Upgrading rectangular and curved reinforced concrete slab bridges using epoxy-bonded carbon fiber reinforced plastic sheets

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There is an urgent need for upgrading existing bridges due to the rapid increase in truck loads in the last few decades. Reinforced concrete slab bridges are one of the most common types of bridges built in Egypt. In this paper, the technique of bonding carbon fiber reinforced plastic sheets (CFRP) using epoxy adhesive is used for upgrading the load carrying capacity (strengthening) of reinforced concrete rectangular and curved slab bridges. The experimental study conducted in this paper included casting, instrumentation, and testing five reinforced concrete slab bridge models subjected to concentrated simulated truck wheel loads in order to evaluate the effectiveness of using such upgrading technique for slab bridges. For all slab bridge models tested the initiation of cracks and its propagation was observed and recorded. Deflections and steel strains were measured. Failure loads and modes of failure were observed for all slab bridge models tested. Furthermore, ductility of tested slabs were evaluated using the ratio of inelastic energy to total energy utilizing load-deflection relationships obtained from the experimental study. Finally, the tested upgraded slab bridge models were analyzed using an elastic-plastic section analysis. Good agreement was observed between the experimental and theoretical results.

إن هناك حاجة ملحة لزيادة حمولة الكبارى القائمة وذلك بسبب التزايد السريع فى حمولة عربات النقل الثقيل فى العقود القليلة الماضية. تعد الكبارى المكونة من بلاطة خرسانية مسلحة أحد أكثر أنواع الكبارى إستخداماً فى مصر. فى هذا البحث تم إستخدام تقنية لصق نسيج كربونى مقوى بإستخدام مادة لاصقة إيبوكسية لزيادة حمولة (تقوية) الكبارى المستطيلة والمنحنيه المكونة من بلاطة خرسانية مسلحة. وقد تضمنت الدراسة العملية التى أجريت فى هذا البحث صب وتجهيز وإختبار خمس نماذج لكبارى مكونة من بلاطة خرسانية مسلحة تحت تأثير أحمال عجلات عربات نقل مركزة وذلك لتقييم مدى فاعلية هذه التقنية فى زيادة حمولة هذا النوع من الكبارى. بالنسبة لجميع نماذج الكبارى المختبرة تم ملاحظة بداية ظهور الشروخ وتطورها مع زيادة الحمل. أيضاً تم قياس سهم الإنحناء والإنفعال. وقد تم تسجيل أحمال الإنهيار وملاحظة شكل الإنهيار لجميع نماذج الكبارى المختبرة. أيضاً تم تقييم ليونة نماذج الكبارى المختبرة عن طريق حساب النسبة بين الطاقة الغير مرنة إلى الطاقة الكلية بإستخدام العلاقة بين الحمل وسهم الإنحناء الناتجة عن الدراسة المعملية. أخيراً تم تحليل نماذج الكبارى المختبرة بإستخدام طريقة تحليل القطاع. وقد لوحظ أن هناك توافقاً بين النتائج المعملية والنتائج النظرية.

Keywords: Carbon fiber, Curved bridges, Epoxy adhesive, Reinforced concrete, Upgrading.

1. Introduction

Upgrading reinforced concrete slabs by gluing steel plates to its tension face have become one of the most common techniques. The method is relatively easy to use and fast. Furthermore, the method can be applied effectively while the structure remains in use. Also, the use of this method minimizes the reduction in the clearance requirements of the structure. Epoxy adhesive bonding provides full interaction between the steel plate and the reinforced concrete slab. However, upgrading reinforced concrete slabs using externally bonded steel plates has several disadvantages [1] such as susceptibility of steel plates to corrosion which reduces the plates strength and destroys the bond between the plate and the epoxy. Another disadvantage of using externally bonded steel plate to upgrade reinforced concrete slabs is that the weight of the steel plate may be excessive in the case of relatively long span slabs.

In recent years fiber reinforced plastic (FRP) plates has found great acceptance as an alternative to steel plates for strengthening (upgrading) reinforced concrete slabs. FRP plates offer the designer an outstanding combination of properties not available from other materials [2]. FRP plates are available made of different materials such as glass fiber

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reinforced plastic (GFRP), carbon fiber reinforced plastic (CFRP) and aramid fiber reinforced plastic. The advantages of using these materials were summarized by Triantafillou [2] as follows: (i) fibers can be introduced in a certain position, volume and direction to obtain maximum efficiency; (ii) lightness; (iii) corrosion resistance; (iv) electromagnetic neutrality; and (v) greater efficiency in construction compared with the more conventional materials. A feasibility study on the use of carbon fiber reinforced plastic (CFRP) sheets in rehabilitation applications was presented by Meier (cited in ref. [2]). It showed that advanced composites can replace steel plates with overall cost savings emanating from the simplicity of the construction method. Recent applications of carbon fiber reinforced plastic (CFRP) plates to strengthen conventionally reinforced concrete bridges in Switzerland were described by Meier (cited in ref. [1]). In one application a 6.2 kg CFRP plate was used in place of a 175 kg steel plate to repair a concrete box girder bridge.

Several investigations have been found in the literature studying flexural strengthening (upgrading) of reinforced concrete slabs using epoxy-bonded steel plates. Ong and Mansur [3] conducted an experimental program on simply supported two-way concrete slabs having externally epoxy-bonded steel plates under a central patch load. They recommended using a double layer of adhesive, in which the first layer is allowed to harden for 24 hours before the second is applied in order to provide adequate bond strength under short term static loads. Lamport and Porter [4] proposed a method for predicting deflections for concrete slabs reinforced externally by steel decking. They used the effective moment of inertia for calculating the instantaneous deflections. Golley [5] reported results of repairing a skew curved slab bridge in Australia where cracking occurred at the obtuse corners of the bridge. The slab bridge was repaired by gluing external steel plates to the soffit of the slab, using epoxy adhesive. The method was successful since constant monitoring since the repair work was carried out in 1993 indicated that further cracking has been prevented.

Many attempts were found in the literature to replace the conventional steel reinforcement with advanced composites in concrete slabs. Michaluk et al. [6] presented test results on the flexural behavior of one way concrete slabs reinforced internally with bars made of glass-fiber, carbon-fiber, and also conventional steel reinforcement under static loading conditions. They concluded that the behavior of FRP reinforced slabs was bilinearly elastic until failure. Stiffness of the slabs reinforced by glass FRP is significantly reduced after the initiation of cracks in comparison to slabs reinforced by carbon FRP or steel bars. Banthia et al. [7] tested concrete plates reinforced internally with FRP grids subjected to transverse impact load. They studied the influence of concrete strength and the use of fiber reinforced concrete. They concluded that plates reinforced with FRP grids failed in a brittle manner and absorb only a third of the energy absorbed by a companion plate reinforced with traditional steel.

Several investigations were found in the literature regarding flexural strengthening (upgrading) of reinforced concrete beams by bonding fiber reinforced plastic plates to the tension face of the beam, [1, 2, 8-11]. The conclusions drawn from these investigations are: (i) the technique of strengthening reinforced concrete beams using fiber reinforced plastic plates is successful since it reduces deflections and increases the load carrying capacity; (ii) reinforced concrete beams strengthened using FRP plates showed brittle behavior and did not demonstrate the yield plateau associated with traditional steel reinforcement, arising the question of ductility; (iii) through proper design FRP plates can develop enough ductility to be utilized as effective concrete reinforcement; and (iv) the bond strength between the FRP plate and the concrete is the most important factor affecting the beam's response.

Comparatively, very little research efforts were directed towards the study of strengthening (upgrading) reinforced concrete slabs using externally bonded FRP plates. Chajes et al. [12] recommended that the concrete surface should be mechanically abraded or sand blasted and a primer should be applied in order to achieve the best possible bond. Also, the surface of FRP plates should be roughened using sand blasting then cleaned with an approved solvent. Mahmoud [13] investigated experimentally the behavior and ultimate flexural strength of one way rectangular concrete slabs reinforced by polypropylene strips with fibers and/or reinforcing bars under uniform load. He concluded that the use of polypropylene strips as strengthening material for plain concrete slabs increases its ultimate capacity by about 4.1 to 10.4 times and by about 2.36 to 2.67 times for reinforced concrete slabs.

