CHAPTER 1 INTRODUCTION

1.1 General Background Information

Over the decades, the use of steel I-girder component in bridge superstructures has become a recognized concern due to its efficiency both on load-carrying capacity and economization. Many bridges built in the past 50 years are composite structures with decks constructed of reinforced concrete and supported by longitudinal steel girders. In particular, the concrete bridge deck is one of a major concern as it always incorporates into the composite bridge superstructure. An essential factor in making a sound decision is knowledge of the strength of the bridge in its existing form. Unfortunately, the inelastic responses, load distribution characteristics, and ultimate strength of multi-girder bridges cannot be realistically assessed by use of simplified analytical procedures currently used in design and evaluation. In general, prediction of this behavior completely requires extensive experimentation or advanced analytical techniques.

In many cases, analytical approaches are more economical and convenient than laboratory or field testing. As a new era in computer technology, a number of researchers have adopted the potential of using Finite Element Analysis (FEA) to predict bridge responses with reinforced-concrete deck compositions. The development of commercial finite element software package, which provide a unique program interface with which to analyze a system, has helped engineers attain a better appreciation for both the usefulness and limitations of finite element modeling of reinforced concrete. Evaluation of specific applications such as reinforced-concrete bridge decks can be handled using this numerical approach. However, to identify possible modeling discrepancies and errors and to verify the accuracy of these numerical models, results from finite element analyses need to be compared against those from actual experiments.

The complexity of reinforced concrete structures is a major factor that limits the capabilities of the finite element method. Until recently, only linear models are used to analyze structural systems composed of complex materials such as reinforced concrete. As a result, several present researches have been studied in many variations of the constitutive model representations of the bridge deck component. Many of them (Westergaard, 1930; Newmark, 1948; Cheung et al., 1970; Pucher, 1977; Jaeger and Bakht, 1982; Jaeger and Bakht, 1985; Cheung et al., 1986; Jaeger and Bakht, 1989; Fang et al., 1990; Hays et al., 1994; Cao, 1996 and etc.) have been acknowledged and referred from time to time. In general, a finite element model consists of a mesh of elements defined by nodes that describe the geometrical properties of an object. Section properties are added to describe the behavior of the elements. Forces can be applied directly to the nodes or elements. For that reason, the element reactions can be determined by response parameters such as displacements and stresses. Nowadays, with the increase in the popularity of the FEA more accurate models of material behaviors have been included in finite element software. Concrete can now be accurately modeled and the analysis can even accounting for the cracking that occurs.

In relation to the composite bridge deck analysis, FEA has become the most powerful and versatile analytical method available at present since the composite-action behavior of bridge superstructures can be analyzed accurately with a sufficiently large computer. In view of that, three-dimensional FEA with an appropriate high and low order element category, e.g., shell, beam and truss elements, is then adopted throughout this study. Hence, the bridge deck responses such as moments and deflections can be readily assessed with least restrain assumptions. This should be contributable to more accurate results in bridge deck evaluation at present.

1.2 Problem Statement and Research Significant

The composite steel-concrete bridge has been widely used, especially in the United States, for a long time. Most of the bridge decks are constructed as reinforced concrete slabs supported by steel I-girders or precast/prestressed girders, as shown in Figure 1.1.

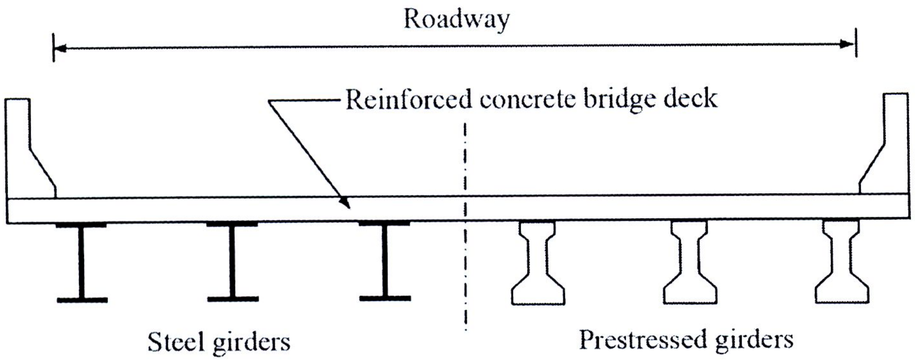

Figure 1.1 Typical cross sections of a reinforced concrete deck slab

Such decks have traditionally been designed using the "strip method" (AASHTO, 2002), based on a conventional beam theory, which assumes that the slab is continuous over fixed supports. As a result, the top part of the slab is reinforced with steel bars to resist the negative moments, and the bottom part of the slab is reinforced with steel bars to resist the positive moments. The concrete deck can be reinforced with a number of bar placements as described in Figure 1.2.

