xu, Cunshu Wang and Ying Dong
- Development of the combination of vertical and horizontal swing techniques for the Dongping Bridge in Foshan (China)**.....797
Tingmin Mou, Jian Liang, Bikun Fan and Bangzhu Xie
- An advanced construction technology for cable-stayed Bailey arch**.....808
Y. Wan, T. Wu, D. Liu and X. ShangGuan

Maintenance, repairs and strengthening of arch bridges

- Diagnosis and repair of a historic stone masonry arch bridge**.....817
Daniel V. Oliveira, Vanessa M. Costa, Jorge F. Sousa and Paulo B. Lourenço
- An overview of Krk Bridge repairs**.....824
Jovo Beslac, Jelena Bleiziffer and Jure Radic
- Survey and analysis of the main defects in reinforced concrete ribbed arch bridges**.....830
Ke Chen and Jianyong Song
- Nonlinear finite element analysis of masonry arch bridges reinforced with FRP**.....838
Yu Zheng, Su Taylor and Des. Robinson
- Case study of the effect on foundation of changing an arch bridge to a slab and girder bridge**.....846
Climent Molins
- Research on strengthening suspended deck system for half-through CFST arch bridge by setting longitudinal steel-tubular trusses**.....853
Guihan Peng and Baochun Chen
- Analysis method of internal force distribution on composite section for arch bridge strengthening**.....860
Haidong Huang, Zhongfu Xiang and Shengfeng Liu

Dynamic behavior and seismic retrofitting method for half-through steel arch bridges subjected to fault displacement.....866
Toshitaka Yamao, Yoshie Tsujino and Zhanfei Wang

Monitoring performance of large Croatian bridges.....875
Jelena Bleiziffer and Jure Radic

Special session II: dynamic testing of arch bridges

Free vibrations and seismic responses of Shin Saikai Bridge and Saikai Bridge.....885
Kazuo Takahashi, Qingxiong Wu and Shozo Nakamura

Seismic vulnerability evaluation of Devil Bridge on Sele River.....893
C. Ceraldi, R. Landolfo, M. Lippiello and F. Portioli

Numerical investigation of concrete-filled steel tubular tied arch bridge under travelling vehicles.....901
Jianrong Yang, Jianzhong Li and Junxin Shen

The accuracy of modal parameters estimation for highway bridges influenced by various ambient vibrations.....910
Md. Rajab Ali, Takatoshi Okabayashi and Toshihiro Okumatsu

Evaluation of the seismic response of masonry arch bridges modeled using beam elements with fiber cross section.....919
Stefano De Santis and Gianmarco de Felice

A static analysis-based method for estimating the maximum inelastic seismic response of upper-deck steel arch bridges.....927
S. Nakamura, O. T. Cetinkaya and K. Takahashi

Index of Authors.....937