There is a rapid increase in truck loads in the last few decades. Sometimes, such truck loads exceed the design loads of existing bridges which were built earlier. Grace et al. [11] reported a 40 % increase in the average bridge service loads in the last few decades. One of the most common type of bridges built in Egypt is reinforced concrete rectangular slab bridges. Also, the employment of horizontally curved bridges has remarkably increased due to the frequent demand for these geometries in modern highway networks. In the case of horizontally curved bridges the flexibility of the longer outer edge increases significantly. Overloading reinforced concrete slab bridges may result in cracking of concrete and spalling of concrete cover which leads to the corrosion of steel reinforcement. Therefore, there is an urgent need for upgrading existing reinforced concrete slab bridges.

In this paper, the technique of bonding fiber reinforced plastic sheets using epoxy adhesive is used for upgrading the load carrying capacity (strengthening) of reinforced concrete rectangular and curved slab bridges. An experimental program was conducted in order to evaluate the effectiveness of using such upgrading technique in the case of slab bridges subjected to concentrated truck wheel loads. The fiber reinforced plastic sheets used were made of carbon .(CFRP). Externally bonded steel plate was used for one of the slab bridge models tested for the sake of comparison. The theoretical study conducted in this paper included the analysis of tested upgraded reinforced concrete slab bridge models using an elastic plastic section analysis. The section analysis performed in this paper is based on the assumptions presented by Ross et al. [1] for predicting the response of rectangular under reinforced concrete beams having a FRP plate bonded to its tension face. However, in the present study the method proposed by Ross et al. [1] was modified to account for the different loading pattern considered in this study and to account for curvature in the case of curved slab bridge models.

2 . Experimental program

The experimental program conducted in this paper included casting, instrumentation, and testing five reinforced concrete rectangular and curved slab bridge models. The main objective of the experimental program was to evaluate the effectiveness of the technique of bonding fiber reinforced plastic sheets using epoxy adhesive as a method of upgrading the load carrying capacity (strengthening) of existing reinforced concrete slab bridges.

Two slab bridge models (S-1 and S-2) were one way rectangular slabs having the same dimensions and reinforcement. The two rectangular slab bridge models had a width of 500 mm, a total length of 1750 mm, a span length of 1600 mm and a thickness of 70 mm. The slab bridge models were supported along the two short sides using a hinged support at one end and a roller support at the other end whereas its two long sides were not supported. The slab bridge models were provided with 6 bars mild steel at the bottom and at the top in the longitudinal direction. The percentage of tension reinforcement μ was 0.0054. It should be noted that such percentage of steel reinforcement was between the upper and lower bounds for an under-reinforced section specified by the Egyptian code [14], (μ_{min} = 0.0046 and μ_{max} = 0.030). However, the percentage of tension reinforcement chosen, μ = 0.0054, was much more closer to the lower bound than the upper bound. This was done in order to clearly evaluate the effectiveness of bonding fiber reinforced plastic sheets. In the transverse direction the slabs were provided with 18 bars of diameter 6 mm mild steel at both the top and the bottom. The yield strength of the steel reinforcement of diameter 6 mm was 235 N/mm^2 and the ultimate strength was 360 N/mm^2.

Three slab bridge models (C-1, C-2, and C-3) were one way curved- in-plan slabs having the same dimensions and same reinforcement. The three curved slab bridge models had a width of 500 mm, a center line total length of 1750 mm, a centerline span length of 1600 mm and a thickness of 70 mm. The three curved slab bridge models had a central angle of 40 degrees and a radius of curvature of 2500 mm. The curved slabs were provided with the same reinforcement as in the case of rectangular slabs. However, this reinforcement was placed in the tangential and radial directions. Figure 1 shows the dimensions of slab bridge models tested. Figure 2 shows the reinforcement details for tested slab bridge models. Table 1. presents summary of details of tested slab bridge models.

The concrete mix used for the tested slabs consisted of locally produced commercially available ordinary Portland cement, type I. Locally available natural desert sand was used as fine aggregate. Crushed stone with 15 mm maximum size was used as coarse aggregate. The mix proportions were 1: 1.8: 3.2 by weight (cement: fine aggregate: coarse aggregate). The water cement ratio w/c was 0.4. Control specimens of 150 mm cubes were casted from each concrete batch and the average cube compressive strength f_{cu} was found equal to 36.5 N/mm^2.

Rectangular slab bridge model S-1 was tested in its original condition without bonding any materials to it. Slab S-1 will serve as a control slab for slab bridge model S-2. Two layers of commercially available high strength carbon fiber reinforced plastic (CFRP) were bonded to the bottom tension face of slab bridge model S-2 using epoxy adhesive in order to upgrade (strengthen) the slab. The two layers of CFRP occupied the complete width of the slab. The first layer had a length of 1450 mm whereas the second layer had a length of 0nly 800 mm, as shown in Figure 3. The CFRP used was in the form of sheets. The sheets were first cut to the required dimensions. Then, a layer of epoxy adhesive mortar composed of two components was applied to the bottom surface of the slab. Following that the CFRP sheets were placed on the bottom surface of the slab on top of the applied epoxy at the required position, then another layer of epoxy mortar was applied on the bottom surface of the slab on top of the CFRP sheets. After that, the second layer of the CFRP sheets was placed on position, then a final layer of the epoxy was applied on the bottom surface of the slab on top of the second layer of the CFRP sheets. The epoxy mortar is completely cured after 50 hours from application.

Curved slab bridge model C-1 was tested in its original condition without bonding any materials to it. Slab C-1 will serve as a control slab for slab bridge models C-2 and C-3. Slab bridge model C-2 was upgraded (strengthened) with one layer of high strength carbon fiber plastic (CFRP) sheets whereas slab bridge model C-3 was upgraded using a 1.5 mm thickness steel plate. Both the CFRP sheets and the steel plate were bonded to the bottom tension surface of the slab bridge models C-2 and C-3 respectively, using epoxy adhesive mortar. Figure 3 shows dimensions of CFRP sheet and steel plate bonded to slabs C-2 and C-3.

The high strength carbon fiber reinforced plastic sheets (CFRP), used for slabs S-2 and C-2, had a tensile strength of 2200 N/mm^2, and a modulus of elasticity of 230,000 N/mm^2. The average value of yield strength for the steel plate used for slab C-3 was 252 N/mm^2, and the average value of the ultimate strength was 362 N/mm^2. The compressive strength, tensile strength, shear strength, and Young's modulus for the epoxy adhesive mortar used was 100, 25, 15, and 12800 N/mm^2, respectively.

All slab bridge models considered in the experimental program were tested under concentrated simulated truck wheel loads as shown in Fig. 1.

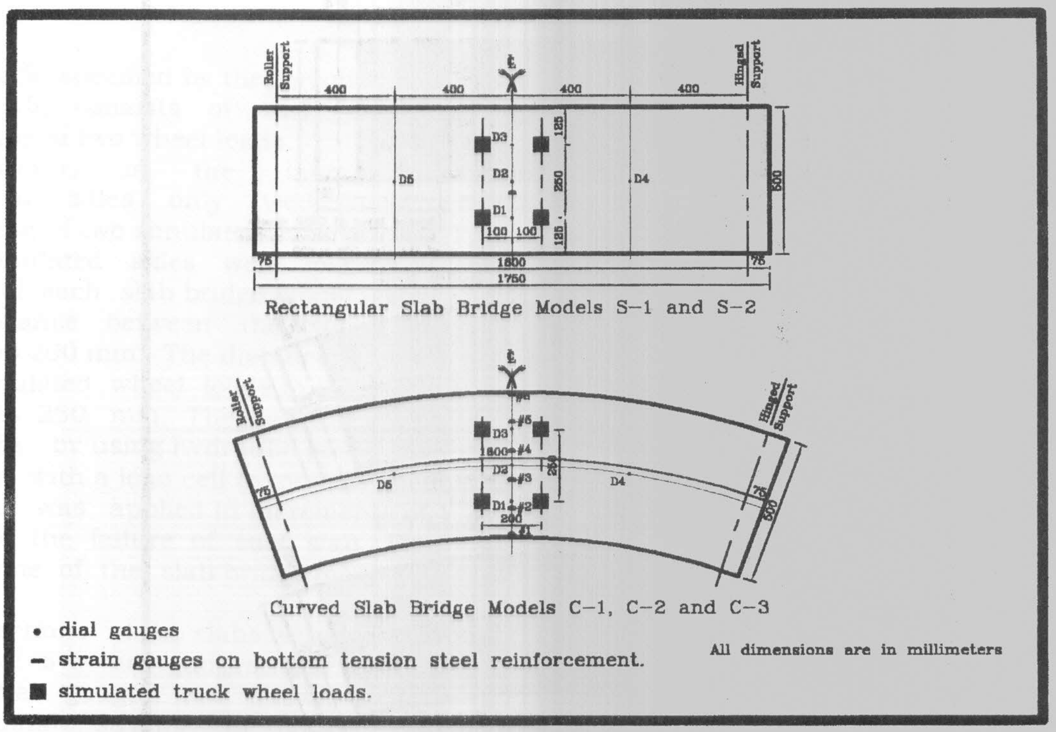


Fig. 1. Dimensions, locations of dial gauges and strain gauges, and loading arrangement for tested slab bridge models.

