ARCH PEDESTRIAN BRIDGES

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SUMMARY

Recent arch pedestrian bridges are discussed in terms their architecture and structural solutions and their static function. Structures that combine an arch with a cable or a stress ribbon are also presented.

Keywords: *Arch, buried arch, deck arch, through and half-through arch, directly walkable structure, true arch, tied arch, cable, stress ribbon.*

1. INTRODUCTION

Arch bridges have been built from the beginning of human history and their development illustrates the progress of science and technology. A properly designed arch expresses the flow of internal forces through the structural system and makes a statement regarding a bridge's function. The arch has therefore become a symbol of bridge structures and many engineering firms and conferences use the arch shape for their logo.

Recent progress in understanding the structural behaviour combined with modern analytical programs allow to design bridges of complex shapes. The bridge deck can be in plan and vertical curves, the supporting arches can be inclined or curved. The deck supporting members or hangers can create a space net.

A correctly designed arch has a funicular shape with respect to the design load and therefore for the dead load it is primarily stressed by compression stresses. Unfortunately, the development of some arch bridges designed by ambitious architects has not arisen from their basic static function, but by a wish to create something new and unusual. These structures are not discussed in this paper.

In recent years, many interesting arch footbridges have been built. The authors have no intention of presenting them all, but they do want to illustrate recent developments and to show those bridges that are – according to them – interesting from the point of view of the architectural or structural solution, or the process of construction. They understand that their selection is personal. Since the authors wanted to present their own ideas, they also present several structures on which design they had an opportunity to participate.

According to the nature of the crossing, buried structures, deck arches or through arches are designed - see Fig. 1. Since pedestrian walkways can be designed with larger slopes, directly walkable structures are also built – see Fig. 2.

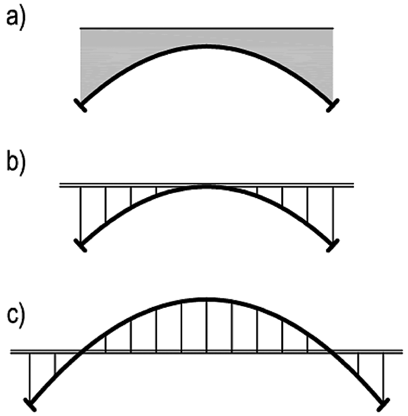

Fig. 1. *Classical Arches.*

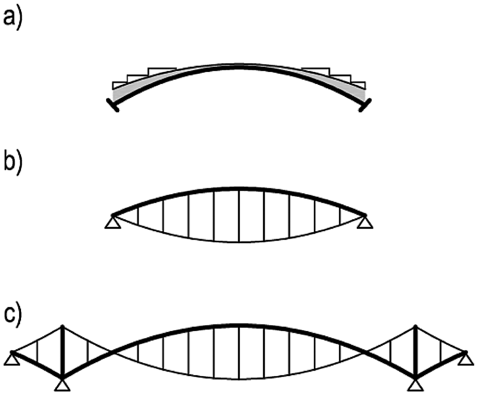

Fig. 2. *Directly Walkable Arches.*

The arch horizontal force can be resisted by subsoil (see Fig. 1 and 2a) or by a steel or prestressed concrete deck (see Fig. 3). The first variant is an example of a true arch, whereas the second variant is a tied arch. In directly walkable structures, tension can be resisted by straight or curved cables (see Fig. 2b and 2c) or by stress ribbons (see Fig. 4).

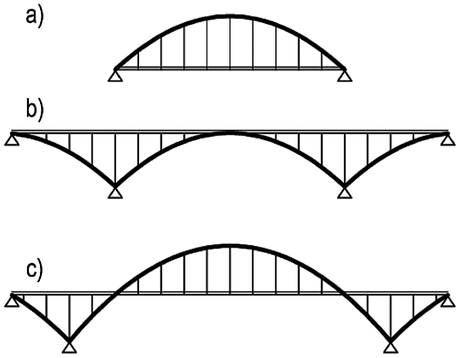

Fig. 3. *Self-Anchored (Tied) Arches.*

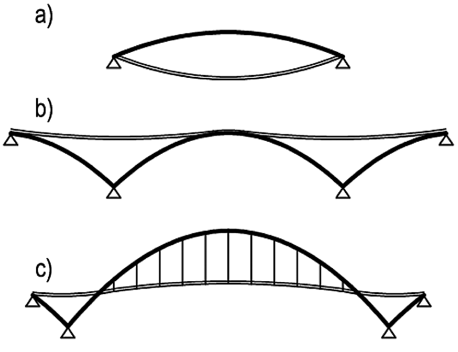

Fig. 4. *Arche & Stress Ribbon Structures.*

2. BURIED STRUCTURES

Buried structures (see Fig. 1a) allow to design walkways that flow across obstacles without an interruption. An excellent example is the *Cannstatter Street Pedestrian Bridge*, built in 1977 in Stuttgart, Germany according to Prof. Schlaich's design – see Fig. 5, [1].

