CHAPTER 1

INTRODUCTION

1.1 Background

Among developing countries, Thailand has exhibited a large volume of elevated highway with prefabricated construction. It is quite essential that technical practice should be conducted with proper design, construction, inspection, maintenance for strength, serviceability and durability. Prefabricated construction of elevated highway should be comprised of precast members erected at the construction site with cast in-situ slab deck. The precast girder is particularly advantageous to a large volume production in a short period of time, uniformed and systematic quality control, site environment and erection with little or no traffic interference. For a span length of less than 40 meters, the precast girders are quite common to cast in one single piece of the main structural elements, then they are lifted into place by mobile cranes or erection gantry. The method of side-by-side erection can also be used for construction with precast elements and cast-in-place slab deck. For medium span bridges longer than 40 meters, segmental construction is normally applied whether by cast in-situ on traveling form work or erected precast on site. The segments are then post-tensioned span by span and are finally placed on the supports. There are many types and sections of precast construction, the most common of which used in Thailand are the I, T, U and box sections as shown in Fig.1.1 which are normally used in accordance with their appropriate span length (20-45 meters) and erection equipment.

In current practice, each span is usually constructed separately for individual spans and provides expansion joints for each single span. Using elastomeric bearing pads and expansion joints in highway construction is common for reasons such as construction procedure, economic prefabricated construction and possibility of the structural deformation from creep, shrinkage and thermal effects. Because of many joints, the driving comfort is not smooth and the maintenance cost is expensive as shown in Fig. 1.2. If the girders have a large deformation, the bridge surface is stumbled over these joints.

Continuity of the bridge deck to eliminate expansion joints between adjacent span supports or jointless bridge decks is desirable to improve the appearance and driving quality, to reduce vibration and noise problems, to eliminate initial cost of joints and their subsequent maintenance, to eliminate malfunction of expansion joints due to debris accumulation, to reduce deterioration of bridge bearings due to water leakage from the deck surface through joints, and to improve long term serviceability, aesthetics, and safety. However, there are still some limitations depending on many factors affecting girder movements due to loads and the serviceability.

In recent years, expansion joints have been eliminated to reduce their number over the total length of overall construction especially for new bridges. The design approach to avoid or minimize the number of expansion joint is less considered, although some jointless bridge decks are constructed. There have been many efforts to provide jointless bridge deck construction in order to utilize their advantages that can be classified into integral bridges with capped-pile abutments and flexible capped-pile piers, semi-integral bridges with capped-pile abutments and semi-rigid piers with movable bearings, and jointless bridge decks supported by simple-supported girders as shown in Fig. 1.3.

A simpler and thus more economical option is to connect simply supported girders through a fully continuous deck, with no continuity between the adjacent girders. Being also suitable for precast construction and complying with the joint-free idea, they appear to be an alternative solution to one of the severe bridge maintenance problems. Beams with a continuous deck provide a simple and efficient solution not only for the construction of new bridges but also for the rehabilitation of old ones, by re-decking the still serviceable and simply supported girders. It is generally more efficient than the integral bridge construction practices (Alampalli and Yannotti, 1998). Moreover, beams made continuous for live loads have proven suitable for precast concrete construction and show remarkable performance as far as continuity is concerned when compared to fully continuous beams, although the fully continuous beam has generally established an excellent performance record.

The section of the deck connecting the two adjacent simple span girders is called the link slab (Fig. 1.4). There are two types of link slab construction depending on the gap between the two main girders which are affected by the shape of cap beams; rectangular cap beams and inverted T cap beams. There is enough space to construct enough span length of link slab to produce low stiffness link slab on the inverted T cap beams. However, if there is not enough space between two main girders on the rectangular cap beams, debonding between deck and girder can be carried out to increase its span length. This system is recommended for unfavorable ground conditions. In addition, a total of 32 overpasses with jointless bridge decks with link slabs in the earthquake region during the 1999 Izmit earthquake in Turkey typically performed well because dislocation of the girders could be controlled (Youd et al., 2000). In addition, the seismic performance of multi-simple span bridges retrofitted with link slabs was also investigated by Caner et al. (2002). The first link slab jointless bridge in the state of North Carolina was instrumented with a remote data acquisition system and monitored for over a year. The link slab was subjected to rotation due to thermal effects greater than those effects caused by traffic loads (Wing and Kowalsky, 2005).

The link slab can accommodate axial deformation, end rotation and end translation from adjacent spans as shown in Fig. 1.5. Both ends of the link slab are subjected to vertical and longitudinal movements due to the flexibility of elastomeric bearing pads as well as longitudinal and rotational movements due to girder deformation.