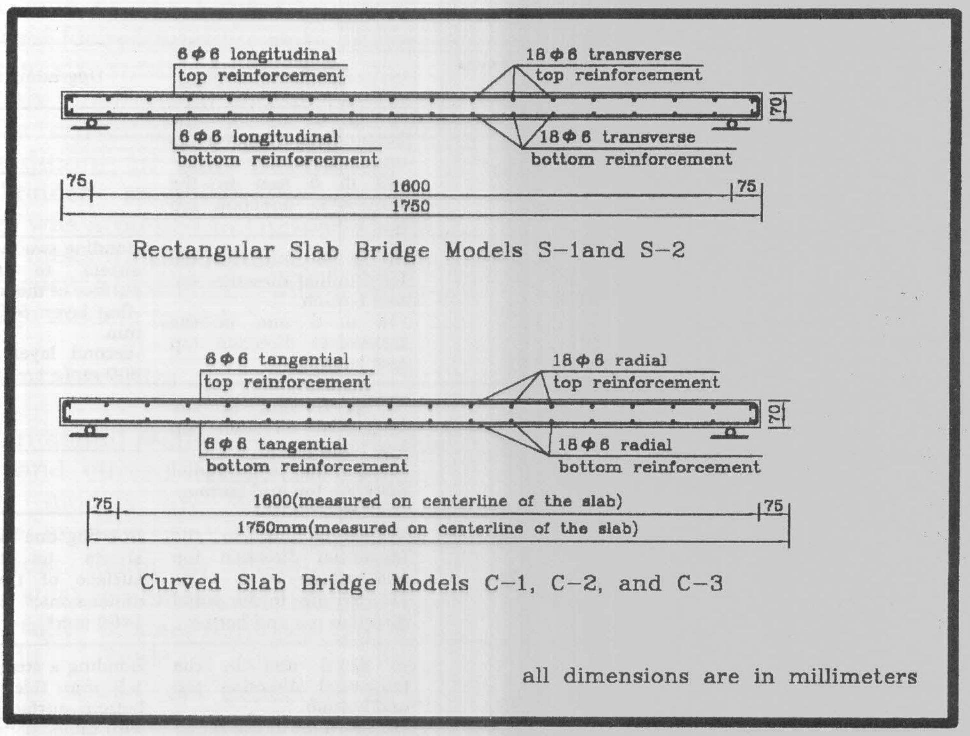


Fig.2. Reinforcement details for tested slab bridge models.

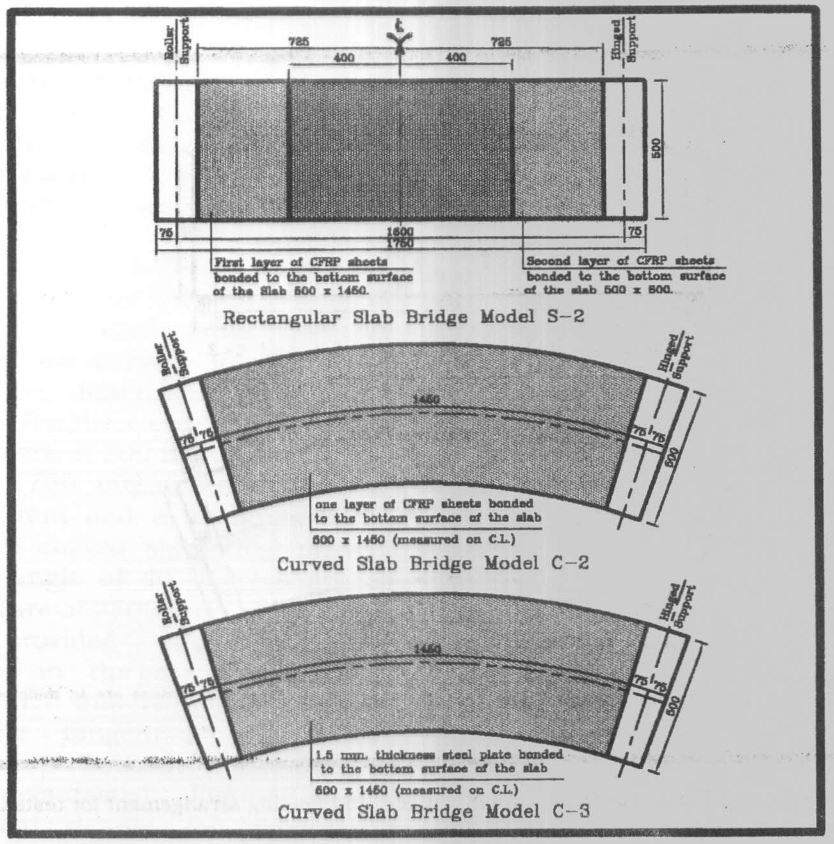


Fig. 3. Upgrading techniques used for tested slab bridge models S-2, C-2, and C-3.

Table 1. Details of Tested Slab Bridge Models.

Slab Bridge Model	Dimensions	Thickness (mm)	Reinforcement	Upgrading technique
S-1	-rectangular. -width = 500 mm. -total length = 1750 mm. -span length = 1600 mm.	70	-6 ф 6 mm in the longitudinal direction top and bottom. -18 ф 6 mm in the transverse direction top and bottom.	------------------
S-2	-rectangular. -width = 500 mm. -total length = 1750 mm. -span length = 1600 mm.	70	-6 ф 6 mm in the longitudinal direction top and bottom. -18 ф 6 mm in the transverse direction top and bottom.	Bonding two layers of CFRP sheets to the bottom surface of the slab. -first layer: 500 mm x 1450 mm. -second layer: 500 mm x 800 mm.
C-1	-curved. -width = 500 mm. -total centerline length = 1750 mm. -centerline span length = 1600 mm. -central angle = 40 degrees. -radius of curvature = 2500 mm.	70	-6 ф 6 mm in the tangential direction top and bottom. -18 ф 6 mm in the radial direction top and bottom.	------------------
C-2	-curved. -width = 500 mm. -total centerline length = 1750 mm. -centerline span length = 1600 mm. -central angle = 40 degrees. -radius of curvature = 2500 mm.	70	-6 ф 6 mm in the tangential direction top and bottom. -18 ф 6 mm in the radial direction top and bottom.	Bonding one layer of CFRP sheets to the bottom surface of the slab with dimensions: 500 mm x 1450 mm*
C-3	-curved. -width = 500 mm. -total centerline length = 1750 mm. -centerline span length = 1600 mm. -central angle = 40 degrees. -radius of curvature = 2500 mm.	70	-6 ф 6 mm in the tangential direction top and bottom. -18 ф 6 mm in the radial direction top and bottom.	Bonding a steel plate with a 1.5 mm thickness to the bottom. surface of the slab with dimensions: 500 mm x 1450 mm*

*The length of curved CFRP sheet or steel plate was 1450 mm measured on the centerline of the sheet or the plate.

The truck specified by the Egyptian code for loads [15] consists of three axles, each consisting of two wheel loads.

However, in the laboratory two simulated axles only were used each consisting of two simulated wheel loads. The two simulated axles were placed at the center of each slab bridge model tested and the distance between the two axles was taken as 200 mm. The distance between the two simulated wheel loads in each axle was taken as 250 mm. The load was applied to the slabs by using hydraulic jack of 200 kN capacity with a load cell to monitor the load. The load was applied in increments of 1.25 kN until the failure of each slab. Figure 4 shows one of the slab bridge models under test.

Deflections of the slabs were recorded by means of five dial gauges. The locations of these dial gauges are shown in Fig. 1 Longitudinal strains in bottom tension reinforcement in the slabs were measured by means of electrical resistance strain gauges with 6 mm gauge length. One strain gauge attached to one of the bottom longitudinal bars was used for rectangular slabs (S-1 and S-2) whereas six strain gauges attached to each of the six longitudinal bottom bars were used for the curved slabs (C-1, C-2, and C-3). In addition, for slab C-3 having an externally bonded steel plate one additional strain gauge was attached to such steel plate in order to measure the strain on the plate. Figure 1 presents locations of strain gauges for slab bridge models tested.

