Behavior of reinforced concrete box girder bridges with and without intermediate diaphragms

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This paper presents results from an experimental-theoretical study on the behavior of reinforced concrete box girder bridges both within the elastic range of loading and also within the post elastic range of loading up to failure. The experimental program included the fabrication, instrumentation, and testing of four deformable thin-walled reinforced concrete box girder bridge models subjected to eccentric loads. Through the experimental study, the effects of the following parameters were investigated: (i) reinforcement ratio of flanges and webs; (ii) the presence of intermediate diaphragms; and, (iii) the presence of openings in the intermediate diaphragms. For all tested bridge models the initiation of cracks and its propagation was observed and recorded. Vertical deflections, horizontal deflections and steel strains were measured thus load-deflection and load-strain relationships were detected. Also, failure loads and failure modes were observed for all tested bridge models. A finite element model was developed. The model was calibrated using the experimental results. The calibrated finite element model was used to conduct a detailed parametric study on prototype reinforced concrete box girder bridges in order to investigate the validity of the equations presented by the American Association of State Highway and Transportation Officials (AASHTO)for the design of reinforced concrete box girder bridges if used in combination with the standard truck specified in the Egyptian code for calculation of loads and forces in structures and buildings. It was found that the equations presented by the AASHTO code leads to an extremely conservative design in some cases and to an unsafe design in other cases. Therefore, alternative empirical equations were developed for the design of reinforced concrete box girder bridges in the case of applying the standard truck specified in the Egyptian code for calculation of loads and forces in structures and buildings.

يعرض هذا البحث نتائج دراسه معمليه-نظريه عن سلوك الكباري الخرسانيه المسلحه ذات الكمرات الصندوقيه خلال مرحلة المرونه و كذلك في مرحلة ما بعد التشريخ و حتي الانهيار. تضمن البرنامج المعملي صب و تجهيز و اختبار اربعة نماذج كباري خرسانيه مسلحه ذات كمرات صندوقيه تحت تاثير احمال لامركزيه. تم خلال الدراسه المعمليه دراسة تاثير عدة متغيرات مثل نسبة حديد التسليح و وجود كمرات عرضيه متوسطه و كذلك وجود فتحات في تلك الكمرات العرضيه المتوسطه، و قد تم ملاحظة بداية ظهور الشروخ و تتبع تطورها لجميع نماذج الكباري المختبره. تم قياس سهم الإنحناء الراسي و الافقي والإنفعال فى حديد التسليح ومن ثم إيجاد العلاقة بين الحمل وكل من سهم الإنحناء والإنفعال. كذلك تم ملاحظة أحمال الإنهيار وشكل الإنهيار لجميع نماذج الكباري المختبره. تم عمل دراسه نظريه باستخدام طريقة العناصر المحدده، و قد تم كذلك عمل دراسه بارامتريه علي كباري خرسانيه مسلحه ذات كمرات صندوقيه بابعاد حقيقيه. كان الهدف الرئيسي من الدراسه البارامتريه هي مناقشة مدي صلاحية استخدام معادلات المواصفات الامريكيه في حالة استخدامها مع احمال عربات النقل الثقيل القياسيه المنصوص عليها في الكود المصري لحساب الاحمال، و قد وجد ان معادلات المواصفات الامريكيه تؤدي الي تصميم متحفظ جدا في بعض الحالات و تؤدي الي تصميم غير امن في بعض الحالات الاخري. وبناء علي ذلك تم اقتراح معادلات بديله لتصميم الكباري الخرسانيه المسلحه ذات الكمرات الصندوقيه و صالحه للاستخدام مع احمال عربات النقل الثقيل القياسيه و المنصوص عليها في الكود المصري لحساب الاحمال و القوي في الاعمال الانشائيه و أعمال المباني.

Keywords: Box girder, Bridges, Codes of practice, Diaphragms, Load distribution, Openings, Reinforced concrete

1. Introduction

Box girders have evolved into a highly efficient and aesthetically pleasing solution for medium span and long span bridges. As span length increases into the range where dead load dominates, saving in self weight becomes more important. It is here that the efficient use of box section, which possesses considerable flexural and torsional stiffness, permits a reduction in the overall section size with a consequential saving in weight. Box girder bridges are often selected over other possible bridge types because of their pleasing appearance, their shallow depth which is appropriate for cities where headroom is limited, and the ideal space that such type of bridges provide for utilities.

From the structural behavior point of view box girder bridges have desirable load-distribution characteristics and they are adoptable to curved geometric configurations because of their large torsional stiffness. Although economic studies of a limited nature have shown cost advantages of box girder bridges, however it was always found that box configuration is not more economical than other configurations in the case of a short span bridge [1]. Furthermore, maintenance also causes concern with bridge engineers. Although, a smaller percentage of the total box girder bridge surface area is exposed than that in the case of other types of bridges, however there are still un-answered questions about the effects of condensation moisture and leakage of water through the concrete deck.

According to their structural response when subjected to static loads, box girder bridges can be classified into two main categories [2]. The first category includes girders having rigid cross-section. In this case the cross-sectional shape of the bridge does not change when rotated about its longitudinal axis. As an example for bridges falling in this category reinforced concrete box girder bridges having relatively thick walls. In this case the transverse frame action is sufficient to maintain the original cross-section. For this category, the box girder may be analyzed using simple beam theory and St. Venant torsion theory, neglecting the distortional and warping effects.

The second category includes thin-walled box girders. Although the behavior of thin-walled box girders is essentially the same as for thick-walled girders under flexural loading. However, under torsional loading the response of thin-walled girders differs considerably. In this case, the box girder cross-section is deformable and possesses sufficient flexibility to undergo distortion [2]. Furthermore, significant out-of-plane warping deformations occur which invalidate the usual assumption of plane sections and require special consideration.

1.1. Thin walled reinforced concrete box girder bridges

The present trend in reinforced concrete box girder bridges is to use thinner webs and flanges in order to decrease self weight [3]. As a result the significance of warping and distortion increases. Generally, two components of warping displacements arise from torsional loading. The first component is the torsional warping and the second is the distortional warping arising from the distortion of the cross section itself. The stress distribution at a cross section due to torsional and distortional warping stresses has zero longitudinal force resultant and zero moment resultant [4]. These stresses can be represented by four forces called "warping forces". These four forces are equal in magnitude and would cause the same warping displacements as the torsional and distortional warping shear stresses. Furthermore, the distortion of the cross section induces significant forces and stresses under eccentric loading [5]. Such resulting stresses may be of the same order as the longitudinal stresses associated with bending, torsional warping, and distortional warping.

1.2. Effect of intermediate diaphragms in the behavior of reinforced concrete box girder bridges

According to the classification presented above for reinforced concrete box girder bridges it is suggested that intermediate diaphragms are not needed for thick-walled box girder bridges where the bending stiffness of the individual plates is such that distortion is largely prevented by the stiffness of the cross section [6]. On the contrary, in the case of thin-walled box girder bridges the associated distortional and warping effects become significant and the intermediate diaphragms become important. It has long been recognized in aircraft structures that, to prevent distortion, thin-walled torsion boxes should be provided with closely spaced rigid diaphragms.

It has been the practice of design engineers to provide diaphragms in box girder bridges but often the position and strength of these diaphragms has been determined arbitrarily rather than on any well founded basis [6]. The presence of diaphragms in box irder bridges introduce some additional dead load. However, this effect is not likely to be a serious factor in design. For example, in a particular 150-ft span girder consisting of a single box, diaphragms at the mid point and quarter points added a total of 5.5% to the dead weight. A much more serious effect is the disruption and delay which arises in the casting cycle when a diaphragm has to be introduced. For this reason alone, any unnecessary diaphragms should be eliminated.

