A Fundamental Study on Strengthening of Steel Girder Bridge with RC Slab by Using GFRP Members

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Strengthening of concrete or steel structures in situ with externally bonded GFRP (Glass Fiber Polymers) appears to be a promising method to enhance the capacity and the stiffness of existing structures. This paper introduces the feasibility and the efficiency of using GFRP Unit System (GFRP plate, GFRP longitudinal and transverse beams) as unique type of reinforcements for increasing the flexural capacities of steel I-girder bridge with damaged RC slab. Four specimens, each specimen composed of RC slab, two steel I-girder and GFRP unit, were prepared and examined under two kinds of loads (static and fatigue loading), only three of these specimens were reinforced by GFRP unit. Test results for both the stages viz., the pre-cracking stage and the stage after strengthening with GFRP unit and the conclusions based on the experimental and analytical results are presented.

Key Words: *strengthening , rehabilitation, glass fiber polymers, GFRP unit system, damaged RC bridge deck.*

1. Introduction

Use of fiber-reinforced plastics (FRP) in structural constructions has been rather limited compared to that of steel and concrete. It should be emphasized that the use of FRP as a construction material is not intended to replace nor to compete with current conventional materials such as concrete, steel and wood. Some of the attractive and unique feature of FRP are their low specific gravities, high strength-to-weight ratio, durability, resistance to marine environment, toughness particularly at low temperatures, electromagnetic transparency and so on. These unique properties can be used to produce an optimum structural system with minimum maintenance expenses, fabrication and construction time.

In the last decade, the use of FRP composites to reinforce concrete members has emerged as one of the most exciting and promising technologies in materials and structural engineering. There is a wide range of potential applications of FRP reinforcement that covers new construction as well as strengthening and rehabilitation of existing structures.

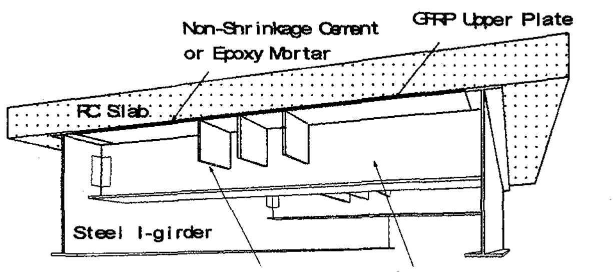

Fig 1. Illustration of Steel I-girder Bridge Retrofitted by GFRP Members.

The justification and motivation for this interest in FRP reinforcement appears to be a worldwide phenomenon with some peculiar geographical connotations. The main stimulant for this study was the decision of the Japanese Road Association in 1993 [1], which increased the maximum truck load of bridges from 196 to 245 kN. Increasing the maximum truck load affects different structural members of the bridges. Enhancing the flexural capacity and stiffness of the bridge members by using steel reinforcements will increase the bridge dead load and will lead to other unexpected problems. In the other hand, using the Carbon Fiber Reinforced Plastics (CFRP) sheets or rods to achieve the required retrofitting for the bridge members will rise up the retrofitting bill and will lead to an economical problems. Therefore, strengthening the structural members of bridges by Glass Fiber Reinforced Plastics (GFRP) seems to be the most appropriate and suitable solution from economical point of view, though its mechanical properties such as strength and stiffness are inferior to CFRP's .

2. Outline of Experiment

2.1 Specimen Types

Four specimens were prepared ; only three of them were reinforced by GFRP unit.

(1) Specimen Type 1 :

The specimen composed of RC slab (2200x1300x100 mm), two steel I-girder (H-steel 350x175x6 mm) with 2000 mm in span length and three steel bars ∅ 35mm,which scaled down to approximately 1/2.5 of the section of an actual steel girder bridges. 22 studs (11 in each longitudinal edge of the RC slab) connected the steel I-girders and the RC slab together, the studs were placed in the holes of the steel I-girders upper flanges then nuts were used to prevent only the slab up-lifting, but not the horizontal slipping. Figure 2 shows specimen Type 1.

(2) Specimen Type 2 :

This specimen had the equivalent steel I-girder and RC slab as Type 1, and also was reinforced by GFRP unit. The gap between the GFRP upper plate and the RC slab, which was 9 mm in thickness, was filled with non-shrinkage cement mortar. Plastic cover was placed between the GFRP upper plate and the non-shrinkage mortar to prevent bonding. The GFRP unit was connected to the steel I-girders in the web holes by 32 steel angles (L45x45x4 mm). Figure 3 shows the specimen Type 2.