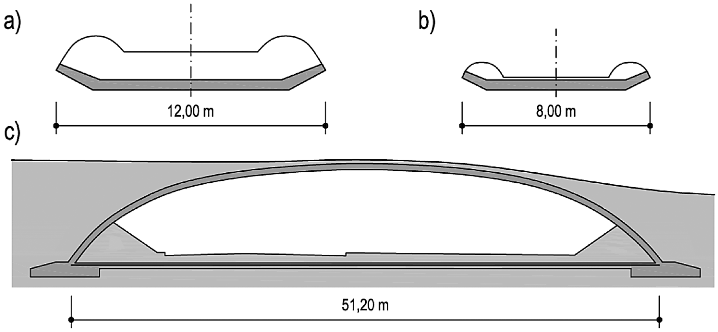

Fig. 5. *Cannstatter Street Pedestrian Bridge, Stuttgart, Germany.*

The bridge is formed by a thin shell arching over a span of 51.20 m, with a thickness of only 400 mm. To increase its stiffness and strength, its longer edges are folded slightly upward. Thus the structure thus consists of three curved planes joined along their sides.

The width of the central surface is six meters at the crown, splaying out to 11 meters at the abutments. The arch is covered in earth, which forms the walking surface and helps stabilize its shape. The arch horizontal force is resisted by prestressed concrete ties buried under the road.

On either side of the walkway, troughs are integrated into the folded-up part of the shell and plants have been encouraged to grow over the sides.

The firm Strasky, Husty and Partners (SHP) has designed two buried structures that transfer pedestrians and animals across the Motorway D1 – see Fig. 6, [2].

Fig. 6. *Bridges across the Motorway D1, Czech Republic.*

The *Bridges across the Motorway D1* are formed by two-span flat shells with spans of 25.00 m and a rise of 3.30 m. The cylindrical shells, with a thickness from 0.550 to 0.365 m, are supported by an intermediate support and end footings. The shell's horizontal force is resisted by prestressed ties – stress ribbons that are situated above the shells. The ties are anchored in anchor blocks that are connected with shell's footings by compressed struts. The anchor blocks, shells' end footings and intermediate supports are supported by drilled piles. In the bridge's transverse direction, the structure is divided into three parts. The edges of the cylindrical shells follow the slope of the fill and therefore the side shells have variable width. The total width of the bridge at the shell's crown is 60.30 m, above the central pier it is 64.10 m, and at footings it is 86.20 m.

3. DECK ARCHES

Deck arches (see Fig. 1b and 3b) have a deck which is supported by struts that can be vertical, inclined or they can form a plane or space truss system (see Figs. 7a through 7c). The arches can be formed by concrete or steel ribs, steel pipes or concrete slabs or shells. In the last option, the arches together with struts can form a space shell structure – see Fig. 7d.

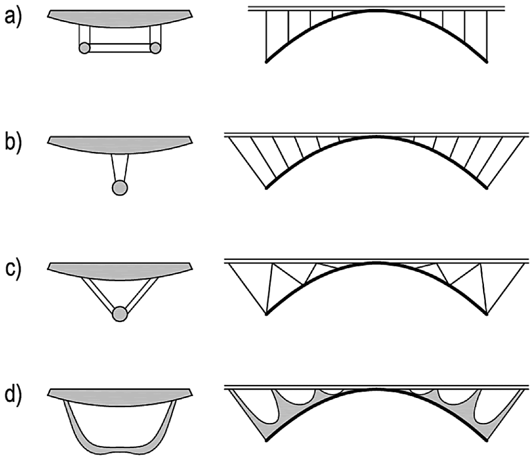

Fig. 7. *Deck arches.*

Arch pedestrian bridges with small and medium spans usually have a concrete deck that is supported by steel pipes or solid bars. The first structures of this type were built in 1993 in Stuttgart [1]. Since that time, many similar structures have been built.

A striking example is the *Streicker Pedestrian Bridge*, built in 2010 in the campus of Princeton University in New Jersey, USA – see Fig. 8, [3]. The bridge of a total length of 106 m and variable width, spans Washington Road, connecting the athletics and science buildings on the east side of the campus with new and existing buildings and facilities on the west side.

