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Development of design and construction of high-speed railway bridges in Germany

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ABSTRACT

Bridges are vital components of high-speed rail (HSR) lines for crossing obstacles such as valleys, rivers, and existing highways or railway lines. The main goal of this paper is to provide a review of the development of HSR bridges in Germany. A short summary of the history of high-speed rail lines is given first. Subsequently, the development of HSR bridges, along with emerging design issues and the two relevant German design guidelines, is reviewed. Further, bridge structure types on German HSR lines, such as simply supported bridges, continuous bridges, arch bridges, integral and semi-integral bridges, composite truss bridges and rigid-frame bridges are discussed. The article concludes with a short discussion about the current situation and future trend of HSR bridges.

1. Introduction

High-speed rails offer a safe, fast, and comfortable mode of travel that improves quality of life and supports economic growth. When the first segment of the Shinkansen (Japanese bullet) train line (Tokyo–Osaka) with an operating speed of 210 km/h was opened in 1964 in time for the Olympic Games, high-speed rail travel was born. In France, the first HSR line (also known as TGV), connecting Paris and Lyon, which had a maximum operating speed of 260 km/h, was opened in 1981. In contrast to the Shinkansen concept, the new European HSR was fully compatible with the existing railways, which facilitated further development of the system on the old Continent. After the success of the Shinkansen and the TGV, HSR construction fever spread across the world. Joining the group of countries offering HSR services were Italy in 1981, Germany in 1988 (ICE trains), Spain in 1992, Belgium in 1997, the United Kingdom and China in 2003, Switzerland and South Korea in 2004, the Netherlands and Turkey in 2009, Austria in 2012, and Poland in 2015. So far, sixteen countries have developed a HSR network (with minimum operating speeds V of 250 km/h). Detailed reviews of the HSR networks in these countries can be found in the literature [1–7]. As Fig. 1 shows, the length of HSR lines constructed worldwide has increased almost exponentially since the first HSR line was opened.

The number of countries boasting HSR networks will likely continue to increase. There are more than 1000 km of HSR lines under construction in Denmark, Iran, Saudi Arabia, and Morocco. Survey data collected by the International Union of Railways (UIC) shows that even more countries, such as the USA and Australia, are currently planning to develop HSR networks [4,5]. According to a UIC report issued in April 2017, there are currently 37,343 km of HSR lines in operation, 15,885 km under construction, and 35,909 km in development. HSR fever will likely continue in the foreseeable future.

Germany was one of the first countries that planned to build a HSR network. Construction on the first line connecting Hanover in Saxony and Würzburg in Bavaria started in August 1973, and the line was opened section by section between 1988 and 1991 [8]. Subsequently, the following segments were opened: Mannheim–Stuttgart in 1991, Hanover–Berlin in 1998, Cologne–Rhine/Main in 2002, Nuremberg–Ingolstadt in 2006, and Erfurt–Leipzig/Halle in 2015. As of 2017, 1475 km of HSR lines are in operation in Germany, a further 368 km are under construction, and 324 km are being designed. The German ICE HSR has been a great success since its inception and has set an example to be followed. Valuable experience has been gained from its operation that is being used in the design of HSR lines all over the world.

Bridges are essential parts of HSR infrastructures for crossing valleys, existing train lines, and other obstacles. In the initial years of German HSR line construction, a large number of simply supported bridges were built. Including the latest trend in bridge construction, integral bridges, more than ten different types of bridge structures can be found on German HSR lines. The history of German HSR bridge development is full of innovations. The objective of this paper is to

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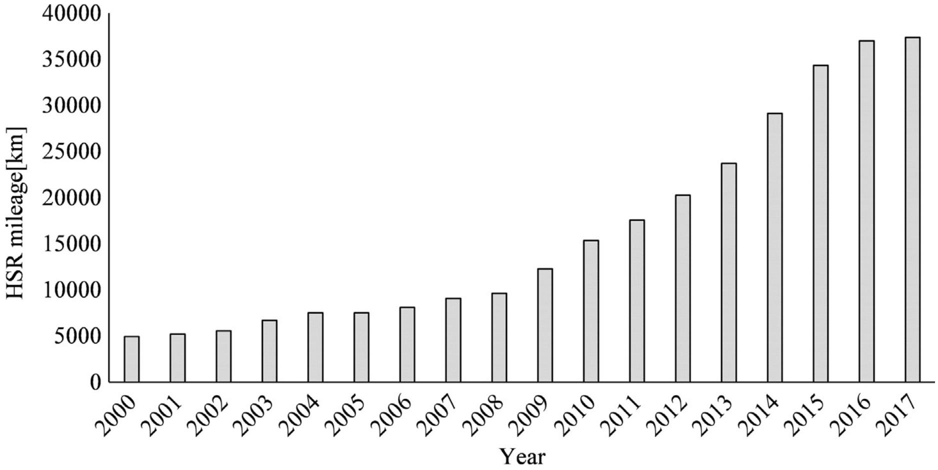


Fig. 1. Global HSR line development.

present an up-to-date review of the design and construction of HSR viaducts and valley bridges in Germany. This paper includes a brief history of HSR bridges, followed by an introduction of two important HSR bridge guidelines. Subsequently, the different types of bridges found in HSR networks are discussed. The discussion, however, only includes bridges with a main span of 20 m or longer.

2. HSR bridge development

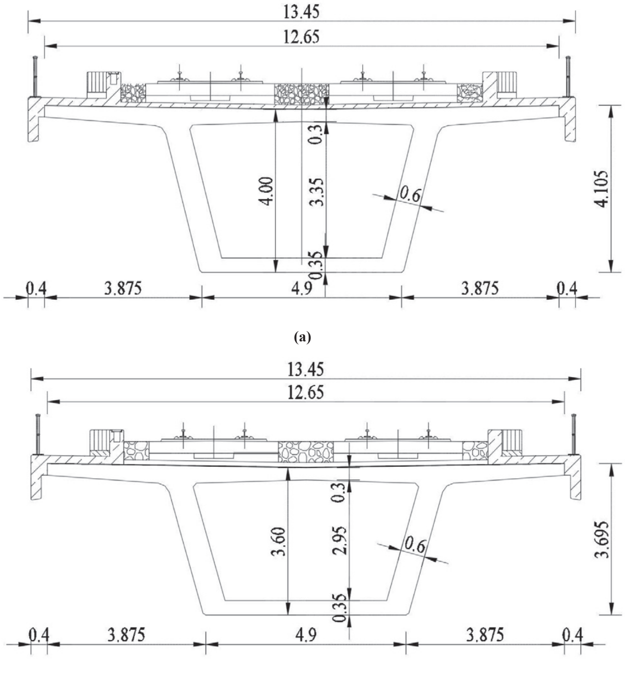
The history of HSR bridge development since the opening of the first HSR line segment in Germany can be divided into two stages (1988–2006 and 2007–today), the beginning of each coinciding with the release of a new guideline.

2.1. 1988–2006: "Rahmenplanung Talbrücken" (bridge design framework)

In 1968, a wheel/rail research program was launched by the German Federal Ministry of Research and Technology. As part of this program, many experimental measurements, investigations, and calculations were carried out to evaluate the behavior of bridges under high-speed traffic loads. Based on the results of this program, the German Railway (DB) Council published the guideline "Rahmenplanung Talbrücken" [9] in the early 1980s. The guideline, which will henceforth be called "Bridge Design Framework," included basic rules for designing bridges on HSR lines. It also provided some standard examples of simply supported and continuous bridges, as shown in Table 1.

The standardized cross sections for a 44-m-span simply supported box girder bridge and a 44-m-span continuous box girder bridge are displayed in Fig. 2. The dimensions in the transverse direction are the same for both cross sections. The major difference between them is their cross-section height: 4.105 m for the simply supported structure, and 3.606 m for the continuous structure.

