1 Introduction and scopes

Segmental construction in the field of prestressed hollow box girders concrete bridges can be considered one of the most interesting and important achievements in bridge engineering in the last decades. The usage of precast elements instead of in-situ concrete leads to an economical, durable and safe design and a fast and versatile construction. That is the reason why precast segmental hollow box girder bridges have become the preferred constructions method for many elevated highway projects in the last years. In urban areas the very fast erection without interrupting the traffic underneath is an important advantage for these types of bridges.

In contrast to classical monolithic constructions, a segmental bridge consists of small pieces or slices called segments, which maybe precast, cast in place in their final position in the structure or a combination of precast and cast in place. In other words, it is opposite to the precast girder concept where the bridge is cut longitudinally. In the precast segmental method, the bridge is cut transversally, each slice being a segment. Thereafter the segments are stressed together by external or internal tendons. The erection process of a segmental bridge can be seen in Figure 1.1.

Figure 1.1 Segmental bridge construction in Bangkok [Br5]

Segmental construction is not a new technique. In the years 1944 - 1946 the first segmental bridges with about 55 *m* span were built over the Marne River in France by Eugene

Freyssinet [Lal]. The main breakthrough came with the usage of hollow box girder segments. More than 300 such structures were constructed between 1950 and 1965 in Europe. Thereafter the concept has spread throughout the world. Nowadays the main segmental bridge construction is carried out in Southeast Asia, where there is a great need to improve the road systems.

Match-cast method especially the short line match casting is most of the time used as a segment production technique for post-tensioned hollow box girder segmental bridges to guarantee a perfect fitting of adjacent segments. When a new segment is to be cast against an old one, a problem can appear. In the quite high heat of concrete hydration the newly concreted segment (new cast segment) causes a thermal gradient in the hardened preceding segment (match cast segment), which acts like a mould to form the contact joint. This gradient leading to spatial deformation causes a bowing of the match cast segment (or banana shape) before the fresh new cast concrete has reached its initial set, which becomes a permanent curvature in the new segment. The resulting segments have one straight and one curved side, whereas the old segments keep bowing in time and return to their original shape after cooling down to constant temperature. The resulting gap between two adjacent elements may significantly reduce the durability and the load bearing capacity of the structure. Few experimental data has been published about this phenomenon and a systematic study is still missing.

A thermo-mechanical finite element model has been developed to simulate the behaviour of segments during match-casting. The temperature distribution within a body and the subsequent thermal stresses and deformations under any stable or variable boundary condition with respect to time can be analyzed. Included in this model is the evolution of temperature produced from the heat of hydration in the new cast segment, the non-linear time dependant behaviour of concrete and the temperature flux between the new and old segment. The method of equivalent moment is used to calculate the deformations due to the thermal gradients, as well as in-situ test results from the San Antonio (*Y* project) and the Bang Na (BBBE) segmental bridges were used to verify the complex numerical model. A good agreement has been obtained. The influence of different environmental conditions, the shape of the segment, and use of insulating materials on the bowing effect have been studied.

At the erection site, the bow shaped segments have particular problems during the epoxy and temporary post-tensioning operations. One may have problems in closing the joints and the bowing deformation reduces the required compressive stresses for the epoxy resin. Moreover, this phenomenon not only poses problems in construction but it also raises questions about stress distribution across joints and it could lead to areas of reduced compression in the segment's centreline, meanwhile stress peaks occur at the tips of the segment's cantilever slab. In some cases, it could be detrimental by causing cracking in the segments. It can be said that bowing effect could cause a reduction in the load bearing capacity and influence the serviceability of segmental bridges. Reported scientific research is quite limited and none, up to date, was conducted to investigate the impact of using match-cast segment on the behaviour of precast segmental bridges.

A numerical simulation of two typical real segmental bridges, namely the Second Stage Expressway System (SES) and Bang Na segmental bridges, consisting of perfectly fitted or bow shape segments with dry joints will be presented in this thesis. The results show that compressive stresses and the load bearing capacity of the structure as well as the durability and deflections are highly influenced by the bowing effect.

