Bratislav STIPANIĆ[*]

# ADVANCES IN BRIDGE ENGINEERING

**Abstract:** The paper treats overall aspects of advances in bridge engineering, affected by rapid development of natural sciences and technical innovations in design & structural analysis (static and dynamic due to wind & earthquake), building materials (high-strength & high-performed concrete, high-strength steel) and construction technology (building procedures, prefabrication, robustness). Consequently, advancements have not been only made in improved realizations of classical structural types (beam, frame, truss, arch & suspension bridges), but futhermore in application of inovative structural types as: integral bridges, cable-stayed and extradosed bridges. Nowadays the Building Information Modeling (BIM) is referred to as a process that connects engineers (involved in bridge design, construction, supervision & management) very efficiently in the various stages of construction.

The prestressed concrete bridges, steel bridges (with orthotropic deck) and steel-concrete composite bridges are dominantly applied nowadays. The number of bridges with super-long (over 500m) and ultra-long spans (over 1000m) has been considerably increased in this century. The tables of longest spans for arch, cable-stayed and suspension bridges are given in the paper.

As the particular new bridge achievements, built in ex-YU region, are noted in the paper: Roadway Cable-Stayed Bridge Ada in Belgrade (2011), Roadway-Railway Arch Bridge in Novi Sad (2018), Highway Beam-Frame Bridge Moračica at Podgorica (2022) and Roadway Multy-Span Cable- Stayed Bridge Pelješac (2022). The Cable-Stayed Bridge Solidarity in Plock (2007), with 375m span (the longest one where pylons are fixed to girder and the longest bridge span in Poland), is designed by the paper author, as the co-author. The paper author's scientific works are the contributions to analysis of cable-stayed and box beam bridges.

---

[*] Bratislav Stipanić, Faculty of Civil Engineering — University of Belgrade, Project Biro UTIBER Novi Sad

## INTRODUCTION

Bridge engineering is a branch of civil engineering, which includes: planning, design, construction, operation and maintenance of bridges, in order to provide safe and operative transportation of vehicles for people & goods. Transportation infrastructures — roadways and railways are vital factor for economy and overall quality of human life. In the frame of transportation networks, bridges are crucial for connecting people and delivering goods.

Bridge is a structure built over some physical obstacle (natural as: river, lake, sea strait, valley, canyon; or artificial as: roadway, railway, waterway, building), for the purpose to provide the passage by crossing over the obstacle.

Bridges are mainly classified according to: function (roadway, railway, footway, cycleway), structural system (beam, truss, frame, arch, cable-stayed, suspension) and building material (concrete, steel, timber, masonry).

Ancient bridges were built as masonry (or wood) arch structures and beam wood structures only. The use of steel as replacement for wrought iron (firstly applied for the Coalbrookdale Bridge in 1779) was extended in last quarter of 19th century: the steel Arch Bridge on Missisipi River (159m span), the Brooklyn Bridge — suspension bridge (486m span) with cables of hard steel-draw wires and the Forth Rail Bridge (521m span) with steel truss cantilever construction. The first half of 20th century was noted by steel trusses for beam, arch and suspension bridges; while arch and beam structures dominated as reinforced concrete bridges.

The development of building material production, design modelling, prestressing technology, welding technology and overall building technique had a crucial influence on bridge constructions from middle 20th century.

Consequently, advancements have been not only made in the realization of previously applied structural types (beam, truss, arch & suspension bridges) but futhermore in application of inovative structural types as: integral bridges, cable-stayed bridges, and extradosed bridges.

The pre-stressed concrete bridges, steel bridges (with orthotropic deck) and steel-concrete composite bridges are nowdays dominant in application.

## BRIDGE DESIGN PROCESS

The bridge design process traditionally contains the stages: concept design, preliminary design, detailed design and construction design.

The most challenging part of bridge design reflects to an optimal choice of concepts with regard to structural systems, span lengths and cross sections.

The successful concept design results not only from solid scientific-technical knowledge of bridge design engineer, but also from experience, awareness of visual form and creative fantasy.

The preliminary design elaborates further the best proposed concept; the feasibility of the selected concept should be ascertained and its cost estimates should be refined.

The details of the bridge structure are finalized in detailed design, in order to be sufficient for tendering and construction design.

Finally, the construction design provides step-by-step procedures for the building of the bridge according to realization methodology of the chosen contractor.

Nowadays the infrastructure tenders are often published in design-build form. It means that the employer (engaging expert consultancy) should prepare so-called design for tender and the construction contractor, chosen by tender, will make the construction design. The design for tender should be based on the previous concept design and preliminary design, that were made by a respectable design office chosen by employer upon a published tender, an invitation or design competition for most significant bridges.

Starting from the end of the previous century, the FIDIC contracts are the most commonly used standard form of international construction contracts for infrastructure projects.

The so-called FIDIC Red Book is construction contract form in infrastructure projects where the design is provided by the employer, following the traditional procurement route of design, bid and build. The contractor to be paid on measurement basis of the actual quantities of performed work, that were based on the design estimation.

The so-called FIDIC Yellow Book, is a standard contract where the design is carried out by the contractor. The Yellow Book is also known as Design-Build contract. The contractor to be paid on a lump sum basis.

The design engineer primary should take care of bridge structural reliability, that means safety, serviceability and durability; and furthermore: constructability, construction & maintenance costs, as well as architecture appearance & urbanistic integration (paying attention to the client's aspiration).

The requirements, that should be fulfilled in process of modern bridge design, can be classified as:

— technical: resistance (loads, actions, building material), serviceability (deflections, vibrations, traffic functionality, easy maintenace) & other (codes, norms, standards)

— architectural & urbanistic: overall layout, structural elements appearance, non-structural elements appearance & details, accessibility, functionality, integration in environment

— constructional: material availability, contactor availability, building technology

— economical: cost efficiency (construction cost, maintenance cost) and time efficiency (construction time, prefabrication time)

— service life (durability, maintenance, monitoring, inspections)

— environmental (sustainability, produced waste, effect on habitat & nature, efficiency in use of resources)

— legal: (building law).

The input data should be collected for design process, such as: traffic data, site data, topographic data, geological & geotechical data, hidraulic data, climatic data (wind, temperature, rainfall, snowfall, ice, floods), seismic data... The new scientific-technical development enabled higher quality of the input data for design.

In design procedure of a bridge it shall be considered a set of influential factors in order to achieve a best bridge solution, such as: structural system, materials, dimensions, foundations, aesthetics, local landscape, environment. The bridge design engineer is required to provide the most effective structural solution.

## STRUCTURAL DESIGN — APPLICATION OF EUROCODES

By the end of previous century, it is established a set of new standards for structural design, so-called Eurocodes — related to different type of structures applied in civil engineering. The Eurocodes, published by CEN, are widely applied for structural design in Europe in 21st century. The Eurocodes provide common structural design rules for everyday use in the design of whole structures and component products.

The Eurocode set [1] comprises the following standards for structural design, consisting of a number of parts, that are periodically updated.

EN 1990 Eurocode 0: Basis of structural design

EN 1991 Eurocode 1: Actions on structures (Part 2 refers to traffic loads on bridges)

EN 1992 Eurocode 2: Design of concrete structures (Part 2 refers to concrete bridges)

EN 1993 Eurocode 3: Design of steel structures (Part 2 refers to steel bridges)

EN 1994 Eurocode 4: Design of composite steel and concrete structures (Part 2 refers to bridges)

EN 1995 Eurocode 5: Design of timber structures (Part 2 refers to bridges)

EN 1996 Eurocode 6: Design of masonry structures

EN 1997 Eurocode 7: Geotechnical design

EN 1998 Eurocode 8: Design of structures for earthquake resistance (part 2 refers to bridges)

EN 1999 Eurocode 9: Design of aluminum structures.

In Basis of structural design (EN 1990) [2] it is explained the complete new „philosophy“ of structural design, enabled by the scientific-technical development of structural analysis.

As the requirements, firstly are defined the basic requirements, where the most significant items are the following ones.