1.2 Review of Previous Studies

The concept of jointless bridge decks built with multiple spans of simply supported girders while the deck is considered as a continuously reinforced pavement supported by the girders was presented by Zuk (1981). In this type of bridge, the cost of construction of continuous girders is eliminated. The investigations included the effects of contraction and expansion of the jointless deck on the interactive forces between the continuous deck and simply-supported girders. The stress built up in the deck and the girder in the longitudinal direction were not abnormally high and could be accommodated generally with proper amounts and types of material. However, one should be aware of the transverse cracks as which developed in the deck and the behavior of slip planes between the deck and the girder, although these phenomena are not serious problems.

An analytical study of the load-deflection response of the jointless bridge deck system using a finite element solution was conducted by Gastal (1986). In the analysis, each bridge span was divided into segments that were modeled by isoparametric beam elements, except the link slab. The link slab was modeled as a spring element with axial stiffness only. His numerical solution can be used for the analysis of linear and non-linear, instantaneous and time-dependent responses as well as the strength of the bridge. An iterative method of solution was used in the program to determine the stresses, forces, and displacements at any location of the bridge. He compared the variety of test results of simply supported beams to the analytical results of these beams and verified the accuracy of the program.

A simplified design procedure for the removal of expansion joints from bridges using partially debonded and continuous decks was conducted by Richardson (1989). The deck was partially debonded from the girders only at the connecting deck over two adjacent girders. The debonded portion of the deck was assumed as a tension member. The analysis and design methods were based on elastic theory. The variables considered were the length of debonding, the amount of deck reinforcement, and the support conditions for the structure. Computer programs were developed also to predict the crack width and spacing in the deck and to calculate the vertical deflection of the structure. His studies indicated that the support conditions had a great influence of the deck stresses and potential cracking in the deck. The crack widths of the link slab and the girder deflections did not change as much as the deck stresses due to this reduction in stiffness.

El-Safty (1994) later modified the finite element program developed by Gastal (1986). He introduced the constant strain through the depth of the link slab whereas Gastal assumed a linearly varying strain through the depth of the link slab. He reported that the optimum debonded length to get the highest ultimate load is in the range of 2% and 6% of the girder span depending on the different conditions of support and loading.

Subsequently, Zia et al. (1995), Caner and Zia (1998) presented a design concept for the link slab based on analytical studies and a test program. Their approaches considered each span of a bridge as simply-supported since the flexural stiffness of the link slab is much smaller than that of the girders and the link slab did not introduce any significant continuity to the test structures. In addition, the debonding of the link slab over the girders for a length equal to 5% of each girder span would not alter the load-deflection behavior of jointless bridge decks with simple-span girders. It was also assumed that the link slab was subjected to flexure rather than axial deformation and cracks occurred at its midpoint. If the moment in the link slab exceeded the cracking moment, the moment of inertia of the cracked section was used at the middle part of the slab and the effective moment of inertia for the debonded portion was computed from Branson's formula (Branson, 1965). Its design was based on crack control.

The first link slab jointless bridge in the state of North Carolina was also instrumented with a remote data acquisition system and monitored for over a year. The link slab was subjected to rotation due to thermal effects greater than due to traffic loads (Wing et al., 2005). Chula Unisearch (2000) has evaluated the Ramindra-Atnarong Expressway, which is a superstructural system is 30 meters and simply supported girder placed on bearing pad with 180 meters continuity of bridge deck, by analysis and monitoring. The problems were unusual movements at the expansion joints. From the analysis, the transverse movement occurred due to shrinkage and thermal effects at approximately 60% and 40% of the total movement respectively. In addition, the longitudinal movement occurred due to shrinkage, creep and thermal effects at approximately 40%, 30% and 30% of the total movement respectively. From site monitoring, the crack mapping and crack width were collected from columns, crossheads, girders and decks including the deformation of columns, girders, elastomeric bearings, and the relative movement of expansion joints.

Kim et al. (2004) proposed a ductile Engineered Cementitious Composite (ECC) material for a link slab due to its ability to control crack width and its high ductility. They performed a full-scale test on ECC link slabs and compared with those of an ordinary reinforced concrete link slab by imposing end rotation from the adjacent spans at an inflection point (zero moment), which was determined from slab stiffness. The inflection point was located within $L/5$ from the support where L denotes the span length (Gilani and Juntunen, 2001). The test results showed that the crack widths of the ECC link slab were substantially smaller than those of the concrete link slab. Recently, partial continuity due to the axial stiffness of link slabs and support configurations was investigated by Okeil and El-Safty (2005) by using a modified three-moment equation. The influence of span length ratio, slab axial stiffness, and girder axial stiffness on the behavior of a two-span jointless bridge was studied for roller and hinged supports. It was found that the bottom of the girders at a hinged support was prevented from longitudinal movement. The support then developed higher continuity moments and tension force in the link slab.

Because the design is difficult and their behavior is unknown, they are not widely used despite the enormous benefits. There are no standardized design procedures for these bridges, only a list of specifications is available.