3. Experimental results

The experimental results from testing five rectangular and curved reinforced concrete slab bridge models are summarized in Table2. 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 2 also lists the corresponding values of deflection in all loading stages. The energy ratio is presented in Table 2 for all tested slab bridge models, as a measure of the ductility of the slabs. Furthermore, the table presents modes of failure for all tested slab bridge models. Figs.5. and 6 show load-deflection and load-strain relationships, respectively, for tested slab bridge models. Fig. 7 shows load-steel plate strain relationship for slab bridge model C-3, upgraded using externally bonded steel plate. Figures 8 and 9 shows failure modes of slab bridge models.

3.1. Deflections

The values of deflections within the elastic range at a load 1.25 kN are listed in Table 2 for all slab bridge models tested. Comparing the deflections of the slabs in the elastic range of loading revealed the following: (i) the value of elastic deflection δ_e was 0.35 mm for the control rectangular slab S-1; (ii) bonding two layers of CFRP sheets to the bottom tension surface of the slab, rectangular slab S-2, resulted in a significant reduction in the elastic deflection δ_e, from 0.35 mm to 0.26 mm, representing a decrease of about 26%; (iii) curvature of slab, curved slab C-1, increased the elastic deflection from 0.35 mm to 0.43 mm, representing about 23% increase compared to that for rectangular slab S-1. This increase in the value of deflection was due to the increased flexibility of the longer outer edge of the slab; (iv) bonding one layer of CFRP sheets or steel plate having a thickness of 1.5 mm to the bottom tension surface of curved slab bridge models C-2 and C-3, resulted in a significant reduction in the elastic deflection. In the case of slab C-2 the deflection decreased from 0.43 mm, for slab C-1, to 0.35 mm (about 19% reduction) and for slab C-3 the deflection decreased to only 0.19 mm (about 56% reduction).

From the above presented results it is concluded that upgrading rectangular and curved reinforced concrete slab bridges using CFRP sheets or steel plates bonded to the bottom tension surface of the slab can successfully control the deflection of the slabs within the elastic range of loading before cracking of concrete.

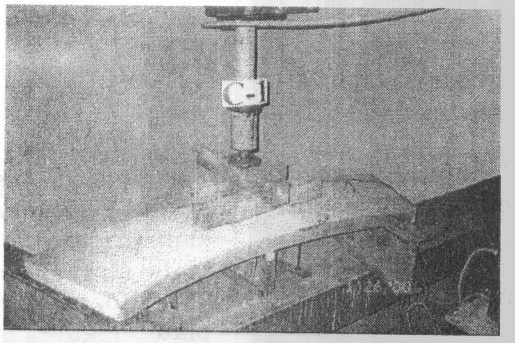


Fig. 4. Loading setup for one of the slab bridge models tested.

The cracking loads were detected only for the un-strengthened slab bridge models S-1 and C-1. The cracking load for the rectangular slab S-1 was 5.0 kN and the corresponding deflection δ_{cr} was 2.0 mm. However, as a result of curvature the cracking load for slab C-1 decreased to 2.5 kN and the corresponding deflection was 0.95 mm. This was due to the increased flexibility of the longer outer edge of curved slab.

The value of deflections corresponding to the loads at which the steel reinforcement yielded δ_y are listed in Table 2. The steel reinforcement yielded at a load P_y = 6.25 kN for rectangular un-strengthened slab S-1 and the corresponding value of deflection δ_y was 3.40 mm. Bonding two layers of CFRP sheets to the bottom tension surface of rectangular slab S-2 resulted in an increase in the yield load and the corresponding deflection. In this case, the yield load was P_y = 16.25 kN and the corresponding deflection was δ_y = 5.83 mm. This means that the deflection at yield load increased by about 71% as a result of bonding two layers of CFRP sheets. This is in contrary to the results from previous investigations on reinforced concrete beams. Results presented by Grace et al. [11] showed that using FRP as strengthening material significantly reduces deflections of beams when compared at yield load.

Curvature of slabs did not affect the yield load and marginally affected the corresponding deflection, as shown in Table 2 for curved slab C-1 compared to the rectangular slab S-1. However, bonding one layer of CFRP sheets and steel plate for curved slabs C-2 and C-3, respectively resulted in a significant increase in the yield load and the corresponding deflection in comparison to the un-strengthened curved slab C-1. The value of yield load for slab C-2 (strengthened by CFRP sheets) increased by 100% and the corresponding deflection increased by 131% in comparison to slab C-1. In the case of slab C-3 (strengthened by steel plate) the yield load increased by about 460% and the corresponding deflection increased by 125%. Similar observations were found for the deflection, δ_u, corresponding to the load at which the steel reinforcement reached its ultimate tensile strength, P_u, as shown in Table 2.

Table 2 also lists the failure loads for tested slab bridge models P_f and the maximum deflections recorded prior to failure δ_{max}. Strengthened slabs (S-2, C-2, and C-3) experienced much larger deflections at failure load than those for the corresponding control un-strengthened slabs S-1 and C-. Furthermore, the strengthened slabs had failure loads much greater than those for the control slabs. The deflections at failure were 19.02 mm and 26.90 mm for the rectangular slabs S-1 and S-2, respectively. This means that upgrading (strengthening) slab S-2 using two layers of CFRP sheets resulted in an increase in the deflection at failure δ_{max} of about 41%. Also, the deflection at failure were 25.80 mm, 35.55 mm, and 11.0 mm for curved slabs C-1, C-2, and C-3, respectively. Therefore, upgrading (strengthening) curved slabs using one layer of CFRP sheets, slab C-2, resulted in an increase in the deflection of the slab at failure, δ_{max}, of about 38%. The deflection at failure of curved slab C-3,

Table 2. Experimental results.

Slab bridge model	Cracking load P_{cr} (kN)	Steel reinforcement yield load P_y (kN)	Steel reinforcement ultimate strength load P_u (kN)	Failure load P_f (kN)	Deflection (mm)					Energy ratio*	Failure mode
					δ_e^a	δ_{cr}^b	δ_y^c	δ_u^d	δ_{max}^e		
S-1	5.0	6.25	8.75	12.50	0.35	2.00	3.40	5.70	19.02	0.77	Flexural
S-2	-------	16.25	17.50	42.50	0.26	------	5.83	6.67	26.90	0.40	Debonding of CFRP sheets at a distance 300 mm from the right support at the end of the second layer.
C-1	2.50	6.25	7.50	11.25	0.43	0.95	3.33	5.69	25.80	0.64	Flexural
C-2	-------	12.50	15.00	35.00	0.35	------	7.70	10.06	35.55	0.34	Rupture of CFRP sheets
C-3	-------	35.00	45.00	45.00	0.19	------	7.47	11.00	11.00	-------	Premature shear failure

[a] : deflection within elastic range at load 1.25 kN.
[b] : deflection at cracking load.
[c] : deflection at yielding of steel reinforcement.
[d] : deflection at ultimate strength of steel reinforcement.
[e] : deflection at failure load.
* : ratio of inelastic energy to total energy at failure.

upgraded using steel plate, was only 11.0 mm. This is due to the fact that the slab failed in a premature shear failure. Fig. 5. shows load-deflection relationships for all tested slab bridge models over the complete range of loading up to the failure of the slabs.

3.2. Strains

The longitudinal steel strains were greatly affected by bonding CFRP sheets or steel plates to the bottom tension surface of rectangular and curved slab bridge models tested, as shown in Fig. 6. For the rectangular un-strengthened slab S-1 the steel yielded at a load 6.25 kN. For the rectangular slab S-2, having two layers of CFRP sheets, the tensile stresses were shared between the internal steel reinforcement and the externally bonded CFRP sheets. Therefore, the steel yield load increased to 16.25 kN, representing an increase of about 160% in comparison to that for the un-strengthened slab S-1.

Furthermore, in the case of the rectangular un-strengthened slab S-1 the steel reached its ultimate tensile strength at a load 8.75 kN, representing about 70% of the failure load of the slab. However, as a result of bonding two layers of CFRP sheets to the bottom surface of slab S-2, such load increased to 17.50 kN, representing about 41% of the failure load of the slab.