In plan, the prestressed concrete deck has an 'X' shape. The central portion of the bridge deck is supported by a weathering steel arch. The V shaped columns made of weathering steel pipes, connecting the arch with the deck, also support the ramps. Railings are composed of stainless steel posts and trim carrying stainless steel mesh guards. The bridge was designed by Prof. Christian Menn of Switzerland in collaboration with the engineering firm HNTB, New York.

Another outstanding example is the *Ripshorst Pedestrian Bridge* built in 1997 over the Rhine/Herne-Canal near Oberhausen in Germany – see Fig. 9, [1]. A curved deck formed by a steel multi-cell box girder is supported by a single steel arch. To obtain pure

Fig. 8. Streicker Pedestrian Bridge, Princeton, New Jersey, USA.

compression in the arch, a hanging model was used for determining the arch geometry. Due to the spatial curve of the arch, numerous V-shaped vertical struts of different geometries had to be connected with the arch using cast steel nodes. The bridge was designed by design firm Schlaich, Bergermann and Partners, Stuttgart.

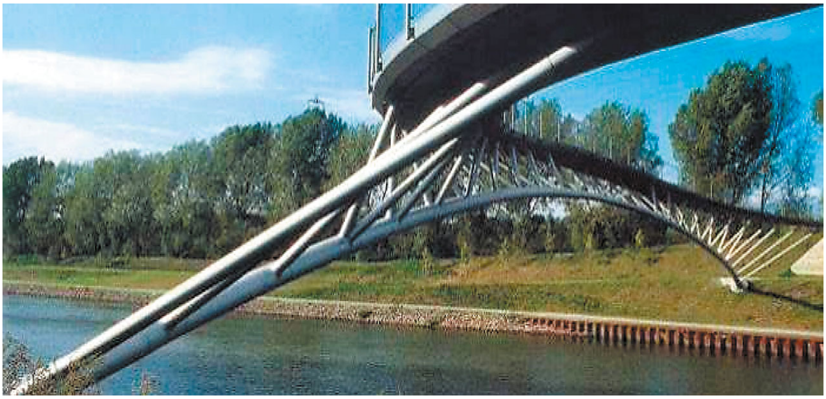

Fig. 9. Ripshorst Pedestrian Bridge, Germany.

A similar approach was used to determine the arch shape of the *Curved Arch Bridges* studied at the Brno University of Technology, Brno, [4]. The study was performed for a circular deck with a radius of 37.5 m. The arch has a vertical rise of 6.0 m. The deck was formed by a steel pipe stiffened by transverse ribs supporting the concrete deck slab, the arch was formed by a steel pipe. The deck was supported by inclined struts connected both with the arch and the deck. The optimum shape of the arch was obtained by an analysis of the curved suspension structure in which the deck was suspended on a suspension cable of zero stiffness.

The static analysis was verified by testing the bridge model, built in the scale 1:10. This test was done together with the sets of the curved structure suspended on the arch – see Fig. 10.

Fig. 10. *Model Test – Brno University of Technology.*

The Streicker and Ripshorst Pedestrian Bridges are assembled from slender structural members that have a human scale. A different approach was used in the design of the *Bridge across the Mondego River in Coimbra, Portugal* – see Fig. 11, [5]. The bridge, of a total length of 274.5 m, has four spans of lengths 30.5 + 64.0 + 110.0 + 64.0 m. In plan, the bridge is composed of two mutually offset straight ramps that are connected at the middle of the main span by a central platform. Both, the arches and the tied girders are formed by robust steel boxes that support a timber deck. The bridge, built in 2005, was designed by Prof. Da Fonseca and ARUP, London.

Fig. 11. *Pedestrian Bridge across the Mondego River, Coimbra, Portugal.*

Although the light, uniform load of pedestrian bridges calls out for the use of shell structures, unfortunately, none has yet been built. However, they are being proposed and studied [6].

4. THROUGH AND HALF-THROUGH ARCHES

Recently, many structures with decks suspended on arches have been built. Though the deck is typically made from steel or concrete, the arches are usually from steel. The arches can be vertical or inclined, and they can be situated in the bridge axis or on deck's edges – see Fig. 12. While simple structures with vertical arches look boring and industrial, more complex structures with inclined arches have a modern, dynamic appearance. Inward inclination gives the user a feeling of safety, outward inclination a feeling of openness. The relatively small deck width of pedestrian bridges justifies the design of one side deck's suspension on inclined arches. This arrangement is suitable for curved bridge decks.