„Structure shall be designed and executed in such a way that it will, during its intended life, with appropriate degrees of reliability and in an economical way: sustain all actions & influences likely to occur during execution & use, and remain fit for the use for which it is required.“

„Structure shall be designed to have adequate: structural resistance, serviceability, and durability.“

„Potential damage shall be avoided or limited by appropriate choice of one or more of the following: avoiding, eliminating or reducing the hazards to which the structure can be subjected;

selecting a structural form which has low sensitivity to the hazards considered; selecting a structural form and design that can survive adequately the accidental removal of an individual member or a limited part of the structure, or the occurrence of acceptable localized damage; avoiding as far as possible structural systems that can collapse without warning; tying the structural members together.“

„The basic requirements should be met: by the choice of suitable materials, by appropriate design & detailing, and by specifying control procedures for design, production, execution, and use relevant to the particular project.“

Afterwards, the general assumptions are listed as: „the choice of the structural system and the design of the structure is made by appropriately qualified and experienced personnel; execution is carried out by personnel having the appropriate skill and experience; the adequate supervision and quality control is provided during execution of the work, i. e. in design offices, factories, plants, and on site; the construction materials and products are used as specified in EN 1990 or in EN 1991 to EN 1999 or in the relevant execution standards, or reference material or product specifications; the structure will be adequately maintained; and the structure will be used in accordance with the design assumptions.“

The requirements are related as well to reliability management, design working life (100 years for bridges), durability and quality management.

The reliability required for structures shall be achieved by design in accordance with Eurocodes and by appropriate execution and quality management measures.

„The levels of reliability relating to structural resistance and serviceability can be achieved by suitable combinations of:

a) preventative and protective measures (e. g. implementation of safety barriers, active and passive protective measures against fire, protection against risks of corrosion such as painting or cathode protection);

b) measures relating to design calculations (representative values of actions and the choice of partial factors;

c) measures relating to quality management;

d) measures aimed to reduce errors in design and execution of the structure and gross human errors;

e) other measures relating to the following other design matters: the basic requirements, the degree of robustness (structural integrity), durability, including the choice of the design working life, the extent and quality of preliminary investigations of soils and possible environmental influences, the accuracy of the mechanical models used and the detailing;

f) efficient execution, *e. g.* in accordance with execution standards referred to in Eurocodes;

g) adequate inspection and maintenance according to procedures specified in the project documentation.

The measures to prevent potential causes of failure and/or reduce their consequences may, in appropriate circumstances, be interchanged to a limited extent provided that the required reliability levels are maintained."

The standard EN 1990 explains the principle of limit state design, with distinction to ultimate limit state and serviceability limit state.

„States prior to structural collapse, which, for simplicity, are considered in place of the collapse itself, may be treated as ultimate limit states."

„The following ultimate limit states shall be verified where they are relevant:

— loss of equilibrium of the structure or any part of it, considered as a rigid body;

— failure by excessive deformation, transformation of the structure or any part of it into a mechanism, rupture, loss of stability of the structure or any part of it, including supports and foundation;

— failure caused by fatigue or other time-dependent effects." „The serviceability limit states that concern:

— the functioning of the structure or structural members under normal use;

— the comfort of people;

— the appearance of the construction works,

shall be classified as serviceability limit states.“

„Design for limit states shall be based on the use of structural and load models for relevant limit states.“

„It shall be verified that no limit state is exceeded when relevant design values for: actions, material properties, or product properties, and geometrical data are used in these models.“

„The verifications shall be carried out for all relevant design situations and load cases“.

„Design situations are classified as persistent, transient or accidental.“

„The selected design situations shall be considered and critical load cases identified.“

„For a particular verification load cases should be selected, identifying compatible load arrangements, sets of deformations and imperfections that should be considered simultaneously with fixed variable actions and permanent actions.“

It is defined the classification of actions (permanent, variable & accidental) with its characteristic values, material and product properties and geometrical data.

It follows structural analysis by structural modelling with models of static & dynamic actions.

It is introduced verification by partial factor method, with determination of design values of actions & effects of actions, design values of material & products properties and design values of geometrical data.

It follows the determination of design resistance.

Afterwards it can be carried out the verification of the static equilibrium and the resistance according to limit state design.

Limit state of static equilibrium of the structure, shall be verified that

$$E_{d,\,dst} \leq E_{d,\,stb}$$

where: $E_{d,\,dst}$ is *design value of the effect of destabilizing actions*; $E_{d,\,stb}$ is *design value of the effect of stabilizing actions*.

Limit state of rupture or excessive deformation of a section, member or connection, shall be verified that:

$$E_d \leq R_d$$

where: $E_d$ is *design value of the effect of actions* such as internal force, moment or a vector representing several internal forces or moments; $R_d$ is *design value of the corresponding resistance.*

Serviceability limit state shall be verified that:

$$E_d \leq C_d$$

where: $E_d$ is *design value of the effects of actions* specified in the serviceability criterion, determined on the basis of the relevant combination; $C_d$ is *limiting design value* of the relevant serviceability criterion.

According to Eurocode 1, the following design loading should be considered: self-weight and imposed loads, wind, thermal actions, actions during execution, accidental actions (impact loads) and traffic loads. As well, it should be considered the other actions, such as: concrete creep & shrinkage, settlements & earth pressures and seismic actions if needed.

Part 2 of Eurocode 1 is related to traffic loads on bridges, containing: classification of actions (variable actions, actions for accidental design situations), design situations, road traffic actions & other actions specifically for road bridges, actions on footways, cycle tracks & footbridges, rail traffic actions & other actions specifically for railway bridges and 8 informative annexes.

Part 2 of Eurocode 2 treats the design and detailing rules of concrete bridges, containing: basis of design, materials, durability & cover to reinforcement, structural analysis, ultimate limit state, serviceability limit state, detailing of reinforcement and prestressing tendons, detailing of memebrs & particular rules, additional rules for precast concrete elements & structures, lightweihgt agggreate concrete structures, plain for lightweight reinforced structures, design for the executing stages and 17 informative annexes. In structural anlaysis, besides the linear elastic analysis with partial distribution, it is introduced plastic analysis, non-linear analysis and analysis of second order affects with axial load; as well it is appropriately treated: geometric imperfections, idealization of the structure and prestressed members & structures. In relation with ultimate limit state it is considered: bending with & without axial force, shear, torsion, partially loaded areas, fatigue and membrane elements. In relation with serviceability limit state it is treated: stresses, cracks control and deflection control.

Part 2 of Eurocode 3 treats the design of steel bridges, containing: basis of design, materials, connecting devices, durability, structural analysis, ultimate limit states, serviceablity limit states, fasteners / welds / connections / joints, fatigue assesment, design assisted by testing and 5 informative annexes (including recommendations for the structural detailing of steel bridge decks). In structural analysis it is introduced: structural modelling for analysis, global analysis, imperfections, methods of analysis considering material non-linearities and classification of cross sections. In relation with ultimate limit state it is considered: resistance of cross sections, buckling resistance of members, built-up compression memebers and buckling of plates. In relation with serviceability limit state it is treated: calculation models, limitations for stress, limitation of web breathing, limitations for clearance gauges, limits for visual impression, performance criteria for railway bridges, performance criteria for road bridges, performance citeria for pedestrian bridges, performance criteria for the effects of wind, accesabilty of joint details & surfaces and drainage.

Part 2 of Eurocode 4 treats the design and rules for composite bridges, containing: basis of design, materials, durability, structural analysis, ultimate limit states, serviceability limit states, precast concrete slabs in composite bridges, composite plates in bridges and an informative annex. In structural analysis it is introduced: structural modelling for analysis, structural stability, imperfections, calculation of action effects (methods of global analysis, linear elastic analysis, non-linear global analysis for bridges, combination of global & local action effects and classification of cross sections. In relation with ultimate limit state it is considered: resistance of cross sections of beams, filler beam decks, lateral torsional buckling of composite beams, transverse forces on webs, shear connection & connecters, composite coloumns & composite compression members, fatigue and tension members in composite beams. In relation with serviceability limit state it is treated: stresses, deformations in bridges (deflections & vibrations), cracking of concrete and filler beam decks.

Part 2 of Eurocode 8 treats design of bridge structures for earthequake resistance, containing: basic requirements & compliance criteria, seismic action, analysis (modelling, methods of analysis), strength verification (materials, resistance verification of concrete sections, resistance verification for steel & composite members, foundations), detailing (cocncrete piers, steel piers, foundations, structures of limited ductil behaviour, bearings & seisimic links, concrete abutments & retaining walls) and bridges with seismic isolation. As methods of analysis can be applied: linear dynamic analysis — response spectrum method, fundamental mode method, alternative linear methods, non-linear dynamic time-history analysis, static non-linear analysis (pushover analysis).

## SOFTWARE PACKAGES IN BRIDGE PROJECTS

The fast development of new technologies and materials initiated the major changes in how bridges are designed. In the past, the tools to provide accurate models or detailed analysis of bridges were very limited. Nowadays, tools and software are available for bridge engineers, following the advancements in technology, structural analysis, construction methods, building materials, etc.