Rahmenplanung Talbrücken was used in the design and construction of HSR bridges built on the HSR network: from the first line opened in 1991, connecting Hanover and Würzburg, to the Nuremberg–Munich line opened in 2006.



(a)

(b)

Fig. 2. Cross sections of two 44-m-span bridges [9] (a) Cross section of the 44-m-span simply supported bridge and (b) Cross section of the 44-m-span continuous bridge.

Table 2 shows the HSR lines that were opened from 1988 to 2006. The last segment of the Hanover–Würzburg high-speed railway line was opened on June 2nd, 1991. This line was the first high-speed railway line for InterCity Express (ICE) trains in Germany. There are more than 45 bridges along this line. At roughly the same time, in May 1991, the 98.8 km Mannheim–Stuttgart line was opened. In the following years, several more lines were constructed and opened. As the terrain from

Table 1
Bridge design information given in Rahmenplanung Talbrücken [9].

Bridge material	Concrete		Steel		Steel–concrete composite
Bridge type	Simply supported	Continuous	Simply supported	Continuous	Simply supported
Length of main span [m]	44/58	44	50	58	58
Cross section type	Box girder	Box girder	Steel truss	Steel truss	Steel truss with concrete deck
Number of tracks	2	2	2	2	2

Table 2
German high-speed railway lines opened between 1991 and 2006.

HSR line	Operating speed [km/h]	Completed year	Length of HSR line [km]	Cumulative length of bridge [km]	Bridge Length proportion [%]
Hanover–Würzburg	280	1991	327	26.03	7.96
Mannheim–Stuttgart	280	1991	98.8	4.87	4.93
Hanover–Berlin	250	1998	258	1.126	0.44
Cologne–Rhine/Main	300	2002	180	6.013	3.34
Nuremberg–Ingolstadt	300	2006	170.08	0.692	0.41
Total	–	1991–2006	1033.88	38.731	3.74

Hanover to Berlin is very flat, not many engineering structures such as bridges and tunnels were required, and hence there are only four bridges on this line: two continuous steel truss bridges, one continuous box girder bridge and one steel arch bridge. There are 19 bridges along the Cologne–Rhine/Main segment: five simply supported bridges, 11 continuous bridges, one WIB (“Walzträger in Beton”: composite construction, consisting of rolled steel girders embedded in concrete) bridge and one concrete arch bridge. On the Nuremberg–Ingolstadt HSR line there are only five bridges, namely one continuous slab (T-beam) bridge, one steel truss bridge, one steel trough bridge, and two continuous box girder bridges.

Fig. 3 demonstrates that simply supported box bridges constitute the main bridge type on the line segments Hanover–Würzburg (74.6%) and Mannheim–Stuttgart (78.55%). Most of these bridges were built following designs suggested by the Bridge Design Framework. Continuous box girder bridges are the most commonly found type on the segments Hanover–Berlin (50.65%) and Cologne–Rhine/Main (50.92%). On the segment Nuremberg–Ingolstadt, constructed in 2006, all bridges are continuous structures.

It appears that from 1991 to 2006 the preference for simply supported box girder bridges changed to continuous box girder bridges and other types of continuous bridges.

2.2. 2007–2017: Leitfaden Gestalten von Eisenbahnbrücken (design of railway Bridges) [10]

Railway bridges are high-performance structures with respect to load-bearing capacity, durability, and serviceability. As society develops, the cultural value of structures becomes more and more essential, and more focus is placed on aesthetic designs of railway bridges and improving their integration into their surroundings. However, this must not at the expense of economy efficiency, functionality, durability and cost of operation and maintenance [11,12].

To encourage new developments and good design in bridge construction, in 2006 Deutsche Bahn AG (DB) established a bridge council, which consists of experienced civil engineers and architects. The aim of the council was to evaluate existing standardized bridge designs and promote innovative designs by compiling a series of design examples for different site conditions. The council suggested that the engineers deviate from common practice, use their imagination and creativity, and in turn achieve high-quality results with respect to the cost of construction and functional requirements of the bridges. Following a great amount of investigation and analysis by the council, novel truss member connections for steel bridges and a longitudinal moveable ballastless slab track system on bridges were developed, along with new designs for composite bridges, trough bridges, network arch bridges, integral bridges, and semi-integral bridges. Integral and semi-integral bridge designs are recommended by the bridge council because of their efficient mechanical structure, transparency, as well as their economic and aesthetic value. The guideline also provides some design examples for bridges spanning valleys and rivers of various sizes. It advises engineers to use shorter spans in bridges crossing flat valleys in order to achieve smaller structural depths, and hence greater transparency [11,10,13]. Some examples of innovative (semi-)integral bridges are introduced in the following sections.

The guideline “Leitfaden Gestalten von Eisenbahnbrücken” was developed not to provide a new set of standard designs, but to challenge designers to come up with a unique design for each bridge.

Between 2007 and 2017 only one HSR line segment was opened: Nuremberg–Berlin. This segment is divided into the following three subsegments: VDB 8.1 (upgraded section Nuremberg–Ebensfeld and new section Ebensfeld–Erfurt), VDB 8.2 (new section Erfurt–Leipzig), and VDB 8.3 (upgraded section Leipzig–Berlin). This line segment was the first large-scale high-speed railway project developed after the guideline “Leitfaden Gestalten von Eisenbahnbrücken” [10] had been published. Many new ideas from the guideline were applied in this project. The cumulative length of the bridge structures and the total segment length of the segments Ebensfeld–Erfurt and Erfurt–Leipzig are 12.245 km/107 km and 13.358 km/123 km, respectively. Fig. 4 shows that various bridge types were constructed on these lines, with steel arch bridges far outnumbering bridges of other types. The first semi-integral and integral bridges in German HSR history were constructed

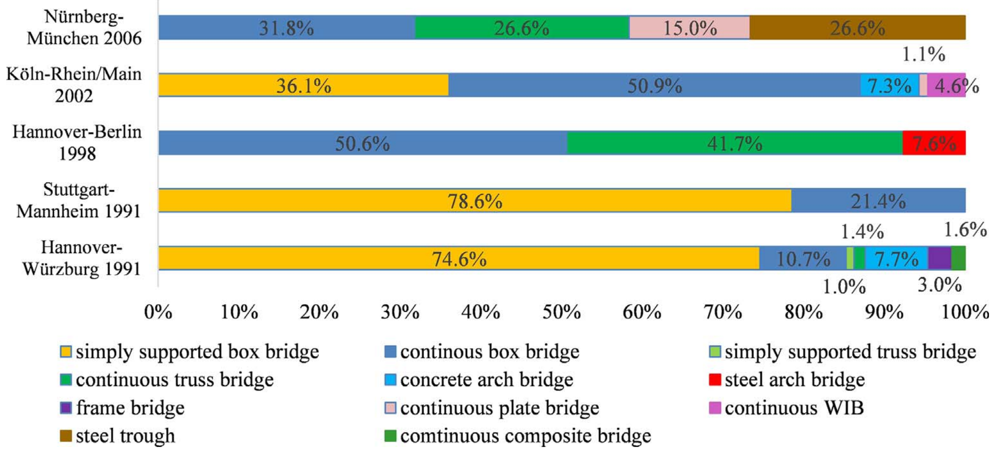


Fig. 3. High–speed railway bridges built in Germany between 1991 and 2006.