The guidance given to design engineers in text books and codes of practice regarding the placing of intermediate diaphragms is scanty [6]. Furthermore, the provisions reveal a lack of appreciation to the true action of intermediate diaphragms. Such true action of intermediate diaphragms was recognized by many researchers. It was found that the deformation of the cross-section of thin-walled reinforced concrete box girder bridges give rise to substantial distortion and warping stresses. Interior diaphragms are effective in reducing warping stresses [7]. Another study showed the beneficial effects of intermediate diaphragms in reducing distortion stresses in thin-walled reinforced concrete box girder bridges [8]. The angle of distortion decreases significantly with increasing the number of intermediate diaphragms. The results presented reflect the beneficial effects of intermediate diaphragms in reducing the shear and normal stresses due to distortion, and also in reducing the warping stresses caused by deformation of cross-section under the effect of torsional loads. On the contrary, it was found that intermediate diaphragms are not required for thin-walled skew reinforced concrete box girder bridges [9].

Diaphragms in reinforced concrete box girder bridges are frequently provided with openings in order to allow for removing the formwork from the inside of the box girder. Also, the openings permit bridge inspection and installation of pipes, cable ducts, etc. along the bridge span. It was found [10 and 11] that while diaphragms are subjected to high stresses and forces due to the large loads transmitted to them from the girder webs, they are weakened by the presence of the opening at the location where the stresses are maximum.

1.3. Behavior of reinforced concrete box girder bridges at the ultimate limit state

Most of the investigations found in the literature have concentrated on the behavior of reinforced concrete box girder bridges within the elastic range of loading before concrete cracking. Very little research efforts were directed towards the study of the behavior of such type of bridges within the post-cracking range of loading [12-18]. It was found that the behavior of reinforced concrete box girder bridges becomes significantly different within the post elastic range of loading especially when considering the action of diaphragms. Although intermediate diaphragms had a marginal effect on the behavior of the bridge within the elastic range of loading, it was found that such effect became significant in the post elastic range of loading. These effects can be summarized as follows: (i) the presence of intermediate diaphragms significantly decreases the deformation of the bridge; (ii) the presence of intermediate diaphragms enhances the distribution of forces between webs especially near failure loads; (iii) the thickness and location of diaphragms has a great influence in the bridge behavior; and (iv) the presence of end diaphragms led to a significant decrease in the bridge deformation, an enhancement in the distribution of forces between webs, and a significant increase in the bridge failure loads. Another study presented by Rasmussen and Baker [3] have revealed that distortion can not be ignored when estimating the ultimate capacity of reinforced concrete box girder bridges.

1.4. The required research

As previously mentioned it is obvious that most of the available previous investigations have been directed towards the behavior of reinforced concrete box girder bridges within the elastic range of loading. Very little research efforts were directed towards the study of the behavior of such type of bridges within the post-cracking range of loading. Furthermore, the development of the equations presented in codes of practice for the design of box girder bridges was based on the standard trucks specified in each code. For example, the equations presented by the AASHTO [19] for the design of reinforced concrete box girder bridges were developed based on an analysis of such bridges using the HS standard truck specified by the code. Different standard truck is specified by the Egyptian code for calculation of loads and forces in structures and buildings [20]. However, no equations are presented in any Egyptian code for the design of reinforced concrete box girder bridges. Therefore, it is important to check the validity of the equations presented by different codes of practice for the design of reinforced concrete box girder bridges in the case of applying the standard truck specified in the Egyptian code for calculation of loads and forces in structures and buildings [20].

1.5. The current research

In this paper the behaviour of reinforced concrete box girder bridges was investigated both within the elastic range of loading and also within the post elastic range of loading up to failure. Firstly, an experimental program was conducted. The experimental program included the fabrication, instrumentation, and testing of four deformable thin-walled reinforced concrete box girder bridge models subjected to eccentric loads. Through the experimental study, the effects of the following parameters were investigated: (i) reinforcement ratio of flanges and webs; (ii) the presence of intermediate diaphragms; and, (iii) the presence of openings in the intermediate diaphragms. Secondly, a finite element model was developed. The model was calibrated using the experimental results. Thirdly, the calibrated finite element model was used to conduct a detailed parametric study on prototype reinforced concrete box girder bridges in order to investigate the validity of the equations presented by the AASHTO [19] for the design of reinforced concrete box girder bridges if used in combination with the standard truck specified in the Egyptian code for calculation of loads and forces in structures and buildings [20]. Alternative empirical equations were developed for the design of reinforced concrete box girder bridges in the case of applying the standard truck specified in the Egyptian code for calculation of loads and forces in structures and buildings [20].

2. Experimental program

Four reinforced concrete box girder bridge models were tested in the current experimental program in order to study its behavior over the complete range of loading up to the failure of each bridge model. All tested bridge models were simply supported with a clear span of 4000 mm and a total length of 4100 mm. The cross-sectional dimensions for tested bridge models were chosen in order to develop a thin-walled section. The limits of thin-walled cross-sections for box girder bridges were presented by Rasmussen and Baker [3]. Following such limits the following cross-sectional dimensions were chosen: (i) for simply supported box girder bridges the span length/depth ratio should be in the range of 13, the span length was chosen to be 4000 mm according to the available laboratory space, therefore the depth was chosen to be 320 mm yielding a span length/depth ratio of 12.5; (ii) the width of the bridge models was chosen to be 450 mm yielding a depth/width ratio of 1.41 which follows the limits presented by Rasmussen and Baker [3]; (iii) the wall thickness/flange width ratio should be in the range of 1/10 and the wall thickness/web depth ratio should be in the range of 1/7. Following that the wall thickness was chosen to be 45 mm yielding a wall thickness/flange width ratio of 1/10 and a wall thickness/web depth ratio of 1/7.11. Box girder bridge model 1 (BGB1) was not provided with any intermediate diaphragms. The bridge model was provided with two layers of stirrups diameter 6 mm ordinary mild steel in each flange and web. The spacing of stirrups was 100 mm over the bridge model span. Such spacing was reduced to 50 mm within the first 600 mm near the supports. The longitudinal reinforcement for both flanges and webs also consisted of two layers of 6 mm diameter ordinary mild steel. Fig. 1 shows cross-sectional dimensions and reinforcement details for all tested box girder bridge models. Box girder bridge model 2 (BGB2) was typically the same as bridge model BGB1 except that the bridge was provided with reinforcement 8 mm ordinary mild steel having the same configuration and spacing as previously described for bridge model BGB1. Comparing the test results for box girder bridge models BGB1 and BGB2 shall reveal the effect of reinforcement ratio on the behavior of box girder bridges. Box girder bridge model 3 (BGB3) was typically the same as box girder bridge model BGB2 except that bridge model BGB3 was provided with six equally spaced intermediate diaphragms having a thickness of 50 mm. Comparing the test results for box girder bridge models BGB2 and BGB3 shall reveal the effect of the presence of intermediate diaphragms on the behavior of box girder bridges. Box girder bridge model 4 (BGB4) was also provided with six equally spaced intermediate diaphragms having a thickness of 50 mm. However the intermediate diaphragms in this case were provided with a centrally placed 100 mm x 100 mm opening. Comparing the test results for box girder bridge models BGB3 and BGB4 shall reveal the effect of intermediate diaphragms openings on the behavior of box girder bridges.

The yield strength and ultimate strength of the steel reinforcement used were 280 MPa and 390 MPa, respectively for diameter 6 mm. and were 250 MPa and 400 MPa, respectively for diameter 8 mm. The concrete mix used for all tested box girder bridge models was made using locally produced commercially available ordinary Portland cement type I, locally available natural desert sand, and broken stones having a maximum size of 10 mm. The mix proportions were 1.0 : 1.6: 2.55, respectively by weight. The water cement ratio w/c was kept in the range of 0.4. Control specimens of 150 mm cubes were made from each concrete batch and the average 28-day concrete cube compressive strength f_{cu} ranged between 37 and 42 MPa. All box girder bridge models were tested to failure under the effect of eccentric concentrated load applied at the mid span of each bridge model as shown in fig. 2. The load was applied to the bridge models using a hydraulic jack of 500 kN capacity. The applied load was monitored by means of a load cell. The load was applied in increments of 10 kN until the failure of each bridge model.

