Analysis of structural solutions of train sheds in Europe

Katarzyna Foljanty

Faculty of Architecture, Warsaw University of Technology
Warsaw, Poland

Great spans were already used in ancient times; however, it was the first and second industrial revolution that laid the roots of the transportation sector. Channels, roads, rail lines were built and consequently train stations followed. Prestige was very important for many railway companies and cities, and this desire was expressed by splendid structures. Although after World War II many train stations were demolished, the high-speed train brought an upturn again. With new technologies available it became possible to create spacious, light structures formed freely.

The train station is the main access point to the transportation system, but it also serves as a public space. Here architecture, engineering and industrial design overlap. Structural elements, despite their loadbearing function have a major impact on the quality of the architectural space. Expression and excitement of architecture are important issues. Proper choice of structural solutions, using shades, shadows and textures make the train station a distinctive place.

I would like to present an overview of the development of railway station design and give an outlook to the latest trends in the construction of passenger transportation hubs.

Key words: train station, transportation hub, wide-span, structural system

Introduction

During my doctoral research stay in Berlin I had the opportunity to research the development of train shed's structural systems from the beginning of the railway era to the most recent projects all over Europe.

For many years prestige expressed by splendid stations was very important for many railway companies, cities and even contractors. Train stations were an inspiration for painters, writers and filmmakers. After World War II many of the original train stations in Europe (and also in the United States) were demolished, despite a considerable public outcry. It resulted in the loss of splendid iron and steel structures such as St. Enoch in Glasgow, Anhalter Bahnhof in Berlin and Euston Station in London, to name only a few of them. Railways had to give way to the cars, and vast terminus stations in the city centers started to become impractical and too expensive to maintain. It was the high-speed train that brought an upturn again and with it a new train station era began. With new technologies and materials available it became possible to create spacious, light structures formed freely, depending on the design principles. Many platform halls built after 1990 are complex projects designed as combined structures. Their designs exhibit the contemporary technical possibilities.

This paper will focus on an overview of the development of railway station design and it will give an outlook to the latest trends in their construction. Two questions structure this article:

- How has the construction of train sheds changed over the years?
- What trends are popular in the twenty-first century?

In the second section a short overview of the history of train station structure development will be presented. The following third section presents European examples of train stations built within the last 10 years.

Historical overview

Great spans were already used in times of Ancient Greece and Rome (arches, domes) and built continuously through the centuries. But it was the First and Second Industrial Revolution that led to the development of industry and communication. Channels, roads, bridges and (passenger) rail lines were built and with them also train stations. The first train sheds were simple, not very high and had pitched roofs, which is why they were called sheds (Biddle, 1986). In the design of early train stations, wooden king-post or queen-post trusses, sometimes stiffened with iron bars, on iron columns, were commonly used (e.g. Liverpool Crown Street, 1830). The sides were usually open. In the late 1830s, wrought iron started to replace timber and the thrust resistance was improved by sidewalls, usually made of brick. In the beginning, great height and width of train sheds were obligatory to disperse smoke of locomotives. Arched roof constructions were used to make spans larger and free the platforms by reducing the number of columns (e.g. Newcastle Central, 1850).

The development of a train shed was not only inspired by requirements of railways but also by possibilities given at that time. Stations constructed through the 1840s, which most often did not survive to our times, were built commonly as wooden pitched roofs, sometimes with iron parts; cast iron resistance to compressive stresses and wood to tensile stresses made both materials work well together. Later, wrought iron started to be used as a substitution for wood, and it stayed dominant for structural applications until the 1880s. When the mass-production of steel began, the usage of iron declined (Bessemer process patented in 1855). With the development of steel construction, the methods of joining parts with each other also changed. Instead of riveting and bolting welding was applied (mostly because of the weight savings). After the invention of corrugated wrought iron sheeting in 1829, a lightweight roofing material without the need of secondary supporting was finally provided (Wilkinson, 1996). Roofs covering only a single platform started replacing train sheds after 1904 when a Bush-type shed was patented. It was cheaper, easier, and faster to build and maintain. Reinforced concrete was commonly used as a main structural material already after a great era of train sheds, though it was used from the early years of the twentieth century in the construction of station buildings. It was rediscovered in railway architecture in the 1980s, mostly in the works of Santiago Calatrava.