In today's bridge engineering ICT is present in design modelling, building material production, construction technology and bridge menagement.

The bridge structural design analysis has been largely advanced by the effective application of finite element method (FEM), enabled by a rapid development of computer hardware from the seventies of last century. The theoretical basis of finite element method was elaborated in scientific papers published by the middle of last century. FEM software is based on mesh discretization of a continuous domain into a set of discrete sub-domains. FEM has been generalized for the numerical modelling of physical systems in many engineering disciplines including bridge structural design. Modern FEM applications software offer variety of simulation options for modelling and analysis.

In modern bridge engineering, FEM algorithms were embedded in many powerful design tools, contributing to raising the standards of engineering and significantly improving the design process. FEM software enables performing simulations of bridge structures, including linear and nonlinear static analyses. The FEM software component allows analyzing of the dynamic response of a structure subjected to time-dependent loads and displacements. The dynamic analysis features support the investigation of response spectrum and time history analysis. As another structural analysis software feature, modal analysis can help determine the eigenvalues and mode shapes of a structure due to vibration. The possibility of analyzing time dependent and rheological materials of bridge structures is present as well.

Modern FEM software packages increasingly develop comprehensive modules incorporating 'wizards' for bridge modelling and construction stage analysis, such as: SAP2000, SOFISTIK, MIDAS Civil, STAAD Pro, CSI Bridge, LUSAS Bridge, ALLPLAN Bridge, BENTLEY (but not only limited to them) are widely used in bridge engineering. Today state-of-the-art engineering software sets the new standards for bridge design and analysis. It is enabled to establish more accurate and reliable bridge design models.

Project management software Primavera and MS-Project are being widely used for project planning and execution for reducing and to increase productivity and efficiency. Construction management software is designed to monitor and track project progress in terms of workforce management, scheduling, time, cost and quality management.

Building information modeling (BIM) is referred to as a process that connects engineers, involved in bridge design, construction, supervision & management, very efficiently in the various stages of construction. BIM engages all participants in a multi-disciplinary collaboration for better insight into the project they are working on. The BIM technology generates instant and accurate outcomes for all phases of the bridge project. Further development of building information modelling (BIM) software goes in the direction from 3D which implies 3-dimensional geographical structures towards 4D and 5D which integrate respectively time scheduling, cost estimation and budget analysis. Benefits of 4D BIM are outlining of duration, timeline and scheduling data while 5D BIM enable real-time cost visualisation with notification of changes in cost simplifying cost and budgetary analysis.

## CONSTRUCTION MATERIALS

The modern bridges are mainly constructed as concrete, steel or combined concrete-steel composite bridges. The wooden bridges today are built for pedestrian/cycle bridges in countryside, recreation areas and temporary bridges, having small spans. The masonry (stone or brick) bridges are now rarely built; the rehabilitation or reconstruction of some old bridges can be present today.

The choice of bridge types, referred to construction material, depends on several factors, such as: bridge total length & span lengths, structural type, kind of traffic, bridge location, available material supplies; all connected with economical, executive, architectural and durability aspects.

### *Concrete*

The concrete material (classification, requirements for concrete & methods of verification, specification of concrete, delivery of fresh concrete, conformity control, production control) is defined in standard EN 206–1.

The mechanical and deformation characteristics of concrete (strength, elastic deformation, creep & shrinkage), reinforcing steels, prestressing steels & devices are defined in part 1–1 of Eurocode 2 (EN 1992–1-1).

The relation between stress $\sigma c$ strain $\varepsilon c$ (compressive stress and shortening strain for short term uniaxial loading) is presented schematically in Figure 1a, as given in part 1–1 of Eurocode 2. The parabola-rectangle diagram for

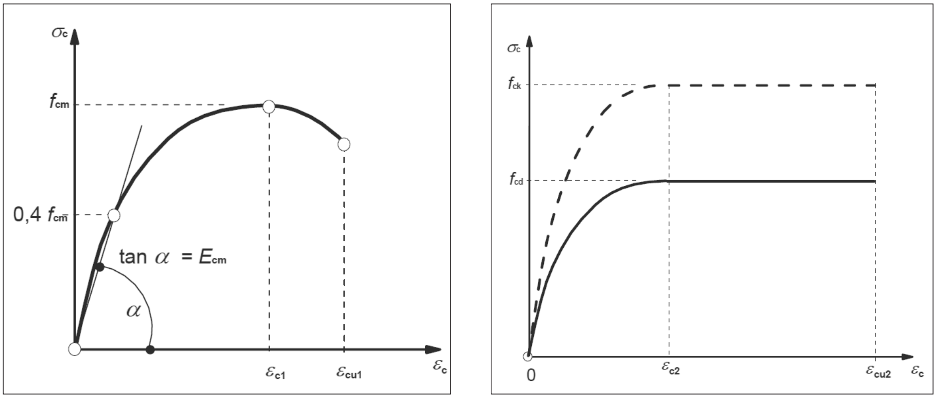

Figure 1a, b: Stress-strain diagrams for concrete under compression

concrete under compression, representing an adoption for design of cross-sections is shown in Figure 1b.

A special emphasis is given to durability in different environmental conditions, classified by description of environments (specified by different exposure classes) as: no risk of corrosion attack, corrosion induced by carbonation, corrosion induced by chlorides, corrosion induced by chlorides from see water, freeze/thaw attack and chemical attack. The values of minimum concrete cover (depending on exposure class & structural class), with regard to durability for reinforcement steel and prestressing steel, are now precisely specified. The corrosion protection of steel reinforcement depends on density, quality and thickness of concrete cover and cracking. The cover density and quality is achieved by controlling the maximum water/cement ratio and minimum cement content, and may be related to minimum class of concrete. The minimum thickness of concrete cover for bridge structural components is nowadays significantly increased — for reinforcement not less than: 40mm for superstructure & piers above soil, 50mm for piers in soil; and for cables not less than 50mm.

The bearing capacity of concrete is directly depending on its compressive strength C, defined in by strength classes of concrete. The minimum strength classes are: C 20/25 for bridge piers, C25/30 for RC (reinforced concrete) superstructures and C 30/37 for PC (prestressed concrete) superstructures. Nowadays the following concrete classes are mostly applied for bridge constructions: C 25/30, C 30/37, C 35/45, C 40/50, C45/55 and C50/60.

The enormous advances in concrete technology, starting from this century, relates to the possibility to obtain ready-mixed concrete with strengths as high as 100 MPa and even much more.

The concrete, according to its strength, nowadays can be classified as follows: normal-strength concrete (20–55 MPa), high-strength concrete (55–100 MPa), ultra high-strength concrete (100–150 MPa) and especial concrete (strength ≥150 MPa).

The application of high-strength concrete may be appropriate for the largely compressed bridge components with exceptional heights, such as pylons (cable-stayed bridges) and towers (suspension bridges), and nowadays as well there are some applications for some superstructures of pedestrian and small-medium span bridges. Manufacture of high strength concrete includes an optimal use of the basic ingredients that constitute normal-strength concrete. It is needed an optimal selection of high-quality portland cement, aggregates, as well as an appropriate combination of materials with selected proportions of cement, water, aggregates, and admixtures. The aggregate shall have the remarkable strength, the optimum size & surface characteristics and the bond with cement paste. The pozzolans, such as fly ash and silica fume, are the usual mineral admixtures in high-strength concrete. These materials introduce an additional strength to the concrete by reacting to portland cement hydration, that generates an additional C-S-H (calcium — silicate — hydrate) gel, which is responsible for the concrete strength. The applied chemical admixtures include a superplasticizer in combination with a water-reducing retarder. The superplasticizer gives the concrete an adequate workability at low water-cement ratios, resulting in greater strength of concrete. The water-reducing retarder slows the hydration of the cement and enables more time to place the concrete.

Starting from the end of previous century, the innovation has been made in application of UHPC (ultra high performance concrete) for certain number of bridges, and more for bearing components of bridges (prestressed beams, arch ribs, joints, deck pavements, etc), constructed in technically most developed countries (USA, Canada, Japan, China, South Korea, France, Germany, etc). High performance concrete is defined basing on performance criteria, such as: high durability, high strength and high workability. UHPC is composed of the following material components: cement, well-graded fine sand, quartz sand, silica fume & other mineral admixtures, steel fiber and superplasticizer. The absence of coarse aggregate can improve the homogeneity of UHPC. The high density of UHPC is improved by application of well-graded fine sand, quartz sand and silica fume, which can reduce the porosity of the UHPC. The steel fiber has a different tensile stress, which effectively reduces the occurrence of concrete cracks. In order to make less the amount of water and increase the strength, a significant amount of effective superplasticizer is added. UHPC has excellent mechanical properties and durability, which can upgrade the connection integrity of bridge component joints, reduce the deformation and crack problems of bridge pavement and increase the load-carrying capacity of bridges. UHPC is currently applied for small and medium-sized bridges or pedestrian bridges in technically most developed countries.