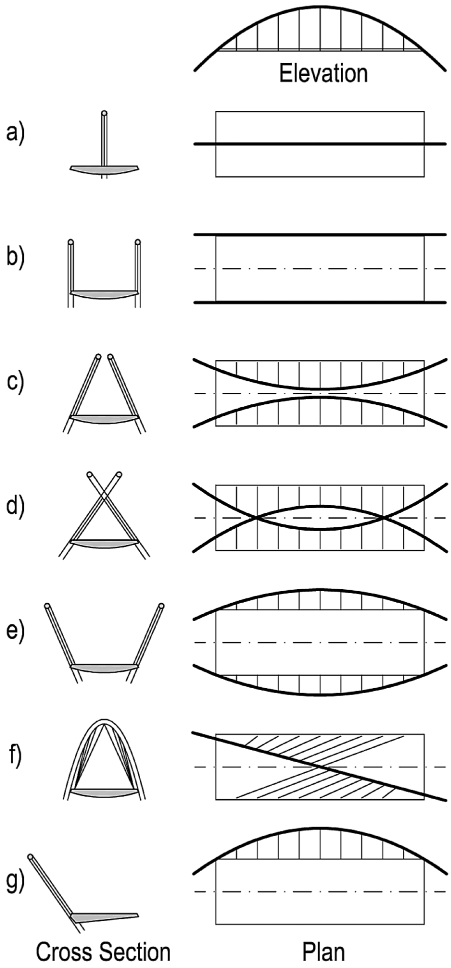

Fig. 12. Through arches.

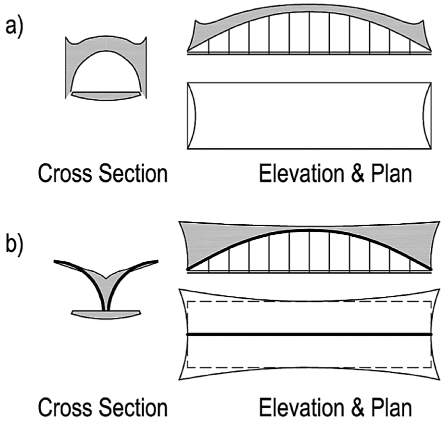

Fig. 13. Shell arches.

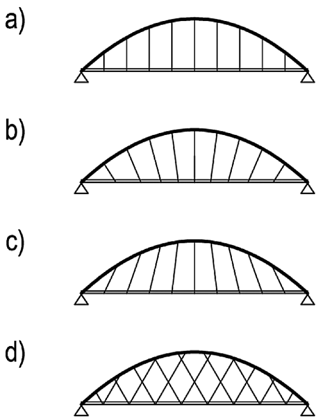

Fig. 14. Suspenders arrangement.

The arches can be substituted by a shell on which the bridge deck be suspended. The suspension can be on the bridge's edges or in its axis – see Fig. 13. Suspenders can be vertical, inclined or can create a net – see Fig. 14.

Serving as an example of a bridge that is suspended along the bridge axis is the *Pedestrian Bridge across the Svratka River* – see Fig. 15. This bridge, built in 2014 in the city of Brno, Czech Republic, connects new sport facilities situated on both banks of the river. The prestressed concrete deck formed by a spine girder with overhangs is suspended on a single steel arch of a trapezoidal cross section and a span length of 58.5 m. The spine girder that protrudes above the deck slab naturally divides pedestrian and cyclist paths. The arch is filled with concrete. The bridge was designed by Strasky, Husty and Partners, Brno.

Fig. 15. *Pedestrian bridge across the Svratka River, Brno, Czech Republic.*

The inward inclination of arches was used in the design of the *McLoughlin Boulevard Pedestrian Bridge, Portland, Oregon* (see Fig. 16), [7]. The bridge is formed by a slender concrete deck suspended on two arches with a of a span of 73.8 m. Because the deck anchor blocks are connected to the arch footings by struts, the structure forms a self-anchored system. Since the deck is suspended on the arches via suspenders of a radial arrangement, the steel arches have a funicular/circular shape.

Fig. 16. *McLoughlin Boulevard Pedestrian Bridge, Portland, Oregon, USA.*

The arches are formed by 457 mm-diameter pipes that are braced by two wall diaphragms. The deck is assembled from precast segments and a composite deck slab. The bridge was designed by OBEC Consulting Engineers, Eugene, OR and by Jiri Strasky.