This thesis is organized as follows: The state of the art is presented in chapter 2. There the construction and design of segmental bridges, the previous studies including the main problems appearing during the manufacturing of the precast segments will be presented. Furthermore the investigations and studies of heat development and transfer in the early age of concrete, which contain the previous concrete thermal measurements and models conducted in order to analyze the temperature distribution within a body will be discussed.
Chapter three presents the approaches and measurements made to conduct the bowing and to estimate the temperatures and deformations during the match-cast process of San Antonio and Bang Na segmental bridges. Numerical simulations and modelling of match-cast segments and the transient thermo-mechanical process will be introduced to conduct the unavoidable complicated behaviour of match-cast segments. In order to verify the thermo-mechanical model, comparisons of the model will be shown with measurements taken in San Antonio and Bang Na bridges. The numerical models will also be compared to a mathematical approach based on the equivalent moment formula.

In chapter four the behaviour of a real segmental span with perfect and imperfect segments is studied. First a numerical simulation of a real segmental bridge (Second Stage Expressway System in Bangkok) will be introduced and verified using the measurements taken from the SES segmental bridge. The mechanical finite element model will be extended to simulate segments having gaps produced from the match-cast method. Their influences on the serviceability and the bearing capacity of the whole structure under the short-term and the long-term loading including creep and shrinkage effects of concrete will be predicted. The time dependant behaviour of the structure could be detrimental or helpful in redistributing the compressive stresses and closing the gaps. The study of the whole structure during different periods of time could give answers about the efficiency as well as prestressing losses of the whole structure. In addition to the before mentioned investigations the Bang Na segmental bridge consisting of very slender elements will be modelled in order to show the obvious influences of large gaps on the structure.
Chapter four finally will include the recommendations and construction approaches in order to predict and to minimize the risks of impact bow shaped segments in the structure. The conclusions are presented in chapter five.

The objectives of this study can be summarized as follows:

1. **Numerical simulation of the match cast process to study the behaviour of match-cast segments during the evolution of temperature produced from the heat of hydration. Characterize relevant measures to reduce the bowing effect.**

2. **To study the impact of using imperfect match-cast segments with gaps concerning the serviceability and load bearing capacity of segmental bridges.**

3. **Investigate the behaviour of segmental bridges under long-term loads including time dependant behaviour of concrete.**

2 Present state of knowledge

This chapter gives a brief description of precast segmental bridge technology and the different production methods of segments. The main problems during the manufacturing of the precast segments will be presented. The various investigations and studies of heat development and heat transfer in the early age of concrete will be discussed, which will include the previous concrete thermal measurements and numerical models conducted in order to analyze the temperature distribution within a body.

2.1 Segmental bridges – Segment production

Segmental bridges with hollow box girder are considered relatively a new development in concrete construction. Hence, most of the segmental field research related to design and improvement of this new technique has been investigated during the past 30 years. The research investigated by Breen [Br1- Br4], Podolny and Muller [Po1, Po2] is considered to be the basics of construction and design of segmental bridges in USA. In Germany, many investigations were conducted by Kupfer [Ku1, Ku2], Kordina [Kor], Fischer [Fi1, Fi2], Eibl [Ei1], Rombach [Ro1- Ro4], Specker [Sp2], and Chaffo [Cha] in construction and design of segmental bridges. The 'Deutsche Beton-Verein' published recommendations for the design of hollow box girder segmental bridges in 1999 [Deu].

Segmental construction can be defined as a method of construction in which the primary load-carrying members are composed of individual precast or cast-in-place segments external and/or internal post-tensioned longitudinally and/or transversely tendons together to form simple or continuous-span bridges. In this research work precast segmental bridges will be treated only. The prefabrication can shorten the construction period without a disruption in traffic. In addition it can be more economical by reducing the mild reinforcement as well as higher quality of concrete can be achieved.