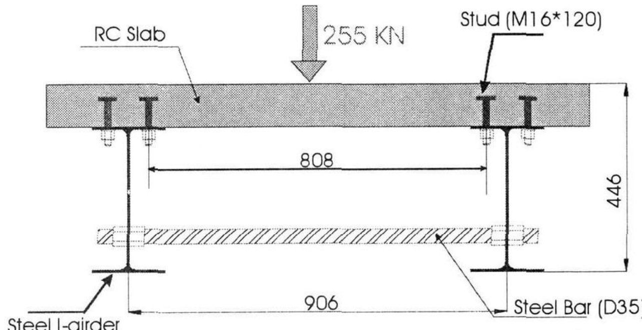

Fig.2 Specimen Type 1 (Unit: mm)

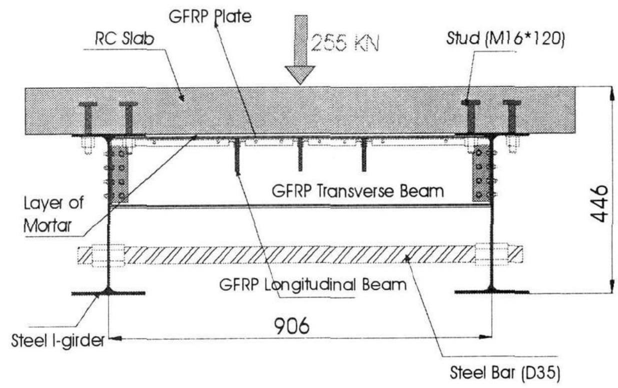

Fig. 3 Specimens Type 2,3 and 4 (Unit: mm)

(3) Specimen Type 3:

Specimen Type 3 is as same as specimen Type 2, the only difference is that the natural bonding was introduced between the GFRP upper plate and the non-shrinkage mortar (Figure 3).

(4) Specimen Type 4 :

There is only one difference between specimen Type 3 and specimen Type 4; it is the use of epoxy mortar to fill the gap between the RC slab and the GFRP plate, instead of using non-shrinkage cement mortar (Figure 3). The thickness of the mortar in specimen types 3 and 4 is the same. Special care was taken during the installation of the GFRP unit to guaranty the good contact with the mortar in specimen Types 3 and 4.

2.2 Material Properties

(1) GFRP Unit:

The GFRP trade mark is PURAAROE®- HR 165. Tension, compression, shear and joint tests were carried out for better knowledge of the GFRP properties. A summery of the GFRP material properties is presented in Table 1 [2),3)] . where the nomination MD and TD represent the glass fibers direction and the fibers perpendicular direction respectively, as shown in Figure 4.

The GFRP unit is composed of upper plate , 8 transverse beams and 3 longitudinal beams. Figure 5 shows the GFRP unit details. The upper plate is

2000x900x3 mm, the length of the transverse beams is 900mm,while their sections are T-shaped 150x75x4 mm , the length of the longitudinal beams are 2000 mm and their rectangular sections are 78x8 mm in size.

(2) RC Slab and Steel Girder

Four identical RC slabs were prepared to be the concrete decks of the test specimen. The slab depth was 10 cm. The slab was reinforced with D10 steel bars spaced at 110 mm and 150 mm in the longitudinal and transverse directions respectively. The used D10 bars had yield strength of 343.4 MPa. The concrete compressive strength was 29 MPa at 7 days and 33.3 MPa at 28 days. Full details about the concrete compressive and flexural test results are presented in Table 2.

Two identical steel I-girders were used in each test structure or specimen, whose size was H350x176x6 mm with 2300 mm in length. The steel of the girder had yield strength 245 MPa specified in Japanese Industrial Standard.

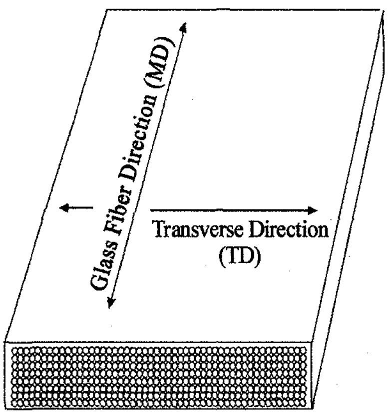

Fig.4 Glass Fiber

2-3 Loading Procedure

(1) Specimen Type 1

Specimen Type 1 was loaded statically in the center of the RC slab with 255 kN, the loading plate was 48x48x5 cm in size. This load caused stress in the main steel reinforcing bars approximately equal to 196 MPa , which exceeded the allowable stress (137 MPa) for steel reinforcement. Also the maximum width of the concrete cracks was 0.2 mm, which approximately equal to the maximum allowable crack width of the concrete in the Japanese standard. Fatigue loading was then applied to cracked specimen for half a million times with a load range (59-255) kN.