### *Reinforcing Steel and Prestressing Steel*

The reinforcing steel material is defined in standard EN 10080. Reinforcement steel is produced in the form of bars (6–40 Ø) and de-coiled rods (6–16 Ø) of quality B500.

The relation between tensile stress σ and strain ε for typical reinforcing steel (hot rolled steel) is presented schematically in Figure 2a, as given in part 1–1 of Eurocode 2.

The reinforcement shall have adequate ductility, as defined by the ratio of tensile strength to the yield stress (*f*t/*f*y)*k* and the elongation at maximum force εuk.

The prestressing steel material is defined in standard EN 10138. Wires, strands and bars are applied as prestressing tendons in concrete structures. The cold drawn wires products are used as: Y1860C (4,0 or 5,0mm Ø) and Y1770C (5,0 or 6,0mm Ø). The 7-wire strands are produced as: class A — Y1860S7 (7–16mm Ø) & Y1770S7 (15,2, 16 or 18mm Ø) and class B — Y2160S7 (6,85mm Ø), Y2060S7 (7mm Ø) & Y1860S7 (9mm Ø). The 7-wire strands compacted are produced as: class A — Y1860S7G (12,7–15,2mm Ø), Y1820S7G (15,2mm Ø) & Y1770S7G (18mm Ø).

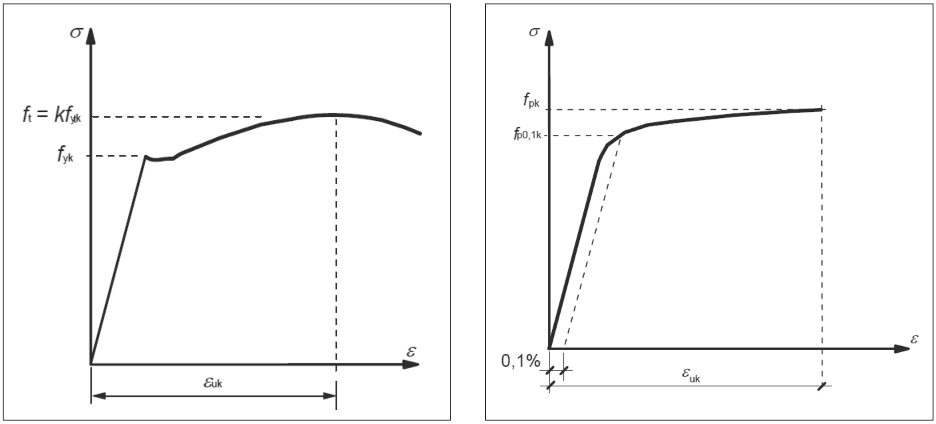

Figure 2a, b: Stress-strain diagrams: a) typical reinforcing steel, b) typical prestressing steel

The relation between tensile stress $\sigma$ and strain $\varepsilon$ for typical prestressing steel is presented schematically in Figure 2b, as given part 1–1 of Eurocode 2, The prestressing tendons shall have adequate ductility, and adequate fatigue strength, as specified in standard EN 10138.

### *Structural Steel*

The hot-rolled products of structural steels are specified in standard EN 10025, where the following products relevant to bridge steelwork are: non-alloy structural steels, fine grain structural steels, weathering steels and quenched & tempered steels. The non-alloy structural steels are the conventional structural steels, nowadays usually applied for bridge structures in 4 yield strength classes 275/355/420/ 460 MPa (steel grades: S275, S355, S420 & S460). Generally, S275 steel grade is often applied for railway bridges, in the case when stiffness rather than strength governs the design, or where fatigue is the critical design factor. S355 steel grade is very often applied for highway bridges, because one gets an optimum balance between stiffness and strength. S460 steel grade application gives the advantages where it is needed to minimize the plate thicknesses or overall self-weight, in the case when the fatigue, stiffness and instability of slender members are not the governing design factors. The thicknesses of plates from 10mm till 40mm are mainly used for steel bridge structures; the thicknesses above 40mm (40mm — 80mm) may be applied for some particular structural components.

The requirements for structural steel for bridgeworks, relating to: material properties, ductility requirements, fracture toughness, through thickness properties and tolerances are contented in part 2 of Eurocode 3 (EN 1993–2). The selection of materials for fracture toughness and the selection of materials for through-thickness properties shall be appropriately made (EN 1993–1-10). The execution shall be carried out according to the technical requirements given in the part 2 of standard EN1090.

The structural steels have to be protected for corrosion by coating system. The majority of steel bridge structures are protected against corrosion by application of paint coatings. The efficient modern coating systems have been improved, applicable for different exposed conditions. Nowadays the advances in coating technology enable the application of protective systems which are expected to last well thirty years (or even more) without maintenance need. Modern duplex coating system has been used, where the paints are applied over thermally sprayed metal coatings. Hot-dip galvanizing is as well a durable coating, but because of the nature of the application process its use is limited to relatively small bridges. The use of unpainted weathering steel, high strength law alloy steel forming adherent protective rust — patina to inhibit further condition, is increasingly popular for modern bridges. The bridges fabricated from unpainted weathering steel can achieve a 100-year design life, with almost no maintenance. Nowadays it has been increased the application of stainless steel in bridge construction, especially in footway bridges and as well for structural components of roadway bridges that are susceptible to corrosion. The advantages of using stainless steel in bridges are: durability in aggressive (acidic & alkaline) environment conditions, high strength to weight ration and overall the aesthetically appealing. The disadvantage of stainless steel application is its relatively high cost, which often limits its use in main bridge supporting parts.

### *Materials for Protection and Repair of Concrete*

The products and systems for the protection and repair of concrete structures are contented in standard EN 1504, covering: general principles for the use of products and systems, surface protection systems for concrete, reinforcement corrosion protection, structural & non-structural repairs, structural bonding, concrete injection, anchoring of reinforcing steel bar, site application of products & systems, and quality control of the works. The main chemical types and constituents of protection and repair products and systems are: additions, additives for hydraulic binders, additives for reactive polymer (plasticizers, flexibilizers, accelerators, retarders, materials regulating the rheology, pigments and fillers), admixtures, coatings, hydraulic binders, hydraulic mortars & hydraulic concretes, hydrophobic impregnation, impregnation, polymer hydraulic cement mortars or polymer concretes, polymer mortars and polymer concretes, reactive polymer binder (epoxies, unsaturated polyesters, acrylics and one or two-component polyurethanes).

### *Innovative Materials*

New building materials have been appeared nowadays.

One of these innovative building materials is self-healing concrete. It is well known that because of the various loads acting on bridges, concrete is prone to cracking. New concrete mixtures with inclusion of limestone-producing bacteria are being developed to fill the cracks as they form. This new technology can prevent the costly repairs of the cracks in concrete.

In order to minimize the damages of bridge structural elements due to earthquakes, which require costly repairs, the new materials are now being applied, such as so-called superelastic reinforcement made from shape memory alloy (SMA). It replaces the classical steel reinforcement in reinforced concrete. The steel reinforcement in concrete subjected to stresses beyond its yield point is plastically permanently deformed, while superelastic SMA return to original shape even after high stressing.

The new materials have been initiated in bridge constructions, to be lighter and relatively stronger.

The steel reinforcements can be replaced with the fiber-reinforced polymer (FRP) bars. The FRP reinforcements besides their high strength to weight ratio, have other advantages such as: non-corrosiveness durability, low thermal conductivity, non-electrical conductivity, and non-magnetic property. The FRP reinforcements can be made from fibers of glass, carbon, basalt, etc. Carbon fiber reinforced polymer (CFRP) have been successfully applied in the USA for construction of prestressed concrete bridges. The FRPs products are nowadays applicable for bridges in different forms, such as: rods, cables/strands, fabric, laminates. The FRP materials are today widely applied for retrofitting and rehabilitation of the bridges.