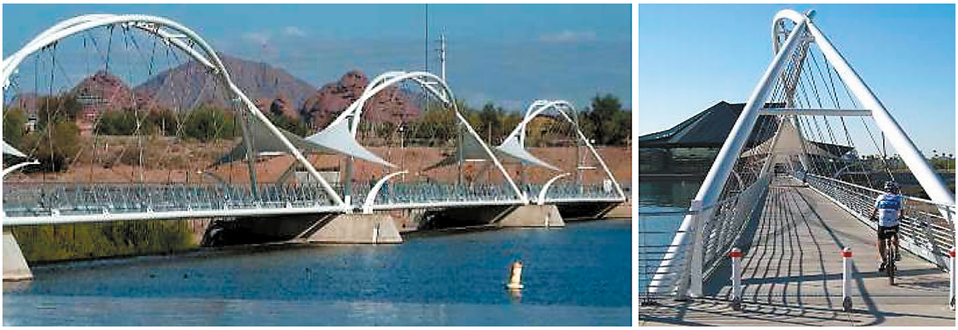

Fig. 17. *Tempe Town Lake Pedestrian Bridge, Arizona, USA.*

Inclined arches can also mutually intersect one another, as they do in a design of the *Tempe Town Lake Pedestrian Bridge, Arizona, USA* – see Fig. 17, [8]. The bridge, built in 2011, connects existing bike and pedestrian paths from the north and south sides of the lake. The structure of a total length of 278 m, consists of four simple span tied arches 68.8 m in length. The supports are formed by the existing Tempe Town Lake Dam's concrete piers. The arches are formed by 406 mm-diameter steel pipes; the deck is formed by longitudinal steel girders, floor beams and a composite concrete slab. The suspenders have a diagonal (net) arrangement. The bridge was designed by T. Y. Lin International, Phoenix.

Outward inclination of arches has been used in many structures. However, the most striking example is the *Butterfly Bridge over the River Great Ouse* built in 1997 in Bedford, UK.

Fig. 18. *Butterfly Bridge over the River Great Ouse, Bedford, UK.*

– see Fig. 18 [9]. The arches of a small span of length of 32 m are formed by steel pipes; the deck is formed by longitudinal steel pipes and floor beams that support a timber deck. The bridge was conceived and designed by Wilkinson Eyre architects.

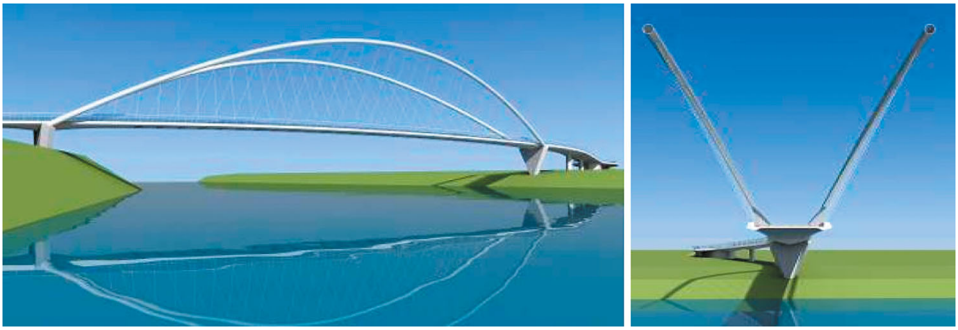

Fig. 19. *Minto Island Pedestrian Bridge over the Willamette River, Salem, Oregon, USA.*

A slender prestressed concrete deck suspended on inclined arches was used in the design of the *Minto Island Pedestrian Bridge*, now being constructed in the city of Salem over the Willamette River – see Fig. 19 [7]. The bridge is formed by a continuous girder of 5 spans, ranging from 15.24 to 93.88 m in length. The main span is assembled from precast segments only 420 mm thick and a cast-in-place concrete slab; the arches are formed by 750 mm diameter steel pipes. The bridge design is the work of OBEC Consulting Engineers, Eugene, OR and by Jiri Strasky.

One-side suspension of a curved deck was utilized in the construction of the outstanding *Gateshead Millennium Bridge spanning the River Tyne in Newcastle, UK* – see Fig. 20 [9]. The bridge, opened in 2001, is the world's first and only tilting bridge. The main span, 105 m in length, is suspended on a parabolic arch; the curved 8 m wide deck is formed by a non-symmetrical box girder.

Six 450 mm diameter hydraulic rams (three on each side) rotate the bridge back on large

Fig. 20. *Gateshead Millennium Bridge spanning the River Tyne, Newcastle, UK.*

bearings to allow small ships and boats (up to 25 m) to pass underneath. The bridge takes as little as 4.5 minutes to rotate through the full 40° from closed to open, depending on wind speed. The award-winning structure was conceived and designed by architect Wilkinson Eyre and structural engineers Gifford.