2) Specimen Types 2,3 and 4

Virgin specimen Types 2,3 and 4 (Virgin specimen is a specimen not reinforced by GFRP unit) were loaded following the same procedure of specimen Type 1.

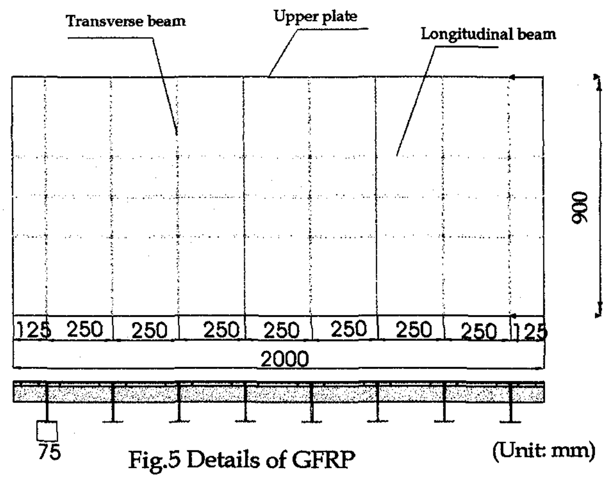

Fig.5 Details of GFRP

Table 1. GFRP Properties

Test Structure	Tensile Strength (MPa)		Tensile Elastic Modulus (GPa)		Compressive Strength (MPa)		Compessive Elastic Modulus (GPa)	
Parts	σ_{MD}	σ_{TD}	E_{MD}	E_{TD}	σ_{MD}	σ_{TD}	E_{MD}	E_{TD}
Upper plate (t=3 mm)	290.1	107.0	22.0	12.0	304.9	80.9	18.9	8.4
Longitudinal Beam (t= 8mm)	304.0	68.0	24.9	12.0	228.3	70.9	18.5	1.2
Transverse Beam (t=4mm)	331.1	24.9	26.0	8.9	412.4	89.7	2.5	8.7

Table 2. Concrete and Mortar Properties

	7-days	28-days	No.1	No.2	No.3	No.4	Cement Mortar	Epoxy Mortar
Compressive Strength (MPa)	29.0	33.3	37.5	37.9	38.8	36.9	45.8	56.4
Flexural Strength (MPa)	-	-	3.9	5.3	4.8	5.1	-	-
Young's Modulus (Gpa)	30.2	30.6	27.7	28.9	26.6	28.4	25.9	8.1

The cracked specimens were strengthened with GFRP unit, then fatigue loading was applied for half a million times with a load range (59-255) kN.

3. Experimental Results

The RC slab in the components of bridge is expected to be the most effected member by the GFRP strengthening process. The GFRP strengthening effectiveness can be easily noticed by comparing the stresses of the cracked and the retrofitted specimen from the same type. Table 3 presents the experimental results of all specimens.

3.1 Specimen Type 1

Figure 6 shows the load-stress curves of the RC slab main steel reinforcement for virgin and cracked specimen Type 1. During the static loading, the concrete of virgin specimen contributed the slab tensile stress up to 196 kN. After cracking, tensile stress was solely bared by the steel reinforcement.

3.2 Specimen Type 2

Figure 7 shows the load-stress curves of main steel reinforcement in the RC slab for specimen Type 2.The concrete in the tension zone of the RC slab was completely cracked before strengthening the specimen with GFRP unit. So, the specimen can be a good representation of a real super–structure such as steel I-girder bridge with cracked RC slab. The stress of the main steel reinforcement of the RC slab in the retrofitted specimen was 48.3% less than that of the cracked specimen for applied load of 255 kN. One of the main factors, which effected the strengthening process negatively, was the cracking of the non-shrinkage cement mortar.

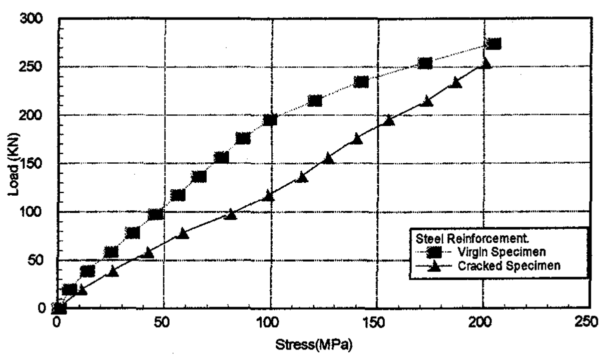

Fig.6 RC Slab Main Steel Reinforcement Load-Stress Curves for Specimen Type 1.