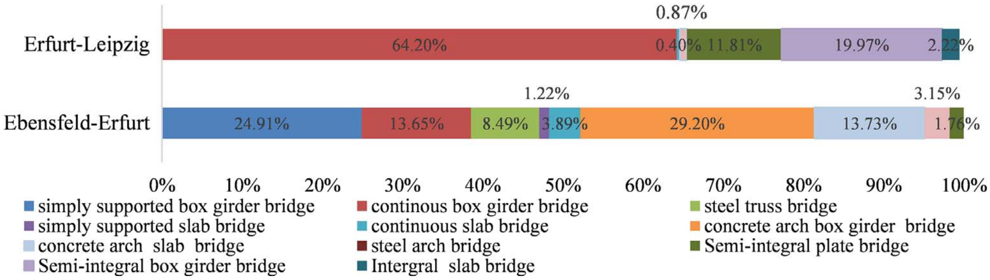


Fig. 4. High-speed railway bridges built in Germany between 2007 and 2017.

on these lines. In the designs, great importance was placed on the cultural and aesthetic value of the bridges.

There are 31 bridges on the Ebensfeld–Erfurt line and eight bridges on the Erfurt–Leipzig line. As shown in Fig. 4, the variety of bridge types increased between 2007 and 2017. Novel and unique structures such as arch bridges were constructed more frequently on these new HSR lines.

3. Bridges

3.1. Simply supported bridges

As a result of the recommendations given in the guideline “Rahmenplanung Talbrücken,” simply supported box girder bridges were the most commonly constructed bridges on the first HSR lines. It is still the most typical and widely used type of bridge structure on the German HSR network. These bridges are predominantly made of concrete. One important reason for the popularity of simply supported box girder bridges in the 1990s was that the box girders could be replaced easily and rapidly without disturbing the substructure and adjacent structures. Fig. 5 displays the cumulative length of all bridge structures and the percentage of simply supported bridges of the cumulative length of all bridges on HSR lines in Germany. The latter is 74.6% and 78.55% on the lines Hanover–Würzburg and Mannheim–Stuttgart, respectively. In the new millennium, the trend to build simply supported bridges obviously reversed. There are no simply supported bridges along the segments Hanover–Berlin and Nuremberg–Ingolstadt.

Typical span lengths of simply supported box girder bridges are 25 m for small overpasses, and 44 m and 58 m for bridges crossing valleys and large viaducts described in the Bridge Design Framework, respectively.

Bridges crossing deep and wide valleys are generally designed to be tall and long. This means that while the stiffness of the piers decreases, the longitudinal forces in the superstructure increase, especially when the trains accelerate or brake on the bridge, and the piers experience large deformations due to bridge track interaction [14,15]. To allow the loads to be carried without causing deformations of the structure and the track, special coupling devices [16] have been invented. They connect adjacent girders so that the horizontal forces are transmitted without influencing the vertical deformation of each span.

For even wider valleys, coupling devices do not suffice and hence an A-shaped pier structure, called an A-frame, was developed (Fig. 6). Because of its particular shape, the A-frame exhibits very high stiffness in the longitudinal direction of the bridge. Due to its great resistance with respect to horizontal forces in the longitudinal direction of the bridge, this type of pier is particularly suited for use as a fixed point in long and tall valley bridges. In addition, the A-frame is comparatively insensitive to deformations of the foundation due to its large height and long span, so that it can be used even in unfavorable ground conditions. Table 3 lists the five simply supported bridges on the HSR lines that feature an A-frame. Four of these bridges are 58-m-long chain bridges, while the fifth one is a 44-m-long chain bridge. The lengths and heights of the bridges range from 570 m to 1450 m and from 45 m to 95 m, respectively. An example of a successfully executed bridge with an A-frame is the 95-m-high Rombach Viaduct, which was completed in 1986 and is composed of 17 spans of 58-m-long simply supported

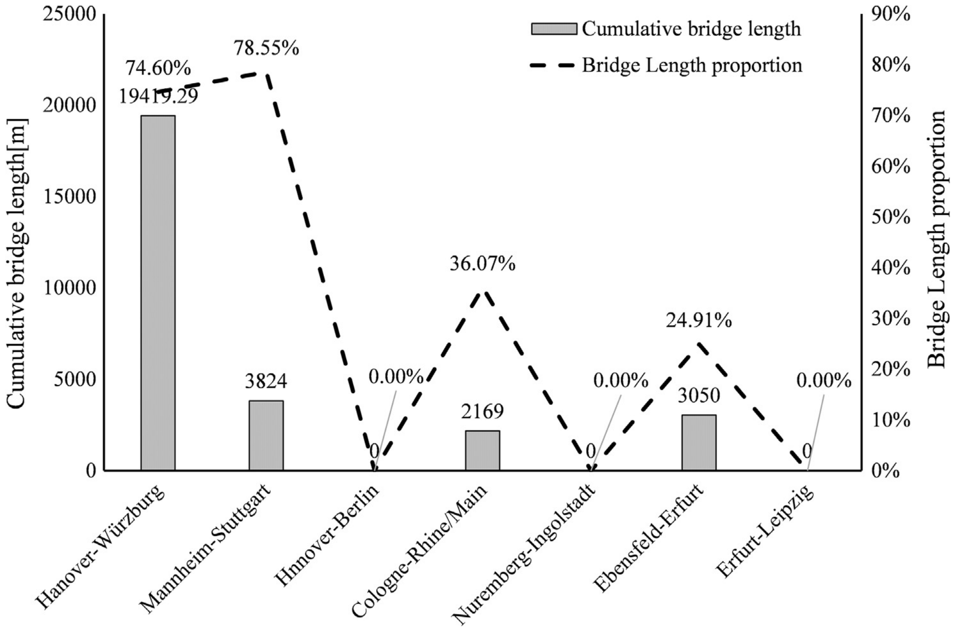
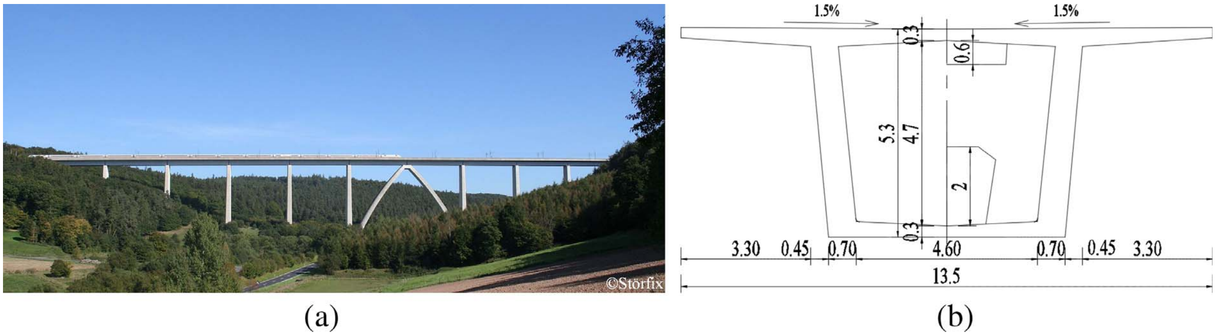


Fig. 5. Cumulative length of simply supported box girder bridges on German HSR lines and percentage of the cumulative length of all bridge structures.



(a) (b)

Fig. 6. Rombach Viaduct (a) Side view (Photo: Störfix) and (b) Superstructure cross section.

girders with an A-frame support at its center. Fig. 6 shows that the superstructure is 5.30 m high and 14.5 m wide, and the thicknesses of the top, web, and bottom plates are 30 cm, 70 cm, and 30 cm, respectively. Adjacent girders are coupled by coupling devices, the compressive forces are transmitted via elastomer coupling bearings, the tensile forces are transmitted via tensioning members, and the transverse forces are absorbed by additional transverse bearings on top of the A frame. The cantilever construction method was used for this bridge. Information on this construction method and other construction details can be found in a publication by Harries et al. [17].