Similar observations were found for the effect of bonding CFRP sheets or steel plates on the tangential steel strains in the case of curved slabs. In the case of curved un-strengthened slab C-1 the steel yielded at a load 6.25 kN. For curved slab C-2, upgraded using one layer of CFRP sheets, the steel yield load increased to 12.5 kN, which means about 100% increase in comparison to slab C-1. Also, for curved slab C-3, upgraded using steel plate, the steel yield load increased to 35.0 kN, representing about 460% increase in comparison to C-1.

In the case of curved un-strengthened slab C-1, the steel reached its ultimate tensile strength at a load 7.50 kN, representing about 67% of the slab failure load. However, for curved slab C-2, upgraded using one layer of CFRP sheets, such load increased to 15.0 kN, representing about 43% of the slab failure load.

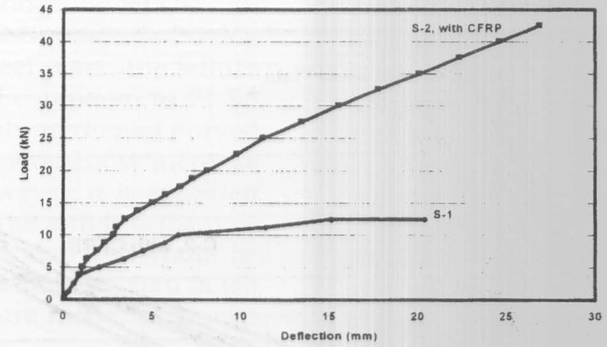
It should be noted that in the case of curved slabs steel strains were measured for all the six tangential bars provided. Results indicated that the strain varies from a bar to another across the width of the slab. The maximum strain recorded was for the bar placed at the most outer longer edge of the slab, strain gauge number 6 in Fig. 1, whereas the minimum strain recorded was for the bar placed at the most inner edge of the slab, strain gauge number 1 in Fig. 1.

3.3. Cracking loads, failure loads, failure modes, and cracking patterns

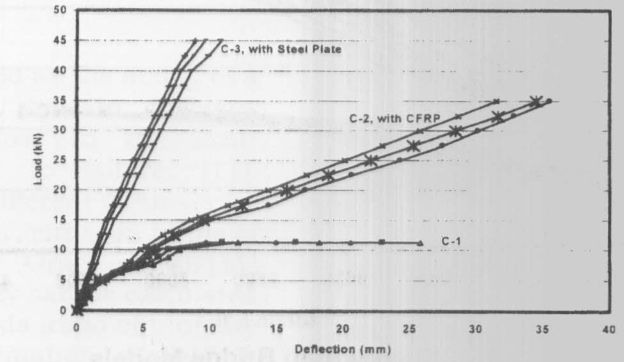
Cracking loads, failure loads, and failure modes are presented in Table 2 for all slab bridge models tested. For the un-strengthened rectangular slab S-1, a transverse crack started at mid span of the slab at a load 5.0 kN. On increasing the load the crack propagated to occupy the complete width of the slab and another two lines of cracks were formed underneath the two axles of the simulated truck. At failure, more lines of transverse cracks were formed within the mid third of the slab span as shown in Fig. 8. Failure of slab S-1 occurred at a load 12.5 kN. The mode of failure of slab S-1 was flexural failure by yielding of longitudinal steel reinforcement followed by concrete crushing. For rectangular slab S-2, upgraded using two layers of CFRP sheets, the failure load increased significantly. In this case the slab failed at 42.5 kN compared to 12.5 kN for the un-strengthened slab S-1. Therefore, bonding two layers of CFRP sheets resulted in a 240% increase in the failure load of the slab. The failure of the slab occurred by debonding of CFRP sheets with some concrete along with the sheets. Debonding of CFRP sheets started from the end of the first layer near the right support and extended to a distance of about 300 mm, at the end of the second layer of CFRP sheets. The failure in this case was brittle and sudden. The failure did not occur at the CFRP sheet-epoxy interface but fracture took place in the concrete cover. The cracking pattern after failure for slab S-2, after the removal of CFRP sheets is shown in Fig. 9. It can be observed that the crack pattern consists of one transverse wide crack across the complete width of the slab at a distance about 300 mm from the right support. It is suggested that this crack occurred at the end of the second layer of CFRP sheets as a result of debonding of the first layer of CFRP sheets.

The cracking load for curved un-strengthened slab C-1 was less than that for the rectangular un-strengthened slab S-1, as a result of curvature, as shown in Table 2. In the case of curved slab C-1 cracks started at a load 2.5 kN at the flexible longer outer edge of the slab. As the load increased cracks propagated towards the inner edge of the slab. At failure, more lines of transverse cracks formed as shown in Fig. 8. The failure load of the slab was slightly affected by curvature. In the case of curved slab C-1 the failure load was 11.25 kN compared to 12.5 kN in the case of rectangular slab S-1. This represents about 10% decrease in the failure load. The mode of failure was not affected by the curvature of the slab. In the case of curved slab C-1, the mode of failure was also flexural by yielding of tangential steel reinforcement followed by concrete crushing.

For curved slab C-2, upgraded using one layer of CFRP sheets, the failure load increased to 35.0 kN, compared to 11.25 kN in the case of the un-strengthened curved slab C-1, representing about 211% increase in the failure load. The failure of curved slab C-2 occurred by rupture of CFRP sheets. The failure in this case was brittle and sudden. Fig. 9 shows the cracking pattern for slab C-2 after the removal of the CFRP sheets.

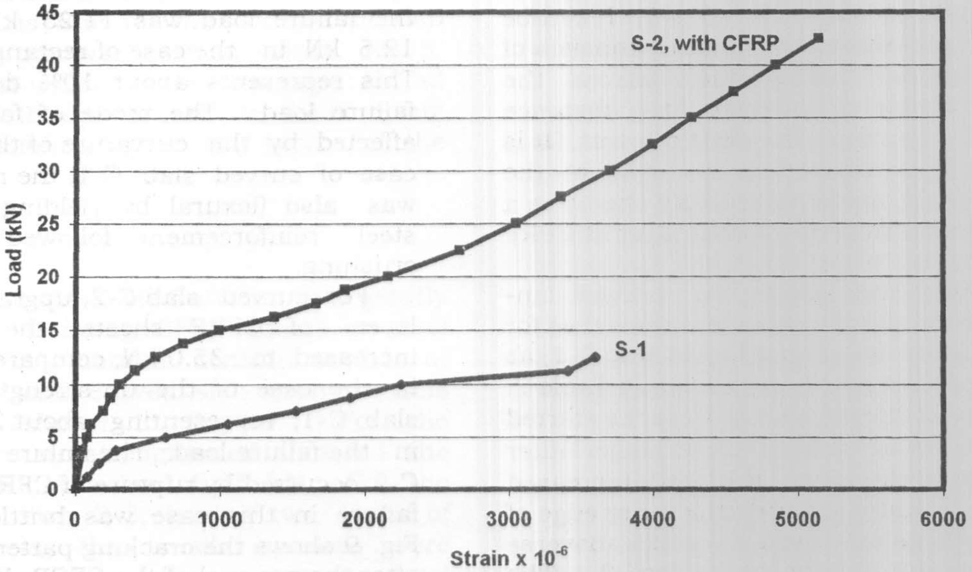


Rectangular slab bridge models

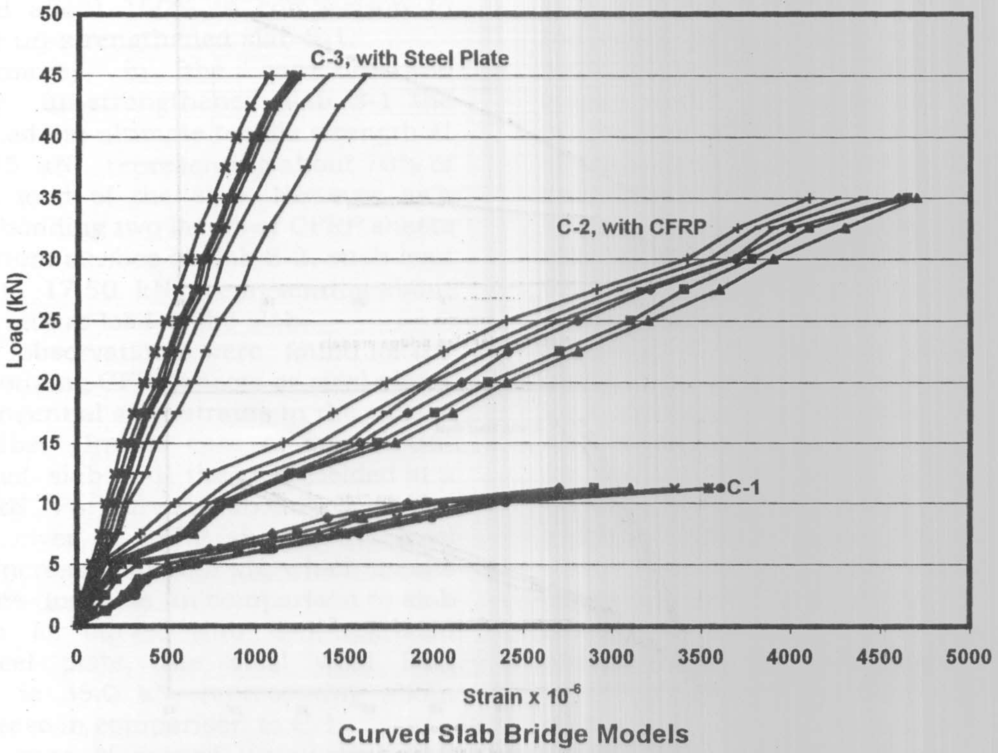


Curved slab bridge models

Fig. 5. Effect of bonding CFRP sheets and steel plates on deflection of tested slab bridge models



