PRELIMINARY ANALYSIS AND DESIGN OF VARIOUS TYPES OF ROADWAY BRIDGE DECKS

By

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ملخص

تحليل و تصميم مبدئى لأنواع متعددة من أسطح الكبارى

مع التطور الكبير الذي حدث فى الفترة الأخيرة فى تطبيقات و استخدامات الحاسب الآلى فى جميع المجالات و منها مجال الكبارى بأنواعها المختلفة فقد أصبح من الضرورى التحول الى هذه التطبيقات و ابتكار العديد منها نظرا لما توفره هذه التطبيقات من سرعة و دقة فى نفس الوقت .

والهدف الرئيسى من هذا البحث هو تقديم طريقة دقيقة و مبسطة فى نفس الوقت لتحليل و تصميم الأنواع المختلفة من أسطح الكبارى لمساعدة المهندس المصمم فى الاختيار المبدئى لنوع الكوبرى المناسب لبحر معين دون الدخول فى حسابات معقدة أو الاعتماد على خبرة المصمم فى إنشاء النماذج اللازمة للتحليل الانشائى سواء كانت ثنائية أو ثلاثية الأبعاد ثم القيام بتصميم هذه الأنواع الممثلة فى البحث طبقا لمتطلبات الكود المصرى لتصميم مثل هذه الأعمال .

وتعتمد خطة البحث على تقديم مجموعة من برامج الحاسب الآلى تقوم بتجهيز ملفات الإدخال لبرنامج التحليل الإنشائى SAP –والذى يعتمد على طريقة العناصر المحددة– تلقائيا دون الاعتماد على خبرة المصمم فى التعامل مع هذا البرنامج طبقا للأحمال الخاصة بالكود المصرى لحساب الأحمال و القوى الصادر سنة 1994, ثم القيام بعد ذلك بتصميم هذه الأنواع من الكبارى طبقا للكود المصرى لتصميم وتنفيذ المنشآت الخرسانية المسلحة الصادر سنة 1995, والكود المصرى لتصميم و تنفيذ المنشآت الحديدية والكبارى الصادر سنة 1993, و الجزء الخاص بتصميم المنشآت الخرسانية سابقة الإجهاد من الكود الأمريكي مع الآخذ فى الاعتبار متطلبات الكود المصرى لتصميم وتنفيذ المنشآت الخرسانية المسلحة الصادر سنة 1995 . وقد تم عمل دراسة مقارنة لتأثير المتغيرات الأساسية فى التصميم و تم الوصول إلى نتائج جيدة بالمقارنة بكبارى منفذة على الطبيعة فى مصر.

ABSTRACT

In order to help the design engineer to choose the most economical design for roadway bridges according to the materials of constructions and the structural forms for various types of bridges, a set of computer programs has been developed to simplify the method of analysis and design. Although computer programs are valid to study numerous types of bridges, the study focuses on prestressed concrete with AASHTO girders, steel plate girders and reinforced concrete box girder bridges. In all types, reinforced concrete deck slabs are used through this study.

This work is a part of the thesis submitted to the faculty of engineering at Cairo University in partial fulfillment of the requirements of the degree of master of science in structural engineering done by the first author under the supervision of the other authors.

The analysis is based on the finite element method using the well known computer program SAP90. A set of computer auxiliary programs has been developed for automatic modeling of different bridges in order to obtain the design forces. In addition, another set of computer programs has been developed to design the main elements of each type.

A parametric study is carried out to verify the programs facilities. The chosen general cases studies are four lanes roadway bridge of 14.0 m width, with a span ranges from 20.0 m to 40.0 m length. For the prestressed model, the distances used between the main girders are taken 2.0 m and 3.0 m. For the steel bridge model, 3 and 4 main girders are used. Finally, a reinforced concrete box girder deck bridges, vertical webs and inclined webs are studied.

The Egyptian codes [1,2 & 3] for loads, design of bridges, concrete and steel structures, have been used through out this study in addition to the ACI 318-89 provisions [4&5] with some modifications to account for the requirements of the Egyptian codes.

