IABSE Bulletins

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Extradosed Bridges

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Structural Engineering Documents

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ISBN 978-3-85748-172-7

DOI: https://doi.org/10.2749/sed017

Publisher:
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Jungholzstrasse 28
8050 Zurich
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Introduction

While the term “Extradosed” was coined in France in the 1980s, the first extradosed bridges were all built in Japan and today more than 200 of them can be found all over the world. Commonly agreed principles or helpful design guidelines about these bridges, however, do not exist in publications.

In 2014 an international group of engineers, all of them experienced in the field of cable-supported bridges were inducted into Working Commission 3 of the International Association for Bridge and Structural Engineering (IABSE) to address this information gap. The members of the group exchanged their views and worked together via e-mails, and meetings in person took place during the IABSE conferences in Geneva 2015, Stockholm 2016 and Vancouver 2017.

Extradosed bridges with their shallow stay cables and stiff decks can be an economic and attractive alternative to girder and cable-stayed bridges for spans between 100 and 250 m.

The structural system of the extradosed bridges can be described as ‘in-between’ or ‘hybrid’ between balanced-cantilever-type girder and cable-stayed bridges. Therefore, there is not “one” narrowly defined extradosed bridge. Rather, there is a smooth transition from girder to extradosed to cable-stayed bridge and this is reflected in this report.

This state-of-the-art report is the collective experience of the group. All aspects that specifically refer to extradosed bridges are covered here. Typical values and, with equal weight, exceptions will be presented. The reader will find helpful information about all aspects that are relevant for designing and constructing such bridges. Not all the experts shared the same opinions. Some of the controversial issues will be highlighted, in order to identify fields for further research. The reader will also find, that in the text certain subjects are described in different ways. Also this reflects the fact that several authors were involved in the preparation of this report.

The report is aimed at not just practicing bridge engineers but also teachers and researchers in the field of extradosed bridges. First the general aspects and the history of this bridge type are presented. Conceptual and Structural Design, Analysis, Cable Technology, Construction issues and Cost Considerations are presented in separate chapters.

Numerous documents on specific subjects which relate to extradosed bridges have been published world-wide. At the end of this document, all the literature known to the group on all subjects that relate to extradosed bridges are summarized. It is a collection of codes, regulations, books, dissertations and technical papers published at IABSE, fib as well as other institutions and journals. The reference numbers in this text refer to this list.

On behalf of the Authors, I would like to thank the External Reviewers who, along with the Bulletin Editorial Board, spent valuable time in reviewing this document: Naeem Hussain, Marcos Sanchez, Roman Geier and Jiri Strasky; and guest reviewers Andreas Apitz, Koneru Bhavani, Werner Brand, Araby El-Shenawy, Kris Mermigas and Hermann Weiher.

Special thanks to contributors and authors of chapters (members of Working Commission 3): Nirmalya Bandyopadhyay, Don Bergman, Alok Bhowmick, Xu Dong, Thierry Duclos*, Akio Kasuga*, Zhao Liu, Serge Montens*, Guido Morgenthal, José Romo*, Chithabaram Sankaralingam*, Robin Sham, Juan Sobrino*, José Turmo and Edo Vonk.
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Chapter

1

General

Mike Schlaich, Germany

1.1 Definition of "Extradosed," Potential, Advantages

Extradosed Bridges are a new bridge form that offer a competitive alternative to more traditional forms such as girders, arches, and cable-stayed systems used in spans ranging from 100 to 250 m. Since its origin in the 1980s, more than two hundred such bridges have been built all over the world.[1] For spans up to 100 m, concrete or composite girders bridges are the most common choice,[2,3] but for spans longer than 100 m, the depth of the boxes above the piers is becoming increasingly unacceptable for aesthetic constructability and cost reasons. For spans longer than 250 m, cable-stayed bridges are usually the most economical solution. Conceptual and structural designs of this bridge type with bridge decks made of steel, concrete, or a combination of the two materials have been widely published.[4,5] For spans shorter than 250 m, cable-stayed bridges often cannot fully exploit their strength and lose their economic advantage.

