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Research Progress and Future Prospects of Steel Bridge Construction Technologies: A Comprehensive Review

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RESEARCH PROGRESS AND FUTURE PROSPECTS OF STEEL BRIDGE CONSTRUCTION TECHNOLOGIES: A COMPREHENSIVE REVIEW

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RESEARCH PROGRESS AND FUTURE PROSPECTS OF STEEL BRIDGE CONSTRUCTION TECHNOLOGIES: A COMPREHENSIVE REVIEW

Abstract

Steel bridges dominate long-span and super-long-span crossings because they carry a great deal for their weight, go up quickly, behave well in earthquakes and can be recovered at end of life. This review examines how such bridges are actually built and what governs the choice of erection scheme. A systematic search of Web of Science, Scopus and Crossref covering 1990 to the present produced fifty-six sources, each resolved against publisher metadata. The literature is organised along three axes that are normally treated separately: structural type, structural composition and service scenario. Five erection methods, namely segmental prefabrication, cantilever erection, incremental launching, cable hoisting and rotary construction, are compared on mechanical principle, applicable span envelope and operational constraints, and the comparison is checked against documented long-span projects. The combination of segmental prefabrication with cantilever erection is examined in detail because it now governs most long-span practice. Work on intelligent construction is grouped into a five-layer framework running from perception through to execution. Three findings emerge: the choice of method is set by structural form, terrain and available plant rather than by span alone; digital tools have tightened process control without removing the dependence on experienced site judgement; and the unresolved problems of data interoperability, cost, extreme environments and whole-life carbon accounting are specific enough to be addressed directly. Four development trajectories are proposed.

Keywords: Steel bridge; Cantilever erection; Segmental prefabrication; Incremental launching; Intelligent construction; Digital twin

1. Introduction

Bridge building has changed a great deal over the past three decades, and steel has changed with it[1]. For medium, long and super-long spans—railway crossings and combined road–rail crossings above all—steel is still the default. It carries a lot for its weight, goes up quickly, behaves well in earthquakes, and can be recovered when the structure comes out of service. None of that comes free. A bridge is usually weakest while going up, and the erection sequence rather than the finished design decides whether a project is safe. Cheng and Li treated the construction stage as governing in their reliability analysis of wind-induced stability failure on a long-span steel arch bridge[2], consistent with how accident records read.

Four systems cover almost everything that gets built: beam, arch, suspension and cable-stayed[3]. Cantilever assembly came first and carried the earliest long-span steel crossings. Purpose-built plant accumulated alongside it—launching bearings, gantries, strand jacks, cable cranes—and full-span hoisting, incremental launching, skidding and swivel erection followed[4]. Which of them is chosen depends on the site: terrain, access, what equipment can be brought in, the geology, and whether navigation or rail traffic underneath has to keep running while the work goes on.

Reviews of steel bridge construction are not scarce, but most of them stay inside a single structural type or a single method. What is still missing is an account that puts structural form, component composition and service function side by side, and that follows intelligent construction through to the point where it changes site practice. Three contributions are offered here:

(i) a three-axis classification, by structural type, structural composition and service purpose, that places every erection method inside one consistent taxonomy;

(ii) a comparison of five mainstream erection methods, cross-checked against documented projects worldwide and expressed as an applicable span envelope rather than a theoretical bound; and

(iii) a five-layer framework for intelligent steel bridge construction, with an explicit mapping from the bottlenecks identified in Section 5 to the trajectories proposed in Section 6.

Section 2 sets out how the literature was gathered. Section 3 classifies the construction technologies and compares them. Section 4 deals with intelligent construction. Section 5 states what still goes wrong, and Section 6 draws the conclusions and looks ahead.

2. Review Methodology

A systematic search was run in Web of Science, Scopus and Crossref, covering 1990 to the present, on combinations of steel bridge, steel arch bridge, steel truss bridge, cable-stayed bridge, suspension bridge, erection, cantilever erection, incremental launching, segmental prefabrication, cable hoisting, rotary construction, intelligent construction, digital twin and building information modelling. Records were kept if they met three tests: the work concerns the construction stage of a steel or steel–concrete composite bridge; it reports a verifiable engineering application, an experiment or a validated numerical model; and it gives a method, a control index or a quantitative outcome rather than a concept. Reference lists of the retained reviews were then searched backwards.