3.2. *Continuous bridges*

Continuous box girder bridges represent another structural type used for crossing valleys or existing highways. This bridge type is described in the Bridge Design Framework and is often the preferred option in design. Compared to simply supported bridges, this bridge type not only exhibits greater slenderness but also lower dynamic responses [18]. Fig. 7 shows the total length of this bridge type on German HSR lines and its percentage of the cumulative length of all bridge structures. There are 18.464 km of continuous box girder bridges on German HSR lines, which corresponds to 27.78% of the cumulative length of all bridges on the network. While ever fewer simply supported bridges are being constructed, an increasing number of continuous box girder bridges are being built on both existing and new HSR segments. The slenderness (ratio of span length and cross-section height L/H) of continuous box girders ranges from 12 to 14 [19]. Continuous box girders can be designed as having either uniform or variable depth.

The superstructure cross-section height of uniform-depth continuous box girder bridges on German HSR lines varies between 2.4 m and 5.35 m, and span lengths range between 28 m and 64.44 m. Sinn Viaduct at Zeitlofs is a typical uniform-depth continuous girder bridge. It is 704 m long and has 16 spans, each of 44 m length. The superstructure cross-section height is 3.6 m, which translates to a slenderness of L/H = 12.2. A simply supported bridge at this location would require a pier cross-section width of 4 m, as opposed to the actual width of 2.7 m [19]. Another example of a uniform-depth continuous bridge is the 1160-m-long Bartelsgraben Viaduct. It is composed of four separate sections, each consisting of five continuous spans of 58 m length. The superstructure cross-section height is 4.75 m. Another example is Wied Viaduct with the following span configuration: 62.77 + 4 × 65.44 + 62.77 = 387.3 m. The height of the cross section is 5.35 m. The superstructure was built using the incremental launching method [20].

There are also two continuous box girder bridges with variable superstructure heights on German HSR lines. Eddersheim Rail Bridge (span configuration 40 + 77 + 130 + 70 = 324 m) on the segment Cologne–Rhine/Main was completed in 1999. The superstructure height increases continuously from 5.5 m at the center of the main span to 8.5 m above the central piers [21]. The mid-span deflection due to trains crossing the bridge at a speed of 220 km/h, obtained from calculations and field investigations, is less than L/1700, and the vertical acceleration is less than 0.44 m/s^2 [22]. The other variable-height continuous box girder bridge is Main-Danube Canal Bridge at Hilpoltstein on the Nuremberg–Munich line, which was completed in 2005. Its span configuration is 30 + 81 + 30 = 141 m. The superstructure heights at the center of the main span and the central piers area are 3.3 m and 6.9 m, respectively.

Besides the great number of continuous box bridges there are also eight continuous concrete slab bridges on German HSR lines (Table 4), all of them either three- or four-span bridges. Except for Schwarzach Viaduct, which is a variable-depth (1.8–2.8 m) plate girder bridge, they are all uniform-depth bridges. Compared to the uniform-depth box girder bridges, the uniform-depth plate girder bridges on the HSR network have not only a much smaller span range (16.5–35 m) but also smaller superstructure heights (1.4–2.2 m), resulting in higher clearances and increased transparency. Therefore, continuous concrete slab bridges are still the preferred type for bridging narrow and shallow valleys.

3.3. *Arch bridges*

Arch bridges are usually built over broad valleys and rivers. Compared to simply supported bridges and continuous bridges, arch bridges can span much longer distances. Table 5 lists the arch bridges on German HSR lines. There are 11 concrete arch bridges and four steel tied-arch bridges. Ten of these bridges were built on the Ebensfeld–Erfurt HSR line after the year 2011. The span lengths of concrete arch bridges and steel arch bridges range between 107 m and 270 m and 73 m and 78.3 m, respectively.

(a) Concrete arch bridges

Table 3
Simply supported box girder bridges with A-frames on German HSR lines.

Bridge	Completed Year	Line	Bridge height [m]	Superstructure height [m]	Span configuration [m]
Rombach Viaduct	1986	Hanover–Würzburg	95	5.3	7 × 58 + 2 × 58 + 8 × 58 = 986
Mülmisch Viaduct	1988		74	5.3	5 × 58 + 2 × 58 + 8 × 58 = 870
Pfieffe Viaduct	1989		59	5.3	5 × 58 + 2 × 58 + 7 × 58 = 812
Fulda Viaduct at Morschen	1989		75	5.3	11 × 58 + 2 × 58 + 12 × 58 = 1450
Wümbach Viaduct	2005	Ebensfeld–Erfurt	45	4.0	43 + 5 × 44 + 2 × 44 + 4 × 44 + 43 = 570

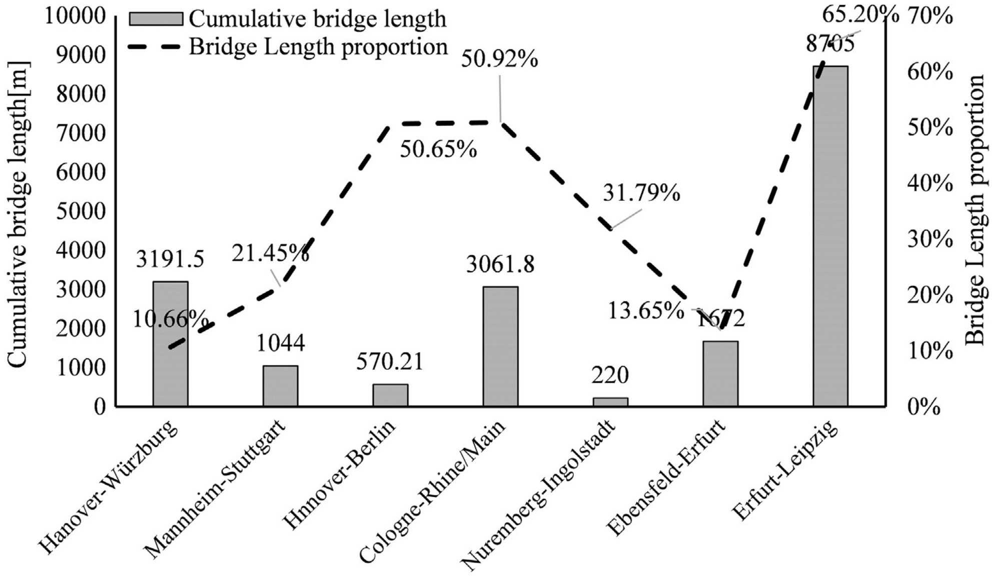


Fig. 7. Cumulative length of continuous box girder bridges on German HSR lines and percentage of the cumulative length of all bridge structures.

Main Viaduct at Veitshöchheim was the first arch bridge completed on the segment Hanover–Würzburg. The arch spans across the River Main with a clear width of 162 m. The prestressed deck has a box cross section and is divided into five continuous sections, as shown in Fig. 8 [23]. Wälsebach Viaduct is the only arch bridge on German HSR lines with more than one continuous concrete arch (Fig. 9). the required geometric and dynamic boundary conditions but also to carry the continuous rail track installed on the bridge [24]. The superstructure of Lahn Viaduct is an eight-span, continuous single-box girder with the spans having a maximum span length of 58 m [25]. The height of the superstructure is 4.75 m; the thicknesses of the deck, web, and bottom flange are 30 cm, 60 cm, and 35 cm, respectively.

Because of the successful construction of a great number of arch bridges and their ease of construction, arch bridges were also used to bridge deep valleys on the segment Ebensfeld–Leipzig. Instead of traditional arch bridges, however, a novel bridge type, called wide-span arch bridge (Fig. 10), was built, which was initially developed by OBERMEYER [26] for required spans of up to 270 m. This kind of arch bridge has been proven to meet all the requirements regarding the ultimate and serviceability limit states. In order to obtain a stiffer and more stable parabolic arch shape, the ratios of the arch cross-section height at the crown and at the bottom of the arch, respectively, and the span of the are 1:60 and 1:40 [26]. Fig. 10 and Table 6 show the characteristic parameters of the wide-span arch bridges constructed on the Ebensfeld–Leipzig HRS line. An example cross section (that of Masse Viaduct) is given in Fig. 11.