Design charts and tables are given to help the designer for primary estimate the efficient type of the required bridge system. Finally, several conclusions have been obtained to demonstrate the capabilities and efficiency of the computer programs and to help the designer in his primary estimation of bridge elements.

Keywords: Computer, Programs, Analysis, Design, Bridges, Decks, Steel Plate Girders, Prestressed, Box Girders, Bending, Torsion.

INTRODUCTION

Bridge decks can be generally classified according to the structural forms to five types as follows:

(1) Beam Deck: A bridge deck can be considered to behave as a beam, Fig. (1), when its length exceeds its width by such an amount that when loads cause it to bend and twist along its length, its cross-sections displaced bodily and do not change its shape. The most common beam decks are footbridges.

(2) Grid Decks: The primary structural member of grid deck is a grid of two or more longitudinal beams with transverse beams (diaphragms) supporting the running slab as shown in Fig.(2). Loads are distributed between the main longitudinal beams by the bending and twisting of the transverse beams. Grid decks are most conveniently analyzed with the conventional computer grillage analysis.

(3) Slab Decks: A slab deck behaves like a flat plate as shown in Fig.(3), which is structurally continuous for the transfer of moments and torsion in all directions within the plan of the plate. When a load is placed on a part of the slab, the slab deflects locally in a “dish” causing a two-dimensional system of moments and torsion which transfer and share the load to neighboring parts of the deck which are less severely loaded.

(4) Beam and Slab Decks: A beam and slab deck consists of a number of longitudinal beams connected across their tops by a thin continuous slab as shown in Fig.(4). To transfer the load longitudinally to the supports, the slab acts in concert with the beams as their top flanges.

(5) Cellular Decks: The cross-section of a cellular or box decks is made up of number of thin slabs and thin or thick webs which totally enclose a number of cells, Fig.(5). These complicated structural forms are increasingly used in preference to beam and slab decks for spans in excess of 30 m (100 ft), because in addition to the low material content, low weight and high longitudinal bending stiffness, they have high torsional stiffness which give them better stability and load distribution characteristics.

Within a time span of approximately 30 years, from roughly 1970 to 2000, the science of bridge analysis and design has undergone major changes, following the advent of the digital computers, and the consequent development of analytical techniques based upon its use. Large number of elements are used for the classical analysis of bridge decks for arbitrary shapes, like plane stress, plate bending, triangular and parallelogram in-plane and bending elements.

Emile [6] used shell elements for deck simulation. Rigid joints were used to connect the girder nodes to the deck slab nodes in order to accommodate the eccentricity of the girders. In Emile's study, a commercial finite element package SAP90 [7] was used to generate the finite element model. Four nodes 3-D shell elements were used to model the concrete slab, while 2-D frame (beam) element is used to model the girders. Under that discretization scheme, the analysis showed good convergence.

Emile [6] carried out a comparison between the different methods of analysis to get the straining actions in box girder bridges. Emile used the complex shell finite element for modeling the single box girder, under different combination of loads. In addition he carried out a computer program using the formulation of finite-beam element for the analysis of thin walled single cell box section. The model had side cantilevers used in simple and continuous bridges, constructed by the use of steel, reinforced concrete or prestressed concrete, with or without intermediate diaphragms.

Andrzej [8] modeled a slab on girder deck using a more complicated approach. In Andrzej's model, the flanges of the I-beam were modeled as beam elements, the webs were modeled as shell elements, and the slab was modeled using shell elements.

From literature survey [9 to 18], most previous work presents particular cases of study and do not cover all the designer cases. In addition modern programs of analysis depend on the users to prepare the input data files and his experience to analyze the output results, which may not be suitable for ordinary engineers. Also, most of the previous works [19 to 29], mainly depend on foreign codes of practice to design different bridge elements and do not consider the requirements of the Egyptian codes.

In order to avoid these disadvantages, an attempt is made to reduce the cost and time by introducing a series of auxiliary computer programs to facilitate the analysis and design process for a various types of bridge decks.