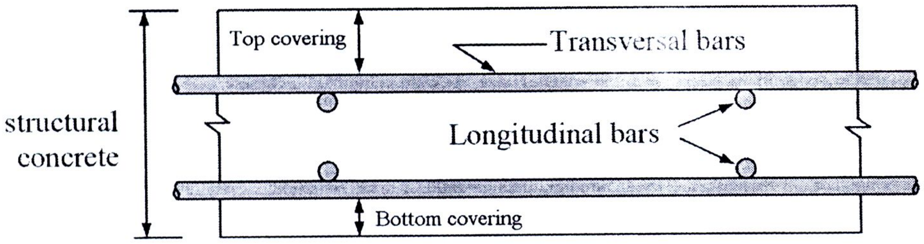

Figure 1.2 Typical reinforcement deck section

Temperature and shrinkage reinforcement is added orthogonally at the top and at the bottom. When cracks occur in concrete, the top reinforcement can be subjected to environmental agents and aggressive chemicals such as deicing salt, and it can start to corrode. The deterioration can result in a lateral expansion of the steel bars, leading to spalling of concrete cover and subsequent formation of potholes as shown in Figure 1.3.

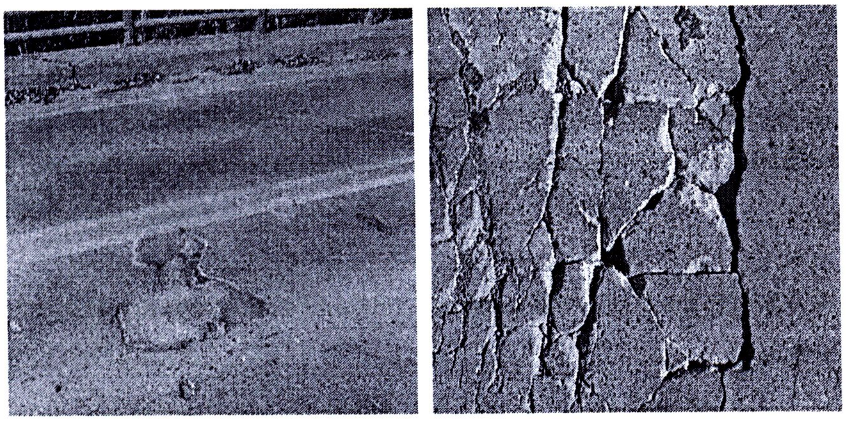

Figure 1.3 Typical cracking and potholes in concrete bridge deck

In real situation, many bridges in the United States had the problem of life expectancy caused by corrosion of top reinforcing steel (Cao, 1996), and this also happened in many concrete bridges especially near the sea port around the world. It is apparent that the composite slab-on-girder bridges currently require high rehabilitation and maintenance costs, either to upgrade them to meet current standards or, in most cases, to combat deterioration of the steel reinforcement members, which is caused by exposure to highly corrosive environments.

Reducing number and size of reinforcement bars of deck slab according to design codes such as AASHTO Specifications may reduce maintenance costs and increases service life of the bridge deck. Several researches in the United States and mainly in Canada showed that the flexural capacity of bridge decks can be increased by the presence of in-plane compressive forces created when the deck is restrained by supports that cannot move laterally. This phenomenon is referred as "arching action" and is the basis of the empirical design provisions of the Ontario Bridge Design Code (OHBDC, 1991) and subsequently Canadian Highway Bridge Design Code (CHBDC, 2006). This empirical method has been afterward adopted in the current AASHTO LRFD code (2004). Canadian Highway Bridge Design Code is referred to as an isotropic reinforcement. According to the empirical method, arching action requires less steel reinforcement than that required by the strip method of AASHTO LRFD code (2004). Therefore, it is believed that the decks designed by empirical method are more resistant to deterioration due to fewer steel rebar leading lower sources of corrosion.

Although many research works about bridge deck moments have been studied by several researchers at present, some discrepancies can be found among them (Westergaard, 1930; Chan, 1996; Cao, 1996; Bapat, 2009) even the codes of practice (OHBDC, 1991; AASHTO, 2002; BD81/02, 2002; AASHTO, 2004; CHBDC, 2006). This discrepancy should be due to the different methods (modified analytical and simplified methods, refined numerical and simplified methods) used in the analytical procedure. There is no investigation available to evaluate this discrepancy. Over the years, some of the notable problems that have been identified from a structural point of view include the following:

- Understanding on the local and global responses of the deck under wheel loading is still unclear.
- Reinforced concrete decks are subjected to susceptible cracking due to improper amount of reinforcing of steel bars in upper part of the deck.
- How much the impact of relative rigidity between the concrete bridge deck and the remaining structural components of the bridge superstructure would have on the behavior of the concrete deck?
- Effect of lateral and longitudinal superstructure flexibility on strength of reinforced concrete bridge decks has leaded to an uncertain discrepancy in deck slab moments to a certain extent.
- While trucks passing the bridge, the actual effect of transient load patterns on deck slab moments is still suspicious for the deck slab design.