Fig. 21. *Pedestrian bridge across the border River Olse, Czech and Polish Tesin.*

One-side suspension of a curved deck was also utilized in constructing the *Pedestrian Bridge across the border River Olse*. The bridge connects two cities: Czech and Polish Tesin – see Fig. 21, [7]. The structure of a total length of 95.40 m, is curved in plan with a radius of 100 m and in a crest elevation. It has four spans of lengths from 13 to 45 m. The deck is formed by a slender box girder with a non-symmetrical streamline cross section that is stiffened by a one-side inclined arch in the main span.

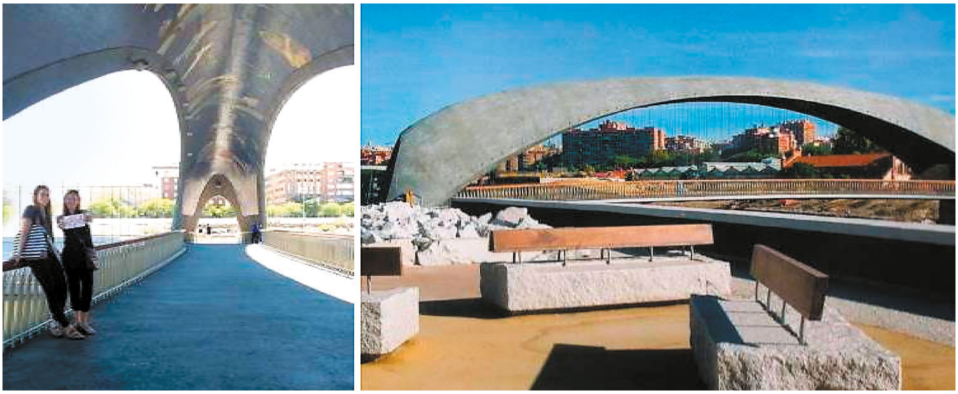

Fig. 22. *Cascara Pedestrian Bridge, Madrid, Spain.*

The deck is fixed into end abutments and is supported by elastomer pads on intermediate piers. To balance the torsional moment due to the dead load, the deck is prestressed using radial cables situated at the edge curbs. Both the girder and the arch are a composite of steel and concrete. The bridge was designed by Strasky, Husty and Partners, Brno.

Concrete shells with a span length of 41 m were used in the construction of the two *Cascara Bridges Madrid Rio*, built in 2007 in Madrid, Spain – see Fig. 22, [10]. The bridges have a steel deck 8 m wide that is suspended from the shell edges. The shell ceilings have a mosaic created by Spanish artist Daniel Canogar. The bridge was conceived by West 8 + MRIO arquitectos.

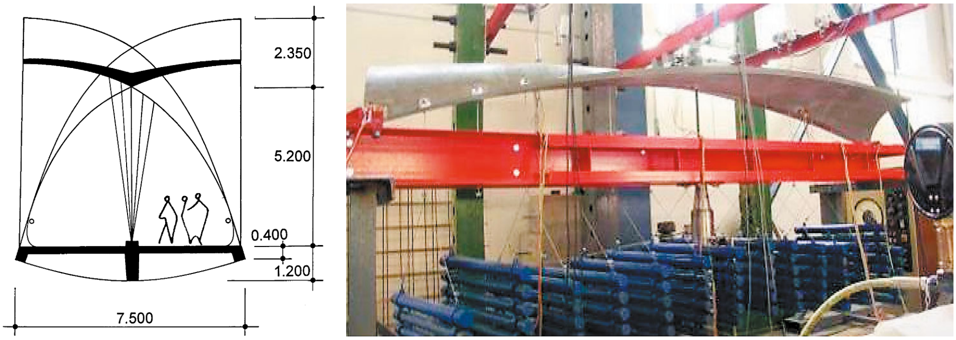

Fig. 23. *Diagonal Arch Shell.*

For a design competition for a *Pedestrian Bridge in Jersey, UK*, on which we were working with architect Cezary Bednarski, we have proposed a shell with a span of 62 m on which a slender composite deck is suspended, [11]. The shell, created by projecting two cylindrical shells, creates a diagonal arch shell. The arch shell diagonally crosses the deck that serves as a tied girder. The shell was made from aluminum. A similar structural solution was also used in one option for the Harbor Drive Bridge in San Diego. In this case, the structure was formed by a concrete shell of two spans of 2 x 53.65 m.

To check our analysis and ascertain the ultimate capacity of the structure, a model of the arch shell at a scale of 1:20 was made – see Fig. 23. The shell was cast from a high strength concrete with a characteristic strength of 150 MPa. The function of the arch shell for different positions of the live load was checked first. Finally, the ultimate capacity was determined.

5. DIRECTLY WALKABLE ARCHES

Flat arches can be used for pedestrian bridges without a stiffening deck. Due to their small rise they are stressed by large horizontal forces. An example is the *Constitution Pedestrian Bridge, Venice, Italy* designed by Santiago Calatrava – see Fig. 24, [12].