OBJECTIVES AND SCOPE

The main objectives of this work can be summarized as follows:

1. Analyze different types of bridge decks under vertical static loads using 2-D and 3-D finite element models.
2. Develop auxiliary programs for automatically build the 2-D and 3-D finite element input data files for SAP90 program, independent of the user experience to save time and effort.
3. Design various types of bridge decks using the Egyptian code of practice, to achieve a set of computer programs, which are considered as tools for optimum design. Most of the modern computer programs, dealing with deck design are mainly based on the conditions and specifications related to the code of each country. Less or may be never of these programs are based on the Egyptian Codes [1,2&3].

   Thus, this work is an attempt to make a convergence with the design requirements relevant to the Egyptian codes, in addition to “the American concrete institute code (ACI 318-89)” [4&5] with some modifications to account for the requirements of the Egyptian code of practice for design of reinforced concrete structures.
4. Help the designer in carrying out a primary estimation based on a reasonable consideration and to carry the necessary comparison between different types of bridges to achieve economical design.
5. Investigate the factors affecting the choice of the bridge deck type through a parametric study for a group of parameters.

The following parameters are considered through out this study:

i. Effect of varying the girder span and the spacing between the main elements;
ii. Effect of varying the girder depth to span ratio to obtain a certain built-up I sections for steel bridges to get an economical design;
iii. Effect of using right and inclined web plates in the box girder deck types;
iv. Effect of adding cross girders and diaphragms on the various systems of bridge decks.

RESEARCH SIGNIFICANCE

With the great advances in computer methods in recent years, it has become possible for engineers to analyze complicated structures without complex or cumbersome mathematics of manipulation. With experienced engineers, it is possible to use physical reasoning and simple computer models for the design of relatively complex decks.

The finite element method is used for analysis of different types of bridge decks. This method is considered as the more accurate and efficient method for analysis at the present time. The analysis is done using the finite element program SAP90. Only main static loads (i.e dead load, live load and impact) are considered in this study. The live load patterns used are in accordance with the Egyptian code for loads. Then, a package of design computer programs has been developed, which employs the output straining action previously obtained from analysis, to achieve the design basis for the estimation of the different types of decks under consideration. In order to verify the facilities of these programs, many cases are studied through out a parametric study.

COMPUTER PROGRAMS

In order to achieve the above mentioned objectives, a group of computer programs were developed to cover different cases of loading for various forms and various materials of bridge decks. The structural analysis of decks is based on the finite element models presented in the SAP90 program. Two auxiliary programs were developed for automatically generate the input data files for SAP90 program without errors to save the user time and effort, [30].

The design of decks was carried out by the development of a set of computer programs based on the Egyptian codes [1,2&3], in addition to ACI code [4&5], for prestressing elements to obtain the necessary economical primary estimation, and to choose the efficient system related to certain parameters. The design requirements for different types of decks were considered as the base of the developed computer programs for design. Furthermore, the description of these computer programs and its flow charts are presented in details elsewhere [30].

The Developed Computer Programs are:

1. **S**lab and **G**irder **M**odeling **P**rogram (SGMP), which considered as an auxiliary to the SAP90 program.
2. **B**ox **G**irder **M**odeling **P**rogram (BGMP), which considered as an auxiliary to the SAP90 program.
3. **Pre**stressed **D**esign **P**rogram (PreDP).
4. **S**teel **P**late girder **D**esign **P**rogram (SPDP).
5. A group of computer programs for design of reinforced concrete sections.

Through out this study, the main parameters, which control the joint positions and shell elements, are:

(a) Width of deck bridge - for example the top width of the box girder (i.e positions of vertical web plates and the line of intersection with the top slab);

(b) Position of the load pattern on the top slab, to define the joints under each concentrated load;

(c) Width of side walks.

As shown in Fig. (6), the mesh modeling change according to the mentioned parameters by decreasing the dimensions of the shell elements at truck load positions and increasing the dimensions of elements at other positions. For the box girder deck modeling computer program, the general input data required to generate the model are shown in Fig. (7). The BGMP program and its complementary files provide database for the AASHTO girders, Fig.(8-a), and WASHINGTON girders, Fig. (8-b), in addition to the possibility to choose other sections.

The BGMP program is flexible to assign comprehensive sections as shown in Fig. (9) which can easily be changed to rectangular sections, T, inverted T sections, and I sections with or without hunches. The properties of the mentioned section are internally calculated. In the case of using other sections not assigned in the program database, the user should assign all the required dimensions and section characteristics.