From all means of previous studies, the effects of joint movement seem to be perfectly considered in their studies. However, in dealing with effects of joint movement, the characteristic of girder type, support conditions and restraint of link slab should be considered. Further investigation on the behavior of link slabs by finite element methods, on site monitoring and some experimental studies should be made.

The reinforcement details would not be investigated, and therefore this study was conducted. Present design criteria and specifications have many variations in analysis and design among states. It is quite obvious that the design criteria, specifications and standards are essential for Thai practices.

1.3 Significance and Objectives

The conditions of link slabs are complex in the behaviors which are related to the accuracies and their degree of reliability in terms of strength, serviceability and durability. The overall response of the highway bridge should be checked to evaluate the force distribution due to the addition of link slabs. To obtain the most accurate structural model, the nonlinear three-dimensional smeared fracture finite element analysis will be done to compare with actual structures which have already operated upon limitation of control and monitoring. Full-scale model testing will be conducted to verify some proper parameters. Design criteria for strength, serviceability and durability will be developed.

A majority of existing studies have considered a link slab as an axial member or a flexural member by using an elastic theory and the assumption of a major crack at the mid-span. However, the behavior of the link slab is predominantly nonlinear due to cracks that occur throughout the slab. In addition, the calculation of the maximum moment in the link slab using gross section properties is quite conservative in determining the partial continuity since cracks will normally occur in the link slab. For example, the effective moment of inertia of the link slab to restrain the adjacent girder movements, the crack width and crack pattern to control the serviceability, and the failure mode for the development of a strut-and-tie model based design can not be correctly predicted without an appropriate model. The restraint end movement of highway girders is directly associated with the link slab stiffness (through the relative stiffness between girders and slabs associated with the supports) and the internal forces developed in the slab (through load-deflection relationship). Moreover, internal forces and effective stiffness of the link slab are also related. Therefore, if the end movements of adjacent girders are appropriately controlled, the internal forces in a reinforced concrete link slab can then be determined provided that the actual stiffness is known. In addition, the relative stiffness can also be changed to accommodate the internal force in the design of a link slab.

The objective of this research is to study structural behaviors related to end restraints of link slabs and to develop design criteria of such structures for continuation of the bridge deck over the supported highway girders to make jointless decks for smooth riding. The girders are prefabricated by individual simple span and simultaneously cast the deck on site to make a continuous deck with an appropriate overlay for the final finished surface. The deck would behave as a partially continuous member to link between spans with complex parameters and complicated behaviors as for short-term and long-term structural performance.

1.4 Research Methodology

This research is divided into six parts, as shown in Fig. 1.6. The methodology has considered the analytical and experimental study toward structural behavior to evaluate performance on strength and serviceability which can be separated into three analytical parts and two experimental parts (Fig. 1.6).

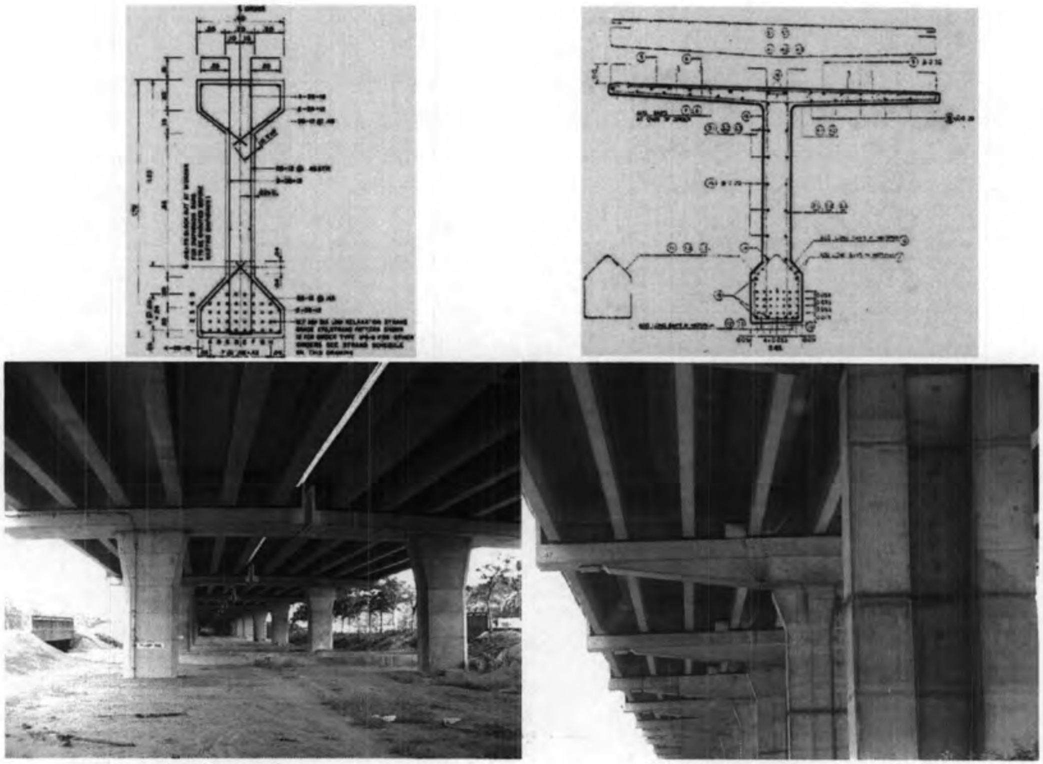
In the analytical study, the end movement of a simply supported girder, the link slab behavior under constraint and the interaction model between girder and link slab are considered.