The bridge of a span of 80.8 m and a variable width from 6.5 to 9.0 m, is formed by a flat arch with a rise of 4.76 m. The rise/span ratio is 1/16. The arch is formed by top and bottom steel cords mutually connected by skew struts. The top cord supports the stairs lined with glass strips. The bridge was built in 2008.

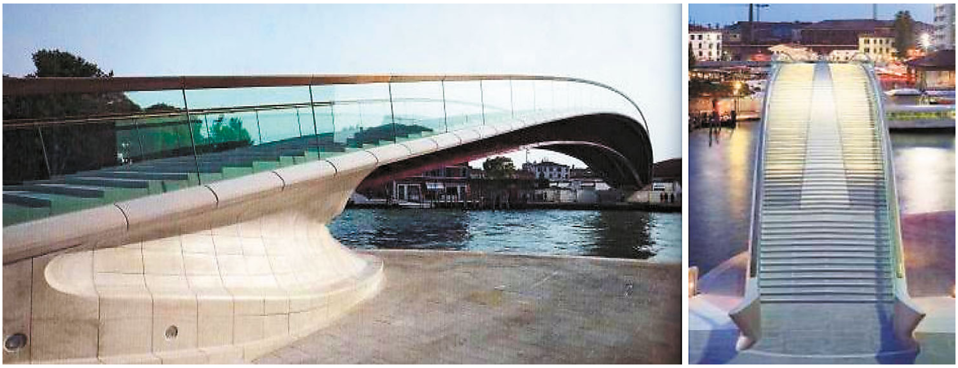

Fig. 24. *Constitution Pedestrian Bridge, Venice, Italy.*

For a design competition for the *Leamouth Pedestrian Bridge, London on which we were working with architect Jan Kaplicky,* we developed a three hinge arch in which the deck and supporting structural member form one structure – see Fig. 25, [11].

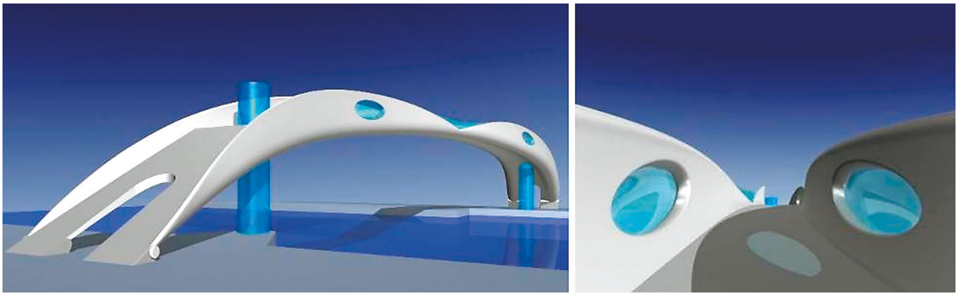

Fig. 25. *Leamouth Pedestrian Bridge, London, UK.*

The span of the arch is 105 m; the rise is 10.3 m. The deck, with a trough cross section, has a variable depth and width. It was formed using a multi-cell box girder stiffened by transverse and longitudinal stiffeners. The structure could be made from or aluminium or high-strength concrete. In the plan of the deck elliptical openings for lifts and viewing platforms were created.

While in the previous designs the arch horizontal force is resisted by soil, in the design of the *Inachus Bridge, Beppu, Japan* the arch force is resisted by a steel tension tie – see Fig. 26, [13]. The bridge has a lenticular shape, with an arched upper chord and a suspended lower chord. The granite upper chord serves not only as the principal structural member, but also forms the deck for pedestrian traffic. The span length of the bridge is 34 m, the distance between the top and bottom chord is 2.20 m. The upper chord is post-tensioned by prestressing tendons running through holes drilled in the granite blocks. This bridge was designed by Prof. Kawaguchi and built in 1994.