## STRUCTURAL EQUIPMENT

### *Bearings*

In the second half of last century the innovative bearings were invented. Classical bridge bearing concepts as: rollers, rockers, pin steel plate and concrete hinges are today historical ones, i. e. rarely applied. The requirements for design, manufacture and installation of bridge bearings have been completely changed. Besides of traditional steel material used in modern bridge bearings, nowadays are present the materials as: austenite steel, synthetic rubber, polytetrafluoroethylene (PTFE), silicone grease, polyurethane and composite materials.

The family of standards EN 1337, named Structural Bearings, published in first years of current century, is nowadays essential for modern bridge bearings, covering: general design rules, sliding elements, elastomer bearings, roller bearings, pot bearings, rocker bearings, spherical & cylindrical PTFE bearings, guide bearings & restraint bearings, protection, inspection & maintenance and transport, storage & installation.

The elastomeric, pot, spherical/cylindrical PTFE, guide and restraint bearings are considered as the modern bridge bearings. They contain sliding element composing of polish austenite steel plate and PTFE dimpled sheet supplied with silicone grease for easy sliding and preventing an excessive wear of PTFE. These modern bearings have, besides the functional one, the other advantages as well, such as: lower height, lower weight, easier transport, easier installation & replacement, lower cost, etc. easier installation & replacement, lower costs etc.

### *Expansion Joints*

Ten years ago were published the Guideline for European Technical Approval of Expansion Joints for Road Bridges (ETAG 032), specifying all types of modern expansion joints as: buried, flexible plug, nosing, mat, cantilever, supported and modular expansion joints. Buried expansion joints are used for displacements maximum 25–30 mm and flexible plug expansion joints are used for displacement maximum 40 mm; the execution is directly on site. Nosing expansion points are used for gap displacements maximum 80 mm; mat expansion points for gap displacements maximum 330 mm and cantilever (finger) expansion points for gap displacements from 80 to 800 mm. Modular expansion joints have the possibility of large movements (over 800 mm). Today, the most applied are nosing, modular and cantilever expansion joints — the latter can be as the supported ones. The modern expansion joints are waterproofing. The noise reducing elements can be installed in modular expansion joints when it is environmental requirement.

### *Anti-Seismic Devices*

In the second half of the previous century began the protection of bridge structures subjected to the risk of earthquakes. Firstly, it was applied only the passive protection of earthquakes based on the plastification of bridge elements chosen in advance. However, after intensive earthquake it often follows major repairs of the damaged protective elements, although generally the bridge structure resists design earthquakes and the protection of human lives are enabled.

Nowadays in seismic zones it has been introduced so-called positive protection; it means that the new bridge structures are equipped with anti-seismic devices to absorb or limit the effects of earthquakes. The positive protection of earthquakes in principle is based on three operational modes: isolation, connection and dissipation. The anti-seismic devices are defined as the elements which contribute to modifying the seismic response of a structure by isolating it, by dissipating energy or by creating permanent or temporary restraints via rigid connections. The standard EN 15129 „Anti-seismic devices“ specifies functional requirements & general design rules of the devices, material characteristics, manufacturing & testing requirements, as well as assessment and verification of constancy of performance, installation and maintenance requirements. This standard covers the types of devices and combinations thereof. The choice of anti-seismic devices depends on various parameters: the seismic level of the site, the type and characteristics of the bridge structure and the maximum response permitted.

## REALIZATIONS OF MODERN BRIDGES

The modern bridges can be nowadays realized as: short span bridges (5–50m span length), medium span bridges (50–150m span length), long span bridges (150–500m span length), super-long span bridges (500–1000m span length) and ultra-long span bridges (above 1000m span).

The most used structural systems of modern bridges nowadays are realized as: beam bridges (simple or continuous beam), truss bridges (simple or continuous beam), frame bridges, arch bridges, extradosed bridges, cable-stayed bridges and suspension bridges.

Referring to building material, the actual realization of bridges can be classified as: concrete bridges (reinforced concrete or prestressed concrete bridges), steel bridges (plated girders, box girders or truss girders) and composite (concrete/steel) bridges. Today the wooden bridges may be suitable only for short span footway/cycle bridges in recreation areas.

### *Beam Bridges*

The reinforced concrete slab bridges are used only for very short span bridges (up to 10m) and culverts. Nowadays reinforced concrete beam bridges (without pre-stressing or post tensioning) are only applied for minor bridges of short spans. The beam bridges can be constructed of steel, concrete or composite (steel girder with concrete deck). The concrete bridge components may be reinforced, pre-stressed or post-tensioned. Steel beam bridges can be different types of plate girders or box girders. The pre-stressed or post tensioned concrete I beam elements can be economically applied for main girders up to maximum 40m span and the concrete box girder and composite girder, with constant depth, are suitable from 40m till 80m spans. The concrete beam bridges, with variable depth, can be economically applied up to about 200m main span and steel box beam bridges, with variable depths till about 250m. Nowadays the continuous beam bridges having main span more than 200m (250m) are mostly constructed as cable-stayed bridges.

The future of beam bridges will be oriented to the application of light, strong, and long-lasting materials as: reformulated concrete with high performance characteristics, fiber reinforced composite materials, electro-chemical corrosion protection systems etc. The modern concrete beam bridges use pre-stressed concrete girders that combine the high tensile strength of steel and the superior compression properties of concrete. The modern steel bridges use the material of high quality steel grades and they have the innovated better corrosion protection. The box girders are mostly applied for concrete, composite and steel beam bridges with longer spans, highway bridges and roadway & railway bridges in curvature.

As special type of beam bridges, the integral bridges have been introduced, in which the conventional superstructure and substructure are integral with each other and the bearings are excluded. It is enabled by more sophisticated design analysis with the interaction of superstructure, substructure and soil where the bridge is founded.

Steel trusses, as simple and continuous beams nowadays are mainly applied for railway bridges or road-railway bridges, the applications for modern road bridges are very rare.

### *Frame Bridges*

Frame bridges have the superstructure and substructure rigidly connected, i. e. the piers and girder are one solid structure. The cross sections of beams are usually box-shaped or I-shaped. The frame bridges have been applied from third decade of 20th century, as reinforced concrete and steel single span bridges, later in prestressed concrete. Nowadays in the application are as well the batter post and V-shaped frame bridges. Single span frame bridges may be effectively used for inner city highways or express ways. The batter post frame bridges are well suited for river and valley crossings because their supports run from the deck to the abutments at an angle; consequently, the abutments are either larger or additional foundations are placed next to the abutments. V-shaped frame bridge is efficiently used when a longer span is not feasible. Each V-shaped pier provides two supports to deck, requiring only one foundation. Gazelle Bridge in Belgrade (1970), with 250m span, is today ranked on 3rd place in the category of batter post bridges.

### *Arch Bridges*

The ancient arch bridges were built as masonry (stone or brick) or wood arch structures. The use of steel as replacement for wrought iron (firstly used for the Coalbrookdale Bridge UK in 1779) was extended in last quarter of 19th century, when (1874) it was built the Steel Arch Bridge in Saint Louis USA over Missisipi River, with 159m span — record one for that time. The first concrete arch bridges were built by the end of 19th century.

Nowadays the materials used for arch bridges are: concrete, steel and combination of both as named CFST (concrete filled steel tube).

Three main types of arch bridges are nowadays governing: deck arch bridges, through arch bridges, and tied-arch (bowstring arch) bridges.

Deck arch bridges are those ones where the deck is completely over the arch rib, supported by the columns rising from the arch.

Through arch bridges are characterized by the arch which base is below and top above the deck, and deck passes through the arch. The deck is partly (or whole) below the arch suspended by cable ties, and if it is partly above the arch than these deck sections are supported by the columns.

Tied-arch bridges have deck connected to two opposite ends of the arch serving as tie. The deck is suspended from the arch rib by cable ties (vertical or inclined). The tie-arch bridge, suitable for 100–250m spans, is nowadays frequently applied for the roadway (or railway) bridges across the rivers. The layouts of modern tie-arch bridges, with different forms of arch rib(s), have an advantageous architecture impression.

The first ten arch bridges today, with the longest spans, are listed in Table 1. It can be noticed that the building material is either steel or CFST. Among 30 arch bridges with longest spans, 25 bridges were built in China, and under construction are now 25 arch bridges with spans above 300m.

The Krk Arch Bridge (1980), with 416m span — ex record (till 1997), is today ranked on 3rd place for arch concrete bridges, and 23rd place in overall ranking for arch bridges with the longest spans.