This research intents to expose above mentioned issues so as to understand insight into the actual behavior of bridge decks under service load, which will thus serve as a decision-making tool for the improvement of the deck slab design.

1.3 Objectives and Scope of the Study

1.3.1 Objectives

In this dissertation, a more robust effective approach for the deck slab moments of concrete slab-on-steel girder bridges is introduced to account for all significant bridge parameters. Live load characteristic is also taken into consideration in the analysis process. A procedure for the ordinary deck slab assessment on moment responses is developed, which is focused on the evaluation and comparison of bridge deck performance based on the present extensive parametric study. A reliable-based method associated with a state of the art refined finite element analysis, calibrated using field tests, is developed in order to understand the structural behavior of the deck slab.

The above objectives are achieved by focusing on the developing of a reliable finite element model of this type of bridge. The current design codes and construction practices synthesizing previous nationwide research results have been comprehensively studied to provide supplemental information in support of outcome conclusions and recommendations. The three dimensional (3D) finite element modeling scheme is discussed, and the model is successfully developed and verified against experimental results. In particular, in order to determine the most appropriate bridge model representative, experimental results of strains and deflections of a test bridge deck were compared to the predictions made by corresponding bridge models based on different finite element modeling techniques.

While truck loadings acting on bridge deck slab-girder system, the difficult task is to obtain stresses and deflections of real behavior of the slab by refined method. Furthermore, most bridge decks are designed with the assumptions that the concrete slabs behave similar as a one-way slab and girders act as a simply support. Nowadays, there is no general closed-form solution or guideline graphical solution available to determine the transverse bending moment in continuous slabs on elastic supports that include all significant parameters. Therefore, this research attempts to find the most suitable modeling techniques for determining the deck slab moments due to transient traffic loadings moving on the bridge.

The disputed need for practical bridges is assessed through 3D finite element simulations of both simple and continuous straight girders. The main motivation was to eventually achieve more economical bridge construction while meeting construction, serviceability, and strength capacity requirements. With the purpose of service analyses, the main objectives are to:

1. Determine the best modeling technique for the bridge deck by developing several practical models of 3D slab-on-girder system using FEA and validated with the existing experimental test data.
2. Perform the parametric impact assessment (bridge physical geometries) on the evaluation of the deck slab moments under all possible truck loading conditions by the best finding technique.
3. Compare the present FEA-based results with selected different methods. The finite element model predictions are compared to AASHTO LRFD (2007), AASHTO Standard Specifications (2002), CHBDC (2006), BD81/02 (2002) and other related research provisions.
4. Provide the alternative design formulas of the design transverse slab moment in applicable ranges, namely girder spacing (***S***): 1.524-3.60 m (5-12 ft), bridge span (***L***) for small (up to 15 m) and medium span bridges (up to 27 m): 15.240 m (50 ft) at each quarter section in terms of sensitive parameters (***S***, ***L***, number of loaded lanes $\boldsymbol{N_L}$ and number of girders N_G).

1.3.2 Scope

In this research, many geometries of bridge deck slabs over three or more steel I-girders are analyzed along bridge span ***L*** at locations of a mid-span, a quarter, and near support; and the moments have been determined from AASHTO design loaded truck by FEA only. Approaching a more accurate FEA is achieved by increasing the number of elements until the mesh refinement is proper in the area of interest, but it is reasonably time consuming to determine the worst-case scenarios. Moreover, it is necessary to perform certain checks and get the physical sense while performing an FEA since the modeling error is probably going to give the wrong result.

In general, the deck slab behaves as a linear elastic plate under normal serviceability of the bridge since concentrated loading level is insufficient to cause cracking. Therefore, the modeling investigation of superstructure database considered herein is applicable for only modern bridge design in a linearly elastic range (stress is proportional to the bending moment).