Two limits deserve stating. Erection research is practice-driven, so the published record under-represents site reality; project documentation for the bridges in Table 1 was consulted alongside it. Every reference was resolved against publisher metadata through Crossref, and sources that could not be resolved were dropped rather than reconstructed. The span envelope in Figure 1 covers the projects consulted, not a theoretical bound. Figure 2 draws the classification together; Figure 3 shows the integrated chain that governs long-span practice.

Table 1. Typical long-span steel bridges worldwide and the construction methods adopted, used to establish the applicable span envelope of each method.

Bridge and location	Type	Span (m)	Main method	Remarks
Chongqing Chaotianmen Yangtze River Bridge, China	Steel arch	552	Cantilever erection	Ribs first, then deck system
Pingnan Third Bridge, China	CFST arch	575	Cantilever erection	Cable hoisting and diagonal pull buckle
Zhoushan Xihoumen Bridge, China	Suspension	1650	Air spinning	Cables first, then deck
Sutong Yangtze River Highway Bridge, China	Cable-stayed	1088	Cantilever erection	Pylons, then stays and deck
Nanjing Dashengguan Yangtze River Bridge, China	Steel truss arch	336	Cantilever erection	Segmental prefabrication, site assembly

Wuhan Tianxingzhou Yangtze River Bridge, China	Cable-stayed, steel truss	504	Cantilever erection	Segmental prefabrication, site assembly
Hong Kong–Zhuhai–Macao Bridge, China	Composite beam	458	Cantilever erection	Factory prefabrication, site assembly
Akashi Kaikyo Bridge, Japan	Suspension	1991	Air spinning	Slipform pylons; floating crane deck
Russky Bridge, Russia	Cable-stayed	1104	Cantilever erection	Slipform pylons; floating crane deck
New River Gorge Bridge, USA	Steel arch	518	Cantilever erection	Symmetrical assembly; temporary bracing
Quebec Bridge, Canada	Steel cantilever truss	549	Cantilever erection	Built out from piers
Forth Bridge, UK	Steel cantilever truss	521	Cantilever erection	Balanced cantilever; temporary towers
Millau Viaduct, France	Cable-stayed, composite deck	342	Incremental launching	Temporary towers; slipform pylons

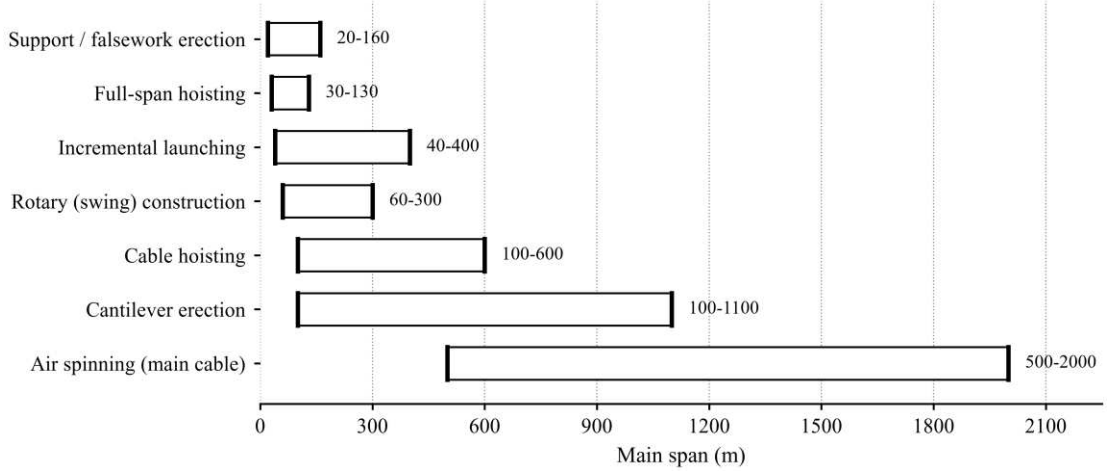


Figure 1. Applicable main-span envelope of the mainstream erection methods, as reported in the projects consulted. Current practice, not a theoretical limit.