Table 1: Arch Bridges — Longest Spans (data: Wikipedia)

| Bridge name | Location | Material | Span length | Year opened |
|---|---|---|---|---|
| Pingnan Third Bridge | Guanxi (China) | CFST | 575 m | 2020 |
| Chaotianmen Bridge | Chongqing (China) | steel | 552 m | 2009 |
| Lupu Bridge | Shanghai (China) | steel | 550 m | 2003 |
| Bosideng Bridge | Sichuan (China) | CFST | 530 m | 2012 |
| New River George Bridge | Fayetteville, Virginia (USA) | steel | 518 m | 1977 |
| Bayonne Bridge | Bayonne, New Jersey (USA) | steel | 510 m | 1931 |
| Zigui Yangtze River Bridge | Chongqing (China) | CFST | 508 m | 2019 |
| Hejiang Yangtze River Bridge | Sichuan (China) | CFST | 507 m | 2021 |
| Sidney Harbor Bridge | Sidney (Australia) | steel | 503 m | 1932 |
| Wushan Bridge | Chongqing (China) | CFST | 460 m | 2005 |

### *Cable-Stayed Bridges*

The modern cable-stayed bridges have been constructed from the second half of 20th century; firstly, in Germany, later worldwide in Europe, Japan, USA, Asia, etc. In 21st century the numerous cable-stayed bridges have been realized in China. This structural type of bridge contains the main girder elastically supported at intervals along its length by the inclined cable stays anchored in pylon(s). The first cable-stayed bridges were constructed mainly as 3-span bridges, main span supported by limited number of inclined cable stays equal with the number of cable stays in back spans; all stays anchored in high pylons and girder. Today the cable-stayed bridges are constructed with multi-stayed cables as 2-spans, 3-spans and multi-spans structures, having one, two or several pylons. Nowadays, the wide variety of cable-stayed bridges has been built all over the world, with steel, concrete or composite deck and steel or concrete pylons. This structural form gives to bridge a prestige and effective architecture appearance, because of the layout combinations related to: configuration of cable stays (harp, modified harp, fan or star) in single or double „planes“ (with back-stays or without); type of steel or concrete pylon (single, double, portal, A-shaped, H-shaped, Y-inverted, M-shaped) — vertical, inclined or spaced; and type of steel, concrete or composite girder (box beam with or without struts, deck of 2 or multi beams) with 2, 3 or multiple spans.

First stays were done as locked coil cables which were subjected to corrosion deterioration with fatigue problems of cable anchorages and vibration problems. Later follows the application of prefabricated stay cables of parallel wire strands, packed in large drums with heavy transport and erection. Nowadays the parallel strand system is largely applied, where the stay cable is compound on site as a bundle of prefabricated 7-wires strands. The stay cable installation is simple, made strand by strand, where each strand is individually anchored by jaws in anchorage block, enabled to sustain remarkable fatigue effects. Each strand is individually protected against corrosion by two redundant corrosion barriers. The strand bundle is protected by a colored polyethylene outer duct. The stay cables can be equipped by special dumpers to prevent the vibrations.

Due to new developments in the modelling and analysis of dynamic behaviour and the use of sophisticated damping against oscillations, the cable-stayed bridge constructions have been expanded to spans in excess of 1000m, before 21st century the span range only applicable for suspension bridges. The advantages of the cable-stayed bridges compared to suspension bridges are the following ones: greater stiffness, easer construction — cable-supported cantilevering procedure and the balance of horizontal forces achieved without need of large ground anchorages.

The notable multi-span cable-stayed bridges have been built in 21st century. Nowadays the cable-stayed bridges are suitable for the spans from 200m till 1200m. Also they are applicable for bridges with modest spans where deck depth should be very limited and for footway/cycle bridges.

Ten cable-stayed bridges, with the longest spans, are listed in Table 2. The record span is doubled in last twenty years and the number of constructed cable-stayed bridges has been largely increased.

Table 2: Cable-Stayed Bridges — Evaluation of Record Spans (data: Wikipedia)

| Bridge name | Location | Deck / Pylon | Main span | Record period |
|---|---|---|---|---|
| Stromsund Bridge | Stromsund (Sweden) | steel / steel | 182 m | 1956–1957 |
| Theodor Heuss Bridge | Dusseldorf (Germany) | steel / steel | 260 m | 1957–1959 |
| Severin Bridge | Cologne (Germany) | steel / steel | 302 m | 1959–1969 |
| Knie Bridge | Dusseldorf (Germany) | steel/concrete | 319 m | 1969–1971 |
| Duisburg Bridge | Duisburg (Germany) | steel / steel | 350 m | 1971–1974 |
| Saint-Nazaire Bridge | Saint-Nazaire (France) | steel / steel | 404 m | 1974–1983 |
| C. F. Casado Bridge | Leon (Spain) | concrete | 440 m | 1983–1986 |
| Alex Frazer Bridge | Vancouver (Canada) | steel/concrete | 465 m | 1986–1991 |
| Skarnsund Bridge | Inderoy (Norway) | concrete | 530 m | 1991–1993 |
| Yangpu Bridge | Shanghai (China) | steel/concrete | 602 m | 1993–1995 |
| Normandy Bridge | Le Havre (France) | steel/concrete | 856 m | 1995–1999 |
| Tatara Bridge | Imabari (Japan) | steel/concrete | 890 m | 1999–2008 |
| Sutong Yangtze Bridge | Suzhou-Nantong (China) | steel/concrete | 1.088 m | 2008–2012 |
| Russki Bridge | Vladivostok (Russia) | steel/concrete | 1.092 m | 2012–2020 |
| Hutong Yangtze Bridge | Suzhou-Nantong (China) | steel/concrete | 1.104 m | from 2020 |
| Changtai Yangtze River Bridge | Changzhou-Tiazhou (China) | steel/concrete | 1.176 m | from 2024<br>in construction |

### *Extradosed Bridges*

The modern extradosed bridges have been constructed from the last decade of 20th century in Europe and Japan and afterwards largely worldwide in 21st century. They are suitable for concrete bridges with medium spans from 100 to 250m. Visually they are similar to cable-stayed bridges with short concrete pylons and with cable stays of shallow angles to concrete deck. Cable stays elastically support the deck and they are as well the external prestressing tendons. Therefore, the extradosed bridges may be considered as a hybrid structure originated from cable-stayed bridge (with short pylons) and cantilever-girder bridge (with shallow deck).

### *Suspension Bridges*

The suspension bridges have been applied for very long spans, nowadays for spans over 1000m. In first half of 19th century the chain suspension bridges were built. From the middle of 19th century wire-cable suspension bridges in USA started the construction of wire-cable suspension bridges. The main structural components of suspension bridge are: long supporting cables, towers, suspender cables, bridge deck (stiffening girder) and anchorage blocks (for supporting cables).

The first suspension bridge having span over 1000m (1067m) is George Washington Bridge (1931), later Golden Gate Bridge with 1280m span (1937) and Verazzano Narrows Bridge with 1298m span (1964); all roadway bridges with steel truss deck as stiffening girder. Later from 8th decade of 20th century, after aerodynamic tests in wind tunnels, the roadway suspension bridges with airfoil box sections of stiffening girder have been designed and constructed, firstly in UK — including Humber Bridge with 1410m span (1981). The suspension bridges with truss deck have been constructed for roadway and railway traffic in two levels, such as: Great Belt Bridge with 1624m span (1998) and Akashi Kaikyo Bridge with 1991m span (1998).

Table 3: Suspension Bridges — Evaluation of Record Spans (data: Wikipedia)

| Bridge Name | Location | Traffic / Girder | Span Length | Record Span |
|---|---|---|---|---|
| George Washington Bridge | New York — New Jersey (USA) | roadway<br>steel truss | 1.067 m | 1931–1937 |
| Golden Gate Bridge | San Francisco (USA) | roadway<br>steel truss | 1.280 m | 1937–1964 |
| Verrazano Narrows Bridge | New York City (USA) | roadway<br>steel truss | 1.298 m | 1964–1981 |
| Humber Bridge | Yorkshire (UK) | roadway<br>steel box beam | 1.410 m | 1981–1998 |
| Akashi Kaikyo Bridge | Japan | roadway & railway steel truss | 1.991 m | 1998–2022 |
| 1915 Canakkale Bridge | Turkey | roadway<br>steel box beam | 2.023 m | from 2022 |
| Zhagjiagang-Jingjian-Rugao South Yangtze River Bridge | Zangjigang Jiangsu (China) | roadway<br>steel box beam | 2.300 m | from 2028 in construction |

The evolution of record spans (over 1000m) is presented in Table 3. The present record span of 2023m belongs to recently constructed the 1915 Canakkale Bridge (2022) [3], with innovative bridge deck consisting of two stiffened closed steel box girders spaced 9m apart and connected by cross-girders every 24m. The 9m air gap between the two box girders enables the aerodynamic stability of the bridge deck in strong winds. Messina Bridge Project design [4] has been developed as roadway-railway suspension bridge, with huge main span of 3300m and 382m height pylons. It is designed triple box deck (with gaps between box girders), connected by cross girders.