In spite of their disadvantages, which can be represented in bad corrosion protection of steel in the joints and their need of thicker webs, the internal tendons were being little applied in segmental construction. In 1992, the Department of Transport in the UK issued a memorandum pointing out the problem of corrosion in post-tensioned prestressed tendons and banned the classical option of internal tendons. The use of external tendons can reduce the period and cost by simplifying the concreting procedures and constructability, besides the tendons can be more readily inspected and replaced. Figure 2.1 shows the external tendons layout of a typical segmental span of the Second Stage Expressway System (SES) in Bangkok. Superstructures of segmental construction are generally of single or multiple box sections or a combination thereof, but precast beam-type sections may also be used.

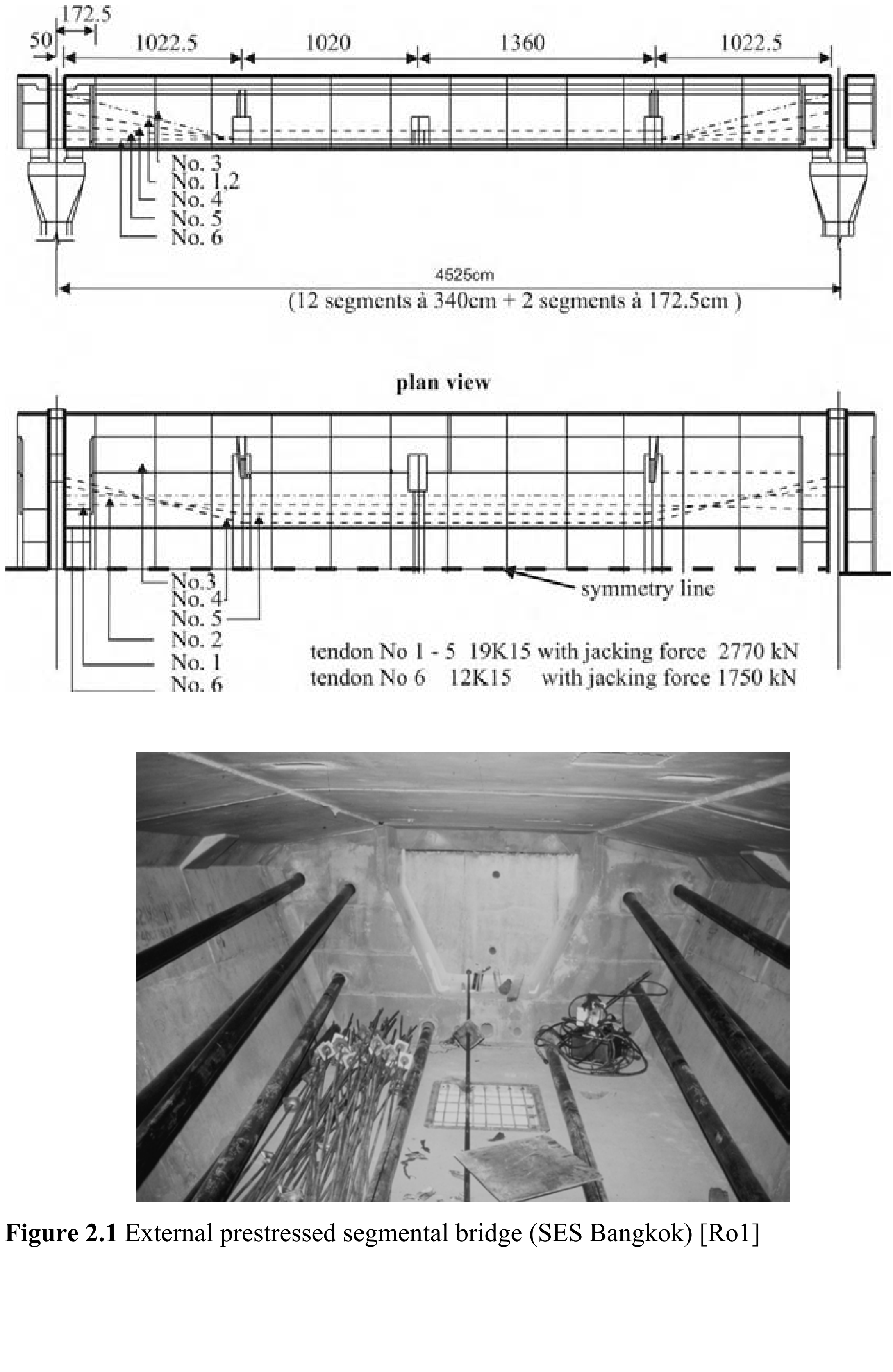

Figure 2.1 External prestressed segmental bridge (SES Bangkok) [Ro1]

Three different segments used in segmental bridges, as a result of using external post tensioning, are called pier, deviator and standard segments, and they can be seen in Figure 2.2.