Deflections of cross section of box girder bridge models were measured at mid span by means of eight mechanical dial gauges with a travel sensitivity of 0.01 mm. The locations of these dial gauges are shown in fig. 2. Strains in both bottom tension reinforcement at mid span and in vertical stirrups near supports were measured using electrical resistance strain gauges with 10 mm gauge length. For each tested box girder bridge model one strain gauge was attached to the central bottom

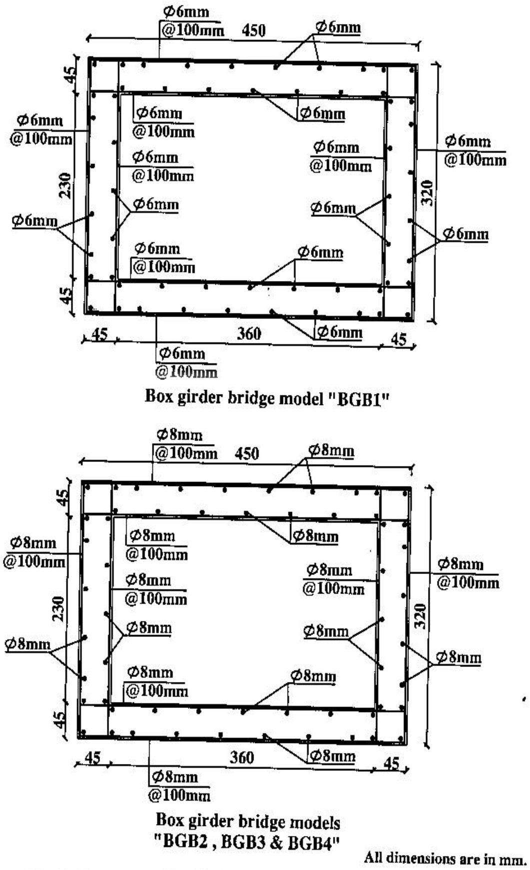


Fig. 1. Cross-sectional dimesions and reinforcement details for tested box girder bridge models.

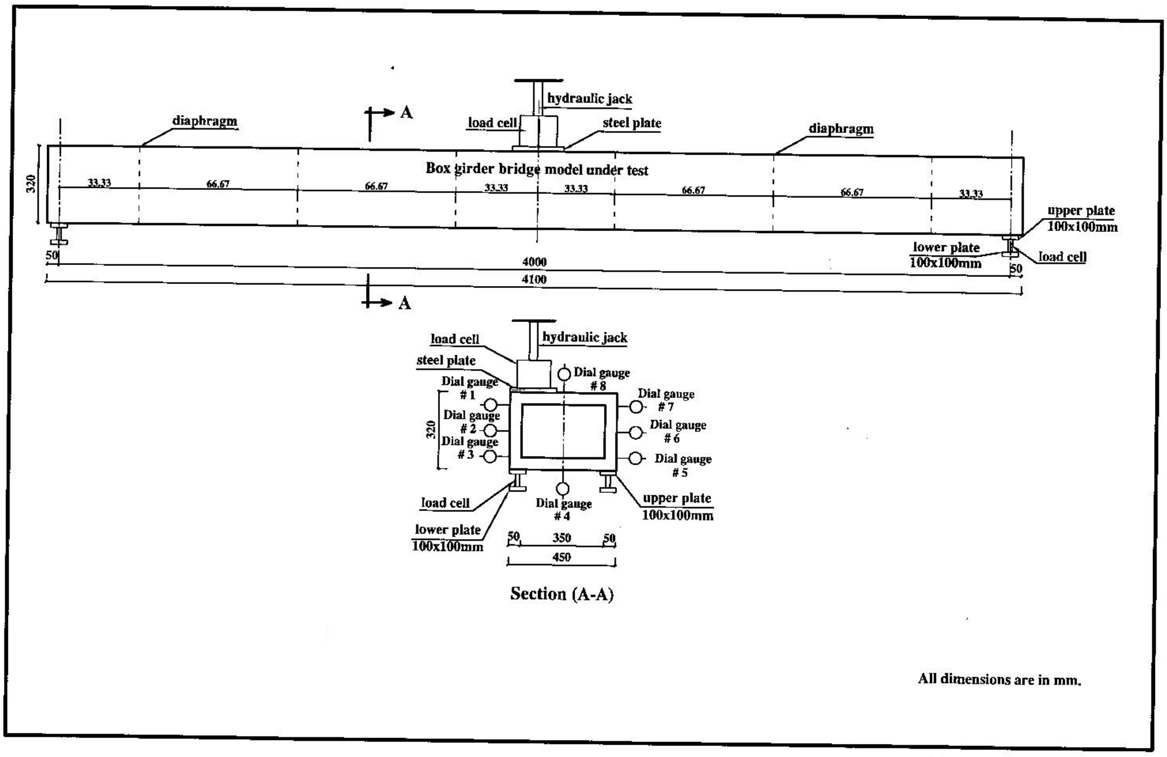


Fig. 2. Loading setup and instrumentation for tested box girder bridge models.

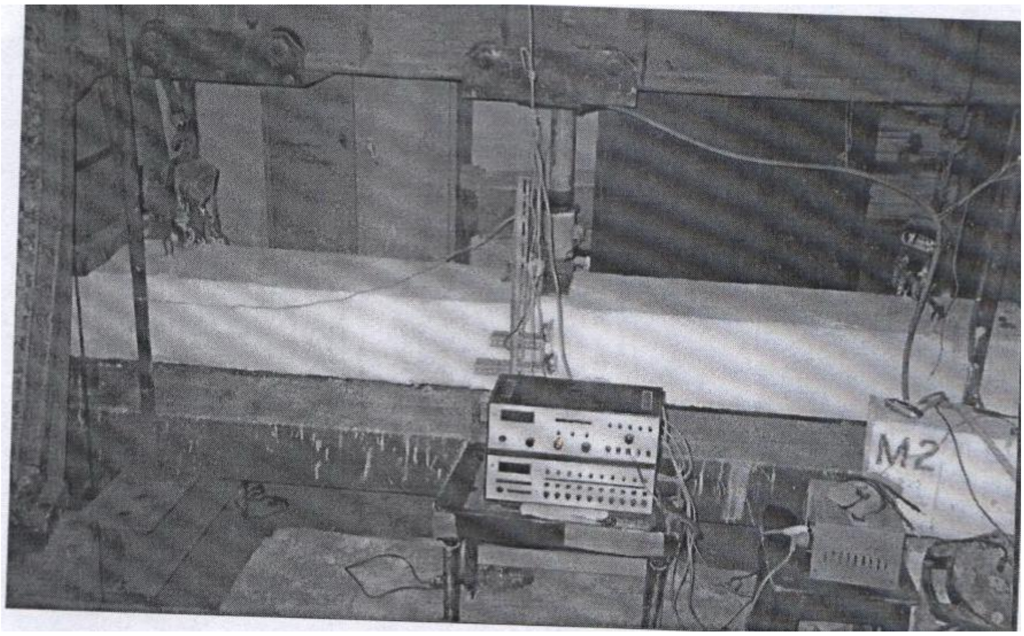


Fig. 3. Loading setup and instrumentation for tested box girder bridge models.

longitudinal bar at mid span. Another strain gauge was attached to the vertical stirrup at a distance 300 mm from the support. Furthermore, support reactions were monitored by means of four load cells each having a capacity of 100 kN as shown in fig. 2. Fig. 3 shows loading setup for one of the tested box girder bridge models.