## CONSTRUCTION OF CONCRETE BRIDGES

Nowadays in Europe the actual concrete bridge structures are constructed according to the standard EN 13670 „Execution of concrete structures“, that gives common requirements for execution of concrete structures related to: execution management, falsework & framework, reinforcement, prestressing, concreting, execution with precast concrete elements and geometrical tolerances.

Today, concrete bridge construction techniques are present as cast-in-situ or precast construction. The *cast-in-situ construction* is a procedure whereby the segments are progressively cast on site in their final positions within the structure. The *precast construction* is a procedure whereby the segments are prefabricated at casting plant, either on site or transported from the factory, and erected as a completed unit in their final positions. The construction methodology may be classified as: *conventional* (on falsework / scaffold), *balanced cantilever*, *incremental launch*ing, *movable scaffold system* (MSS) / *advanced shoring* and *span-by-span* techniques.

*Balanced cantilever* construction methodology is usually performed as cast-in-situ and can be precast also. The concrete structure is constructed outward from a fixed point, without temporary support, as a cantilever structure, using staged cast-in-situ construction. The balanced cantilever construction method is realized when two opposing free cantilever structures are attached as a single structure and erected in the same step. It is often appropriate and cost-effective for the construction of long span concrete bridges where because of height, topography or geotechnical conditions the application of conventional formwork is uneconomical. Nowadays the economical span lengths for cast-in-situ cantilever construction are considered from 70m and extends to beyond 250m. The precast balanced cantilever construction is suitable for 45m — 135m spans.

*Incremental launching* is a suitable construction method of continuous post-tensioned multi-span bridges. It includes casting 15–30m long sections of the bridge superstructure in a stationary formwork behind an abutment and pushing a completed section forward with jacks along the bridge axis. The sections are cast contiguously and then stressed together. The superstructure is launched over temporary sliding bearings on the piers. The steel launching nose is connected to the front of the bridge deck, in order to reduce bending of the superstructure during construction. The incremental launching method is suitable for restricted and limited sites over deep valleys, rivers, highways, railways, as well as in poor soil conditions or environmentally protected areas.

*Movable scaffold system (MSS)* is developed for multi-span bridges over difficult terrain or water where scaffolding is not suitable. It comprises an application of launching girder that moves forward on the bridge piers, span-by-span to allow placing of the cast-in-situ concrete. This methodology can be adapted for a wide range of spans and types of superstructure.

Nowadays, the *conventional falsework / scaffold* is suitable for construction of bridge structures with single spans up to 80m This construction methodology today is not convenient for longer bridges with multiple spans, because the scaffolding needs to be moved between the different sections of the bridge during construction. Therefore, it is developed the *advanced shoring* technique. The construction method uses a movable supporting beam, gantry, for the falsework that can reach over the length of one or two spans. The special roller bearings and launching jacks enable that the gantry can move forward along the bridge as the construction proceeds. The travelling gantry system can be economically applicable for spans from 30m to 60m.

The *precast span-by-span* bridge construction methodology can enable a significant speed of construction. It is often applied in conjunction with an erection truss under the bridge segments or an overhead erection gantry to guide the precast elements into position. The precast segmental span-by-span method is suitable for construction of long viaducts with spans of similar length. This method is appropriate for spans from 25m to 45m.

*Heavy lifting* is a special hydraulic cable lifting technique developed for exceptionally heavy loads. This technique, as timely and economic solution, is particularly applicable for the projects based on modular construction methods where large, heavy, pre-fabricated elements are present. The heavy lifting technique can be applied to: lifting and lowering of heavy precast beams and entire structural elements by means of strands and hydraulic jacks; lifting of bridge structures for the erection or repair of bearings; sliding of bridge structures from the assembly area to final position.

## CONSTRUCTION OF STEEL BRIDGES

Nowadays in Europe the steel bridge structures are constructed according to standard EN 1090 „Execution of steel structures and aluminium structures“, that regulates the fabrication and assembly as well. It comprises the requirements for conformity assessment for structural components and technical requirements for the execution. The technical requirements for execution of steel structures are specified for: constituent products (structural steel products, steel castings, welding consumables, mechanical fasteners, studs & sheer connectors, grouting materials, expansion joints for bridges, high strength cables & rods & terminators, structural bearings), preparation & assembly (identification, handling & storage, cutting, shaping, holing, cut outs, full contact bearing surfaces, assembly, assembly check), welding, mechanical fastening, erection, surface treatment, geometrical tolerances, inspection, testing and corrosion protection.

Construction of steel bridges consists of fabrication of steel structure in the workshop (from the delivered steel plates and profiles) and the assembly with the erection on site. In the steelwork workshop is performed the production of steel segments suitable for transport by roadway, railway or waterway. The steel structure can be produced in large blocks, or in segments convenient to be packed and transported in containers. On site it can be prior carried out the preassembling and (or directly) assembling in erection units. The trial assembling of erection units is carried out in the workshop. Nowadays the site assembly joints and segment splices are performed by welding or by pre-stressed high strength bolts. Besides the segments that are produced as welded in the factory, today often mostly (or completely) the entire steel bridge structure is assembled by welding at site from the delivered segments.

The modern workshops are today equipped for computer added manufacturing (CAM) and the workshop drawings are produced by computer added design (CAD). The modern construction sites today can be equipped for erection by all kinds of cranes of high capacities: mobile cranes, derick cranes, portal cranes, tower cranes & floating cranes, as well as huge hydraulic jack systems.

The erection of steel bridge is the most sensitive operation of bridge construction. During different stages of construction, the bridge structure passes through different states of stresses and deformations. The appropriate choice of construction stages can be crucible for dimensioning and final alignment of bridge structure.

As it is well known, the usual types of erection of steel bridges are: installation on the temporary piers, free cantilever erection, incremental launching, span/segment lifting and adequate combination of the cited types.

The choice of steel bridge erection procedure depends on: structural system of bridge (beam bridge, arch bridge, frame bridge, batter-post bridge, cable-stayed bridge, suspension bridge), bridge type (plated, box or truss bridge), bridge deck (steel or composite), bridge size; terrain configuration and type of obstacle; transport possibilities from the structure workshop to the construction site; available equipment for erection and contractor's experience.

## NOTABLE BRIDGES RECENTLY BUILT IN EX-YU REGION

### *Ada Bridge in Belgrade*

The Ada Roadway (and light railway) Bridge across the Sava River [5] on Belgrade inner city semi-ring road, was completed in 2011. Bridge length: 996m. The main structure is designed as cable-stayed bridge with originally shaped single concrete pylon, steel deck in 376m main span and concrete deck in 200m back span (as well in 388m side spans & 50m end span). The 376m span is ranked as one of the longest span in the category of cable-stayed bridges with single pylon.

### *Arch Bridge in Novi Sad*

The Railway-Roadway Arch Bridge across the Danube in Novi Sad [6], was completed in 2018 on the foundations of former arch concrete bridge. Bridge length: 474m. The main bridge structure consists of two steel tied network arches (*l/h*=219/42m & *l/h*=177/34m) with composite deck. The 219m span is the longest one in the category of tied network arch bridges with two rail tracks.

### *Moračica Bridge in Podgorica*

The Moračica Roadway Bridge [7] across the Morača River canyon, was completed in 2022, near Podgorica on the highway section Podgorica-Mateševo. The bridge is designed as a ballanced cantilever concrete bridge structure of beam-frame type, with spans: 95 + 170 + 3x190 + 125m. The maximum height of the bridge above the terrain exceeds 175m i. e. 205m above the riverbed.

### *Bridge Pelješac on Adriatic Coast*

The 2404m long Pelješac Roadway Bridge [8], across Mali Ston Bay of Adriatic sea, completed in 2022, is designed as a multi-span cable-stayed bridge with a semi-integral hybrid structure (steel deck & concrete pylons) with five 285 m long main spans. The Pelješac Bridge, located in high seismic area, belongs to the most attractive European bridges at sea cost.