1. The basic parameters of the end movements of typical highway girders will be studied. They include girder types/span length, creep, shrinkage, steel relaxation, thermal effects to determine the longitudinal movement and end rotation. The most commonly used precast construction are I, T, U and box sections with a span length of 20-45 meters and construction procedure with some outstanding consequences will be considered.

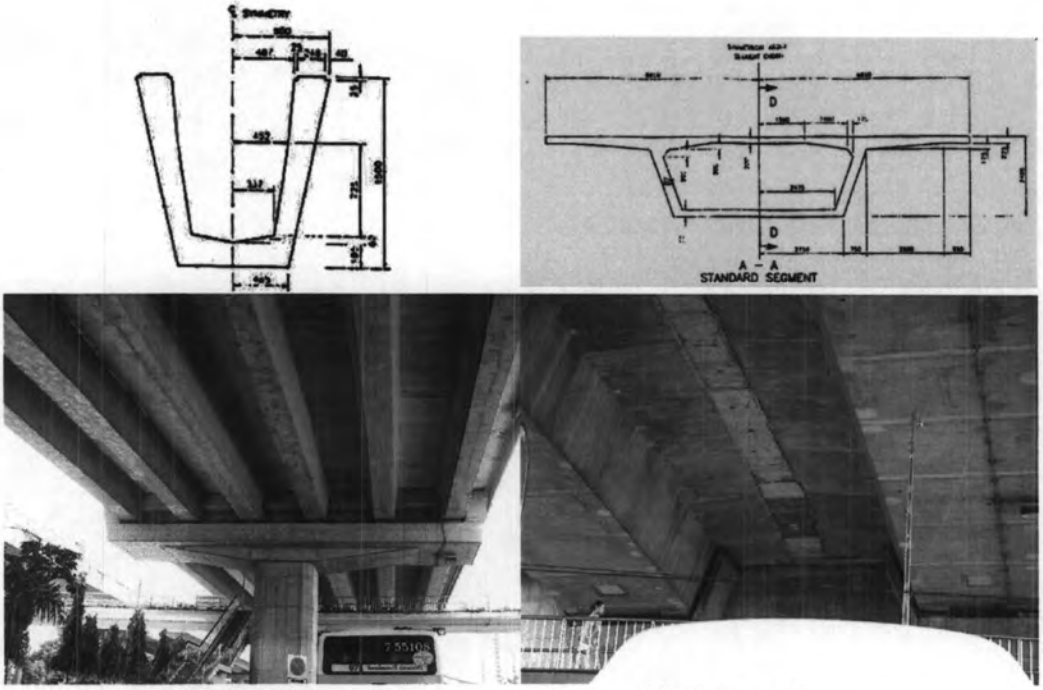
2. The structural model of link slabs will be developed to accommodate all movements of the girders as the restraints onto the structures as axial force, flexure, and shear to govern the most outstanding behaviors using the finite element method which would lead to its stiffness, cracking behavior and deformation. The link slab thickness/span length and reinforcing arrangement will be considered.
3. The interaction model between the girder movements and link slab behavior including support conditions will be determined. Because the behavior of multiple-span bridges is partially continuous, the amount of continuity due to this link slab on the girders is also determined. Then the design is developed for optimizing these parameters.
4. In the experimental study, the full-scale testing on link slabs under mid-span loading and the monitoring on end movement of multi-span bridge with link slabs are considered. Experimental testing on link slabs under mid-span loading will be performed to investigate the behavior of link slabs such as the effect of reinforcement details, cracking behavior, stiffness and failure mode. Finite element results will be verified by the experimental results in this stage. Bridges constructed with link slabs in Thailand are selected for use as case studies by collecting field data such as bridge specifications, amount of continuity, crack patterns, crack width/spacing, etc. Field data and assessments could verify the interaction model.
5. Finally, the design criteria and design method for link slabs of multiple spans of specific provisions are developed to attain the service life under the strength limit state and serviceability limit state.

1.5 Scopes and Limitations

Only the straight route of elevated multi-span highways with link slabs without differential elevation and pier settlement have been studied. Torsion effects of box girders are neglected. The dimensional properties of girders, support conditions at both sides of link slabs are considered to be similar in this study. The variation of concrete strength of prestressed girder and cast in-situ slab deck is not included in this study, including the movements of the structures below the supports of girder.