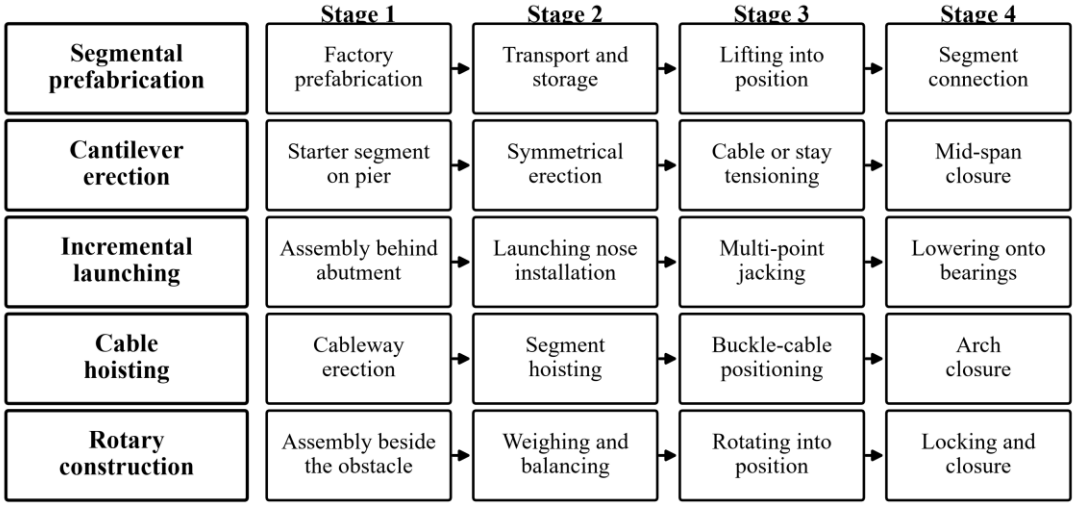


Figure 2. Comparative process chains of the five mainstream erection methods, from preparation to closure.

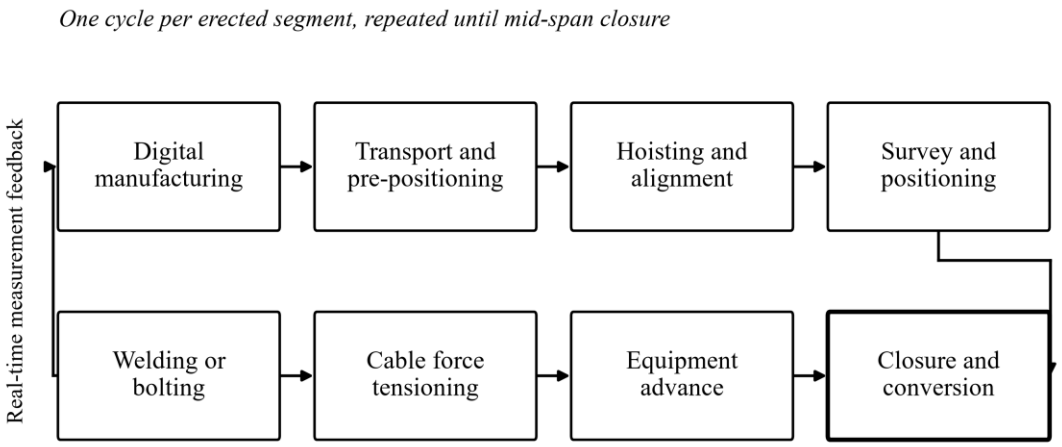


Figure 3. Integrated construction process of segmental prefabrication with cantilever erection, repeated once per segment until mid-span closure.

3. Classification and Application of Steel Bridge Construction Technologies

Span, structural type, site and available plant all bear on the choice of scheme, and the right choice removes a good part of the risk before work starts. The methods are grouped below by structural type[3] (Figure 2).