According to Edwards (1997) "Stations are plays of structural forces held in tension and compression" (p. 177). The decision about the structural needs to be chosen has to be based on many reasons, such as economy, materials, localization, client requirements, building character, etc. According to their shape, type of load and building materials, structural systems can be categorized in various ways, but "[…] the neatness of our categorization of structural systems eventually breaks down, since variations within one system tend to produce different systems, and overlapping between categories exists" (Ambrose, 1967, p.93).

In this paper the following categorization of structural systems was chosen:

- Post and beam systems
- Truss systems
- Frame systems
- Arch systems
- Shell structures
- Grid structures/ Lamella systems
- Special systems (composition of two or more systems in a new special structure)

Each of these groups is organized in two sections regarding internal action of forces under an external loading: 2D (in one plane) and 3D (in space).

Table 1. Structural systems of train sheds

No.	Year opened	Station	Localization	Max. single width (m)	Structure system
1.	1830 (demolished 1836)	Crown Street Station	Liverpool		trussed pitched roof
2.	1837	Euston Station	London	6	trussed pitched roof
3.	1848	Gare de Marseille-Saint-Charles	Marseille		Polonceau system
4.	1854	Paddington Station II	London	31	two-hinged arch with tie rods
5.	1868	St Pancras	London	74	latticed two-hinged arch with tension cable
6.	1871	Lime Street III (northern nave)	Liverpool	56-65	crescent truss
7.	1880	Anhalter Bahnhof	Berlin	62	trussed two-hinged arch with tie rods
8.	1888	Frankfurt am Main Hauptbahnhof	Frankfurt am Main	56	trussed three-hinged arch
9.	1899	Antwerp Central Station	Antwerp	65	three-hinged arch with tie rods
10.	1906	Hamburg Hauptbahnhof	Hamburg	73	trussed three-hinged frame
11.	1909	Prague Central Station	Prague	33	trussed two-hinged arch
12.	1915	Leipzig Hauptbahnhof	Leipzig	45	trussed two-hinged arch
13.	1929	Barcelona Estació de França	Barcelona	48	trussed two-hinged arch
14.	1931	Milano Centrale	Milan	72	trussed three-hinged arch
15.	1937	Reims railway station	Reims	35	two-hinged arch with tie rods
16.	1948	Bilbao-Abando	Bilbao		trussed two-hinged arch
17.	1993	Waterloo International	London	32-48	three-hinged arch
18.	1998	Gare do Oriente	Lisbon		beam grid on tree-like supports
19.	2003	Leipzig/Halle Airport Railway Station	Schkeuditz	44	two-hinged frame
20.	2003	Köln/Bonn Airport Railway Station	Cologne	38	two-hinged arch
21.	2003	Zaragoza Delicias	Zaragoza	110	arch with tie rods stiffened with shell
22.	2006	NMBS Train Station	Leuven		arched structure stiffened with cables
23.	2006	Berlin Hauptbahnhof	Berlin	66	arch with grid shell
24.	2007	Bijlmer Arena station	Amsterdam		cantilever girder
25.	2009	Liege-Guillemins Station	Liege	160	two-hinged arched frame
26.	2017 (planned)	Oslo Central Station	Oslo		beam grid on tree-like supports
27.	2020 (planned)	Stuttgart Hauptbahnhof	Stuttgart	80	shell

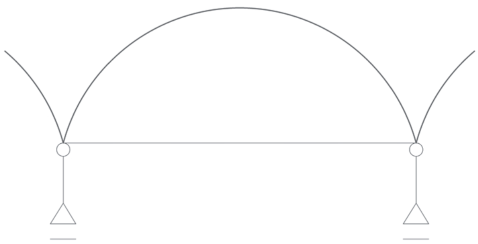

Fig. 1. Paddington Station II, London (1854)

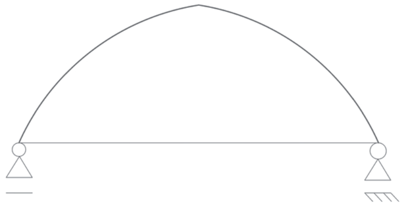

Fig. 2. St Pancras, London (1868)

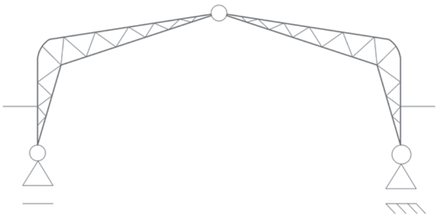

Fig. 3. Hamburg Hauptbahnhof (1906)