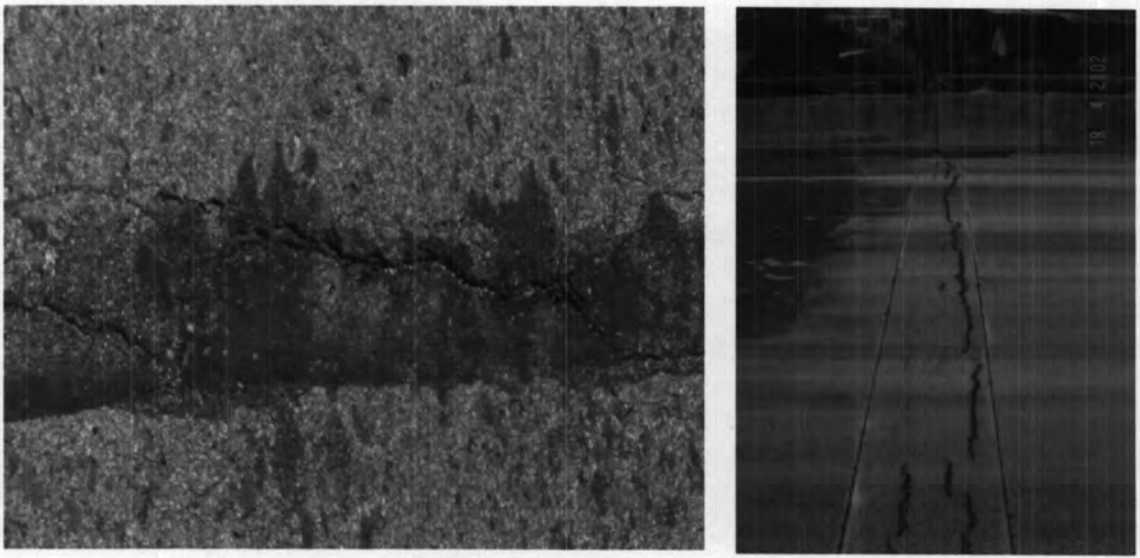


(a) I-section (b) T-section

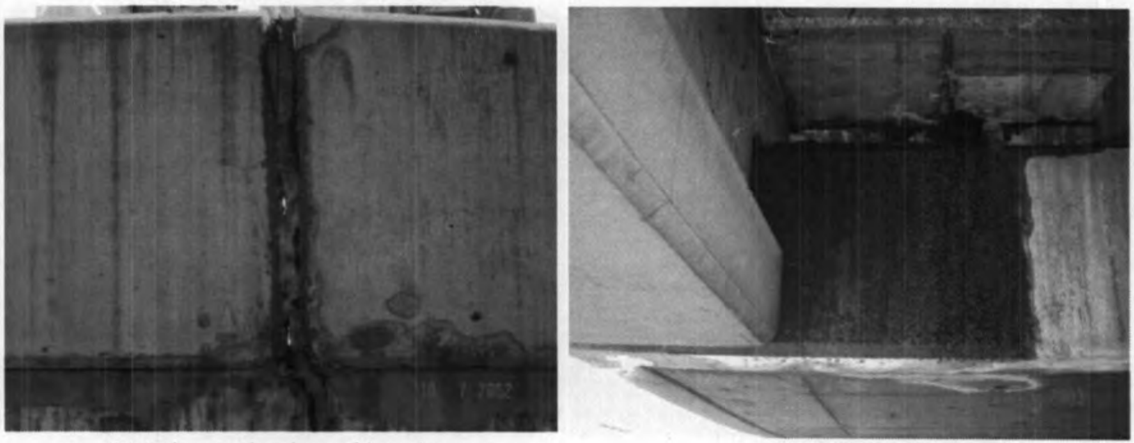


(c) U-section (d) Box-section

Fig. 1.1 Typical cross-sections of precast highway girders



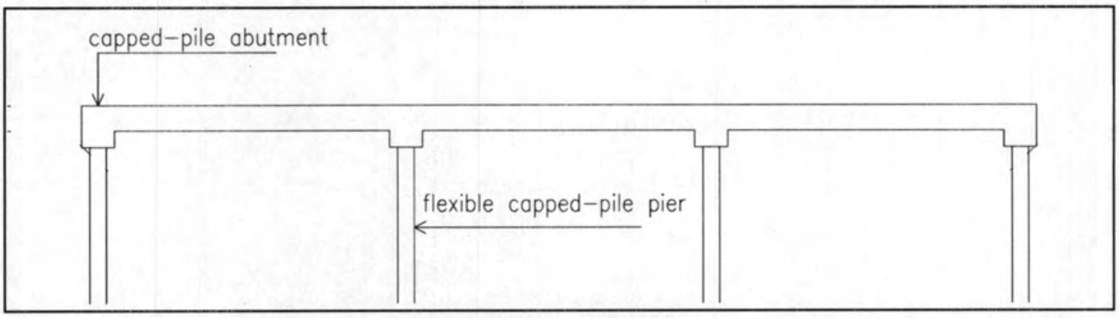