3.1 Construction Technologies for Steel Arch Bridges

Steel arches carry well and look good, which is often why they are chosen. How one is built follows from span, terrain and navigation. An arch is not a structure until it closes, so the half-built ribs must be stabilised throughout, and wind usually sets the terms[2].

i Incremental launching. Used for large-span deck-type steel truss arches, with the column reaction force taken as the stability control index. It shortens the on-site programme and suits crossings over existing lines or flat ground[5]. The difficulty is concentrated in multi-point jacking, which has to be synchronised while stress and alignment are watched continuously.

ii Vertical erection and rotation. Where a lift is combined with a rotation about a horizontal axis, the arch can be put together at or near ground level and swung into place[6]. High-altitude work largely disappears. Weighing, balancing and holding the rotation trajectory are the operations that decide the outcome.

iii Cable hoisting. The mainstream method for large-span steel arches in China. Segments go up on cable cranes and are held by buckle cables and transverse wind cables. It is fast and adapts well to deep valleys and navigable rivers. Cable forces cannot be written down once: the geometry changes at every hoisting stage, so they have to be solved iteratively[7]. Free-vibration behaviour of the partly erected arch also needs checking, since resonance during hoisting or rotation is a real risk[8].

iv Segmental hoisting. The arch ring is prefabricated in pieces and assembled on site. Loading on the substructure stays low, the plant is reusable, and the programme is easier to hold.

v Cantilever erection. Ribs are built out symmetrically from the springings to mid-span. Temporary supports are kept to a minimum, which is why the method suits long spans over difficult ground—the Chongqing Chaotianmen Yangtze River Bridge, at 552 m, is a familiar example. Deflection at the cantilever tip, member stress and wind stability all have to be held within limits, and temporary cable bracing is normally added to stiffen things up[2].

3.2 Construction Technologies for Steel Truss Bridges

Steel trusses carry most long-span railway and highway traffic, and three methods account for nearly all of them.

i Incremental launching. Truss segments are assembled behind an abutment and pushed forward longitudinally, which keeps crews off the water and out of the air. Launching bearings, guide devices and the thrust system form the mechanical core of the operation[9,10]. Two things have to be reconciled throughout: the geometry as launched against the target alignment, and the local stresses in members that pass over temporary supports[11]. Case studies from British Columbia show how much the detail depends on site constraints, even where the principle is identical[12].

ii Sliding and rotary construction. Suited to tight sites and to crossings over live rail. Stress and stability of both the girders and the temporary works are followed by finite element simulation, and the dynamics of the moving system need their own check[8]. Rotation of several thousand tonnes within a few hours is routine now. Temperature alone moves the horizontal rotation angle at beam ends appreciably, which matters when a closure is planned to tolerance[13].

iii Cantilever erection. Used for continuous trusses. Anti-overturning, bearing pre-offset and temperature-controlled closure are the standard controls. Because the system changes as the cantilever grows, tracking eigenfrequencies gives a cheap way of noticing that a stiffness or a boundary condition is not what the model assumed[14]. Truss forms have also been pushed into cable-stayed configurations for high-speed rail, where stiffness requirements tighten everything up[15].

3.3 Construction Technologies for Steel Beam Bridges

Simply supported, continuous and cantilever steel beam bridges leave more room to manoeuvre:

i Full-span hoisting: factory-made box girders lifted whole. Common on urban viaducts and interchanges at medium spans, limited by crane capacity and storage space[4].

ii Cantilever erection: stability, member stress, deflection, vibration and closure accuracy all need holding at once.

iii Incremental launching and dragging: keeps traffic interruption short; member stress is controlled in real time and the launched geometry is corrected continuously against the target[11].

3.4 Construction Technologies for Cable-Stayed Bridges

Long-span cable-stayed bridges are built out from the pylons, deck segments going on symmetrically with the stays. The maximum cantilever condition is where the trouble is: wind response and torsional stability dominate, particularly on exposed coastal sites, so wind-tunnel work on the erection stages is normal practice[16]. Documented projects such as Phu My in Vietnam[17] and the Second Nanjing crossing[18] show the pattern. Cable force is the other quantity that has to be known, and combining measurement methods rather than trusting one has proved the more reliable route on completed structures[19]. Where a crossing sits over operating railway, swivel construction has become attractive precisely because it keeps the occupation time short[20].