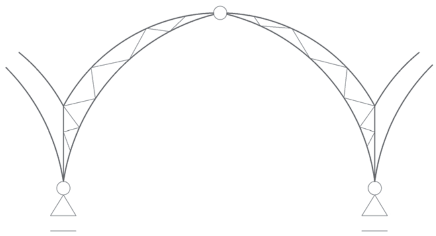

Fig. 4. Milano Centrale (1931)

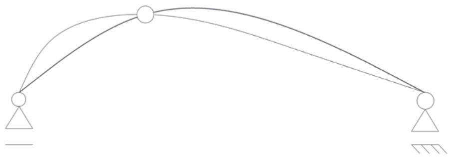

Fig. 5. Waterloo International, London (1993)

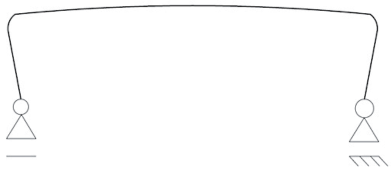

Fig. 6. Leipzig/Halle Airport Railway Station (2003)

Fig. 7. Berlin Hauptbahnhof (2006)

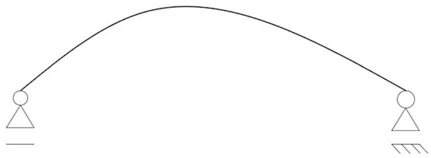

Fig. 8. Liège-Guillemins Station (2009)

During the early years, many canopies used truss (or trussed) systems, which were supported by side masonry walls or/and an iron pillar grid. Many truss types were developed among them; often used in English train sheds were the bowstring and the crescent truss. The arch system, enabling great distances between supports was (and still is) a very popular solution. In the first half of the nineteenth century in England, engineers commonly applied a two-hinged arch, often with iron tie rods. Many German train sheds built after 1860 were trussed three-hinged arches. This difference was a result of the structural approach of these two countries. After the WWII, many extraordinary train sheds fell gradually into decline and the construction of large stations was suspended. Partly because it was often sufficient to modernize existing stations, but also because of the emergence and popularization of new means of transport: airplane, bus and automobile. Since the late 1980s we observe railway renaissance and new train stations are being built, mainly due to the expanding high-speed rail network.

Examples

The renaissance of railways and new technological developments brought the train station as an important building back to the cities. Below six contemporary examples of European stations are presented, focusing on their structural solutions.

3.1. Waterloo International, London

Number of naves: 1
Length: 400 m, width: 32-48 m
Opened: 1993
Architect: Grimshaw Architects
Structural Engineer: Anthony Hunt Associates, Sir Alexander Gibb & Partners
Structure system of the platform hall: three-hinged (bowstring) arch, 2D
Building materials: steel, roofing: glass, stainless steel panels

Waterloo International station was the first London passenger hub for Eurostar between 1994 and 2007. The building is located on the western side of Waterloo railway station. Ticketing, security, waiting areas are accommodated under the new station. On top of them, five two-story viaducts carry new rail lines. A grid of cylindrical concrete columns supports the viaducts. The curving structure of the train shed consists of 36 three pin arches made of two curved asymmetrical trusses; the shorter, external inverted truss with two outer compression tie rods with a single tension boom below and the longer, internal truss with a single compression tie rod. The latter has sides to the east to support a solid roof area. The trusses are connected with steel joints and pins. Truss dimensions vary with bending moment requirements. The trusses are wider at the center of the span. The secondary structure provides line bracing between trusses and supports the two-pitched cladding and glazing.

3.2. Zaragoza Delicias

Length: 500 m
Width: 110 m, height: approx. 30 m (ceiling level)
Built: 1999-2003
Architect: Carlos Ferrater (OAB), José Mª Valero, J.Diaz, Elena Mateu, Félix Arranz
Structural Engineer: Juan Calvo (PONDIO engineer) Juan Luis Bellod – CESMA
Structure system of the platform hall: arch with tie rods stiffened with shell, 3D
Building materials: steel, reinforced concrete, roofing: glass, wood, wire mesh