A modified version of the wide-span bridge was built in 2011 over the very wide Ilm Valley (Fig. 12). Ilm Viaduct has a length of 1681 m and consists of three arches with spans of 175 m, 155 m, and 125 m (the span arrangement is 46 + 8 × 58 + 125 + 5 × 58 + 155 + 68 + 62 + 2 × 61 + 175 + 3 × 58 = 1681 m). The width of the superstructure is 14.1 m and its height is about 5.0 m. The superstructure is a box girder and is divided into four sections of continuous girders with lengths of 471 m, 459 m, 415 m, and 336 m. The deck slab is post-tensioned in the transverse direction. Because the three horizontally fixed supports are located at the crowns of the arches, the arches take all the horizontal forces occurring in the longitudinal direction of the bridge [27].

(b) Steel tied-arch bridge

The five steel tied-arch bridges on German HSR lines are arch bridges with box cross sections. Except for the bridge over the Main at Wiesen, which boasts three continuous arch spans, the bridges are all single-arch span bridges. The distance between the axis of the vertical ties is 7–10 m, while the heights of the arches and cross sections vary between 14.55 m and 21 m, and 2.55 m and 4 m, respectively [28].

A recently constructed tied-arch bridge forms a part of Saale–Elster Viaduct, which is the longest high-speed railway bridge in Germany. The arch rise is 17.5 m, resulting in an arch-to-span ratio of 1:6. The distance between the vertical tie members is 10 m, and the width of the bracing girders is 1.00 m. The steel ties are 50 mm thick and 280 mm wide, with the width increasing to 400 mm at the connections of the arch and the stiff girders. The height of the arch cross section is 1.90 m. Due to the relatively large end tangent angles of the girder, compensating plates have been installed at the joints. They bear the longitudinal forces even if both train tracks on the bridge experience simultaneous braking/acceleration load. Fatigue calculations have confirmed that the service life of the bridge is more than 100 years. A detailed dynamic model under HSLM A (high speed load model A) [29]

Table 4
Continuous concrete slab bridges on German HSR lines.

Bridge	Completed Year	Line	Total length [m]	Superstructure height [m]	Span configuration [m]
Bärntal Viaduct	–	Hanover–Würzburg	67	1.8	21 + 25 + 21
Viaduct over the A66		Cologne–Rhine/Main	120	1.75	28 + 2 × 31 + 30
Kutscheid Viaduct	2002		67	1.7	20.5 + 26 + 20.5
Schwarzach Viaduct	2005	Nuremberg–Munich	104	1.8–2.8	30 + 44 + 30
Stadelbach Bridge	2014	Ebensfeld–Erfurt	90	1.75	27.5 + 35 + 27.5
Kiengrund Bridge	2014		108	2.2	24 + 30 + 30 + 24
Saubach Bridge	2013		55	1.5	16.5 + 22 + 16.5
Schobse Viaduct	2013		87	1.4	20 + 23.5 + 23.5 + 20

Table 5
Arch bridges on German HSR lines.

Type	Bridge name	Year	HSR line	Bridge length [m]	Length of main span(s) [m]
Concrete arch bridge	Wälsebach Viaduct	1988	Hanover–Würzburg	721.2	127.5
	Main Viaduct at Veitshöchheim	1987		1280	162
	Lahn Viaduct	2001	Cologne–Rhine/Main	437.85	116
	Froschgrundsee Viaduct	2011	Ebensfeld–Erfurt	798	270
	Grümpen Viaduct	2011		1104	270
	Truckenthal Viaduct	2011		425	161
	Dunkel Viaduct	2013		291	141.05
	Reh Viaduct	2013		203.45	107
	Masse Viaduct	2013		385	164.99
	Oelze Viaduct	2011		370	164.99
	Ilm Viaduct	2011		1681	155/175
Steel tied-arch bridge	Havel Canal Bridge at Wustermark	1997	Hanover–Berlin	86	86
	Gera Viaduct at Bischleben	2005	Ebensfeld–Erfurt	323	78.3
	Main bridge at Wiesen	2014		219	73
	Flutmulden Bridge at Wiesen	2014		88	88
	Saale–Elster Viaduct	2013	Erfurt–Leipzig	8577	110

Fig. 8. Main Viaduct at Veitshöchheim (Photo: Störfix).

Fig. 9. Wälsebach Viaduct (Photo: Klaus with K).

was established, and it was found that there are no significant resonance problems of the main support structure, due to the asymmetric oscillation of the arch and the relatively long span [30]. The tied-arch bridges on German HSR lines are shown in Fig. 13.

3.4. Integral and semi-integral bridges

Integral and semi-integral bridges are designed according to a novel holistic design philosophy. A special feature of these bridges is the use of continuous, multi-span prestressed concrete girders, as well as the omission of structural bearings for the superstructure. Instead of bearings, monolithic connections between the substructure and the superstructure are used. Therefore, these structures are more slender than conventional bridges, and they are very robust and durable because of the absence of bearings and dilatation joints [31,32]. These bridge types are therefore "integral" bridges. "Semi-integral" bridges have bearings or joints only at some of the piers or abutments [33]. On the whole, the integral load-bearing behavior proves itself to be extraordinarily advantageous compared with that of superstructures resting on bearings. Firstly, a slender structure increases the elegance and transparency of the bridge. Secondly, the lack of bearings and joints contributes to the robustness of the structure and results in lower maintenance costs. Thirdly, the slender and solid piers need no internal formworks. Despite their very slender dimensions, these piers are often less prone to stability problems than the more common piers with bearings on top because of their reduced buckling lengths [34,10]. Integral and semi-integral bridge constructions are gaining more and more acceptance in Germany and are increasingly being built on German high-speed railway lines owned by DB AG, as they boast good functionality, long service life, as well as low maintenance costs and high aesthetic value [35]. There are four semi-integral bridges on the segments Erfurt–Leipzig and Ebensfeld–Leipzig. There is one integral bridge on the segment Erfurt–Leipzig; see Table 7 (see Fig. 14).

Scherkonde Viaduct was the first semi-integral bridge constructed in German HSR history. It was designed to replace the original continuous box girder bridge (13 spans of 44 m length), the design of which was based on the guideline "Rahmenplanung Talbrücken". Compared to the original continuous bridge, a reduction of the superstructure height of 50% was achieved, thereby dramatically increasing the clearance under the bridge. For static and design reasons, the outer spans were shorter than in the original bridge (44 m vs. 36.5 m). The final span arrangement of the bridge is 27 + 2 × 36.5 + 10 × 44 + 36.5 m = 576.5 m. The pier thickness was reduced from 4.0 m to 1.5 m compared to the original bridge. The columns were monolithically connected to the superstructure. The occurring constraint forces were taken into account during the bridge design. Their magnitude was decreased by choosing

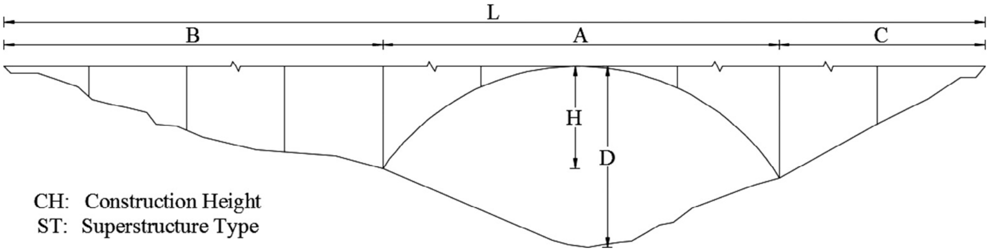


Fig. 10. Wide-span arch bridge.

Table 6
Wide-span arch bridges on German HSR lines.