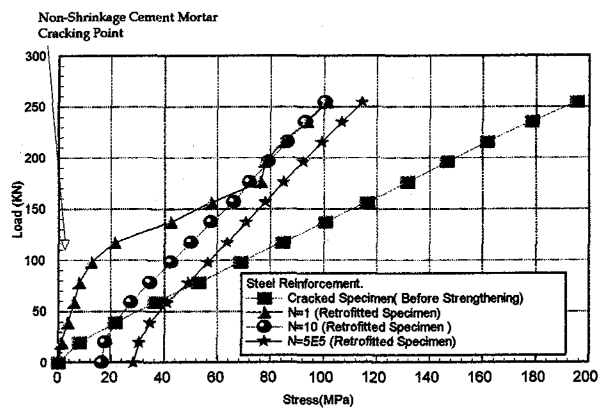

Fig .7 RC Slab Main Steel Reinforcement Load-Stress Curves for Specimen Type 2.

Table 3. Experimental Results

Specimen Type	State	GFRP Strengthening	Load Type	Gap	RC Slab Deflection (mm)	Main Steel Reinforcement Stress (MPa)	Steel I-girder Deflection (mm)	Stress of the Upper Flange in I-girder (MPa)		Stress of the Lower Flange in I-girder (MPa)	
								(*)	(**)	(*)	(**)
Type 1	Virgin	NO	Static	NO	3.09	188.9	1.35	-30.7	-49.3	55.8	70.1
	Cracked		Fatigue N=1		3.22	200.4	1.32	-31.1	-52.3	56.9	71.3
			Fatigue N=5E5		3.92	254.0					
Type 2	Virgin	NO	Static	NO	3.6	255.1	1.42	-38.4	-53.2	54.7	73.9
	Cracked		Static		2.96	195.3	1.26	-36.8	-48.0	54.1	69.8
	Retrofitted	Yes	Fatigue N=1	Non-shrinkage Cement Mortar With Plastic Cover	2.05	100.8	1.2	-26.4	-32.5	50.7	59.3
			Fatigue N=5E5		2.3	114.2					
Type 3	Virgin	NO	Static	NO	3.05	255.5	1.18	-32.3	-49.3	50.6	67.8
	Cracked		Static		2.63	189.9	1.09	-28.0	-43.4	50.6	64.6
	Retrofitted	Yes	Fatigue N=1	Non-shrinkage Cement Mortar	1.97	97.9	1.26	-32.1	-39.0	51.1	58.0
			Fatigue N=5E5		2.19	106.7					
Type 4	Virgin	NO	Static	NO	2.79	186.0	1.29	-18.7	-34.7	47.7	62.0
	Cracked		Static		2.32	127.8	1.14	-14.9	-27.5	46.9	58.6
	Retrofitted	Yes	Fatigue N=1	Epoxy Mortar	1.49	48.0	1.12	-8.0	-11.4	43.1	48.5
			Fatigue N=5E5		1.62	63.1					

(*) The results of strain gauge attached to the inside part of the flange.
(**) The results of strain gauge attached to the outside part of the

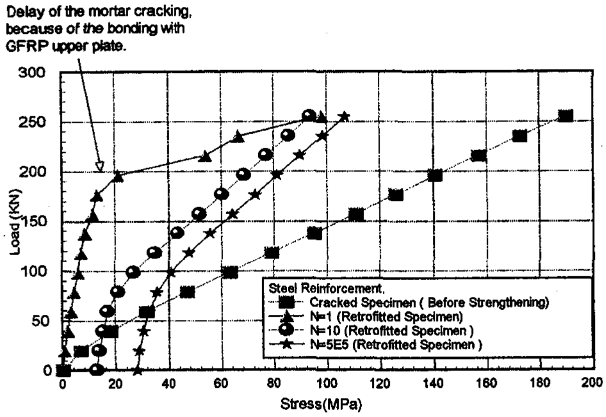

Fig 8. RC Slab Main Steel Reinforcement Load-Stress Curves for Specimen Type 3.