Fig. 9. Waterloo International, platform hall in 2012
source: own work

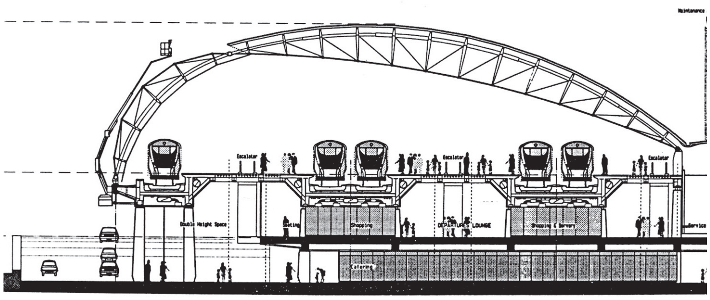

Fig. 10. Waterloo International, section through the platform hall, *source: http://eat-a-bug.blogspot.de/2010/07/geometry-of-structural-form.html*

Fig. 11. Waterloo International (on the left) and Waterloo station (on the right), *source: http://commons.wikimedia.org/wiki/File:Waterloo-Station-2013.JPG?uselang=de*

Fig. 12. Waterloo International, platform hall, *source: http://grimshaw-architects.com/project/international-terminal-waterloo/*

Fig. 13. Zaragoza Delicias, platform hall *source: upload.wikimedia.org/wikipedia/commons/e/e8/Zaragoza_-_Delicias_3.JPG*

Fig. 14. Zaragoza Delicias, roof construction, *source: http://www.railwaymania.com/docs/imgdb/renfe_station_011.jpg*

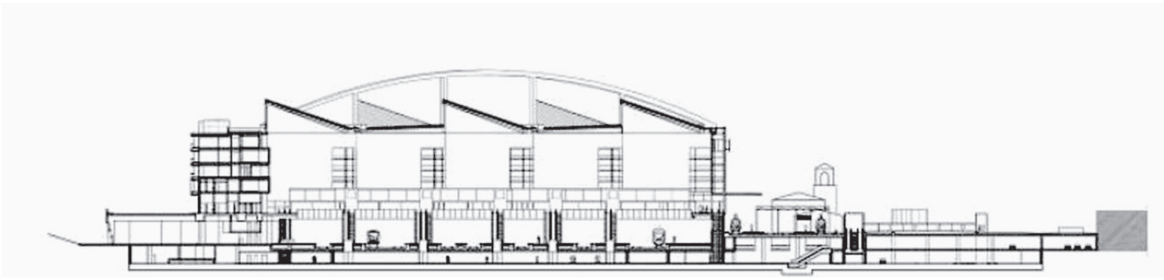

Fig. 15. Zaragoza Delicias, section
source: Ferrater, C. (2011). OAB Carlos Ferrater and Partners. N.p.: Actar.

The roof is suspended on nine steel arches and a large tetrahedron mesh. It covers 40 000 sq. meters. Concrete elements, hanging over the interior, are placed in a triangular composition, in which open and closed areas alternate. On top of the open areas triangular glass pyramids were placed to provide natural light. The pyramids are borne by three-sided Vierendeel grinders of the same profile as the roof mesh and the arches. This construction allows a span of 500 by 110 meters. The ceiling covering is also kept in a triangular configuration of wood and wire mesh. Massif concrete exterior walls case the station.

3.3. Leipzig/Halle Airport Railway Station
Length: 405 m (shelter: 320 m)
Width: max. 44 m, height: max. 8,5 m
Membrane area: 5 600 m2
Opened: 2003
Architect: AP Brunnert & Partner
Structural Engineer: Schlaich Bergermann und Partner
Structure system of the platform shelter: two-hinged frame with membrane, 2D
Building materials: steel, roofing: Teflon-coated membrane

By crossing below the central building of the airport, the new railway line allows for an optimal interconnection with the shortest possible walking distances between trains, road and airport terminal. For the time being, the 405 meter-long station has only one side platform on each side, but the space for a potential future extension of two additional platforms was reserved. 320 meters of the platforms are sheltered by a basket-arch steel construction made of welded I-profiles. The steel construction bears the railway infrastructure (such as signaling and overhead wires) and also the translucent, Teflon-coated membrane spanning between the frames. Every part of the membrane is pre-stressed by a centrally located cable anchored to the ground. The frames of the construction stand in intervals of 14 meters. The frames are connected with each other with purlins that ensure the structural stability in longitudinal direction.