Bridge	CH [m]	ST [–]	A [m]	B [m]	C [m]	L [m]	H [m]	D [m]	H/A [–]
Froschgrundseetal	3.60	Continuous	270	6 × 44	6 × 44	798	56	65	0.207
Grümpental	3.60	Continuous	270	43 + 6×44	11 × 44	1104	63.4	71	0.235
Truckenthal	3.60	Continuous	161	3 × 44	3 × 44	425	37.8	57	0.235
Dunkeltal	2.70	Continuous	141	3 × 25	3 × 25	291	33.9	65	0.240
Rehtal	2.70	Continuous	107.5	2 × 24	2 × 24	203.5	24.7	54	0.230
Masseta1	3.60	Continuous	165	3 × 44	2 × 44	385	40	78	0.242
Oelzetal	3.60	Continuous	165	30 + 35+40	40 + 2×30	370	40.7	71	0.247

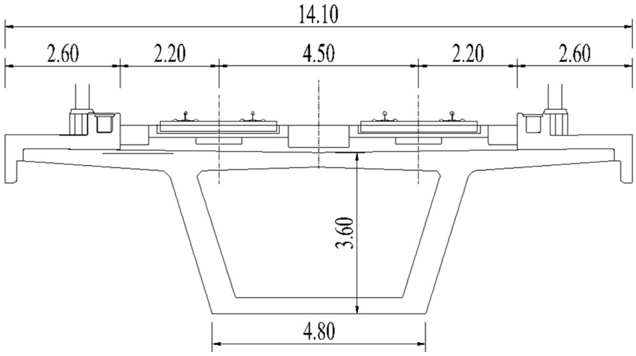


Fig. 11. Masse Viaduct superstructure cross section.

Fig. 12. Ilm Viaduct.

an advantageous distribution of the stiffness in the structure, especially the substructure [36]. The slender and transparent structure blends perfectly into the surrounding landscape. Dynamic calculations considering the acceleration and deformation limit values given in the “DIN-Fachbericht” [37] and Guideline 804 [9] proved that the dynamic behavior of the bridge is on the safe side of the stipulated limitations, despite its slenderness. The maximum acceleration along the entire superstructure is 0.098 m/s^2. Details about the interaction between the bridge and the connecting embankment and tunnel can be found in the publication by von Wolfersdorff et al. [38].

The 35-m-tall semi-integral Gruben Viaduct has the following span arrangement: 2 × 25 + 90 + 3 × 25 = 215 m. The double-T-beam superstructure is supported on a double-hinged arch. The structure has a main span of 90 m and a stiff crown area. The thickness of the arch varies from 1.70 m at the foot of the arch to 3.30 m at its crown. The arch is monolithically connected to the massive arch crest, which is why the large longitudinal forces introduced by braking and acceleration of the trains are mostly carried by the arch. The width of the piers at the bottom of the superstructure is 5.9 m in the transverse direction, and it decreases with a slope of 1:70 towards the bottom of the piers, where it is 6.40 m. In order to ensure sufficient resistance of the structure to constraint forces such as those caused by temperature differences, the thickness of the piers in the longitudinal direction of the bridge varies between 60 cm and 90 cm. Keil et al. [39,40] carried out dynamic calculations and construction monitoring on this type of bridge, thereby proving its efficiency. Another, similar bridge is Unstrut Viaduct [41], which has the following span arrangement: 3 × 58 + 4 × (4 × 58 + 116 + 4 × 58) + 3 × 58 = 2668 m. As the 58 m spans are much longer than the 25 m spans of Gruben Viaduct, the superstructure has been designed as a box cross section.

Stöbnitz Viaduct consists of four sections, two consisting of two spans (22 m and 24 m long), and two sections with the following span configuration: 24 + 24 + 6.5 + 24 + 24 = 102.5 m. The double-T-beams are monolithically connected to the piers. The abutments and double-coupled piers are stiff enough to bear the longitudinal forces from the superstructure. The foundations of the other piers consist of rows of piles. The longitudinal distance between adjacent pile rows changes from 15 m in the middle of each section to 35 m at the end of each section, which leads to a stiffness reduction in the longitudinal direction of the substructure. As a result, the longitudinal constraint forces can be reduced. The sliced piers (Fig. 15) allow longitudinal movement of the girders, which makes the structure more flexible and enables the longitudinal stresses to be partly released. Most of the traffic-induced natural oscillations of the bridge range from 5.4 Hz to 5.7 Hz. These are relatively low frequencies that lead to an increased susceptibility of the bridge to vertical excitations. In the unfavorable case of LM 71 [29], the damping of the structure of $\Delta\zeta = 0.005$ resulting from the actions induced by train crossing the bridge on an adjacent track can also be disregarded. The maximum vertical acceleration is about 2.5 m/s^2 [9], the comfort criteria can be met [29].

Gänsebach Viaduct is a monolithically prestressed concrete double-T-beam bridge with circular columns (Fig. 16). In the longitudinal direction, the bridge consists of ten segments (52.5 + 8 × 112 + 52.5 = 1001 m) separated by joints. The span configurations of the 112 m and 52.5 m frames are: 1.5 + 24.5 + 24.5 + 11 + 24.5 + 24.5 + 1.5 = 112 m, and 1.5 + 2 × 24.75 + 1.5 = 52.5 m. The fixed, coupled piers are located at the center of the 112 m segments (Fig. 16). Their heights are between 10 m and 12 m, depending on the distance of the superstructure from the terrain and the ground conditions. Therefore, the lengths of the individual spans deviate slightly from the average value of 24.5 m. The first natural frequency under bending vibration determined with dynamic calculations is 3.6 Hz, and the maximum acceleration is 3.44 m/s^2 under traffic loads. The maximum dynamic enhancement factor is 1.17, hence only slightly greater than the maximum allowed dynamic coefficient $\phi = 1.08$ proposed in Technical Report 101 issued by the DIN [42].

3.5. *Composite truss bridges*

There are six truss bridges on German HSR lines (Table 8). The span lengths of the bridges are between 58 m and 105.7 m. Except for Main Viaduct at Nantenbach, all the bridges are uniform-depth truss bridges. Fulda Viaduct at Kragenhof, which was completed in 1988, was the first deck truss bridge in German HSR history. Due to the poor geological site conditions and because at the time it was thought that the bridge would be easy to replace, the bridge was designed as a simply supported structure. The heights of the bridge superstructure and the truss are 9.02 m and 7.55 m, respectively. The truss panels of the bridge are

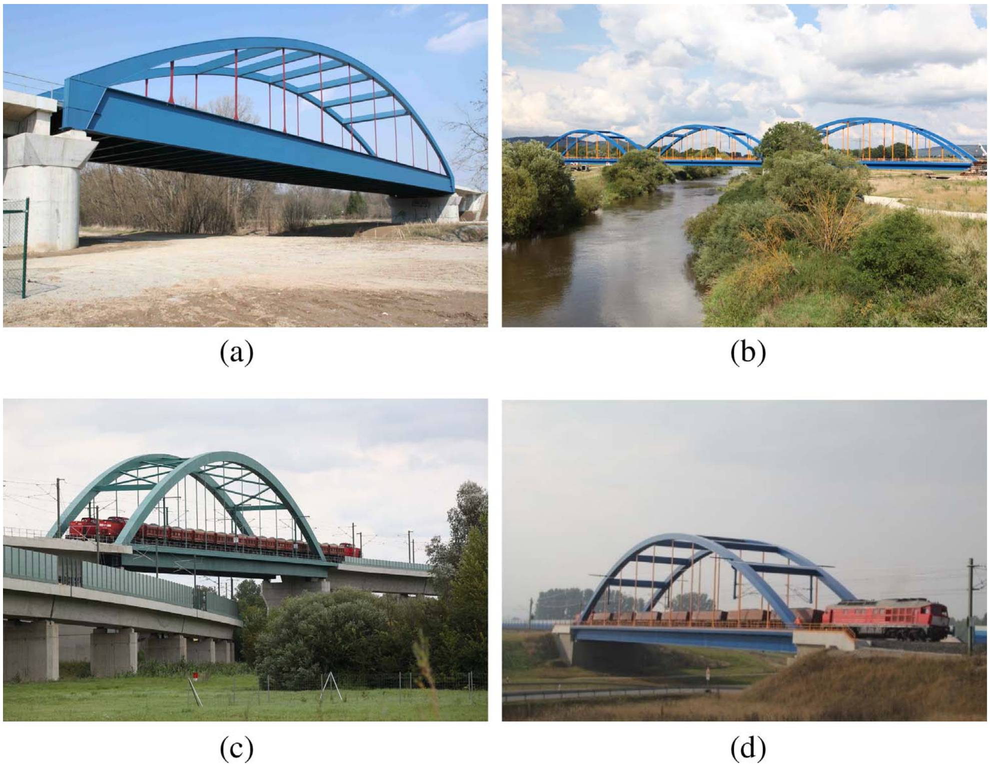
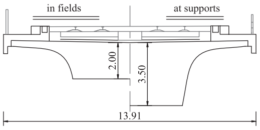
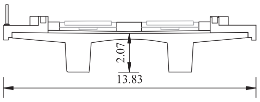
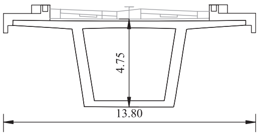
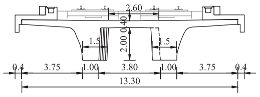
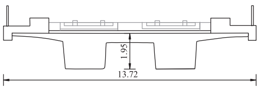