In general, it was not necessarily expected that axial tensions would be generated in the decks under vehicle loadings. If anything, a little compression was possibly expected due to internal arching. In this regard, however, recall that Fang. et al. (1990) observed no deck cracking and observed in-plane tension membrane stresses in the decks up until cracks occurred at three times the AASHTO service load. Also recall the statements by Fang et al. (1990) and Cao (1996), which indicate that cracking of the bottom of the deck is a critical prerequisite to the internal arching phenomenon. Therefore, in the absence of cracking, no compressive dome action is expected in this study. To further validate the credibility of the empirical deck design method, Cao (1996) reviewed several research projects related to internal arching behavior in bridge decks. One laboratory experiment proved that bridge decks with two mats of reinforcement fail in punching shear at loads six times larger than the design wheel load. All of the reviewed studies confirmed that the ultimate capacity and serviceability of the empirical deck design is comparable to the traditional deck design methods.

Moreover, the slab thickness *t* is a negligible parameter to the slab moment due to its insignificant effect (Cao, 1996; Tangwongchai, et al, 2011); consequently, the major physical parameters are *S* and *L*. In accordance with the AASHTO, the majority ranges of the geometry of the associated bridge deck considered in the present study are selected as follows:

- 1.5 m (5 ft) or $S_{MIN} \leq$ Girder spacing $S \leq$ 3.5 m (12 ft)
- Short span lengths of girder, 15 m (50 ft) or $L_{MIN} \leq L \leq$ 27 m (90 ft)
- Outside height of girder, $H \leq$ 0.91 m (36 inch)
- Slab thickness t = 0.20 m (8 inch), 7.50 $\leq S/t \leq$ 18 (CHBDC, 2006)

Throughout this study, pinned-roller restraints are used for the sake of simply supported and continuous supported conditions for 1-span truck loading and 2-span truck loading, respectively. Generally, compressive strength of concrete slab is also assumed to 36 MPa (5.16 ksi) resulting in the slab elastic modulus E_c of 28,270 MPa (4,100 ksi) according to recommendation of ACI 318-08 (AISC, 2008). For steel girders, the magnitude of girder elastic modulus E_g is selected to 199,950 MPa (29,000 ksi). The integer number of the Modulus ratio *n* (E_g/E_c) of 7 is used. The delimitations of this study are based on the reasonable scope as described bellows:

1. Corresponding to common types of AASHTO girder sections specified in AASHTO Specifications (Standard, 2002) and ASTM designation for steel material (grade A36) in practical design, the bridge's characteristics used in geometric models are considered as follows:
    - Plan-geometry: normal (or right) of slab on girder system
    - Number of lanes loaded; N_L = 1, 2 and 3 lanes
    - Number of girder; N_G = 3, 4, 5, 6 and 7
    - Equal girder spacing ***S*** range: using the most economical values according to the practical range of ***S***
    - Girder types; rolled and built-up sections with large steel girders (AISC, 1986) using the variation in girder size (which varies girder stiffness, K_g) according to each its span length

- Minimum thickness of slab according to AASHTO WSD, $t = 0.040$ (S+3.05) in meter unit, and not less than 0.18 cm (7 in)
- Width of slab overhangs less than, or equal to, one half of the girder spacing
- Slenderness ratio; λ (the center-to-center girder spacing/slab thickness) < 15 (LRFD 2007); 15 < λ < 18 (CHBDC, 2006) also concerned in an example.
- Live load; AASHTO H 20-44 and HS 20-44
- Transverse diaphragms; using the same at mid-span and side edges locations
- Smooth bituminous wearing surface; thickness = 0.075 m (0.30 in)

2. Supports of girders are assumed to be located at the bottom of the girders.
3. In view of the conservative side, sidewalks, parapets and bearing supports are not considered to be a part of concrete structure.
4. Only statically applied truck loadings will be considered in the FEA.
5. Flexural strength consideration is the primary design when the deck is subjected to live load as shear is not critical in the deck design.
6. Crack free sections and reinforcing steel contribution in a top deck slab are ignored for flexural rigidities

1.4 Dissertation Outline

Chapter 1 of this dissertation introduces the general information of slab-on-girder bridges together with the problem statement and describes the specific problem addressed in the study as well as the research scope.

Chapter 2 presents a review of literature and relevant research associated with the problem addressed in this dissertation.

Chapter 3 presents the methodology and procedures used for the present analysis to meet the requirement of FEA-based accuracy and reliability. The most appropriate FEA modeling technique for slab-on-girder bridges is found out and will be subsequently used for the present parametric study.

Chapter 4 mentions about all possible parameters that can affect on deck slab moments. To be specific, the variation of bridge physical parameters, such as girder spacing and span length, and loading characteristic including types of boundary conditions and loading location is discussed.

Chapter 5 presents the results of parametric impact assessment of parameters mentioned in Chapter 4. The effect of all considered parameters is investigated by performing a multivariate approach. The FEA-based formulas are also proposed to directly calculate the slab moments in a basis of the refined analysis and the ease of use.

Chapter 6 offers a summary and concluding remark of the researcher's findings, implications for practice, and recommendations for future research.