3.4 Berlin Hauptbahnhof
Number of naves: 1
Length: 320 m (designed: 450 m), max. width: 66 m, height: 12-16 m
Opened: 2006
Architect: gmp Architekten von Gerkan, Marg und Partner
Structural Engineer: Schlaich, Bergermann & Partner, IVZ/Emch+Berger
Structure system of the platform hall: cable-supported arch with grid cylindrical shell, 3D
Building materials: steel, roofing: glass

The new main train station in Berlin was established in the same location as the former station Lehrter Bahnhof, demolished in 1959. Berlin Central Station is a hub for long-distance trains, and regional and local transport

Fig. 16. Leipzig/Halle Airport Railway Station, platform hall, *source: own work*

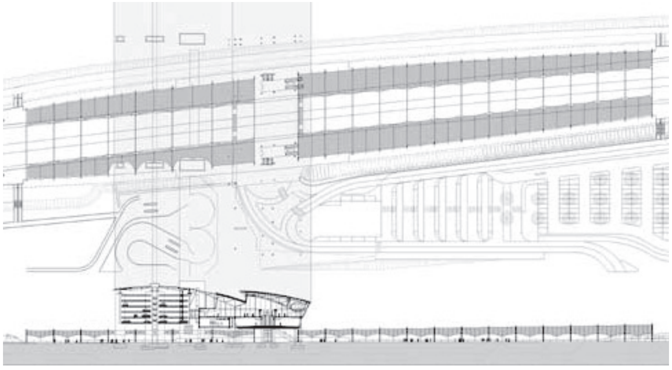

Fig. 17. Leipzig/Halle Airport Railway Station, *source: http://www.ap-brunnert.de/dna/5148_ice%20bahnhof%20leipzig-halle.html*

(S-Bahn). Lines running in a north-south direction were placed in a tunnel located 15 meters underground. Access to public and individual transport is at the ground level. Long-distance railway lines in the east-west direction and S-Bahn trains were located 10 meters above street level. The curved main platform hall consists of a glazed roof of elliptical cross-section supported by three-centered steel arches suspended on cables and placed every 13 meters. Between the arches, a mesh measuring from 1,40 to 1,60 meters with diagonal double cables (diameter of 12 mm) is placed. Cable support changes between the inside and the outside. The roof is covered with glass panels (1,20 m x 1,20 m) stiffened by edge members and bow braces. Each of these panels has a different shape. At some places glass panels are coated with solar cells. At its two ends the roof has a span 44 and 56 meters, expanding in the middle to 66 meters. Here it intersects with a perpendicular 40-metre-wide and 200-metre-long nave.

Fig. 18. Berlin Hauptbahnhof, *source: own work*

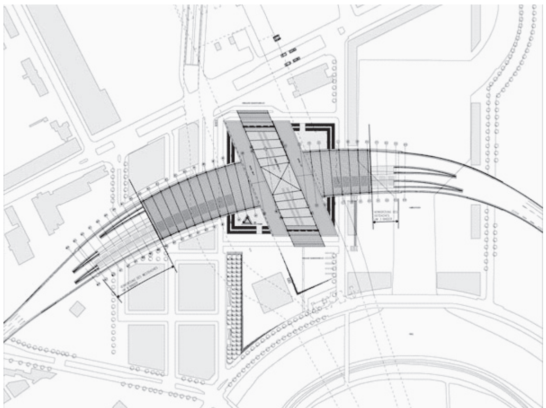

Fig. 19. Berlin Hauptbahnhof, *source: http://www.constructalia.com/repository/transfer/en/resources/ContenidoProyect/01666451Foto_big.jpg*

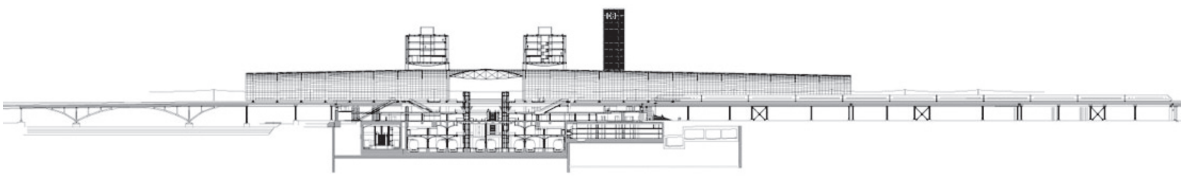

Fig. 20. Berlin Hauptbahnhof, section through the north-south axis, *source: http://www.constructalia.com/repository/transfer/en/resources/ContenidoProyect/01666453Foto_big.jpg*