(a) (b) (c) (d)

Fig. 13. Tied-arch bridges with box-sections arches on German HSR lines (a) Gera Viaduct at Bischleben (Photo: Störfix), (b) Main bridge Wiesen (Photo: Störfix), (c) Saale–Elster Viaduct (Photo: Claus Rudolf) and (d) Flutmulden Bridge at Wiesen (Photo:DB AG/ Hannes Frank).

Table 7
Integral and semi-integral bridges on German HSR lines.

Bridge	Line	Completed year	Superstructure cross section	Length [m]	Main span length [m]	Construction cost [million €]
Scherkonde Viaduct	Erfurt–Leipzig	2011		576.5	44	20
Gänsebach Viaduct		2012		1001	24.75	25
Unstrut Viaduct		2012		2668	108	60
Gruben Viaduct	Ebensfeld–Leipzig	2013		215	90	–
Stöbnitz Viaduct	Erfurt–Leipzig	2012		297	24	8

5.6 m long in the longitudinal direction. The thickness of the bridge deck at the center of the superstructure cross section is 40 cm. The material of the steel truss consists of 95% St52-3 and 5% RSt37-2, as specified in DIN 17100 and TL 91802. Altogether, 1000 tons of steel were used in this bridge. Detailed information on the bridge can be found in a paper written by Keller et al. [43]. The 868 m Itztal Bridge is the only other uniform-depth truss bridge on German HSR lines. This bridge construction consists of a three-span continuous bridge flanked by three two-span continuous bridges on either side. The heights of the superstructure and truss are 7.425 m and 6.5 m, respectively. The distance between truss panel points in the longitudinal direction is 6.8 m (see Table 9).

The only variable-depth truss bridge, Main Viaduct at Nantenbach, has a total length of 694.5 m and a 2650 m horizontal radius. The heights of the superstructure at the center of the span and at the piers are 7.66 m and 15.66 m, respectively (Fig. 17), which corresponds to a ratio L/H of 27 and 13, respectively. The length of the truss panels is 10.4 m; the distance between the truss members in the transverse


(a) (b) (c)

Fig. 14. Integral and semi-integral bridges on German HSR lines (a) Scherkonde Viaduct, (b) Gruben Viaduct and (c) Unstrut Viaduct.


(a) (b)

Fig. 15. Stöbnitz Viaduct (left); Sliced pier between frames (Right photo: störfix).


(a) (b)

Fig. 16. Gänsebach Viaduct (Right photo: Störfix).

direction is 6.0 m. In the region of negative bending moments both the top and the bottom chords have a steel–concrete composite cross section [44]. Based on structural analysis the admissible deformation was decided to be 1/2000 = 10.4 mm instead of 1/2200 = 9.45 mm as stipulated in standard DS 899/59 [45]. Details about the design, structural analysis, and construction can be found in Schwarz et al. [44–46].

3.6. *Rigid-frame bridges*

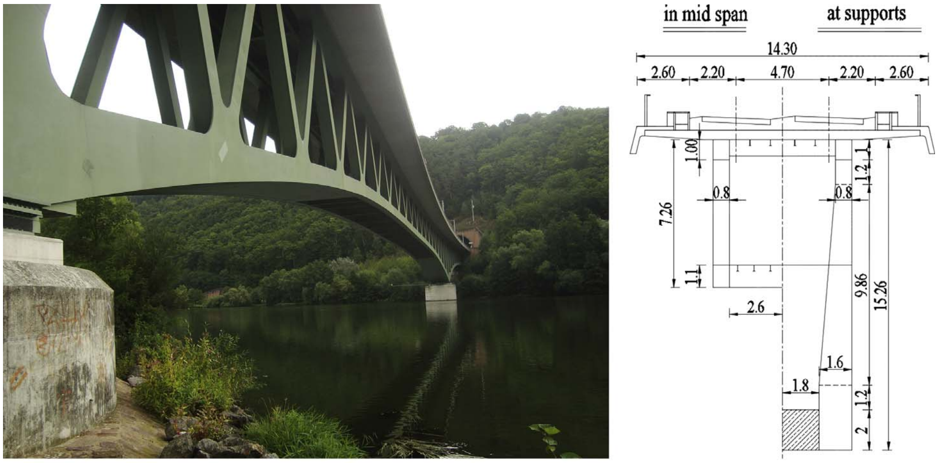
There are two frame bridges on German HSR lines: Main Viaduct at Gemünden in 1984, and the viaduct at Weissenbrunn am Forst, completed in 2012. The choice of frames rigidly connected V-shaped piers resulted in large spans, great slenderness, as well as an elegant and robust bridge design.

Table 8
Truss bridges on German HSR lines.

Bridge	Type	Completed year	Line	Static system	Span configuration [m]	Superstructure/truss height [m]
Fulda Viaduct at Kragenhof	Deck truss	1988	Hanover–Würzburg	Simply supported	57.60 + 72.00 + 2 × 57.60	7.55/9.02
Havel Bridge at Rathenow	Through truss	1992	Hanover–Berlin	Continuous	70 + 90 + 70	11.0
Main Viaduct at Nantenbach	Deck truss	1993	Hanover–Würzburg	Continuous	83.2 + 208 + 83.2	7.66–15.66
Elbe Bridge at Hämerten	Through truss	1996	Hanover–Berlin	Continuous	66.99 + 105.77 + 66.9	12.75
Itz Viaduct	Deck truss	2005	Ebensfeld–Erfurt	Continuous	57 + 13 × 58 + 57	6.5/7.425
Wipfra Viaduct	Through truss	2002	Ebensfeld–Erfurt	Simply supported	57 + 58 + 57	1.65/9.80

Table 9
Rigid-frame bridges on German HSR lines.