There are four suggested definitions of the Extradosed Bridge:

- An Extradosed Bridge can be considered as a hybrid concept in the region of transition between girder bridges and cable-stayed bridges. A large number of options are available to designers for configuring such a bridge type to suit specific constraints for a particular project. The large number of Extradosed Bridges built over the last two decades is testament to that.
- Extradosed Bridges are considered as "in-between" girder bridges and cable-stayed bridges. In a cable-stayed bridge, the loads (permanent as well as live loads) are globally carried predominantly by the stay cables. In a girder bridge, loads are carried by shear and flexure of the girder and internal pre-stressed or post-tensioned cables, which produces permanent stresses that act opposite to those produced by self-weight and moving loads.
- With a stiff deck and shallow angled cables, an extradosed girder behaves like a pre-stressed concrete girder although it has similarity in looks with cable-stayed bridges. The shallow angle of the cables ensures that the extradosed cables directly carry only a small portion of the live load. This is the basic behaviour of an Extradosed Bridge. However, the actual configuration of the girder and cables decides how close its behaviour is to a prestressed girder bridge.
- An Extradosed Bridge has its deck partially supported by a system of cables, which are connected to a pylon of small height (pylons have two legs, and masts only one. For simplicity

Chapter

2

Conceptual Design

Serge Montens, France

2.1 General Layout and Structural Scheme

2.1.1 General

As for cable-stayed bridges, there is a wide variety of possible solutions for the general layout, static scheme, deck type and pylons/masts of Extradosed Bridges. The typical value for the main span length of Extradosed Bridges is between 100 and 250 m.

The general layout of Extradosed Bridges will be described in this section. Decks and pylon/mast will be described in greater detail in Sections 2.2 and 2.3. For reasons of simplicity, only the term pylon will be used for the rest of the document even so sometimes mast, that is, single-leg supports would be correct.

2.1.2 Elevation

Although most Extradosed Bridges have two or more supports with pylons along the bridge (i.e. pylons located above two different piers), they may have only one (i.e. a pylon located above only one pier), or also multiple pylons (i.e. pylons located above more than two piers).

Bridges with only one pylon are not frequent. They generally have a symmetrical layout for the spans and the extradosed cables (Miyakodagawa Bridge,[14] Saint-Rémy-de-Maurienne Bridge in France[15]). However, the layout can be asymmetrical, continuous with another span on one side only, for special topographical situations (Yumekake Bridge in Japan,[16] *Fig. 2.1*). The design of an Extradosed Bridge with only one pylon can be a valid solution for an asymmetrical topographical layout, or if it is impossible to place an intermediate pier in two adjacent long spans. It could also be a good solution, for example, in case of an island in the middle of a river.

Bridges with pylons located on two piers are the most frequent type. Generally, they have three spans. Side spans are then approximately 50–70% the length of the main span. If the side spans are longer, the bending moments will be excessive. If they are shorter, there could be some uplift reaction at the end support. If the bridge is longer, it is also possible to create a continuity between

Chapter

3

Analysis

José Romo Martín, Spain

3.1 Structural Behavior and Analysis

Extradosed Bridges are highly redundant structures; their structural behaviour varies with the relative stiffness of the deck, pylon, and cable system.

As discussed in previous chapters, the use of a stiff deck in Extradosed Bridges allows live loads to be transferred to piers mainly in bending of the deck girder. This results in little activation of the cables under live loading and thus a corresponding small stress variation range. Hence, with regard to vertical loading, the cables in an Extradosed Bridge are designed to carry predominantly dead loads from the deck.

The Extradosed Bridges built to date have varied in the locations of cable anchorages along the span. In several recent Japanese designs, the anchorages can be found concentrated towards the mid span, while the deck nearer to the pylon supports its weight and superimposed permanent load though the vertical stiffness and capacity of the deck section. This can be further enhanced by increasing the deck depth or haunching the deck near the pylon location.

Conversely, it is possible to use a slender deck by stiffening the pylon and increasing the extent of live load taken by the cables. This is desirable for longer spans, which tend towards a conventional cable-stayed system, but it should be noted that the cable tensioning in this case may need to be reduced to accommodate the increased live load stress range.

There is a clear interaction between design and construction of Extradosed Bridges. As a result, the selection of the structural type, span arrangement, and materials should consider the method of construction at the design stage. Construction stage considerations such as the changing structural system during construction, temporary supports, erection equipment on the structure, movements of form traveller, and sequence of post-tensioning tendons and stays, among others, may influence the design choices for the structure.

The structural analysis of the bridge should consider the changing structural system during the course of construction, including varying internal effects and stresses at the construction stages. The analysis must consider the redistribution of bending moments in the deck due to long-term creep and shrinkage in the concrete.