PARAMETRIC STUDY

There are many parameters that control the efficiency of the bridge deck type for certain configuration. These parameters can be related to the functional requirements, the site conditions, the number and span(s) length, the materials properties and the used method of construction. These factors are all interrelated so that there are usually several alternative solutions that may be competitive. The objective of the designer is therefore, to find the combination that gives an optimum solution in terms of the functional requirements and cost. As there are so many alternatives and details that are relevant to this discussion, it will only be feasible to discuss the more important factors in broad outline to give general guidelines.

Series of four lane bridges with deck width of 14.00 m and span ranges between 20.00 m to 40.00 m were studied under vertical static loads based on the "Egyptian code for loads and forces on structures and building works 1994"[1]. The following parameters have been studied:

1. Deck material; (i.e prestressed, steel and reinforced concrete) assuming linearly elastic materials;
2. Structural form of the deck; (i.e girder, slab and girder, cellular or box type);
3. Spacing between main girders; (for slab and girder type);
4. (Depth / Span) ratio of the main girders; (i.e various AASHTO girders for the same span in case of prestrssed and different ratios for the steel main girders);
5. Cross girders effect in case of the prestressed decks; (check of the efficiency of the middle cross girder in addition to the end cross girders);
6. Cell shape effect in case of box girder bridge (vertical webs and inclined webs).

Eight cases have been studied to investigate the effect of the previous factors as shown in Figures (10 to 17). The parametric study's results include both the straining actions at the critical sections and the output design data representing the case under consideration according to the specified conditions and load patterns.

ANALYSIS OF RESULTS

1. Prestressed Decks

Two critical sections were analyzed for each case. The first one was for moment at mid span, and the other one was for shear near supports. The analysis was carried out for all load patterns, and the output results of SAP90 at the critical sections are listed in tables [30]. The design is carried out for all the above mentioned case.

Comparing the results of the two main cases, the following points were observed (Table (1)):

1. Although the stresses are higher than the permissible values, the ductility of the section is still within the accepted limits. It is clear that the stresses through out the transfer stage are less than the allowable values for both tension and compression fibers since the computer program for design (PreDP) is developed to keep these conditions true for all cases. On the other hand, the excess stresses than the allowable limits through permanent stages are resisted by using non-prestressing steel.
2. As the span increases, the total calculated percentage of the immediate losses increases and the total percentage of the time dependant losses decreases.
3. The ultimate limit state is satisfied if the additional non-prestressed steel is added in both tension and compression sides to satisfy the stress requirements, i.e no additional non prestressed steel is required to satisfy the ultimate limit state.
4. It was found that, the recommended span ranges valid for the studied AASHTO sections are less than the allowable ranges according to ACI [4&5], because the truck loading according to the E.S [1], is more conservative than the ACI truck loading.

Thus, it may be concluded that:

a. If the conditions of case (1) are satisfied, the AASHTO girders are suitable for the following span ranges:

- Girder type (IV) for span range from 20 up to 28.0 m;
- Girder type (V) for span range from 26 up to 34.0 m;
- Girder type (VI) for span range from 32.0 up to 38.0 m.

b. If the conditions of case (2) are satisfied, the AASHTO girders are suitable for the following span ranges:

- Girder type (IV) for span range from 20 up to 22.0 m;
- Girder type (V) for span range from 22 up to 26.0 m;
- Girder type(VI) for span range from 26.0 up to 34.0 m.

5. The ultimate shear stress is found to be safe. Then minimum stirrups are provided for case (1). On the other hand, the working shear stress is found to be more than the allowable shear stress.

6. The stress in the prestress tendon f_{ps} decreases as a result of using of non-prestresssed steel.

2. Steel Decks

Similar to the prestressed decks, two critical sections were analyzed. The first one is for moment at mid span, and the other one is for shear near supports. The analysis was carried out for all load patterns, and the output results of SAP90 at the critical sections are listed in tables.