Fig. 21. NMBS Train Station, platform hall
source: www.samynandpartners.be

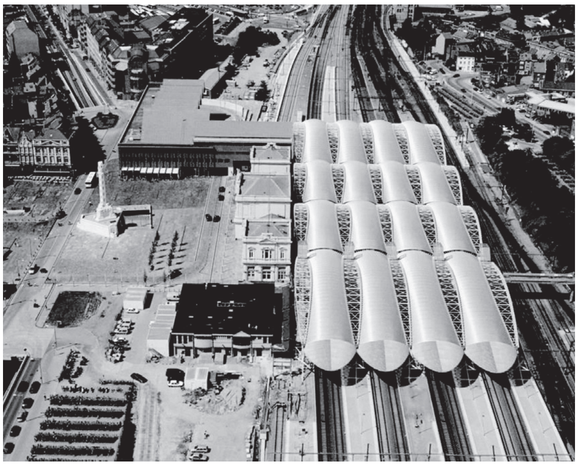

Fig. 22. NMBS Train Station,
source: www.samynandpartners.be

Fig. 23. Bijlmer Arena Station, platform hall,
source: own work

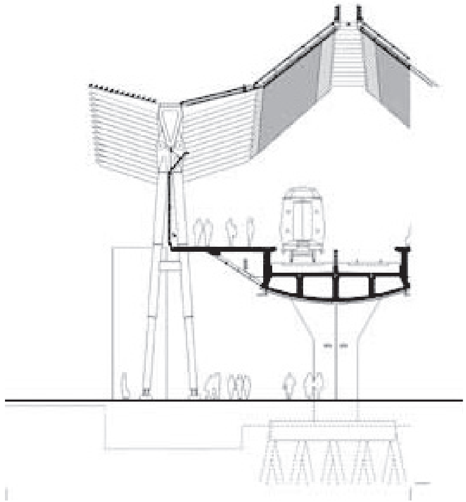

Fig. 24. Bijlmer Arena Station, section through the platform hall, *source: Grimshaw Architects LLP*

3.5 NMBS Train Station, Leuven

Built: 1999-2006
Architect: Samyn and Partners
Structural Engineer: Samyn and Partners with SETESCO
Structure system of the train shed: arched structure stiffened with cables, 3D
Building materials: steel, roofing: glass, aluminum profiles, expanded steel sheets

The platform hall is propped with 25 cylindrical supports, in the central part made of four inclined pillars and three columns on the outside, where the load distribution is uneven. The high voltage cables are attached to the pillars. The supports are located at the intersection of two perpendicular series of five axes. The longitudinal axes, at a distance of 14.54 meters from each other are adapted to the gauge. The transverse axis, respectively spaced 52, 39, 39 and 52 meters follow high-voltage cables supports. The construction of the roof consists of 20 steel, parabolic, twin arches. They are set symmetrically at an angle of 17°10' with the vertical plane of the supports, and joined every 3,25 meters to increase their lateral stiffness. Lateral forces transferred by the parabolic arches pass on regularly spaced pair of beams. The aluminum roof cladding is supported by parabolic pre-formed steel decking. Insulation is pressed between aluminum profiles and the steel decking. Glazed lens-shaped openings are placed between twin arches to provide daylight.

3.6 Bijlmer Arena Station, Amsterdam

Height: 6,5 m (centre) to 3,2 m (ends)
Opened: 2007
Architect: Grimshaw Architects, Arcadis Architects
Structural Engineer: Arcadis Bouw/Infra
Structure system of the platform shelter: cantilever girder, 3D

Building materials: steel, roofing: wood panels, glass, metal plates

Amsterdam Bijlmer station had to remain open during the construction process; this had a significant impact on the project. Architects sought to create a pleasant and safe area. To let daylight in, tracks and platforms were split into four groups. Roofing has a modular design: each of 20-metre modules is supported at the ends, on one column by cantilever „saddle". Steel roof elements in a concave-shaped „V" contain cantilever arms on both sides with a length of 18 meters. This shape increases the feeling of „linearity" and highlights their direction. The roof is covered with wooden elements that have been opened at the ridge level by reason of natural ventilation. Glazing, composing 1/3 of the roof surface, is only placed above the platforms.