Chapter

4

Structural Design – The Japanese Experience

Akio Kasuga, Japan

4.1 General

Structural design of Extradosed Bridges is similar to conventional girder bridges with extradosed cables, which are essentially large eccentricity external tendons. Compared with cable-stayed bridges, the height of pylon is almost a half. Therefore, variation of pylon configuration is more limited than is the case for cable-stayed bridges. The ratio of the back span to centre span is similar to typical girder bridges. Although Extradosed Bridges utilize extradosed cables, the features of the Extradosed Bridge are different from cable-stayed bridges. The girder is much stiffer and is not carried entirely by the cables. The back span of Extradosed Bridges is generally slightly longer than half the main, typically in the range of 0.55–0.60 of main span length. The significance of partially pre-stressed concrete was that it successfully combines pre-stressed concrete and reinforced concrete into a single concept. A similar success has been achieved with the development of Extradosed Bridge technology, which is significant because it enables engineers to combine design principles already established for cable-stayed bridges and ordinary girder bridges. The Extradosed Bridge is a revolutionary high-performance structural system that greatly increases the degree of freedom for the design of cable-stayed and cable-supported structures. Building on J. Mathivat's ideas and the achievement of the Odawara Blueway Bridge, Extradosed Bridges have written a major new page in the history of bridge engineering.

4.2 Structural Components and Details

4.2.1. Deck Cross Sections

The sectional configurations of some of the important Japanese Extradosed Bridges are shown in *Fig. 4.1.* The deck cross sections are of many types, for example, single box, multiple boxes, and twin boxes. Moreover, as shown in *Fig. 4.1e and f*, there are special structures, such as corrugated steel web or butterfly web to reduce the deck weight. These special solutions are effective in earthquake-prone areas. The arrangement of stay cable is deeply related to the deck cross sections. There are two options of stay-cable arrangement: single plane and double planes. For structural efficiency, stay-cable anchorage should be located near the webs. In the deck cross

Chapter

5

Technology of Extradosed Cables

Thierry Duclos, France

5.1 Foreword

Since the emergence of Extradosed Bridges as a concept, the majority have utilized stay cable technology for the extradosed cables. A few have utilized a different type of cable that mixes stay cable technology with the external prestressing technology. Regardless, the aim has been to provide a durable system for the design life of the bridges and to provide the most cost-effective solution given the demands on extradosed stays.

A few publications currently provide the accepted international standards for the basis of design, testing, and installation of stay cables and, to a lesser extent, extradosed cables. These standards address the important technical issues for stay cables and extradosed cables, including durability, fatigue, dynamic response, and technical system details. These standards are as follows:

- SETRA—CIP Stay Cable Recommendations, 2002.[8]
- PTI Recommendations 6th edition, 2012.[10]
- fib Bulletin 89, 2019 (supersedes fib Bulletin 30, 2005).[50]
- JPCEA 2000 Japanese Recommendations: Specifications for Design and Construction of Cable-stayed Bridges and Extradosed Bridges.[9]

These publications continue to evolve as stay-cable technologies and materials have evolved. Some have advanced further than others and the standards vary in some cases among the publications. These publications have evolved primarily to address stay cable technology, often developing progressively to address the learned through actual design, testing, and installation. The development of standards for extradosed stays has been more recent and has lagged that for stay cables. This has resulted in more varied, and in many cases, less robust guidance available to designers for extradosed stays. Work groups with the standards organizations continue to improve and progress updates to the documents and newer more robust recommendations are expected to be incorporated in future versions of these documents.

International bridge design standards typically do not adequately address stay cables. AASHTO does not specifically address stay cables so designers in North America typically rely upon the PTI Recommendations. Similarly, Eurocode[51] gives general requirements for the design of

Chapter

6

Construction Issues

Chithabaram Sankaralingam, India

6.1 Introduction

The Extradosed Bridges usually have main spans between 100 and 250 m and side spans between 50 and 150 m. For such type of bridges, the precast/cast in place segmental construction method is considered most suitable. Segmental construction for both side and main spans may be constructed by the balanced cantilever method. Alternatively, the side span may be constructed by span by span erection method, by using temporary trestles if necessary and the segmental construction of the main span may follow using the free cantilevering method.

The method of erection is influenced by the stiffness of the pylon cable anchorage system, viability of installing temporary supports, maximum unsupported spans permitted, ease of transporting materials, and so on. However, since stability of the system largely depends upon transferring the horizontal component of the force in a cable through the girder, it is imperative to have girder continuity between each pair of stays.

Several Extradosed Bridges have been successfully built in the last two decades with differing spans, pylon heights and stay cable arrangements. The various erection techniques and construction methodologies are discussed under the forthcoming headings.

The type of deck plays a vital role in the construction stage analysis of Extradosed Bridges. The stay cables of concrete decks are normally installed in such a way that the deck under dead load will not deflect vertically. Accordingly, the bending moment distribution along the deck length will be similar to the bending moment distribution of a continuous beam on rigid supports and, consequently the effect of creep is minimised and the achieved desired alignment does not change with time. The stay cables may then be installed to predetermined unstressed lengths to achieve the desired alignment and the desired bending moment distribution under dead load regardless of the construction method/sequence.