The following points were observed:

1. As the permissible span to depth ratio decreases, the weighs of the required main girders decreases and the relevant moment of inertia increases. For example, the reduction of the own weigh is about 10 % if this ratio equals to 12 instead of 14.
2. The required size of fillet weld between the flanges and the web plate remains minimal for all cases.
3. The factor of safety against web buckling, for cases of pure shear and pure moment, increases as the number of panels increases. For example, the factor of safety equals to 1.8 if one panel is used. On the other hand, the factor of safety in case of pure shear equals to 2.31 and 2.03 for first and second panels, respectively.

3. Reinforced Concrete Box Girder Decks

One critical section at mid span were analyzed including the following:

(a) Transverse Direction: six different sections corresponding to the critical section at mid span were considered, where sections (1) and (2) are at the top slab, sections (3) and (4) are at the webs and sections (5) and (6) are at bottom slab as shown in Fig. (18.a).

(b) Longitudinal Direction: also four different sections were considered, where section (A) at the top slab, sections (B) and (C) at webs and section (D) at the bottom slab as shown in Fig. (18.b).

The analysis was carried out for all load patterns, and the output results of SAP90 program at the critical sections have been studied, for vertical webs (case 7), and for inclined webs (case 8).

The following conclusions can be drawn:

a. Transverse Direction

1. Transverse moments in all sections are nearly constant for all spans under consideration and also for the two studied cases, i.e transverse moments do not depend on the span, since the top slab acts as one way slab over the two webs.
2. The change in the transverse moments when using inclined web plates for all sections is small and can be neglected when the inclination angle with the vertical is small.

b. Longitudinal Direction

1. Generally, the longitudinal moments can be neglected since the top slab acts as a one way slab in the short direction (transverse direction).
2. For case (7), the percentage of the longitudinal tension force in the bottom slab due to dead load w.r.t that due to the total load in the same slab when the span

equals to 20.0 m is about 35.0 %. This value becomes 57.0 % when the span equals to 40.0 m. This is due to increase of the bridge own weight.

3. For case (8), the percentage of the longitudinal tension force in the bottom slab due to dead load w.r.t that due to the total load in the same slab when the span equals to 20.0 m is about 33.0 %. This value becomes 56.0 % when the span equals to 40.0 m.

Thus, the total straining action percentages due to dead load are directly proportional to the span, that is due to the increase of the bridge own weight. On the other hand, the total straining action percentage due to live load is inversely proportional to the span because the rate of live loads straining action increase is less than the rate of dead load straining action increase.

4. For top slab, the main straining action is the compression force along the span. The rate of total ultimate axial compression force increase per 1.0 m increase of the span is equal to 3.80 % and 5.55 % for cases (7) and (8), respectively (relative to span equals to 20.0 m).
5. For bottom slab, the main straining action is the axial tension force along the span. The rate of total ultimate axial tension force increase per 1.0 m increase of the span is equal to 2.70 % and 3.35 % for cases (7) and (8), respectively (relative to span equals to 20.0 m).
6. For web plates, the designed sections can be considered as follows:
   i. Sections at the connection between the web plates and the top slab affected by compression force. The rate of total ultimate axial compression force increase per 1.0 m increase of the span is equal to 5.77 %, and 6.70 % for cases (7) and (8), respectively (relative to span equals to 20.0 m).
   ii. Sections at the connection between the web plates and the bottom slab affected by tension force. The rate of total ultimate axial tension force increase per 1.0 m increase of the span is equal to 6.58 % and 3.25 % for cases (7) and (8), respectively (relative to span equals to 20.0 m).
7. The inclination of the two web plates results in an increase in the total ultimate tension force in the bottom web plate, due to the decrease of its cross section.

Thus, the change of the transverse moments at all sections due to web plates inclination is small and can be neglected, but the changes of the axial compression/tension force, relevant to the moments at the designed sections, are significant and affect the design of some sections. The inclination of the web plates results in increase of the main reinforcement ratios in the longitudinal direction due to the decrease of the bottom slab cross section.

CONCLUSIONS

Several parameters that may affect the choice of the suitable highway bridge relevant to a certain span have been studied using the developed computer programs for analysis and design. Based on the results the following conclusions can be emerge:

(a) Analytical Results

1. By comparing the results obtained from the structural analysis of the prestressed decks, it is clear that, the effect of adding cross girder at mid span is minimal enough to be neglected. The reduction in the total moments is about 1.5 % and 0.1 % in cases of spacing between main girders equal to 2.0 m and 3.0 m, respectively (Cases 3 and 4).