Conclusion

Train stations are part of a transportation system and also public space frequently combined with shops and leisure activities. Here architecture, engineering and industrial design converge and overlap. It is important to remember the historical role of train stations for the development of wide-span structures by pushing further the contemporary limits of construction of each era. In a complex project like the design of a train station, many problems occur that need to be solved. Cleaning of the outside and inside, maintaining and repairing of canopies, acoustic solutions, etc. should be taken into consideration during the design process. Train stations' structural elements, despite their loadbearing function, are closely related to architectural space. We can assign numerous functions to a structure, such as emphasizing the two speeds perceptible at the station: faster movement of trains and slower movement of people.

The pace of platform columns passing by outside the train window helps to establish the speed of the train in the mind of the passenger. The engineer may see the column as merely a means of supporting the station canopy, but the designer exploits the same column as a mobility guide-post. (Edwards, 1997, p. 176).

Expression and excitement of architecture and its aesthetics are important issues; a station needs to capture the attention of the traveller. The first impression of the station is formed from the view out of the train window or waiting on the platform. Large-scale elements and details should be in balance. Proper choice of materials and structural solutions, using shades, shadows, textures and colours make the train station a distinctive, unique place. Today, train stations once more have become buildings of great importance for urban development and innovation of structural systems.

Acknowledgement

This work is part of the research scholarship at the TU Berlin (Institute for Civil Engineering, Chair of Conceptual and Structural Design) under the supervision of Prof. Dr. sc. techn. Mike Schlaich and Dr.-Ing. Arndt Goldack. It was financed by the German Academic Exchange Service (DAAD).

References

1. Ambrose, J. (1967). *Building structures Primer.* New York: Wiley.
2. Barnes, M., & Dickson, M. (Eds.). (2000) *Widespan roof structures*. London: Thomas Telford Ltd.
3. Biddle, G. & Nock, O.S. (1983). *The railway heritage of Britain*. London: Sheldrake Press.
4. Binney M. (1995) *Architecture of Rail- the way ahead*. London: Academy Editions.
5. Bögle, A., & Schmal, P., & Flagge, I. (Eds.). (2004). *Leicht weit / Light Structures*. Munich: Prestel.
6. Edwards, B. (1997).*The Modern Station- approaches to railway architecture.* London: E & FN Spon.
7. Ferrater, C. (2011). *OAB Carlos Ferrater and Partners*. N.p.: Actar.
8. Kubinszky, M. (1969). *Bahnhöfe Europas- ihre Geschichte, Kunst und Technik; für Eisenbahnfreunde, Architekten und kulturgeschichtlich Interessierte*. Stuttgart: Franckh.
9. Meeks, C. L. V. (1995) *The railroad station- an architectural history*. New York: Dover Publications.
10. Niedenthal, C. (2008). *Bahnhöfe in Deutschland-Moderne Städtische Zentren*. Berlin: Jovis.
11. Parkyn, N. (2004). *Superstructures: The World's Greatest Modern Structures*. London: Merrell Publishers.
12. Wilkinson, Ch. (1996). *Supersheds- the architecture of long-span, large-volume buildings*. Oxford: Butterworth- Heinemann Ltd.
13. *Renaissance der Bahnhöfe: Die Stadt in 21 Jahrhundert*. (1996). Braunschweig/Wiesbaden: Vieweg.
14. http://grimshaw-architects.com (2012, October).
15. http://www.gmp-architekten.com (2012, November).
16. http://www.london-se1.co.uk/news/view/5751 (2012, November).
17. http://www.engineering-timelines.com/scripts/engineeringItem. asp?id=243 (2012, December).
18. http://www.samynandpartners.be (2012, November).
19. http://www.archityepereview.com/17-train-stations/projects/456-nmbs-train-station-canopy/description (2012, November).
20. http://www.ap-brunnert.de (2012, December).
21. http://www.sbp.de/de/build/sheet/962-Flughafen_Leipzig_Halle_-_Bahnsteigdächer.pdf (2013, January).

MSc(Arch) Katarzyna Foljanty
e-mail: kasia.k.kot@gmail.com
Faculty of Architecture, Warsaw University of Technology
ul. Koszykowa 55, 00-659 Warszawa, Poland
e-mail: info@arch.pw.edu.pl