3. Experimental results and discussions

The experimental results from testing four reinforced concrete box girder bridge models are summarized in table 1. The experimental results included cracking loads, loads at yielding of the longitudinal steel reinforcement, loads at the ultimate strength of steel reinforcement, and failure loads. Table 1 also lists the vertical and horizontal deflections within the elastic range of loading at a load 20 kN as an example. Furthermore, the table lists the vertical and horizontal deflections at failure. Fig. 4 shows load-strain relationships for tested box girder bridge models. Both longitudinal steel strains and transverse stirrups strains are presented. Figs. 5 and 6 show load-deflection relationships for tested box girder bridge models. Both vertical and horizontal deflections are presented. Fig. 7 shows failure modes of tested box girder bridge models BGB3 and BGB4. The effects of reinforcement ratio, presence of intermediate diaphragms, and the inclusion of openings in the intermediate diaphragms on the behavior of thin-walled reinforced concrete box girder bridge models will be discussed in the following sections. Such discussion shall include: (i) vertical and horizontal deflections; (ii) longitudinal and transverse steel strains; (iii) cracking loads and failure loads; and (iv) cracking patterns and failure modes. The effect of reinforcement ratio will be obtained when comparing the results of testing box girder bridge model (BGB1) to those of box girder bridge model (BGB2). Also, the effect of the presence of intermediate diaphragms will be obtained when comparing the results of testing box girder bridge model (BGB2) to those of box girder bridge model (BGB3). Furthermore, the effect of the inclusion of openings in the intermediate diaphragms will be obtained when comparing the results of testing box girder bridge model (BGB3) to those of box girder bridge model (BGB4).

3.1. Vertical and horizontal deflections

The vertical deflection measured on the lower flange of the box girder bridge models was significantly affected by the above mentioned parameters both within the elastic range of loading and also in the post-elastic range of loading up to the failure of the models. Such effects can be summarized as follows: (i) as the reinforcement ratio increased the vertical deflection in the elastic range of loading (at a load 20 kN) decreased from 1.33 mm to 0.95 mm, representing about 28.6% decrease; (ii) however such vertical deflection increased at failure load from 14.0 mm to 18.6 mm, representing a 32.9% increase; (iii) the presence of intermediate diaphragms resulted in a decrease in the vertical deflection in the elastic range of loading (at a load 20 kN) from 0.95 mm to 0.54 mm, representing about 43% decrease; (iv) such vertical deflection decreased at failure load from 18.6 mm to

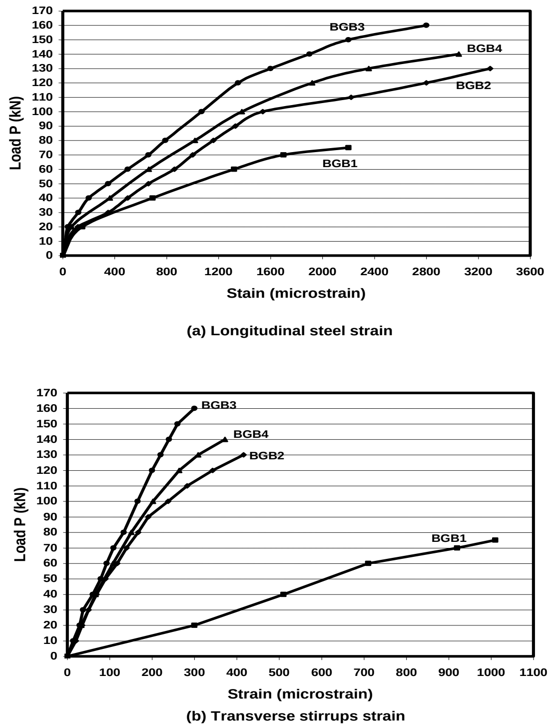


Fig. 4. Load-strain relationship for tested box girder bridge models.

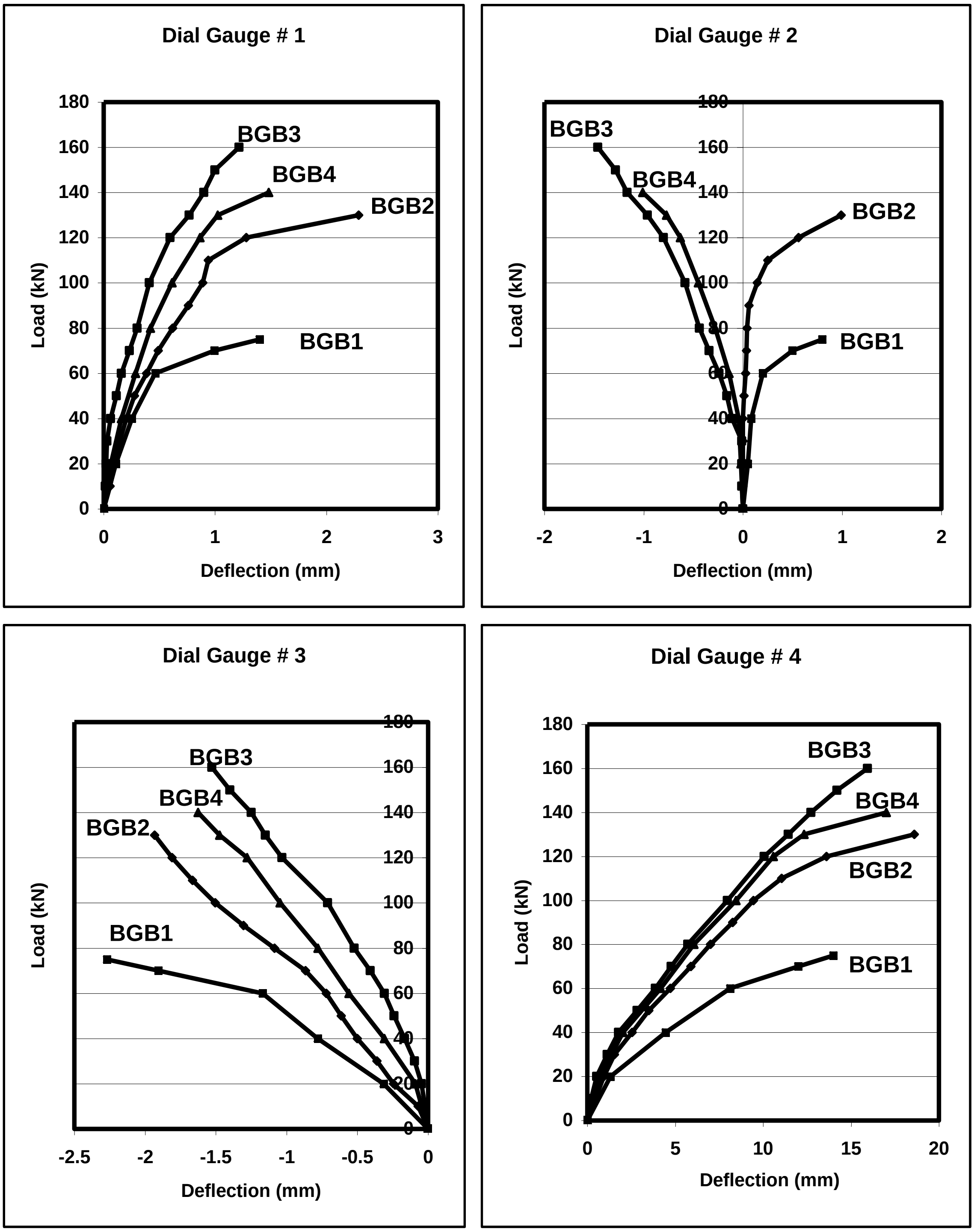


Fig. 5. Load-deflection relationship for tested box girder bridge models (Dial gauges # 1, 2, 3, and 4).