- Pier segment: Is used to stiffen the webs by using a thick diaphragm to diffuse the support forces and for the anchorage of the external tendons process. The external tendons are not anchored in the webs; therefore the eccentric forces are considerable.
- Standard segment: In this element, the dead load could be minimized as a result of thinner webs of 35 *cm* or less relied on the shear forces. Neither tendons are deviated nor anchorages are carried out herein.
- Deviator segment: The layout of the external tendons needs some regions where the tendons must be deviated; this leads to high vertical loads, which have to be diffused to the webs.

The shear keys are designed to carry the shear loads at the joints, where also the friction between the joint surfaces takes part in resisting shear forces.

The dimensions and weight of the segments can depend on the possibility of transportation available since normally the precast yard is not located in the construction site [Br6, Rog].

In precast segmental construction, segments are generally manufactured in a plant due to the need of big storage area or near the erection site, and then transported to their final position for assembly. Initially, joints between segments were of a conventional type: either concrete poured wet joints or dry mortar packed joints (Fig. 2.5). Modern segmental construction calls for the match-casting technique, whereby the segments are precast against each other, preferably in the same relative order they will have in the final structure. The joints are either left dry in areas where climate permits, or made of a very thin film of epoxy resin or mineral complex, which does not change the match-casting properties. There is no need for any waiting period for a joint cure, and final assembly of segments by prestressing may proceed as fast as practical.