Rectangular Slab Bridge Models



Curved Slab Bridge Models

Fig. 6. Effect of bonding CFRP sheets and steel plates on longitudinal steel strain for tested slab bridge models.

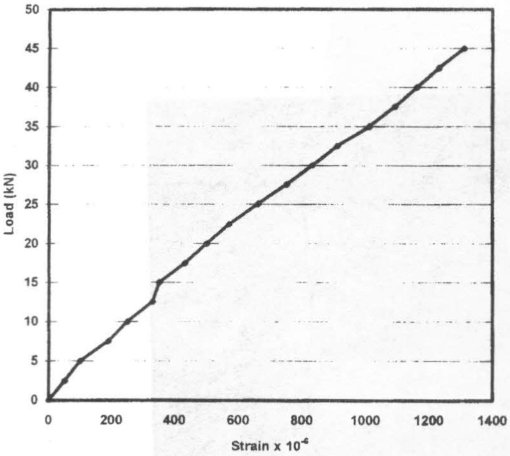


Fig. 7 Load-steel plate strain relationship for tested slab bridge model C-3

Figure 10. shows the rupture of CFRP sheets bonded to slab bridge model C-2. In the case of curved slab C-3, upgraded using a 1.5 mm thickness steel plate, the failure load increased to 45.0 kN compared to 11.25 kN in the case of the un-strengthened curved slab C-1, representing about 300% increase in the failure load. However, it is expected that this percentage of the enhancement in the failure load of curved slab C-3 would be much greater than that since the slab failed in a premature shear failure mode, as shown in Fig. 9.

3.4. Ductility

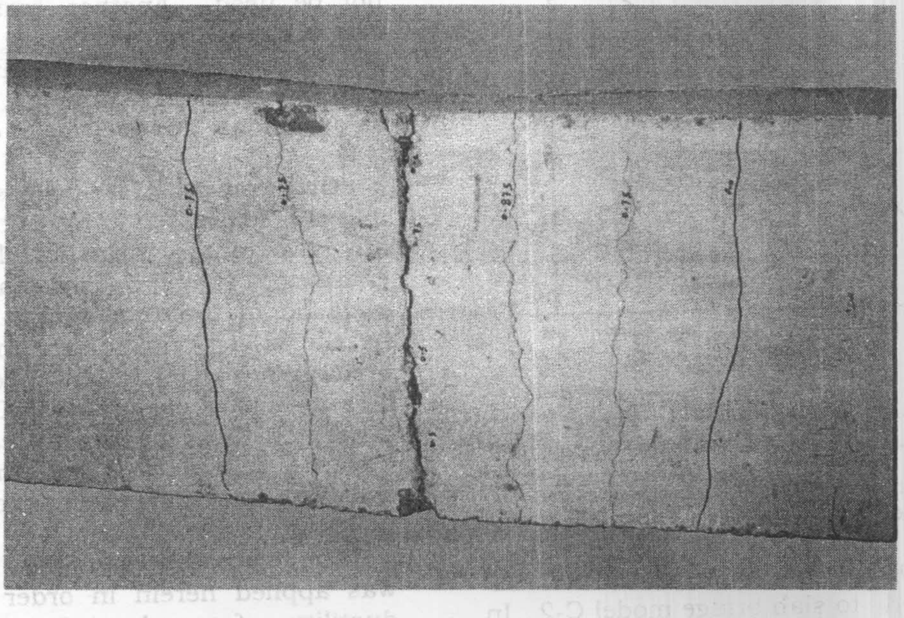
Ductility can be defined as the ability of a structural member to sustain inelastic deformations without loss in the load-carrying capacity prior to failure, [11]. Generally, there is two different methods for the definition of ductility, either in terms of deformations or energy. Grace et al. [11] pointed out that ductility can be calculated using deformation methods (ratio of ultimate deformation to the deformation at yield) in the case of reinforced concrete members where there is a clear plastic deformation of steel at yield. However, there is no clear yield point in the case of members strengthened with FRP and the deformation methods can not be used. Another reason for not using deformation methods is that members strengthened with FRP materials exhibit large deformations. However, these large deformations do not mean ductile behavior, [11].

Grace et al. [11] proposed that ductility may be expressed in terms of a ratio relating any two of the inelastic, elastic, and total energies. They proposed that the ratio of the inelastic to the total energy be considered to be the energy ratio. The total energy is the area under the load-deflection curve which can be easily calculated. Grace et al. [11] presented a method for the calculation of the inelastic energy by calculating the slope of the line separating the elastic energy and the inelastic energy.

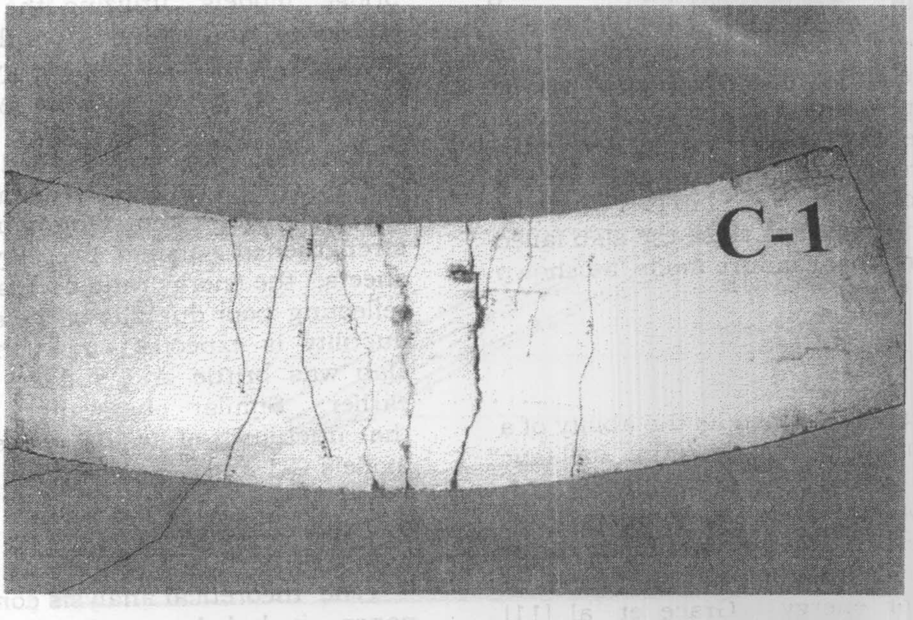
The method presented by Grace et al. [11] was applied herein in order to evaluate the ductility of tested reinforced concrete slab bridge models utilizing the load-deflection relationships obtained from the experimental program. The resulting energy ratios (ratio of inelastic energy to total energy) are presented in Table 2. The energy ratio for the rectangular un-strengthened slab S-1 was 0.77, which reflects reasonable ductility. However, for the rectangular slab S-2, strengthened using two layers of CFRP sheets, the energy ratio decreased to only 0.4 reflecting poor ductility of the slab. This poor ductility is expected since the failure of the slab was brittle and sudden, as mentioned earlier. Similar observations were found for the ductility of tested curved slab bridge models C-1 and C-2, as shown in Table 2.

4. Theoretical analysis

The theoretical analysis conducted in this paper included an elastic-plastic section analysis in order to predict the response of reinforced concrete slab bridges having externally bonded CFRP sheets or steel plates on its bottom tension surface.