   The percentages of total moments due to dead loads w.r.t total moments are directly proportional to the span. On the other hand the percentages of total moments due to live loads w.r.t total moments are inversely proportional to the span. This is due to the increase of the bridge own weigh, in addition to the fact that, the rate of live load straining action increase is less than the rate of dead load straining action increase. Similar trend is valid also for shearing force.

   Table (2) shows the rate of changes of straining actions for the different cases due to the dead load relative to the total load.

2. In case of reinforced concrete box girder decks the main straining action in the longitudinal direction can be classified as shown in Table (3).

3. In case of reinforced concrete box girder decks, the following conclusions can be drown:
   - i. The inclination of the two web plates results in an increase in the total ultimate tension force in the bottom plate, due to the decrease of its cross section.
   - ii. The transverse moments in all sections are nearly constant for all spans under consideration and also for the two studied cases, i.e transverse moments do not depend on the span, since the top slab acts as one way slab over the two webs.
   - iii. The change in the transverse moments when using inclined web plates for all sections is small and can be neglected, as the inclination angle with the vertical is small.
   - iv. Generally, the longitudinal moments can be neglected since the top slab acts as one way slab in the short direction (transverse direction).

(b) Design Results

1. Although the actual stresses are higher than the permissible ones, the ductility of the section is still within the accepted limits in both cases of prestressed decks with spacing between main girders equal to 2.0 and 3.0 m, respectively (Cases 1 and 2). The stresses through out the transfer stage are less than the allowable stresses at both tension and compression fibers since the computer program for design (PreDP) is developed to keep these conditions true for all cases. On the other hand, the excess stresses than the allowable through out the permanent stage are resisted by using non-prestressing steel.
2. As the span increases, the total calculated percentage of immediate losses increases and the total percentage of time dependant losses decreases in the prestressed decks, due to the increase of the friction losses which take place immediately and directly proportional to the span.
3. The ultimate limit state is satisfied if the additional non-prestressed steel is added in both tension and compression sides to satisfy the stress requirements, i.e no additional non prestressed steel is required to satisfy the ultimate limit state.

4. The recommended span ranges valid for the studied AASHTO sections, in case of prestressed decks, are less than the allowable ranges according to ACI [4&5], because the trucks loading according to the E.S [1], is more conservative than the ACI loading. Thus, it may be concluded that:

a. If the spacing between main girders equals to 2.0 m (in addition to the other conditions of case 1), the AASHTO girders are suitable for the following span ranges:

- Girder type (IV) for span range from 20 up to 26.0 m;
- Girder type (V) for span range from 26 up to 34.0 m;
- Girder type (VI) for span range from 32.0 up to 38.0 m.

b. If the spacing between main girders equals to 3.0 m (in addition to the other conditions of case 2), the AASHTO girders are suitable for the following span ranges:

- Girder type (IV) for span range from 20 up to 22.0 m;
- Girder type (V) for span range from 22 up to 26.0 m;
- Girder type (VI) for span range from 26.0 up to 34.0 m.

5. The stress in the prestress tendon f_{ps} decreases as a result of using of non-prestresssed steel.

6. In case of steel plate girders decks, as the permissible span to depth ratio decreases, the weighs of the required main girders decreases and the relevant moment of inertia increases. The reduction of the own weigh is about 10 % if this ratio equals to 12 instead of 14.

7. For all cases of steel plate girder decks:

(a) The required size of fillet weld between the flanges and the web plate remains minimal.

(b) The factor of safety against web buckling, for both cases of pure shear and pure moment increases as the number of panels increases.

8. In case of reinforced concrete box girder, the change of the transverse moments at all sections due to web plates inclination is small and can be neglected, but the changes of the axial compression/tension forces, relevant to the moments at the designed sections, are significant and affect the design of some sections. In addition, the inclination of the web plates results in increase of the main reinforcement ratios in the longitudinal direction due to the decrease of the bottom slab cross section.

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