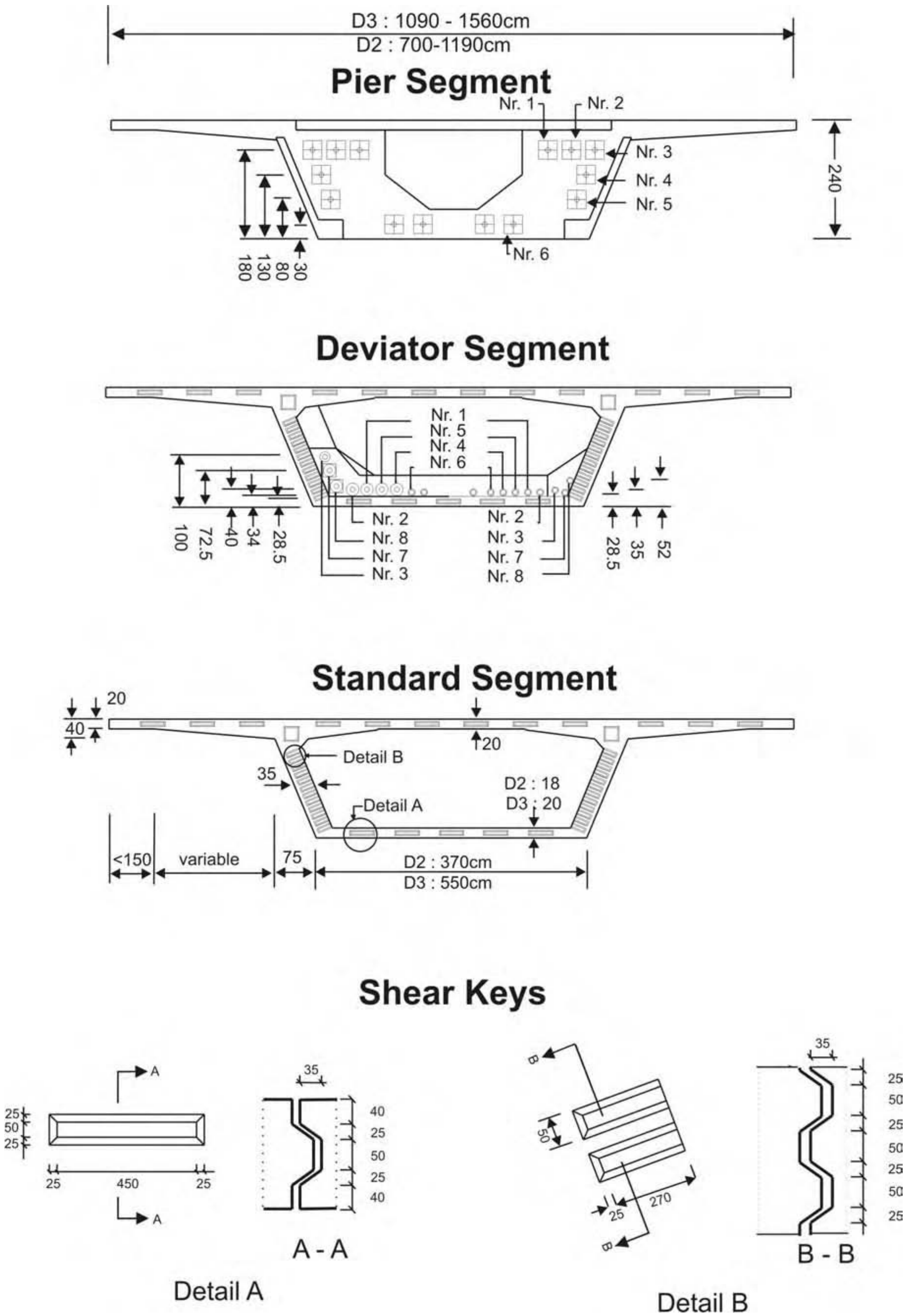

Figure 2.2 Cross-sections of segments and shear keys (SES) [Ta1]

The various methods used until now for precasting segments fall into two basic categories:

1. Long-line casting, where all segments of a span are manufactured on a fixed bed with the formwork moving along the bed for the successive casting operations as can be seen in Figure 2.3. In this technique the segments are cast in their correct supposed position on a long bed, which represents the profile of the real structure at one time. The pier segment is cast first between the fixed bulkhead and the removable formwork, then the next segments. As segment casting continues, the first cast segments can be removed for storage. This method was used for constant-depth box girders; thereafter it was extended to the case of variable-depth decks. The advantages of this technique can be seen in its simplicity of set out and control deck geometry after removing of the form as well as it is not necessary to move the segments directly to storage. The relatively big manufacturing space, all the equipment for casting and curing must be mobile and a firm foundation that should resist the casing bed are considered to be disadvantages in the long-line method.

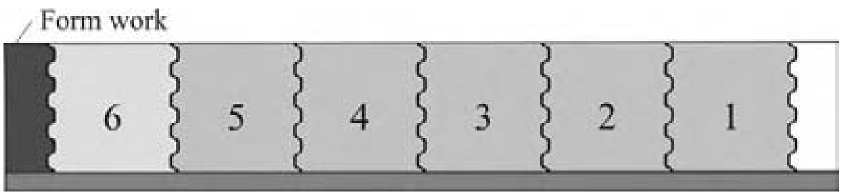

Figure 2.3 Long-line match-cast method

2. Short-line casting, where segments are manufactured in a step-by-step procedure with the forms maintained at a stationary position. Figure 2.4 shows the standard old match-cast segment of the SES Bangkok bridge against the formwork prepared to cast the new match-cast segment.

   In the short-line casting method all segments are required to be cast at the same site using stationary forms, next to the previously cast segment in order to get a homogeneous perfect fitting match-cast joint. The previously cast segment is removed for storage after casting and initial curing, and the freshly cast segment is placed into its position; the cycle of casting is then repeated. The larger the segments get, the more the tendency is going towards the short-line method. The small space where all equipment remains at a stationary site is a basic advantage of the short-line method, besides the horizontal and vertical curves as well as the superelevation are obtained more readily than in the long-line casing method that