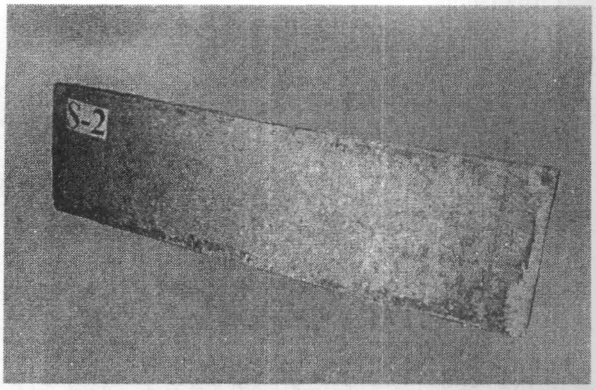


Slab bridge model S-1

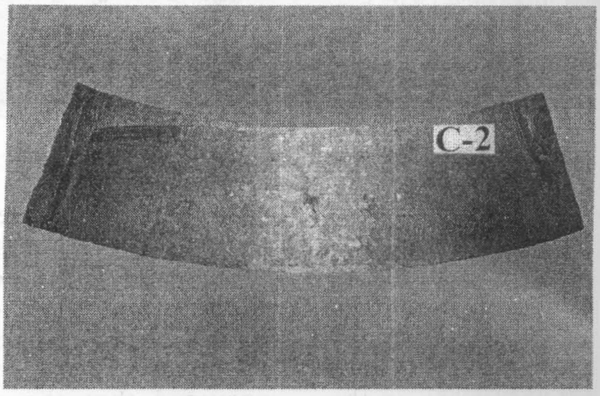


Slab bridge model C-1

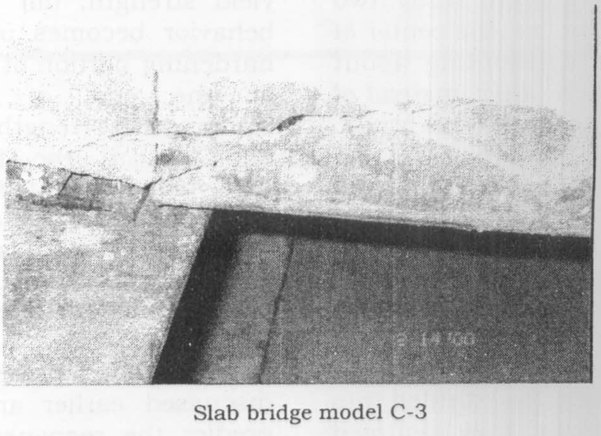
Fig. 8. Cracking patterns for tested non-strengthened slab bridge models.



Slab bridge model S-2



Slab bridge model C-2



Slab bridge model C-3

Fig. 9. Cracking patterns for tested upgraded slab bridge models.

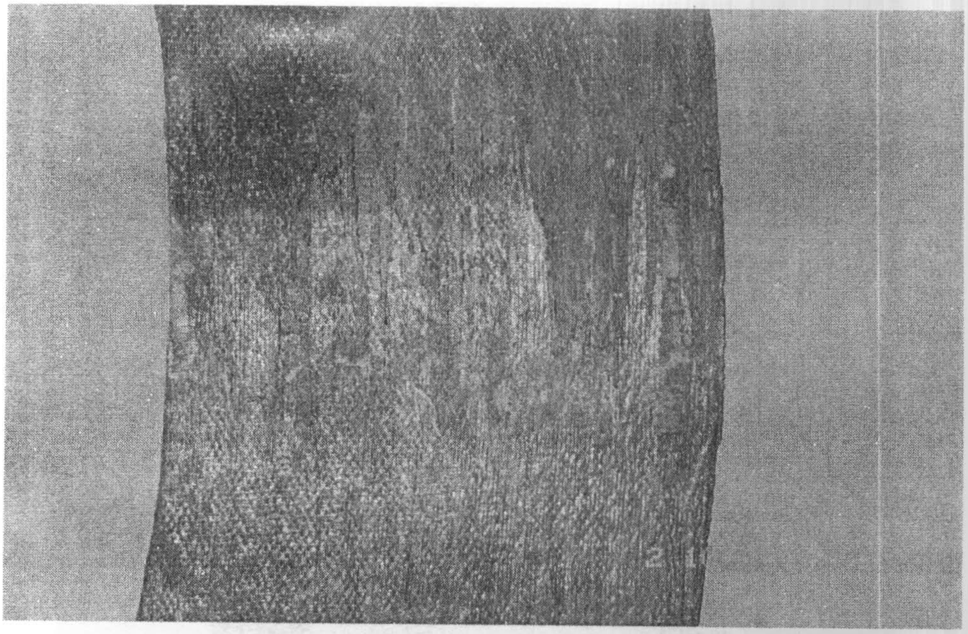


Fig. 10. Rupture of CFRP sheets used for bridge model C-2.

The section analysis conducted in this paper is based on the assumptions presented by Ross et al. [1] for predicting the response of rectangular under reinforced concrete beams having a FRP plate bonded to its tension face, loaded statically in third points bending to failure. However, in the present study the method proposed by Ross et al. [1] was modified. The first modification done was to account for the different loading pattern considered in the current study: two concentrated loads applied at the center of the slab at a distance representing about 0.125 of the span from each other, instead of a distance 0.33 of the span in Ross study. The second modification done was to account for curvature in the case of curved slabs, since it was observed from the current experimental study that curved slabs exhibited greater deflections at the flexible longer outer edge of the slab in comparison to those for rectangular slabs.

Ross et al. [1] suggested that the load-deflection relationship may be divided into four regions. In each region, they assumed that the load deflection relationship is linear. The assumptions made by Ross et al. [1] in each of the four regions are shown in Fig. 11 and can be summarized as follows: (i) in the first region the materials behavior are assumed elastic and at the end of this region the concrete tensile strength reaches the modulus of rupture of concrete; (ii) in the second region it is assumed that the concrete portion below the neutral axis is cracked and therefore it is not effective in bending and at the end of this region the steel reinforcement is assumed to reach its yield strength; (iii) in the third region the steel behavior becomes inelastic reaching the work hardening portion of the stress-strain curve and at the end of this region the concrete compressive strength reaches its ultimate value; and, (iv) in the fourth region the concrete behavior in the compression zone becomes inelastic and it is assumed that the flexural rigidity of the cross section is developed by the CFRP sheets and the tension steel only. At the end of this fourth region failure of CFRP sheets takes place.

The above presented method is modified as discussed earlier and then it was applied to predict the response of tested upgraded slab bridge models S-2, C-2, and C-3.