Shorter spans go up by full-span hoisting, canyon and river crossings by launching, awkward decks by rotation.

3.5 Construction Technologies for Suspension Bridges

Suspension bridges own the super-long-span range, and the hard part is the cable.

(1) Main cable erection. Whether prefabricated parallel wire strand or air spinning is used, geometry has to be established to a tight tolerance. What happens where the wires seat has been measured rather than assumed: tests at the splay band[21] and at the pylon saddle[22] both show behaviour a simplified model misses. Unstressed length, saddle pre-offset and target shape must be solved together, since errors propagate into the finished system[23]; sequences built around unstressed strand length start from that coupling[24].

(2) Stiffening girder installation. Segmental, floating and inverted lifting are all used, with simulation supporting precision control; floating cranes are standard at sea, where the hydrodynamic effect during the lift has to be carried. The girder is most vulnerable before the deck closes. Aerostatic and aerodynamic stability in early erection stages has been investigated directly[25], as has flutter under erection[26], and staged temporary countermeasures are a recognised way through[27]. Prefabricated deck slabs over a steel truss girder, as at Jindong, cut work done in the air[28]. Akashi Kaikyo at 1991 m remains the reference case, for erection and for the seismic verification that went with it[29,30].

3.6 Construction Technologies for Special Steel Bridges

Corrugated steel web composite bridges and road–rail steel truss arches use asynchronous construction, spatial six-point positioning and inclined pull buckle hanging. Small spans and the rebuilding of old bridges often go by fishing and transverse movement. Composite and hybrid forms have widened what is available[31], and the joints and erection procedures that come with them are still moving[32]. Cable-stayed arch configurations are a useful reminder that erection requirements can shape the structural form rather than the other way round[33].

In corrugated web composite bridges, asynchronous construction reduces the secondary stress that shrinkage and creep would otherwise produce. Shear lag in the corrugated web acting with a steel bottom flange changes the stress distribution enough to matter in both design and erection staging[34].

Table 1 lists representative bridges and their methods; Tables 2, 3 and 4 sort the methods by structural type, composition and service purpose. Segmental assembly and cantilever erection account for most

large-span work. Selection should follow structural form, ground conditions, plant capacity and construction simulation together (Figure 1); Figure 3 sets out the integrated chain.

Table 2. Construction methods of steel bridges by structural type.

Type	Common methods	Core characteristics
Steel beam bridge	Segmental prefabrication, incremental launching, full-span hoisting	Simple process; medium and short spans; modest lifting
Steel truss bridge	Cantilever erection, segmental prefabrication, air spinning	Long spans; high precision; heavy lifting and cable plant
Steel arch bridge	Cantilever erection, segmental prefabrication, rotary construction	Long spans; high precision; lifting or rotary plant
Suspension bridge	Air spinning, segmental prefabrication, main cable erection	Super-long spans; complex cable systems
Cable-stayed bridge	Cantilever erection, segmental prefabrication, incremental launching	Long spans; high precision; stay installation

Table 3. Construction methods of steel bridges by structural composition.

Part	Components	Common methods	Core differences
Superstructure	Main girder	Cantilever erection, segmental prefabrication, incremental launching, full-span hoisting	Cantilever for long spans; segments for speed; launching for low traffic impact
	Deck	Prefabricated assembly, cast-in-situ, composite, orthotropic plate	Prefabrication for speed; cast-in-situ for complex geometry
Substructure	Piers and abutments	Cast-in-situ, prefabricated assembly, slipform, steel pipe pile	Cast-in-situ flexible; slipform efficient for tall piers
	Bearings	Prefabricated installation, site welding	Factory quality versus site adaptability
Auxiliary	Guardrails, lighting, signs	Site installation, prefabricated assembly	Site flexible; prefabrication efficient
	Expansion joints	Prefabricated installation, site welding	Standardised parts; site connection reliability

Table 4. Construction methods of steel bridges by service purpose.