(a) Severe cracks on deck



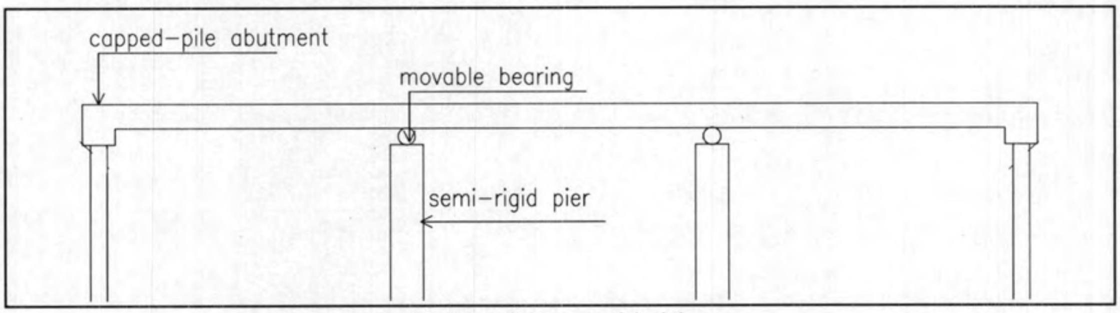
(b) Discontinuity of barrier (c) Water leakage

(d) Non-smooth deck (e) Maintenance cost on expansion joint

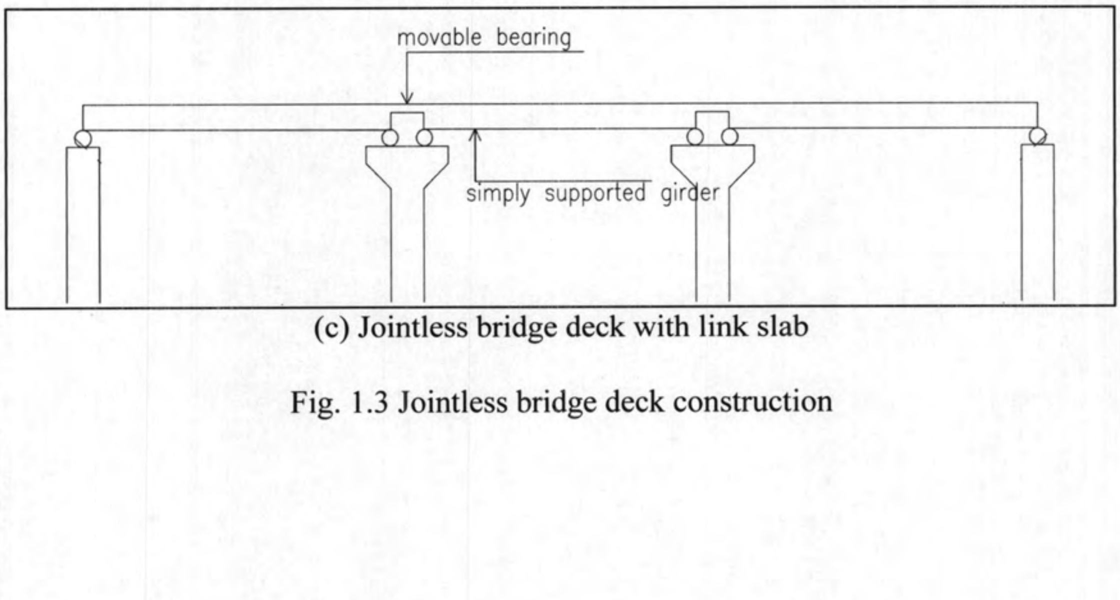
Fig. 1.2 Some disadvantages of bridge deck with joints