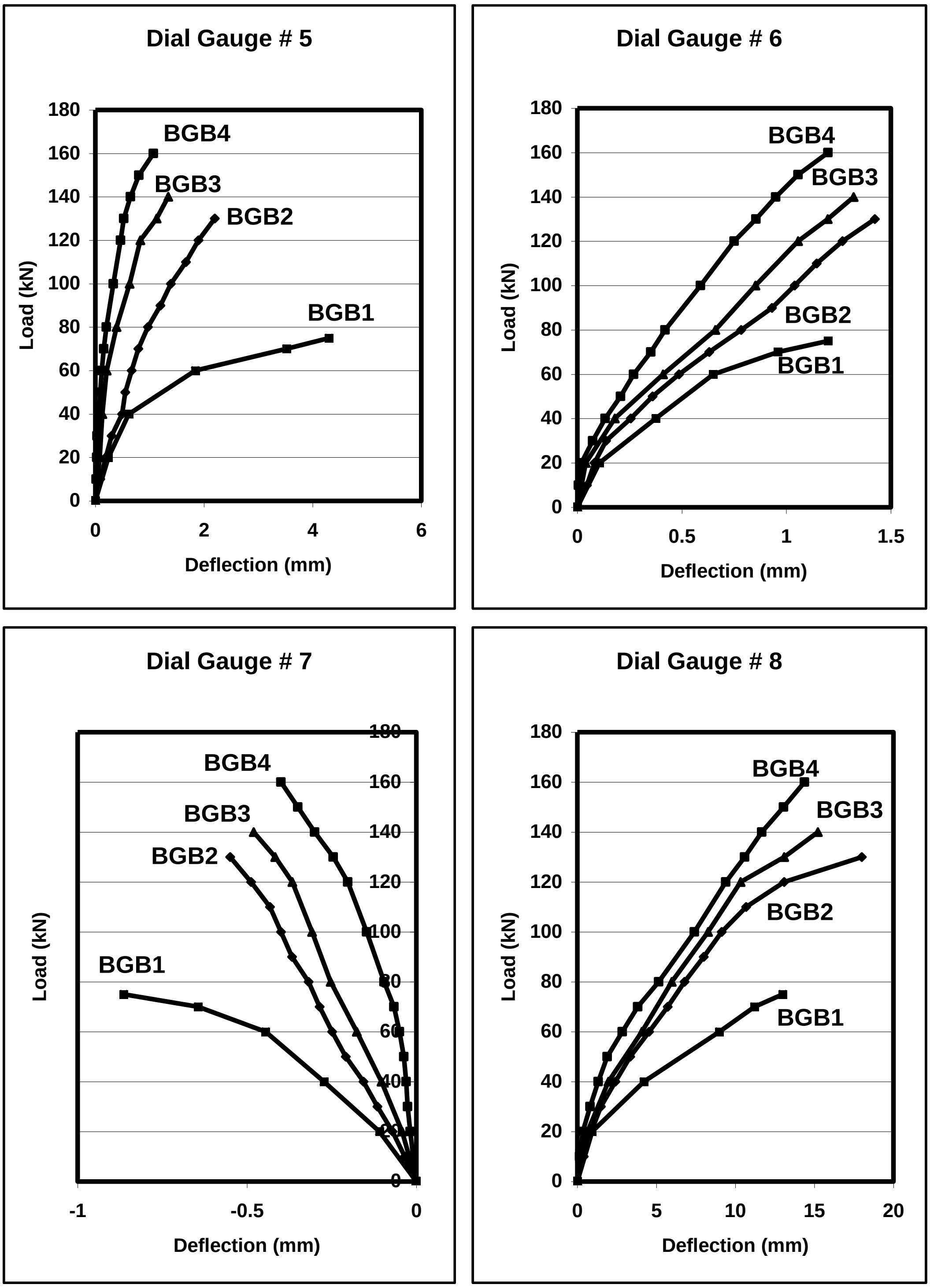
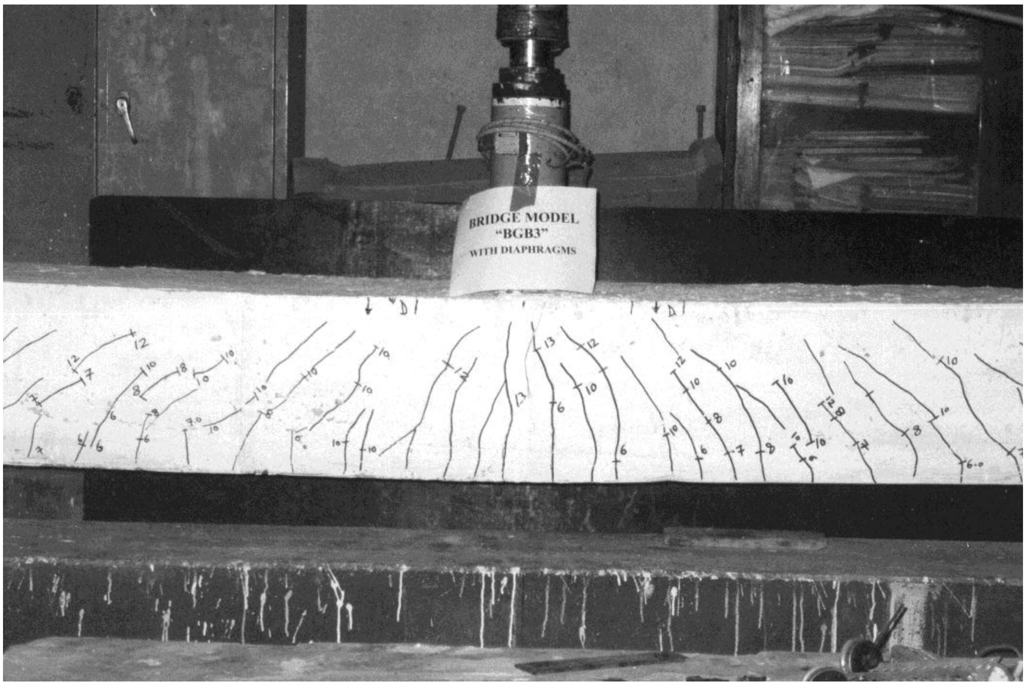
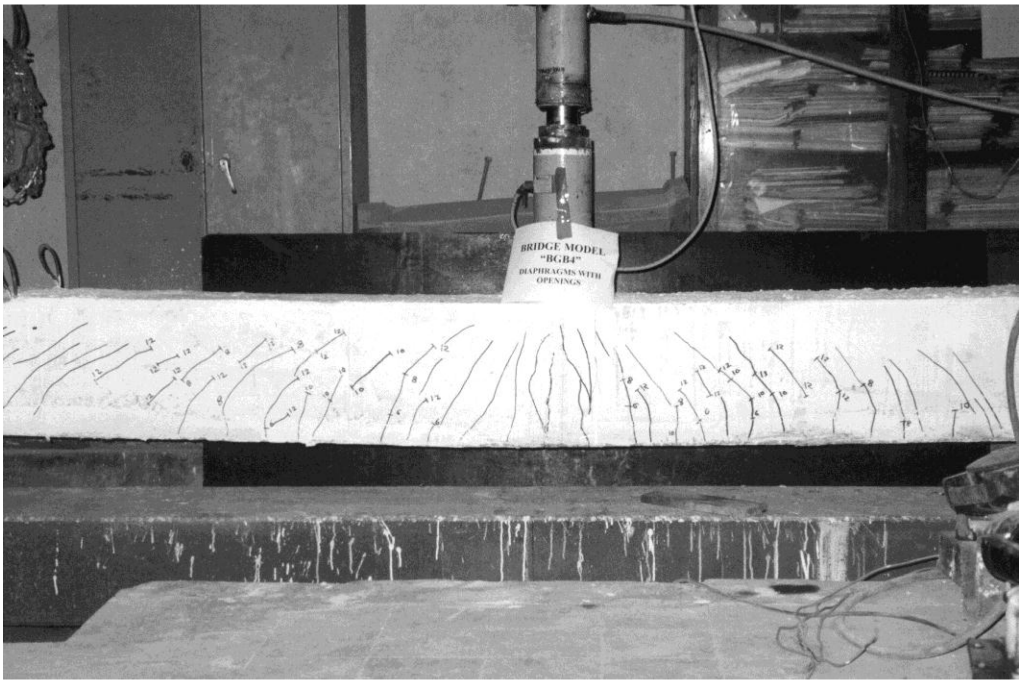


Fig. 6. Load-deflection relationship for tested box girder bridge models (Dial gauges # 5, 6, 7, and 8).