Service purpose	Common methods	Core requirements
Highway	Cantilever erection, incremental launching, segmental prefabrication	Wide deck; heavy load; appearance
Railway	Cantilever erection, incremental launching, segmental prefabrication	High stiffness; minimal interference with operations
Pedestrian	Segmental prefabrication, cantilever erection	Light load; comfort and appearance
Municipal	Incremental launching, segmental prefabrication	Low traffic and environmental impact; tight programme
Road–rail dual-use	Cantilever erection, incremental launching, segmental prefabrication, air spinning	Complex heavy load; very high stiffness
Special purpose	Cantilever erection, air spinning	Unusual span or conditions; maintainability

4. Intelligent Construction Technologies for Steel Bridges

Much of what is now called intelligent construction is measurement and feedback wrapped around work that has not fundamentally changed. It is still worth organising, because the layering makes the gaps

visible. Five layers are used here: perception, transmission, data, decision and execution, spanning design, fabrication, erection and operation (Figure 4).

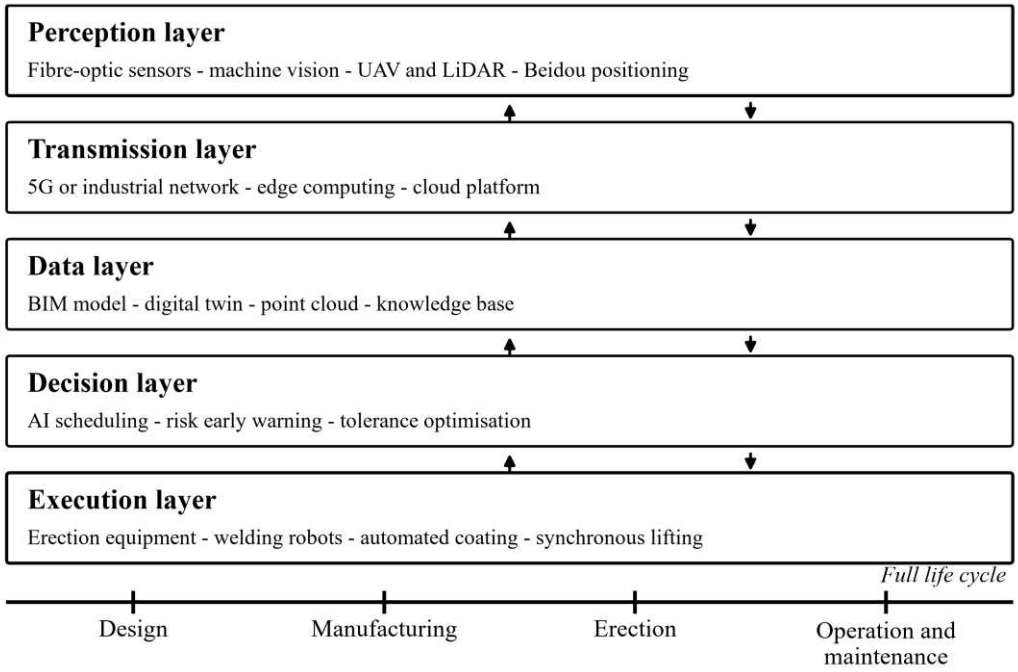


Figure 4. Five-layer technical framework of intelligent steel bridge construction, spanning design, fabrication, erection and operation.

4.1 Intelligent Monitoring and Perception

Sensing is the layer that has matured furthest. Fibre Bragg grating gauges give continuous internal force readings in members, and vision-based inspection has moved from research curiosity to something with published detection and false-positive rates[35]. Convolutional models now segment cracks on bridge surfaces as well as flag them[36], and unmanned platforms have been shown to find fatigue cracks in steel fracture-critical details with a reliability that compares against conventional hands-on inspection[37]. Three-dimensional localisation of crack distribution, rather than isolated alerts, is what makes the output usable[38].