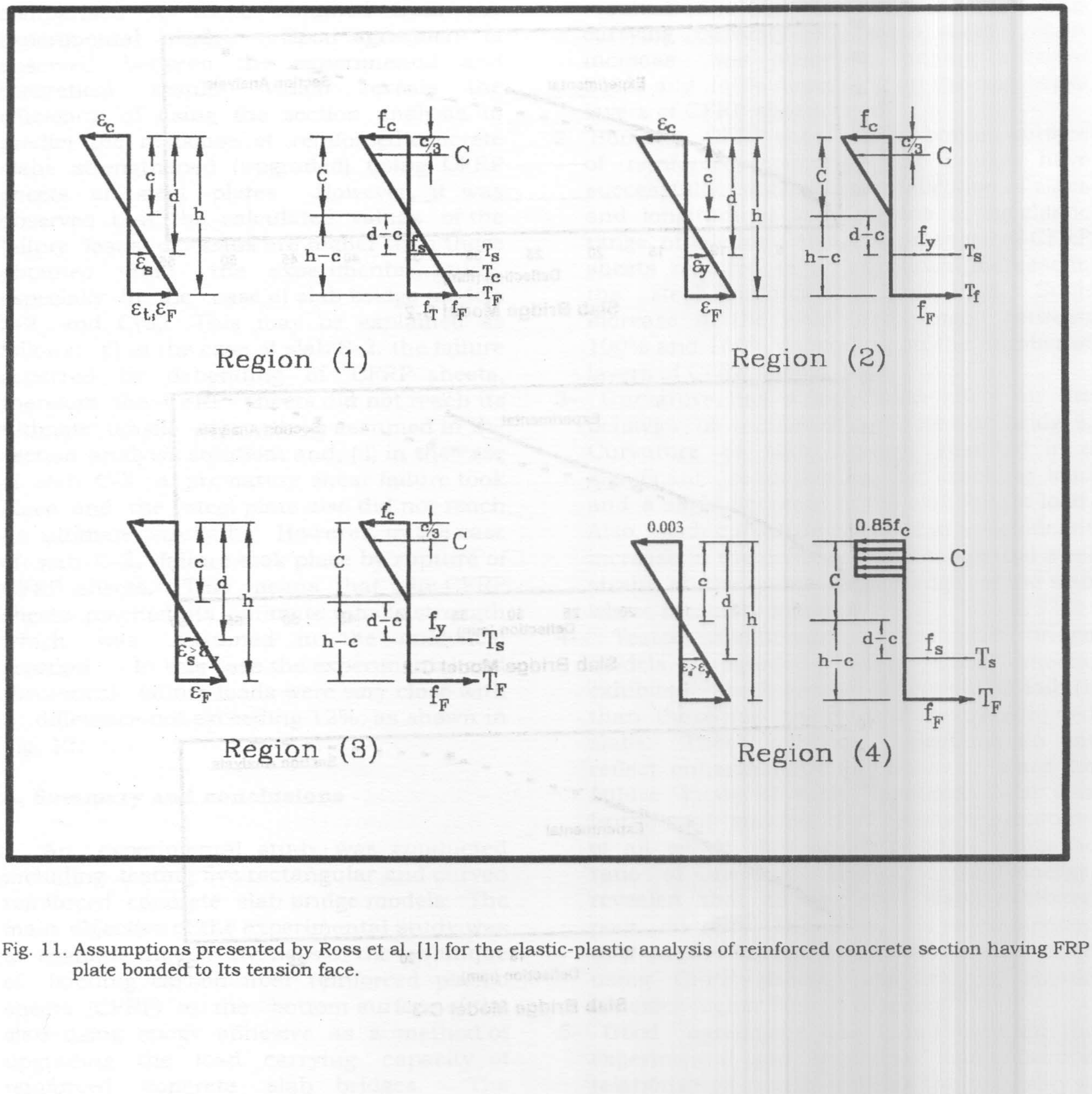
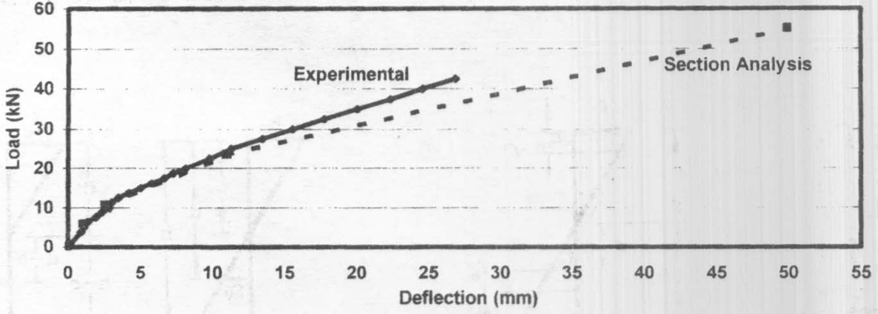
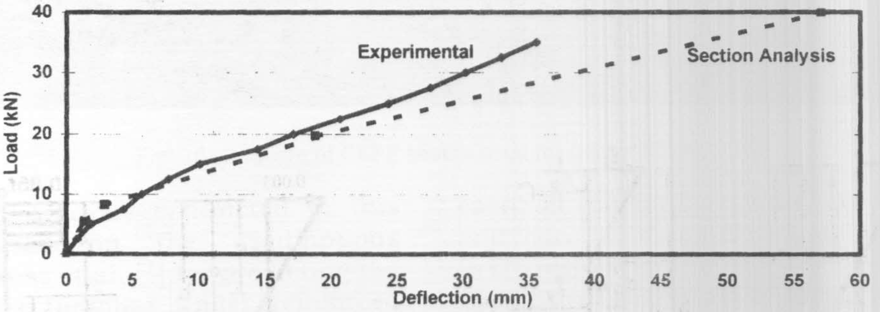


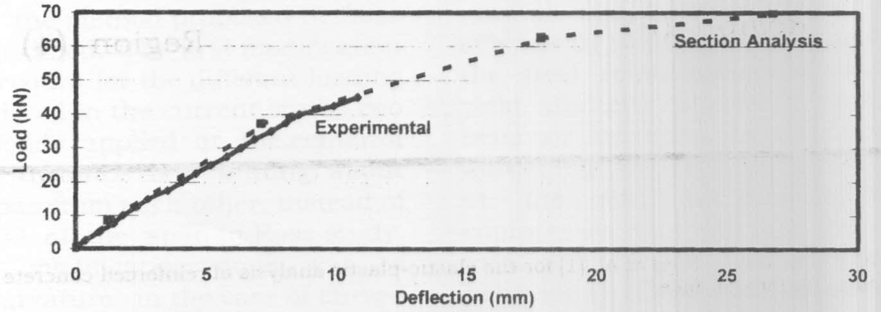
Fig. 11. Assumptions presented by Ross et al. [1] for the elastic-plastic analysis of reinforced concrete section having FRP plate bonded to Its tension face.



Slab Bridge Model S-2



Slab Bridge Model C-2



Slab Bridge Model C-3

Fig. 12. Comparison of experimental deflections to theoretical ones for tested slab bridge models upgraded using CFRP and steel plates

The resulting theoretical load-deflection relationships are presented in Fig. 12 in comparison to those obtained from the experimental study. Good agreement is observed between the experimental and theoretical results which reveals the efficiency of using the section analysis to predict the response of reinforced concrete slabs strengthened (upgraded) using CFRP sheets or steel plates. However, it was observed that the calculated values of the failure loads of slabs are higher than those obtained from the experimental study, especially in the case of slab bridge models S-2 and C-3. This may be explained as follows: (i) in the case of slab S-2, the failure occurred by debonding of CFRP sheets, therefore the CFRP sheets did not reach its ultimate tensile strength as assumed in the section analysis solution; and, (ii) in the case of slab C-3, a premature shear failure took place and the steel plate also did not reach its ultimate strength. However, in the case of slab C-2, failure took place by rupture of CFRP sheets. This means that the CFRP sheets reached its ultimate tensile strength which was assumed in the analytical solution. In this case the experimental and theoretical failure loads were very close with a difference not exceeding 12%, as shown in Fig. 12.

5. Summary and conclusions

An experimental study was conducted including testing five rectangular and curved reinforced concrete slab bridge models. The main objective of the experimental study was to evaluate the effectiveness of the technique of bonding carbon fiber reinforced plastic sheets (CFRP) to the bottom surface of the slab using epoxy adhesive as a method of upgrading the load carrying capacity of reinforced concrete slab bridges. The ductility of tested slabs was evaluated using the ratio of inelastic energy to total energy. The theoretical study in this paper was performed using elastic plastic section analysis. Based on this study the following conclusions can be drawn:

1- The technique of bonding CFRP sheets using epoxy adhesive is effective in upgrading rectangular and curved reinforced concrete slab bridges. Using such technique resulted in a significant increase in the load carrying capacity of tested slabs. Such increase was observed ranging between 211% and 240% depending on the number of layers of CFRP sheets used.

2- Bonding CFRP sheets to the bottom surface of reinforced concrete slab bridges have successfully controlled the deflection of slabs and longitudinal steel strains in the elastic range of loading. Also, the presence of CFRP sheets resulted in a significant increase in the steel reinforcement yield load. Such increase in the yield load ranged between 100% and 160% depending on the number of layers of CFRP sheets used.

3- Curvature has a significant effect on the behavior of reinforced concrete slab bridges. Curvature of slab bridges resulted in a significant reduction in the cracking load and a slight decrease in the slab failure load. Also, such curvature resulted in a significant increase in the deflection and tangential steel strain at the outer longer edge of the slab where flexibility increases.

4- Tested reinforced concrete slab bridge models, upgraded using CFRP sheets, exhibited much greater deflections at failure than those for the control un-strengthened slabs. These increased deflections do not reflect enhanced ductility behavior, since the failure mode of such upgraded slabs was brittle and sudden. Evaluating the ductility of all tested slab bridge models, using the ratio of inelastic energy to total energy, revealed that all upgraded slabs exhibited poor ductility. Therefore, it is recommended that in the design of slab bridges upgraded using CFRP sheets, the designer should consider higher factors of safety.

5- Good agreement was found between the experimental and theoretical load deflection relationships which reflects the reliability of using an elastic plastic section analysis to predict the response of reinforced concrete slabs having externally bonded CFRP sheets at their bottom tension surfaces.

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