For bridges with composite deck cross sections (concrete/concrete or steel/concrete), the installation of the cables to predetermined lengths, similar to the case of conventional bridges with concrete-only sections or steel-only sections, does not lead necessarily to the desired forces and

Chapter

7

Cost/economics

Juan Sobrino, Canada

7.1 Introduction

Selection of the most appropriate structural type for a specific bridge is very much dependent on the cost of the bridge, its character, context, environmental and sustainability considerations, site conditions and constraints, life-cycle cost, and construction methods. Construction cost among others is one of the most relevant considerations. Therefore, this chapter provides some guidance on preliminary estimate of the construction cost based on unit quantity ratios and assesses the cost-effectiveness compared to other structural types, such as girders and cable-stayed bridges.

Extradosed Bridges, as other cable-supported structures, are perceived as an expensive structural type for medium-span bridges, probably because these bridges require a more sophisticated design and construction process. However, it has been proved in Japan, and more recently in Europe and America, that Extradosed Bridges are cost-effective for span lengths ranging from 150 to 250 m. For this span length range, Extradosed Bridges can be a competitive alternative compared with steel girders, concrete girders built in balanced cantilever, arches, steel trusses, and cable-stayed bridges, depending on site conditions and project requirements.

Based on the statistics and typical price units (Florida-based) it is possible to make cost comparison between both alternatives. *Figure 7.1* illustrates the results of a cost estimate per unit deck surface area versus the span length. The comparison should be interpreted in a qualitative way, as unit cost depends on site conditions. According to this study, construction cost of Extradosed Bridges is similar to balanced cantilever bridges for span lengths varying between 110 and 150 m and more economical for longer span lengths.

Reliable comparable construction cost to a specific bridge are difficult to find and interpret because each bridge project is unique. Construction cost are not only related to material quantities, labour, and unit prices, but to construction methods, geotechnical, environmental, seismic, construction site constrains, design codes, future maintenance provisions, finishes and many other factors to be considered. For this reason, this chapter summarizes the statistics of quantities that would allow the Transportation Agencies and bridge engineers to conduct a first rough construction cost estimate during the preliminary phases of the design and alternative bridge cost comparison. The curves have been prepared from data provided by designers and contractors[67]

Chapter

8

Bridge Data and Case Studies

Andreas Apitz, Germany

8.1 General

This chapter provides a general overview of the Extradosed Bridges (EDBs) built so far. With the help of the members and guests of the IABSE Working Commission 3 and by reviewing existing literature,[7,16,28,40,42,53,54,73–79] it was possible to collect data of about 241 EDBs worldwide. The bridge data table in Section 8.4 is perhaps the largest database of its kind until now even though it is certainly not complete. The geometric properties of EDBs are evaluated in Section 8.2. Section 8.3 shows the great diversity of Extradosed Bridges by presenting Case Studies of some selected bridges.

Around 59 % of the Extradosed Bridges in the list have two pylons in longitudinal direction (= three spans). Nearly 19 % have one and 22 % have three or more pylons (multi-span EDBs). Some facts reveal the large field of application of the bridge type:

- Longest main span: 312 m (Wuhu Yangtze River Bridge).
- Shortest main span: 43.5 m (Viaduct over the S8 Expressway in Olesnica).
- Longest multi-span EDB: 9759 m (Kacchi Dargah Bridge, completion expected 2022, see case studies).
- Highest pylon above bridge deck level: 57 m (New Yanggang Bridge).
- Lowest pylon above bridge deck level: 3.2 m (Deba River Bridge).
- Widest bridge deck: 61 m (Guijiugou Bridge).
- Narrowest bridge deck: 7.7 m (Hinase Bridge).

As can be seen from *Fig. 8.1*, the world´s leading countries in building Extradosed Bridges are China and Japan. The latter can be considered the motherland of EDBs, since the first “real” EDB (Odawara Blueway Bridge, see Section 8.3) was built there in 1994. After further development of EDBs and its technology in Japan, the first EDBs were built in Europe and in some Asian countries in the late 1990s. In the year 2000, the first EDB was built in China. Currently, most EDBs are being built in China and India.

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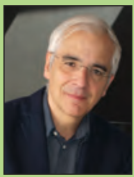

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Extradosed Bridges

Extradosed bridges can be an elegant and economic solution for bridges with spans ranging between 100 and 250m. This novel type of cable-supported bridges has become quite successful in recent years first in Japan and then all over the world.

Experienced members of the international bridge community have come together in Working Commission 3 of IABSE to share their knowledge and to prepare an SED which provides the reader with guidance and practical advise that was not available so far. This book contains useful information regarding conceptual and structural design, analysis, construction, cost and typical properties of Extradosed Bridges.

ISBN 978-3-85748-172-7

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