Two qualifications keep this in proportion. Detection is not assessment: whether a crack matters depends on the detail, and rib-to-deck welds in orthotropic decks have their own fatigue behaviour[39], modelled probabilistically for macro-crack initiation[40] and as a stochastic process for condition assessment[41]. Repair is the other half. Lightweight reinforcement for cracked decks exists because the conventional repair is heavy and slow[42]. Non-contact measurement can also identify structural properties without

closing the bridge[43], and long records from major crossings show what continuous instrumentation buys[30].

4.2 UAV and Robotic Construction Technology

Unmanned aerial vehicles carrying LiDAR or high-resolution cameras produce site photogrammetry fast enough to be useful for progress tracking as well as survey, and the same payload serves defect inspection[37,38]. The bottleneck has moved from acquisition to interpretation, which is why curated point cloud datasets for bridges have started to appear as shared research infrastructure[44].

Welding robots and automated coating lines take high-altitude welding and corrosion protection off the backs of crews. The Ya Bridge in Norway, the first highway bridge welded robotically, is the case usually cited (Further Information). Fatigue performance of the weld itself is where automated processes have to prove themselves, and post-weld treatment of ultra-high-strength steel fillet welds has been measured at high stress ratio[45].

4.3 Intelligent Lifting and Precision Positioning

Satellite positioning tied to total station measurement gets steel components to centimetre-level placement, and multi-point synchronous lifting systems hold large segments level while their attitude is trimmed. This is enabling rather than decorative: a prefabricated segment only reaches the structure with the tolerance a controlled closure needs if the positioning is right. Temperature effects of the kind recorded on railway steel truss bridges set a practical floor on what can be achieved outdoors[13].

4.4 Digital Twin and BIM Integrated Management

Digital twin. A twin is only worth the sensing and communication behind it. Reviews of civil infrastructure twins[46] and bridge-specific work on twin-enabled BIM for life cycle management[47] converge on the same point: the model is the easy part, keeping it fed is not. Where the twin is driven by real measurement it can map a construction sequence, predict response under working conditions yet to occur, and propose a better order of operations[48].

Building information modelling. Visual management, clash detection, construction simulation and AR/VR training all reduce rework. Three-dimensional information models for bridge engineering have

been in national use long enough to have produced documented practice rather than pilots[49]. Interoperability remains the standing complaint: exchange between heterogeneous platforms still loses information[50].

4.5 Digital Manufacturing and Advanced Materials

Digital production control tracks steel truss fabrication and material flow in real time, and additive manufacturing is being used for complex connectors and awkward geometry. Smart coatings and corrosion-resistant systems extend service life, though coating choice carries an environmental cost that is measurable over the life of the bridge[51]. Weld quality is the recurring theme in automated fabrication, and post-weld treatment rather than the welding process often decides the fatigue outcome[45].

5. Current Technical Challenges

5.1 Technical Standardisation Deficiency

Data standards are the binding constraint. Design, fabrication and construction each keep their own models, and the exchange between them is lossy[50]. Industry Foundation Classes still does not carry steel bridge information completely, so full-discipline transfer is not achievable today[47].

5.2 High Cost Barriers

Sensors, robots and twin platforms are expensive up front and pay back slowly, which limits them to projects large enough to absorb the cost[47]. Reviews of infrastructure twins report the same economic pattern outside bridges[46]. On a conventional medium-span steel bridge the business case is usually not there yet.

5.3 Insufficient Adaptability to Extreme Environments

Cold, marine corrosion and high wind each degrade construction control in a different way. Steel and plant behave differently at low temperature, wind raises the risk on every lift, and aerodynamic stability under erection is a distinct problem from stability of the finished bridge[25,26]. Erection-stage wind reliability is known to be the governing case on long steel arches[2]. Seismic performance of very long

spans adds another layer[29], and staged aerodynamic countermeasures remain a response rather than a solution[27].