Bridge	Year completed	Line	Span configuration [m]	Superstructure height [m]
Main Viaduct at Gemünden	1984	Hanover–Würzburg	82 + 135 + 82	4.5–6.5
Weissenbrunn am Forst Viaduct	2012	Ebensfeld–Erfurt	50 + 76 + 50	4.0–5.0



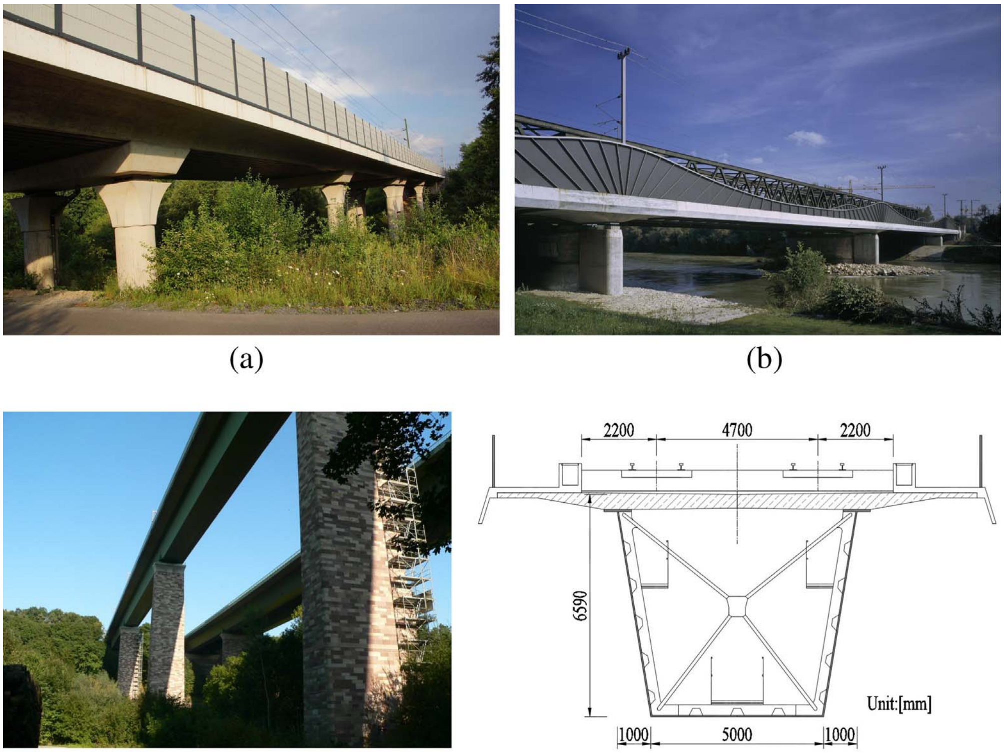
(a) (b)

Fig. 17. Main Viaduct at Nantenbach.

(a) (b)

Fig. 18. Rigid frame bridges on German HSR lines (a) Main Viaduct at Gemünden and (b) Weissenbrunn am Forst Viaduct (Photo: Störfix).

With a span arrangement 82 + 135 + 52 = 269 m, Main Viaduct at Gemünden (Fig. 18) on the HSR line Hanover–Würzburg was the first German railway bridge with unreinforced concrete joints [47]. The main frame bridge is connected to a 330.5 m continuous approach bridge on its north side and a 164.0 m continuous approach bridge on its south side. The total length of the bridge structure is 793.5 m. The height of the superstructure/the width of the bottom plate vary between 6.5 m/6.0 m above the frame pier and 4.5 m/5.4 m at the center of the span. The superstructure is monolithically connected to the V-shaped piers [48,49]. There are three expansion joints along the bridge. The bearing forces are transmitted to the shallow foundation by way of concrete hinges at the bottom of the V-shaped piers [50]. The hinges are designed not to have any reinforcement crossing the hinge throat at the bottom of the V-shaped piers. The maximum occurring normal forces of 121 MN result in an average stress of 47 MN/m^2 in the hinge throat. To reduce the impact of the shear force, the hinges were installed at an angle to the horizontal [51]. The viaduct at Weissenbrunn am Forst (Fig. 18) on the HSR line Ebensfeld–Erfurt was completed in 2012. Its span arrangement is 50 + 76 + 50 m = 176 m.



(a) (b)

(c) (d)

Fig. 19. Other bridge types on German HSR lines (a) Hasenpohl Viaduct (Photo: Tohma), (b) Ingolstadt railway bridge (Photo: Roland Halbe), (c) Werra Viaduct at Hedemünden (Photo: prseee03) and (d) Cross section of Werra Viaduct at Hedemünden.

3.7. Other bridge types

Besides the aforementioned bridges, there are other bridge types such as steel trough bridges, WIB (hot-rolled steel sections embedded in concrete) bridges, and composite box girder bridges (steel box, concrete deck) on German HSR lines. Some examples of these bridge types are shown in Fig. 19.

Ingolstadt railway bridge, completed in 2002, is the only steel trough bridge with a concrete deck on German HSR lines. It has the following span arrangement: 13.42 + 19.0 + 22.3 + 55.15 + 54.72 + 19.5 = 184 m. The shape of the walls of the steel trough was designed taking into account the moment flow along the bridge. This contributes to the slender and elongated form of the bridge, which hovers like a natural wave above the River Danube [13]. The height of the trough girder varies from 2.50 m to 5.35 m.

WIB girders consist of a composite concrete slab incorporating hot-rolled steel profiles and transverse reinforcement made of steel bars. They are often used to achieve very slender superstructures. There are two WIB bridges on German HSR lines: Hasenpohl Viaduct and Kochenbach Viaduct [52], which have the following span configurations (continuous spans): 27 + 24 + 18 + 27 + 6.5 + 24 = 126.5 m and 23.5 + 24 + 24 + 6.5 + 24 + 24 + 23.5 = 149.5 m, respectively. The superstructure heights of these bridges are 1.17 m and 1.21 m, respectively. The only steel box bridge with a concrete deck is Werra Viaduct at Hedemünden [53] on the segment Hanover–Würzburg, with the span configuration 76 + 96 + 96 + 80 + 67.5 = 415.5 m. The cross-section height of the superstructure is 6.59 m.

4. Summary

High-speed railways are a safe, comfortable, and fast mode of transportation. They are not only the fastest way to travel (for distances between 150 km and 800 km) but also more ecological compared to highway and air travel [2]. The demand for high-speed railways is likely to keep growing. This paper contains a review of HSR bridges constructed in Germany in the past decades, and the relevant design specifications and structural design. It is shown that simply supported box girder bridges make up the majority of bridges built on the first HSR lines, Hanover–Würzburg and Mannheim–Stuttgart. On subsequently built HSR lines, however, preference was given to continuous box girder bridges. This type of bridge constitutes more than 50% of the cumulative bridge length on the HSR segments Hanover–Berlin and Cologne–Rhine/Main. On the recently constructed HSR lines, Ebensfeld–Erfurt and Erfurt–Leipzig, only 3.05 km of simply supported box girder bridges and more than 10 km of continuous box girder bridges were built. On the segment Erfurt–Leipzig 4.54 km (31.78%) of integral and semi-integral bridges, which are relatively recently developed types of structures, were built. In locations on the German HSR network where longer spans ($L > 60$ m) were required, arch bridges were the most commonly used bridge type. In the past 30 years, 12 concrete arch bridges (main spans ranging between 107 m and 270 m) were built on the network. Four steel arch bridges (main spans ranging between 73 m and 110 m) were completed between 1988 and 2014. In addition, four truss bridges (main spans 72–208 m) were completed between 1988 and 1996, one steel–concrete composite bridge (96 m main span) was completed in 1989, two frame bridges (135 m and 76 m main span) were completed in 1984 and 2012, respectively, and two semi-integral bridges (108 m and 90 m main span) were completed in 2012 and 2013, respectively. Arch bridges, integral bridges, and semi-integral bridges have been the most commonly constructed bridge types in recent years. The preference of stiff deep girders like simply supported box girder and continuous box girder (3.0–4.0 m) has changed to stiff structures such as continuous slab bridges, integral and semi integral bridges with thick slab beams (1.4–2.8 m). Rapid developments in the area of high-speed railways over the past decades have contributed to a well-functioning HSR network in Germany. Further investigations will likely focus on more efficient, beautiful and environmentally friendly structure types, the use of high-performance materials and structural maintenance. The vast experience gathered from German HSR bridge design and construction offers solutions and ideas for other countries developing their HSR networks.

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