(a) Integral bridge

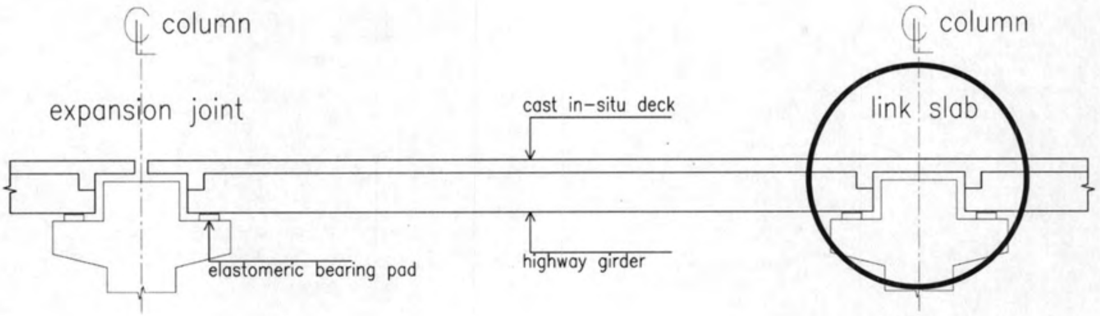


(b) Semi-integral bridge

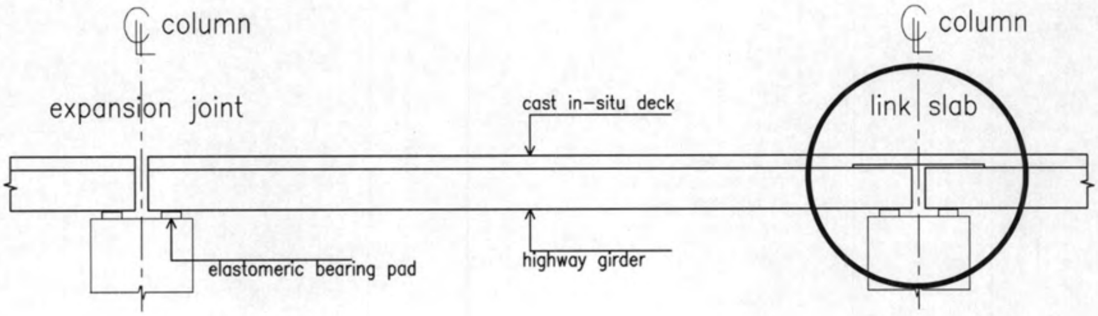


(c) Jointless bridge deck with link slab

Fig. 1.3 Jointless bridge deck construction

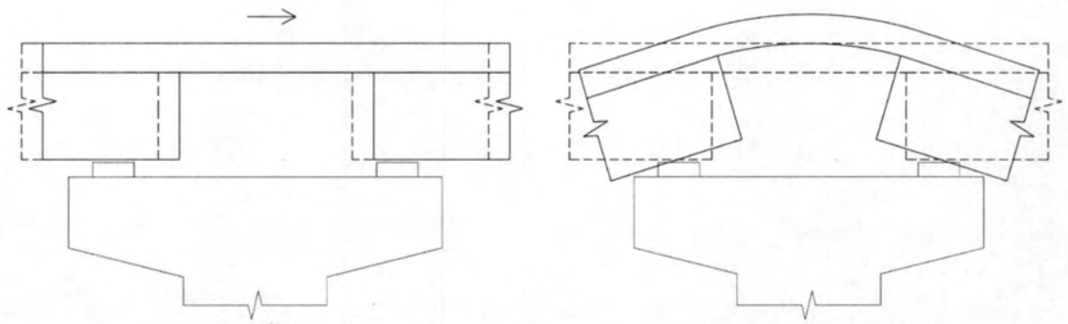


a) Long span link slab without debonding part



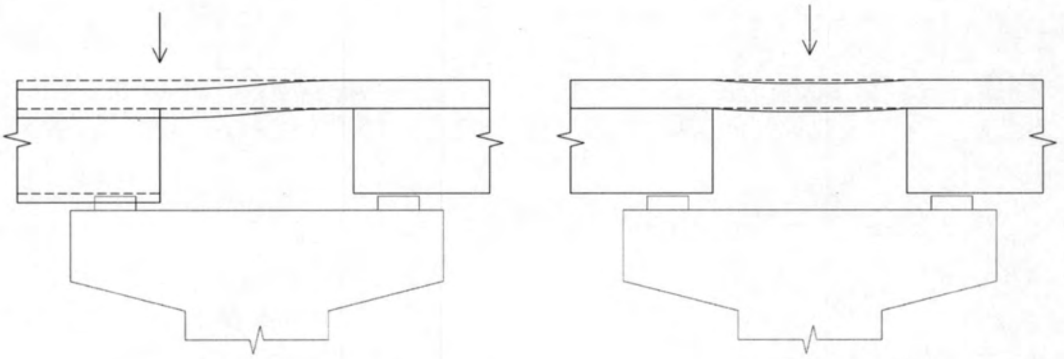
b) Short span link slab with debonding part

Fig. 1.4 Long span link slab and short span link slab (with debonding part)