Box girder bridge model (BGB3)



Box girder bridge model (BGB3)

Fig. 7 Cracking patterns for tested box girder bridge models (BGB3 & BGB4).

15.94 mm, representing a 14.3% decrease; (v) the inclusion of openings in the intermediate diaphragms resulted in an increase in the vertical deflection in the elastic range of loading (at a load 20 kN) from 0.54 mm to 0.73 mm, representing about 35% increase; (vi) such vertical deflection increased at failure load from 15.94 mm to 17.0 mm, representing a 6.6% increase. Similar observations can be obtained when examining the values of vertical deflection measured on the upper flange of the box girder bridge models.

The horizontal deflection of all tested box girder bridge models were monitored at the six locations shown in fig. 2. Results for one of these locations are presented in table 1 as an example. It was found that such horizontal deflection was significantly affected by the chosen test parameters both within the elastic range of loading and also in the post-elastic range of loading up to the failure of the models. Such effects can be summarized as follows: (i) the horizontal deflection in the elastic range of loading (at a load 20 kN) decreased from 0.24 mm to 0.19 mm as the reinforcement ratio increased, representing about 20.8% decrease; (ii) such horizontal deflection decreased at failure load from 4.3 mm to 2.2 mm, representing a 48.8% decrease; (iii) the horizontal deflection in the elastic range of loading (at a load 20 kN) decreased from 0.19 mm to 0.03 mm as a result of the presence of intermediate diaphragms, representing about 84.2% decrease; (iv) such horizontal deflection decreased at failure load from 2.20 mm to 1.07 mm, representing a 51.36% decrease; (v) the horizontal deflection in the elastic range of loading (at a load 20 kN) increased from 0.03 mm to 0.08 mm as a result of the inclusion of openings in the intermediate diaphragms, representing about 166.7% increase; (vi) such horizontal deflection increased at failure load from 1.07 mm to 1.34 mm, representing a 25.2% increase.

From the above presented results it can be concluded that increasing the reinforcement ratio leads to a significant reduction in both vertical and horizontal deflections within the elastic range of loading which was expected since such increase in the reinforcement ratio results in a significant enhancement in the bridge stiffness. The increase in the vertical deflection at failure load with an increase in the reinforcement ratio reflects an enhancement in the bridge ductility. Also, it can be concluded that the presence of intermediate diaphragms in thin-walled box girder bridges can control the vertical and horizontal deflections of the bridge both within the elastic range of loading and also within the post-elastic range of loading up to failure. Examining the results presented above one can notice that the presence of intermediate diaphragms is much more effective in controlling the horizontal deflections than that in the case of vertical deflections. This is due to the fact that in the case of thin-walled reinforced concrete box girder bridges the thin web thickness results in significant associated distortional and warping effects. Such distortional and warping effects are minimized as a result of the presence of intermediate diaphragms and therefore lateral deflections decreased significantly.

It was also found that a large portion of the beneficial effects of the inclusion of intermediate diaphragms in controlling vertical and horizontal deflections was lost as a result of the inclusion of openings in such diaphragms. This is in accordance to findings in previous investigations which concluded that the intermediate diaphragms are weakened by the presence of openings especially when placed at the location of maximum stress [10 and 11]. Therefore, it can be recommended herein that design engineers should avoid providing openings in intermediate diaphragms in thin-walled reinforced concrete box girder bridges.

3.2. Longitudinal and transverse steel strains

Examining the load-strain relationships for tested box girder bridge models shown in fig. 4 one can observe the effects of test parameters on the longitudinal and transverse steel strains both within the elastic range of loading and also within the post-elastic range of loading up to failure. It is observed that such effects were much more significant in the post-elastic range of loading than those within the elastic range of loading.

Table 1 presents the loads at which the longitudinal steel reinforcement yielded and also those at which the longitudinal steel reinforcement reached its ultimate strength. The effects of test parameters on those loads can be summarized as follows: (i) as the reinforcement ratio increased the yield load increased from 60 kN to 90 kN, representing about 50% increase; (ii) such increase in the yield load was from 90 kN to 120 kN as a result of the presence of intermediate diaphragms, representing about 33.3% increase; (iii) however such yield load decreased from 120 kN to 100 kN as a result of providing openings in the intermediate diaphragms, representing about 16.7% decrease; (iv) as the reinforcement ratio increased the load at which the longitudinal reinforcement reached its ultimate strength increased from 75 kN to 110 kN, representing about 46.7% increase; (v) such increase in the ultimate load was from 110 kN to 150 kN as a result of the presence of intermediate diaphragms, representing about 36.4% increase ; and (vi) however such ultimate load decreased from 150 kN to 120 kN as a result of providing openings in the intermediate diaphragms, representing about 20% decrease.

It can be concluded that the presence of intermediate diaphragms in thin-walled box girder bridges significantly reduced the longitudinal and transverse steel strains both within the elastic range of loading and also within the post-elastic range of loading up to failure, and therefore enhancing the box girder bridge capacity.

Again it was also found that a large portion of the beneficial effects of the inclusion of intermediate diaphragms in reducing the longitudinal and transverse steel strains was lost as a result of the inclusion of openings in such diaphragms. This supports the recommendation presented above that design engineers should avoid providing openings in intermediate diaphragms in thin-walled reinforced concrete box girder bridges.

3.3. Cracking loads and failure loads

Cracking loads (P_{cr}) and failure loads (P_f) are presented in table 1. for all tested box girder bridge models. Examining the values of cracking loads (P_{cr}) one can observe the following: (i) increasing the reinforcement ratio resulted in a significant increase in the cracking load from 30 kN to 50 kN, representing about 67% increase; (ii) the presence of intermediate diaphragms resulted in a marginal increase in the cracking load from 50 kN to 55 kN, representing only about 10% increase; and (iii) however, providing openings in the intermediate diaphragms resulted in a marginal decrease in the cracking load from 55 kN to 50 kN, representing only about 9% decrease.

Also, the effects of test parameters on the failure loads (P_f) can be summarized as follows: (i) the failure load increased from 75 kN to 130 kN as a result of increasing the reinforcement ratio, representing about 73% increase; (ii) the failure load increased from 130 kN to 160 kN as a result of the presence of intermediate diaphragms, representing about 23% increase; and (iii) the failure load decreased from 160 kN to 140 kN as a result of providing openings in the intermediate diaphragms, representing about 12.5% decrease.

From the above presented results it can be concluded that increasing the reinforcement ratio leads to a significant enhancement in both cracking and failure loads of box girder bridges which was expected since such increase in the reinforcement ratio results in a significant enhancement in the bridge stiffness. Also, it can be concluded that the presence of intermediate diaphragms in thin-walled box girder bridges has only a marginal effect in enhancing the cracking loads of such bridges. However, the presence of intermediate diaphragms has a significant effect in enhancing the failure loads of thin-walled box girder bridges.

Furthermore, the beneficial effects of the inclusion of intermediate diaphragms in enhancing the failure loads of thin walled box girder bridges was not significantly affected in the case of the inclusion of openings in such diaphragms.