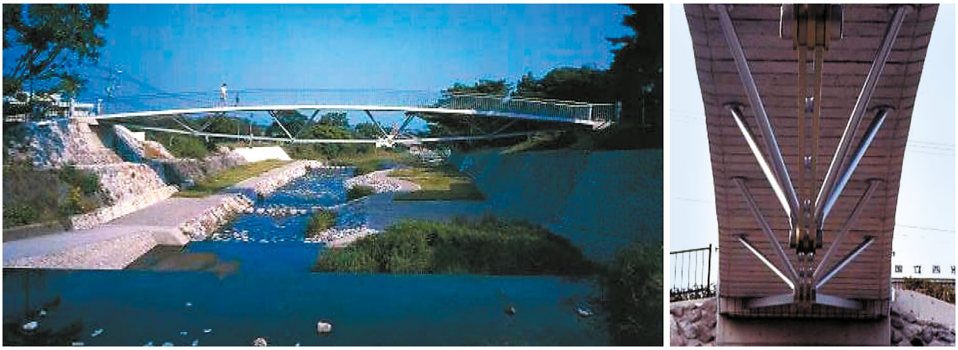

Fig. 26. *Inachus Bridge, Beppu, Japan.*

6. ARCH & STRESS RIBBON STRUCTURES

If the cable shown in Fig. 2c is substituted by a stress ribbon, we get the the structural system used in the design of the *Simone de Beauvoir Pedestrian Bridge, Paris, France* – see Fig. 27, [10] The bridge of a total length of 304 m and width of 12 m, combines a flat arch with a stress ribbon. The central portion of a lentil shape has a length of 106 m. The stability of the flat arch is given by its connection with the stress ribbon. Both the arch and stress ribbon are made from structural steel. The bridge, built in 2006, was conceived by Dietmar Feichtinger Architectes.

Fig. 27. *Simone de Beauvoir Pedestrian Bridge, Paris, France.*

The static system presented in Fig. 4b was used in a design for the *Pedestrian Bridge across the Expressway R35 near the city of Olomouc, Czech Republic* – see Fig. 28, [11]. The bridge is formed by a stress-ribbon of two spans that is supported by an arch. The stress-ribbon, which is 76.50 m in length, was assembled of precast segments 3.00 m long supported and prestressed by two external tendons. The bridge was built in 2007.

Fig. 28. *Pedestrian Bridge across the Expressway R35 near a city of Olomouc, Czech Republic.*

Recently we have been studying a *Curved Arch & Stress Ribbon Structure*, [14], utilizing the static scheme displayed in Fig. 4a. In the longitudinal direction, the structure forms a self-anchored structural system combining a curved stress ribbon and a curved flat arch. The deck of both structures is formed by an eccentric steel pipe stiffened by L-shaped diaphragms. Its horizontal part supports a slender concrete deck; the vertical part supports a steel pipe in which prestressing cable is situated. Since both the arch and stress ribbon are fixed into end abutments, the horizontal components of prestressing radial forces not only balance the dead load's torsional moments, but also create uniform compression in the deck.

This static scheme was studied on a pedestrian bridge of the span of 45 m that was in a plan curvature of a radius of 32.212 m. The maximum longitudinal slope at the abutments was 7%. This structure was not only analyzed, but its function was verified on a static model built in the scale 1:6 – see Fig. 29.

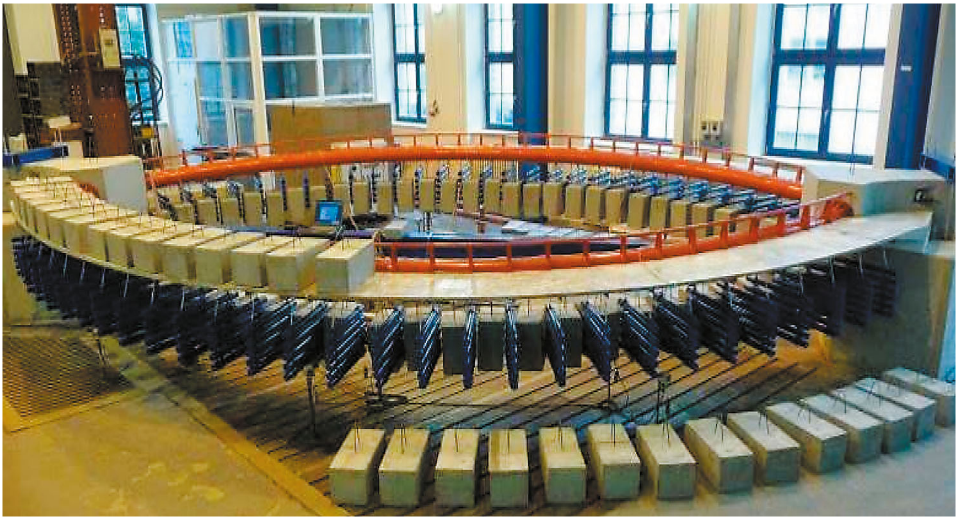

Fig. 29. *Model Test of the Curved Structure Combining Flat Arch & Stress Ribbon.*

7. CONCLUSIONS

From the presented examples it is clear that arch pedestrian bridges can have different architectural and structural arrangements that can be used for a large variety of crossings. Although the arch is one of the oldest structural members, arch structures can continue to be developed further.

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