5.4 Low-Carbon Development Level To Be Improved

Whole-life carbon accounting for steel bridges is still immature, and recycled steel and low-carbon processes remain at pilot scale. Material production dominates the cradle-to-gate burden[52], and assessment frameworks are reaching real renewal decisions[53]. The erection method is itself a lever: launching and other techniques differ measurably in emissions and life cycle performance[54]. Direct reuse of steel members is established but rarely specified[55]; coatings carry their own burden over the service life[51]. Specification will have to follow the shift to a low-carbon circular steel economy[56].

6. Conclusions and Future Prospects

6.1 Conclusions

High-performance steel and newer connection details have raised both capacity and durability[32], and modular prefabrication has shortened programmes. Segmental prefabrication combined with cantilever erection governs long-span practice; incremental launching is the choice where traffic underneath must keep running; air spinning remains preferred for the longest suspension spans.

Intelligent techniques—BIM, digital twins, high-precision positioning and construction robots—have brought design and construction closer together and tightened process control[46,47]. They have not yet removed the dependence on experienced site judgement.

6.2 Future Prospects

Intelligence and automation. The near-term gains are in closed-loop execution: autonomous lifting, robotic fabrication and risk warning that is tied to measurement rather than to schedule[46,48]. Unmanned erection systems remain a long way off for long-span work.

Green and low-carbon development. Whole-life carbon assessment needs to become routine input to scheme selection, not an afterthought[53]. Because the choice of erection method carries an emissions

consequence[54], specification practice will have to follow the shift towards a low-carbon circular steel economy[56], and reuse of steel members needs to move from possible to specified[55].

Resilience enhancement. Erection-stage wind and seismic behaviour deserve more attention than the finished structure usually gets[2,25], and plant qualified for cold and corrosive sites is still thin.

Multidisciplinary integration. Progress now comes from materials, information technology and structural engineering meeting rather than from any one of them[31,32].

Figure 5 maps the four challenges in Section 5 onto these trajectories and the research priorities that follow.

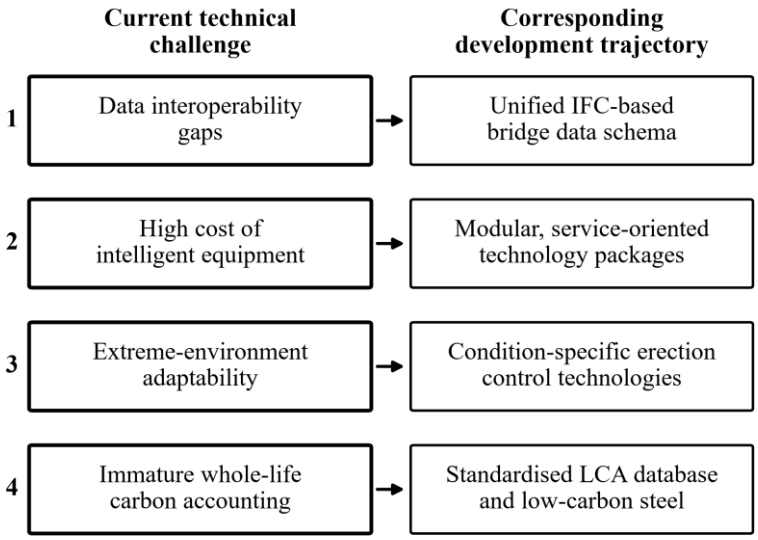


Figure 5. Mapping between current technical challenges in steel bridge construction and the corresponding development trajectories.

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Declarations

CRediT Authorship Contribution Statement

Qitai Wang: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft.

Genli Ren: Validation, Formal analysis, Writing – review & editing, Supervision.

Disclosure of Interest

The authors report there are no competing interests to declare.

Data Availability Statement

Data sharing is not applicable to this article, as no new data were created or analysed in this study. All information supporting the findings of this review is contained within the article and its cited sources.

Declaration of Generative AI Use

Generative AI tools were used to assist with language editing and the structuring of the literature synthesis during preparation of this manuscript. The selection of the reviewed literature, the engineering interpretations, the comparative analysis and the conclusions are the work and responsibility of the authors. The authors reviewed and edited all AI-assisted output and take full responsibility for the content of the publication.

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Further Information

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