(a) Axial deformation

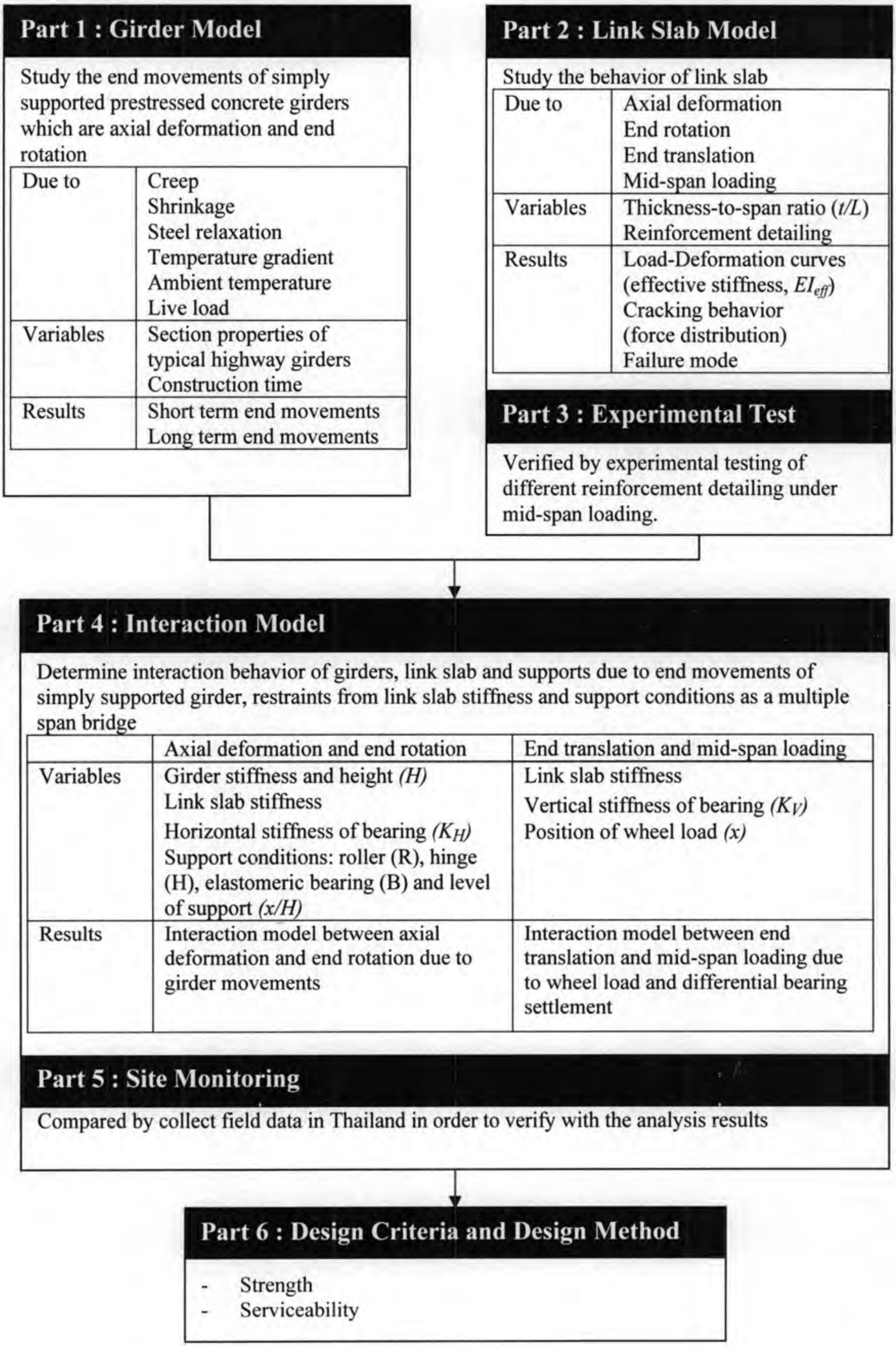
(b) End rotation



(c) End translation

(d) Mid-span loading

Fig. 1.5 Load and end movement actions on link slab



Part 1 : Girder Model

Study the end movements of simply supported prestressed concrete girders which are axial deformation and end rotation

Due to	Creep Shrinkage Steel relaxation Temperature gradient Ambient temperature Live load
Variables	Section properties of typical highway girders Construction time
Results	Short term end movements Long term end movements

Part 2 : Link Slab Model

Study the behavior of link slab

Due to	Axial deformation End rotation End translation Mid-span loading
Variables	Thickness-to-span ratio (t/L) Reinforcement detailing
Results	Load-Deformation curves (effective stiffness, EI_{eff}) Cracking behavior (force distribution) Failure mode

Part 3 : Experimental Test

Verified by experimental testing of different reinforcement detailing under mid-span loading.

Part 4 : Interaction Model

Determine interaction behavior of girders, link slab and supports due to end movements of simply supported girder, restraints from link slab stiffness and support conditions as a multiple span bridge

	Axial deformation and end rotation	End translation and mid-span loading
Variables	Girder stiffness and height (H) Link slab stiffness Horizontal stiffness of bearing (K_H) Support conditions: roller (R), hinge (H), elastomeric bearing (B) and level of support (x/H)	Link slab stiffness Vertical stiffness of bearing (K_V) Position of wheel load (x)
Results	Interaction model between axial deformation and end rotation due to girder movements	Interaction model between end translation and mid-span loading due to wheel load and differential bearing settlement

Part 5 : Site Monitoring

Compared by collect field data in Thailand in order to verify with the analysis results

Part 6 : Design Criteria and Design Method

- Strength
- Serviceability

Fig. 1.6 Research program