3.4. Cracking patterns and failure modes

It was found that the chosen test parameters did not affect the cracking patterns and failure modes for tested box girder bridge models. The reinforcement ratio does not affect the cracking pattern and failure mode of thin walled box girder bridges since such pattern and mode was identical for tested box girder bridge models BGB1 and BGB2. Also, providing openings in the intermediate diaphragms of box girder bridges does not change the cracking pattern and failure mode of thin walled box girder bridge models since such pattern and mode was identical for tested bridge models BGB3 and BGB4. However, the presence of intermediate diaphragms significantly affects the cracking pattern and failure mode of thin walled box girder bridges, even if those diaphragms were provided with openings. Box girder bridge models BGB3 and BGB4 failed in a pure bending mode, as a result of the presence of intermediate diaphragms, although such diaphragms were provided with openings in the case of BGB4. In the case of box girder bridge models BGB1 and BGB2, without intermediate diaphragms, it was found that distortion started to influence the failure mode. The larger distortion of the cross section at failure have led to the formation of a longitudinal corner hinge near mid span between the back web and the top flange. It should be noted that such corner hinge was concentrated only around the mid span in the case of box girder bridge model BGB1. However, in the case of box girder bridge model BGB2 such hinge line between the back web and the top flange extended all the way to the quarter span. Furthermore, since the distortion of the cross section in the case of box girder bridge models BGB3 and BGB4 was small as a result of the presence of intermediate diaphragms, such small distortion was not able to create a crushing hinge line at failure. However, in the case of box girder bridge models BGB1 and BGB2, without intermediate diaphragms, the distortion was large enough to create hinge line in the loaded corner at failure. Cracking patterns for box girder bridge models BGB3 and BGB4 are shown in fig. 7.

4. Theoretical study

The development of the equations presented in codes of practice for the design of box girder bridges was originally based on the analysis of such type of bridges under the application of loads from standard trucks specified in each code. For example, the equations presented by the AASHTO [19] for the calculation of the distribution factors for the design of box girder bridges are in the form of:

$$D.F. = \frac{2\,N_L}{N_B} + K\,\frac{S}{L}. \tag{1}$$

$$K = 0.07W - N_L\ (0.10\ N_L - 0.26) - 0.20\ N_B - 0.12. \tag{2}$$

Where: $D.F.$ = distribution factor; N_L = number of traffic lanes; N_B = number of beams; S = beam spacing in feet; L = span length in feet; and W = numeric value of the roadway width between curbs expressed in feet.

The above presented equations were originally developed based on an analysis of box girder bridges using the HS standard truck specified by the AASHTO [19]. Such equations were extensively investigated by several researchers [21]. However, different standard truck is specified by the Egyptian Code for calculation of Loads and Forces in Structures and Buildings [20], as shown in fig. 8. However, no equations are presented in any Egyptian Code for the design of box girder bridges. The use of the equations presented by the AASHTO code [19] in combination with the standard truck specified by the Egyptian Code may sometimes lead to extremely conservative design and in other cases to an unsafe design. Therefore, it is important to check the validity of the equations presented above in the case of applying the standard truck specified in the Egyptian Code for the calculation of Loads in Structures and Buildings [20].

Table 1
Experimental results

Box girder bridge model	Cracking load P_{cr} (kN)	Longitudinal steel reinforcement yield load P_y (kN)	Longitudinal steel reinforcement ultimate strength load P_u (kN)	Failure load P_f (kN)	Deflection (mm)***					
					δ_{4e}	δ_{5e}	δ_{8e}	δ_{4f}	δ_{5f}	δ_{8f}
BGB1	30	60	75	75	1.33	0.24	0.94	14.00	4.30	13.00
BGB2	50	90	110	130	0.95	0.19	0.88	18.60	2.20	18.00
BGB3	55	120	150	160	0.54	0.03	0.35	15.94	1.07	14.37
BGB4	50	100	120	140	0.73	0.08	0.64	17.01	1.34	15.22

***

δ4e = vertical deflection within elastic range at load 20 kN (dial gauge # 4). δ4f = vertical deflection at failure load (dial gauge # 4).

δ5e = horizontal deflection within elastic range at load 20 kN (dial gauge # 5). δ5f = horizontal deflection at failure load (dial gauge # 5).

δ8e = vertical deflection within elastic range at load 20 kN (dial gauge # 8). δ8f = vertical deflection at failure load (dial gauge # 8).

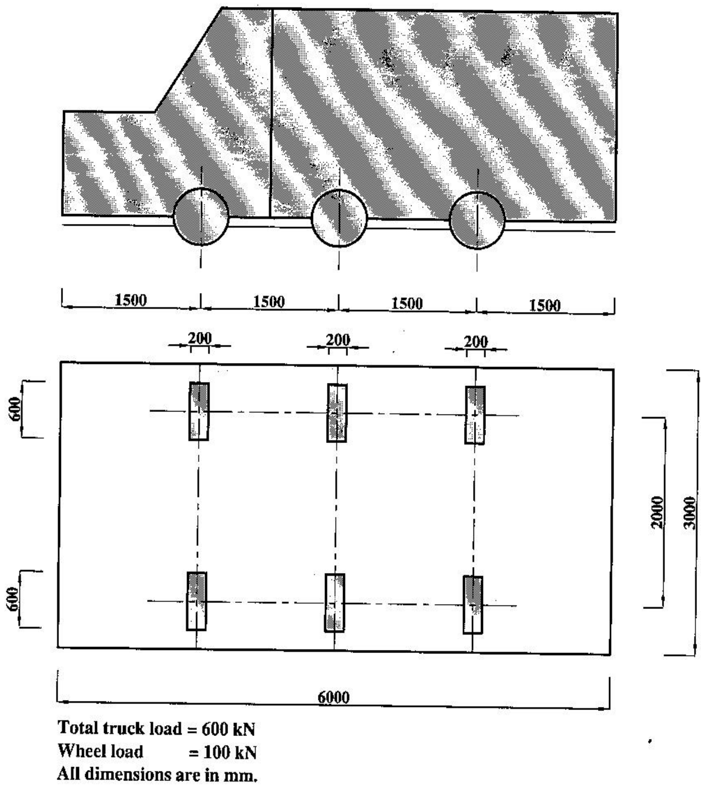


Fig. 8. Comparison of the distribution factors calculated using the AASHTO equation of those obtained from the finite element analysis.

4.1. Parametric study

The theoretical analysis conducted in this paper included a three-dimensional finite element modeling of box girder bridges using a commercially available finite element program. The model was verified and confirmed using results from the current experimental program. The calibrated model was then used to perform an extensive parametric study on prototype box girder bridges. The parametric study conducted in this paper included more than 400 bridge cases. The top flanges, bottom flanges, and webs of the bridges were modeled using four-node shell elements having six degrees of freedom at each node. The parametric study was based on the following main assumptions: (i) all box girder bridges considered in the parametric study are simply supported at both ends; (ii) all materials are elastic and homogeneous; and (iii) the effects of the curbs are ignored. The main objectives of the parametric study were: (i) to check the validity of the equations presented by the AASHTO code [19] for the calculation of the distribution factors of box girder bridges when used in combination with the standard truck specified in the Egyptian code [20]; (ii) to generate a database for load distribution factors for box girder bridges under the application of the truck specified in the Egyptian code [20] including more than 400 bridge cases; and (iii) to develop an empirical formula for the calculation of the load distribution factors for box girder bridges under the application of the truck specified in the Egyptian code [20]. The parameters chosen for this parametric study were: (i) number of traffic lanes; (ii) number of beams; (iii) beam spacing; (iv) span length; and (v) bridge width. The number of lanes considered was two, three, and four lanes with bridge width of 8000 mm for two lane bridges, 12000 mm for three lane bridges, and 16000 mm for four lane bridges. The number of beams considered ranged between four beams and ten beams. The beam spacing ranged between 2000 mm and 3300 mm. The span length ranged between 20000 mm and 50000 mm.

4.2. Results from the parametric study

The results of the parametric study for reinforced concrete box girder bridges showed that the use of the equations presented by the AASHTO code [19] in combination with the standard truck specified by the Egyptian Code sometimes leads to extremely conservative design and in other cases leads to an unsafe design. An example for that is shown in fig. 9 which presents a comparison of the distribution factors calculated using the AASHTO code equations to those obtained from the current finite element analysis under the application of the standard truck specified in the Egyptian code for the calculation of Loads in structures and buildings [20]. Examining the results presented in the figure one can observe the following: (i) the results of the AASHTO code equations are extremely unsafe in the case of two-lane reinforced concrete box girder bridges having any number of beams; (ii) the AASHTO code equations becomes more unsafe with decreasing the bridge aspect ratio (span length/width); (iii) the results of the AASHTO code equations are extremely conservative in the case of three-lane and four-lane reinforced concrete box girder bridges having any number of beams; (iv) the AASHTO code equations becomes more conservative with increasing the bridge aspect ratio in the case of three-lane box girder bridges; and (v) the AASHTO code equations becomes more conservative with decreasing the bridge aspect ratio in the case of four-lane box girder bridges.