## Contribution of Paper Author to Bridge Engineering

The paper author has been actively engaged in bridge engineering in three fields: professional (design engineer & supervision engineer), scientific (cable-stayed bridges, wide-flanged box girder structures, thin-walled structures) and educational (lectures on steel structures & bridges).

The Solidarity Roadway Bridge across the Vistula River [9] in Plock (Poland), open for traffic in 2007, is designed by the paper author, as the co-author (with N. Hajdin) and the main design & supervision engineer. The entire bridge, with 1200m total length, consists of 615m long main bridge part and 585m long access bridge part. The main bridge structure is designed as steel cable-stayed bridge with two pylons, having 375m main span and side spans 2 x 60 m each (Photo 1).

The main span of 375 m belongs to the longest ones in the category of cable-stayed bridges with the cables in a single plane; it is the bridge with the longest span built up to now in Poland.

The concept design proposal of Roadway Bridge across the Bokokotorski Bay (location: Rt Sveta Nedjelja — Rt Opatovo), submitted by the coauthors (B. Stipanić, N. Hajdin & M. Maletin) to the international competition of Montenegro government for the choice of location & concept solution of Bokokotorski Bay Crossing, was awarded by third prize (1999).

Photo 1: Cable-stayed bridge over Vistula River in Plock (Poland)
— open for traffic in 2007

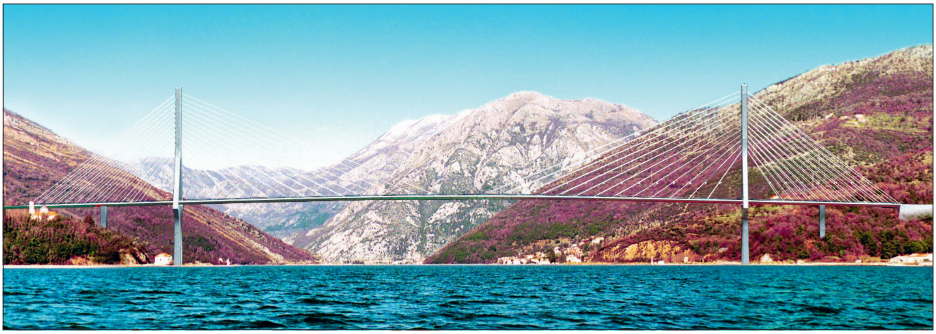

Photo 2: Visualisation of Cable-stayed bridge across Bokokotorski Bay — concept design solution

The design proposal of 960m long entire bridge, consists of 690m long main bridge part and 270m long access bridge part. The main bridge structure is designed as cable-stayed bridge with steel deck and two concrete pylons, having 450m main span and both-sided 2x60m spans (Photo 2).

## CONCLUSION

Thanks to the rapid development of natural sciences and technical innovations, the advances have been achieved and permanently up-dated in all fronts of bridge enginering: planning, design (software packages), structural analysis — static & dynamic (due to actions of traffic, wind, earthquake), building materials (high-strength, high-performed & self-healing concrete, high-strength & weathering steel, SMA superelastic reinforcements, FRP bars/strips/cables/strands, new products for protection & repair of concrete structures), construction technology (building procedures, prefabrication, robustness), monitoring, maintenance and retrofitting of bridges.

Consequently, the advancements have not been only made in improved realizations of classical structural types (beam, frame, truss, arch & suspension bridges), but futhermore in application of inovative structural types as: integral bridges, cable-stayed bridges (with 2, 3 & multiple spans), extradosed bridges and hybrid bridges. The application of cable-stayed bridges has been largely increased for roadway bridges with spans from 200m to 1200m and for footway bridges; all designed with wide range of pylon shapes. This year it was completed the suspension bridge with main span longer than 2000m, and now in construction is a suspension bridge with 2300m main span. Two years ago, it was built 165km long bridge for high-speed railways.

Today the digital technology is impacting and modifying the construction industry. The artificial intelligence, virtual reality, drones, robots, monitor devices, GPS surveillance, etc. are now being used in construction and fabrication sites.

In today's bridge engineering ICT is present in design modelling, building material production, construction technology and bridge menagement.

Recently, the Building Information Modeling (BIM) has been introduced as a process which very efficiently connects engineers (involved in bridge design, construction, supervision & management) in the various stages of construction.

## BIBLIOGRAPHY

[1] EN 1990 „Eurocode" — EN 1999 „Eurocode 9", CEN, Brussels.

[2] EN 1990: 2002 + A1 „Eurocode: Basis of structural design", *CEN. Brussels.* December 2005. p. 1–118.

[3] J. Pihl: „The design of the 1915 Canakkale Bridge", *Proceedings of 16th ASES Congress, September 2022. p. 71–75.*

[4] F. Brancaleoni, G. Diana, E. Facioli, G. Fiamenghi et al: „The Messina Strait Bridge: A challenge and a dream", *Stretto di Messina S. p. A, Taylor & Francis Group.* London. 2010. p. 1–324.

[5] B. Stipanić, N. Hajdin, Z. Rubinjoni and M. Kozlović: „Project of new Belgrade Bridge across Sava River in the scope of the Inner City Semi-Ring Road". *Proceedings of 7th international conference on bridges across the Danube — Bridges in Danube basin: Theory & practice in bridge engineering.* Sofia 2010. p. 333–342.

[6] A. Bojović, A. M. Munoz, Z. Marković and N. Novaković: „Network arches over the Danube — Railway-Road Bridge in Novi Sad*", Baingenieur.* No 93. March 2018. p. 110–115.

[7] Ž. Ličina, L. Huatu, V. Ćipranić and Y. H. Gang: „Main design and construction of Moračica Bridge on highway E-763, section Smokovac-Mateševo". *Proceedings of 16th ASES Congress,* September 2022. p. 9–14.

[8] M. Pipenbaher: „Pelješac Bridge, Croatia — Design and construction", e-mosty 1/2022. p. 1–24.

[9] B. Stipanić, N. Hajdin, J. Krawczyk: „Project realization of Roadway Bridge across Vistula River in Plock". *Zbornik 30 zborovanja gradbenih konstruktorjev Slovenije.* October 2008. p. 35–50.

Bratislav STIPANIĆ

# GRADITELJSTVO MOSTOVA DANAS

## *Sažetak*

U ovom radu se razmatraju sveukupni aspekti napretka u graditeljstvu mostova, proistekli iz ubrzanog razvoja prirodnih nauka, kao i tehničkih inovacija u pogledu: projektovanja i računske analize statičke i dinamičke (dejstvo vetra i zemljotresa), građevinskih materijala (beton visokih čvrstoća i visokovredni beton, visokovredni čelik), kao i tehnologije izvođenja radova (metodologija izgradnje, prefabrikacija, robusnost). Sledstveno, značajan napredak se ne ogleda samo u poboljšanim realizacijama klasičnih konstrukcijskih tipova mostova (gredni, ramovski, rešetkasti, lučni i viseći mostovi), već osim toga i u primeni inovativnih konstrukcijskih tipova mostova kao što su: integralni mostovi, mostovi sa kosim kablovima i ekstradosni mostovi. Danas se primenjuje BIM informaciono modelovanje izgradnje, po kome su tokom raznih faza građenja sveobuhvatno vrlo efikasno povezani inženjeri uključeni u projektovanje, izvođenje, nadzor i menadžment.

Prednapregnutobetonski mostovi, čelični mostovi (sa ortotropnom pločom kolovoza) i spregnuti (čelik-beton) mostovi su danas dominantni u primeni. U ovom veku broj izvedenih mostova sa vrlo velikim rasponima (preko 500 m) i ultradugim rasponima (preko 1000 m) je u znatnom porastu. U radu su date tabele mostova najvećih raspona za lučne, mostove sa kosim kablovima i viseće mostove.

Kao izuzetna nova dostignuća u mostogradnji, ostvarena u eksjugoslovenskom regionu, izdvojeni su: putni most sa kosim kablovima na Adi u Beogradu (2011), putno-železnički lučni most u Novom Sadu (2018), autoputni gredno-ramovski most Moračica kod Podgorice (2022) i putni višerasponski most sa kosim kablovima Pelješac (2022). Putni most sa kosim kablovima Solidarnost u Plocku (2007), sa rasponom od 375 m (najveći za most sa pilonima uklještenim u gredu i most sa najvećim rasponom u Poljskoj) je koautorski isprojektovan od autora ovog rada. Autor ovog rada je u naučnom smislu dao doprinose analizi mostova sa kosim kablovima i grednih sandučastih mostova.