Based on the data generated from the parametric study, conducted in this paper, analyzing more than 400 cases of prototype reinforced concrete box girder bridges, empirical formulas were developed for the load distribution factors, *D.F.*, using a statistical package for best fit. Three formulas were developed for two-lane, three-lane, and four-lane reinforced concrete box girder bridges. The empirical formulas deduced in this paper are in terms of the following significant parameters: (1) number of beams, N_B; (2) beam spacing, S, in meters; and (3) bridge aspect ratio, A_R = span length/width. The empirical formulas deduced in this paper can be presented as follows:

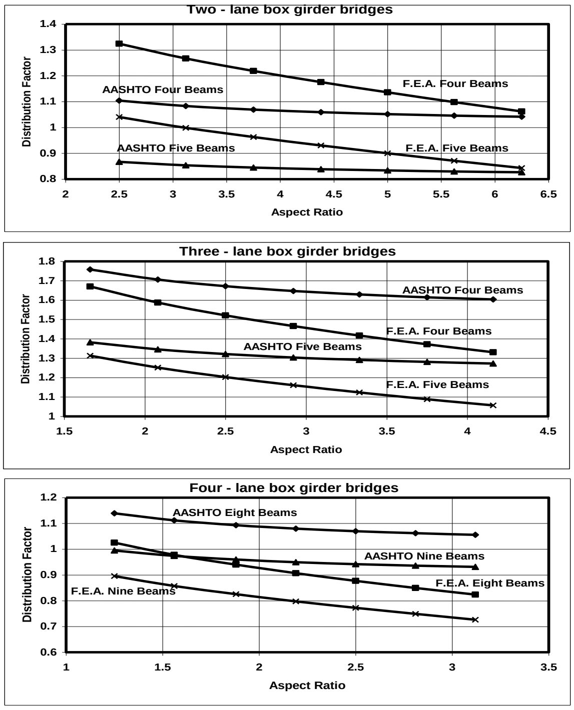


Fig. 9. Comparison of the distribution factors calculated using the AASHTO equation to those obtained from the finite element analysis.

(i) For two-lane reinforced concrete box girder bridges:

$$D.F. = 0.02\, N_B + 0.68\, S - 0.06\, A_R. \quad (3)$$

(ii) For three-lane reinforced concrete box girder bridges:

$$D.F = 0.25 \backslash -0.005\, N_B + 0.51 S - 0.09\, A_R. \quad (4)$$

(III) For four-lane reinforced concrete box girder bridges:

$$D.F = 0.44 - 0.012\, N_B + 0.46 S - 0.17\, A_R. \quad (5)$$

The above presented equations are valid for the design of reinforced concrete box girder bridges when applying the standard truck specified in the Egyptian code for calculation of loads and forces in structures and buildings [20].

5. Summary and conclusions

Detailed literature review was conducted including all previous investigations on reinforced concrete box girder bridges. It was observed that most of the available previous investigations have been directed towards the behavior of reinforced concrete box girder bridges within the elastic range of loading. Very little research efforts were directed towards the study of the behavior of such type of bridges within the post-cracking range of loading. Therefore, the behavior of reinforced concrete box girder bridges was investigated in this paper both within the elastic range of loading and also within the post elastic range of loading up to failure. Firstly, an experimental program was conducted. The experimental program included the fabrication, instrumentation, and testing of four deformable thin-walled reinforced concrete box girder bridge models subjected to eccentric loads. Secondly, a finite element model was developed. The model was calibrated using the experimental results. Thirdly, the calibrated finite element model was used to conduct a detailed parametric study on prototype reinforced concrete box girder bridges in order to investigate the validity of the equations presented by the AASHTO [19] for the design of reinforced concrete box girder bridges if used in combination with the standard truck specified in the Egyptian code for calculation of loads and forces in structures and buildings [20]. Alternative empirical equations were developed for the design of reinforced concrete box girder bridges when applying the standard truck specified in the Egyptian code for calculation of loads and forces in structures and buildings [20]. Based on this study the following conclusions can be drawn:

1. Increasing the reinforcement ratio leads to a significant reduction in both vertical and horizontal deflections of reinforced concrete box girder bridges within the elastic range of loading which was expected since such increase in the reinforcement ratio results in a significant enhancement in the bridge stiffness. The increase in the vertical deflection at failure load with an increase in the reinforcement ratio reflects an enhancement in the bridge ductility.

2. The presence of intermediate diaphragms in thin-walled reinforced concrete box girder bridges can control the vertical and horizontal deflections of the bridge both within the elastic range of loading and also within the post-elastic range of loading up to failure. However, the presence of intermediate diaphragms is much more effective in controlling the horizontal deflections than that in the case of vertical deflections. This is due to the fact that in the case of thin-walled reinforced concrete box girder bridges the thin web thickness results in significant associated distortional and warping effects. Such distortional and warping effects are minimized as a result of the presence of intermediate diaphragms and therefore lateral deflections decreased significantly.
3. A large portion of the beneficial effects of the inclusion of intermediate diaphragms in controlling vertical and horizontal deflections is lost as a result of the inclusion of openings in such diaphragms. Therefore, it can be recommended herein that design engineers should avoid providing openings in intermediate diaphragms in thin-walled reinforced concrete box girder bridges.
4. The presence of intermediate diaphragms in thin-walled reinforced concrete box girder bridges significantly reduced the longitudinal and transverse steel strains both within the elastic range of loading and also within the post-elastic range of loading up to failure, and therefore enhancing the box girder bridge capacity. A large portion of the beneficial effects of the inclusion of intermediate diaphragms in reducing the longitudinal and transverse steel strains was lost as a result of the inclusion of openings in such diaphragms.
5. The presence of intermediate diaphragms in thin-walled reinforced concrete box girder bridges has only a marginal effect in enhancing the cracking loads of such bridges. However, the presence of intermediate diaphragms has a significant effect in enhancing the failure loads of thin-walled reinforced concrete box girder bridges.
6. The beneficial effects of the inclusion of intermediate diaphragms in enhancing the failure loads of thin walled reinforced concrete box girder bridges was not significantly affected in the case of the inclusion of openings in such diaphragms.
7. The reinforcement ratio does not affect the cracking pattern and failure mode of thin walled reinforced concrete box girder bridges without intermediate diaphragms. In this case it was found that distortion started to influence the failure mode. The larger distortion of the cross section at failure have led to the formation of a longitudinal corner hinge near mid span between the back web and the top flange.
8. The presence of intermediate diaphragms significantly affects the cracking pattern and failure mode of thin walled reinforced concrete box girder bridges. In this case the failure mode is a pure bending mode. Furthermore, since the distortion of the cross section in this case was small as a result of the presence of intermediate diaphragms, such small distortion was not able to create a crushing hinge line at failure.
9. Providing openings in the intermediate diaphragms of box girder bridges does not change the cracking pattern and failure mode of thin walled reinforced concrete box girder bridges.
10. The results of the AASHTO code equations for the calculation of the distribution factors when used in combination with the truck specified in the Egyptian code are extremely unsafe in the case of two-lane reinforced concrete box girder bridges having any number of beams. The AASHTO code equations becomes more unsafe with decreasing the bridge aspect ratio (span length/width).
11. The results of the AASHTO code equations for the calculation of the distribution factors when used in combination with the truck specified in the Egyptian code are extremely conservative in the case of three-lane and four-lane reinforced concrete box girder bridges having any number of beams. The AASHTO code equations becomes more conservative with increasing the bridge aspect ratio in the case of three-lane box girder bridges. The AASHTO code equations becomes more conservative with decreasing the bridge aspect ratio in the case of four-lane box girder bridges.

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