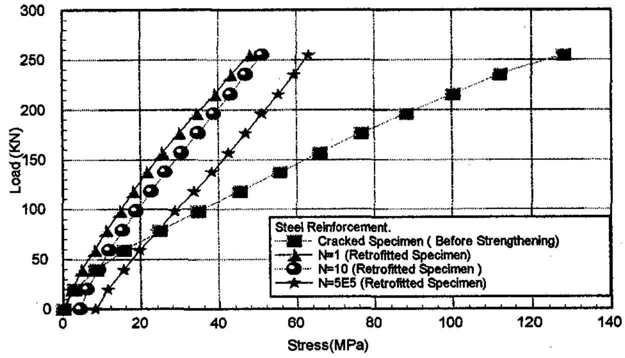

Fig 9. RC Slab Main Steel Reinforcement Load-Stress Curves for Specimen Type 4.

3.3 Specimen Type 3

The effect of the strengthening process at main steel reinforcement in the RC slab was better than that in specimen Type 2. The GFRP upper plate and the non-shrinkage mortar delayed the cracking of the mortar. This delay had good effects in reducing the steel reinforcement stress, as shown in Figure 8.

After the cracking of the non-shrinkage cement mortar the effectiveness of the strengthening process had become almost like the one in specimen Type 2, and the reductions of the stress in the RC slab main steel reinforcement was 48%,which is equal to that in specimen Type2, for applied load 255 kN.

3.4 Specimen Type 4

Figure 9 shows load-stress curves of main steel reinforcement in the RC slab. The strengthening results of specimen Type 4 were improved, due to the physical properties of the epoxy mortar. The high elastic behavior of the epoxy mortar prevented the mortar cracking, in its turn helped reducing the stress in the steel reinforcing bars. The stress reduction in the RC slab main steel reinforcement reached 62% for applied load 255 kN.

3.5 Strengthening Effectiveness

Table 4. shows a summary of the strengthening effectiveness. Strengthening specimen Types 2, 3, and 4 by GFRP unit had good effects not only in reducing stress and the deflection of the RC slab, but also had noticeable effects on the functionality of the steel I-girder. The GFRP unit caused large reductions in the stresses of the reinforcing steel. These reductions were 48%, 48% and 62% in specimen Types 2, 3 and 4, respectively.

Comparing the stress reduction ratios of the steel reinforcement of specimen Types 2 and 3 shows that the bonding in model Type 3 was not effective, due to the cracking properties of the non-shrinkage cement mortar. That was not the case in specimen Type 4, as the elastic properties of the epoxy mortar was able to prevent the occurrence of the cracks. Therefore, keeping the bonding of the epoxy mortar with the GFRP upper plate and the RC slab was completely intact and effective.

The strengthening results of the GFRP unit on the steel I-girders were not as good as those of the RC slab. The strengthening process was not able to reduce the stresses and the deflections of the steel I-girders in the same way it did in the RC slab. But it was able to

Table 4. Strengthening Effectiveness.

Specimen Type	Reduction (%)						
	RC Slab		Steel I-girder				
	Stress of main Steel Reinforcement	Deflection	Deflection	Stress of Upper Flange		Stress of Lower Flange	
				Outside	Inside	Outside	Inside
Type 2	48.3	30.8	5.0	28.3	32.2	6.3	15.2
Type 3	48.4	25.6	-13.5	-14.8	10.3	-1.0	10.3
Type 4	62.4	35.7	1.75	46.0	69.6	8.2	17.3

balance the stresses between both sides of the steel I-girder in a good way.

4. Comparison between Experimental and Analytical Results

Analytical studies were completed using FE package (LUSAS Version 12.3)[4),5)] to simulate the behavior of the cracked and the retrofitted specimen Types 2,3 and 4.

4.1 Analytical Assumption

(1) Assumption

It is worthy to list in brief the general assumptions, which were considered to simplify the analytical modeling.

(A) Full composite joints (rigid joint) to connect the GFRP unit with the Steel I-girders.

(B) Partial composite joints to connect RC slab with the upper flange of steel I-girder and the GFRP unit upper plate, which allow the horizontal displacement but prevent the upper flange of steel girder and the GFRP upper plate from moving up in case of the RC slab uplifting.

(C) The GFRP unit behaves elastically under static and cyclic loads.

(2) Loading

A static loading of 255 kN was applied to specimens by using 48x48x5 cm loading plate. The load was assumed to be distributed through the slab's height as it is shown in Figure 10.

(3) Material Properties

Material properties of concrete and steel were determined experimentally (Table 1 and 2) and incorporated into the models. The material tests showed that the used GFRP has four different Young's moduli in compression and tension for the TD and MD directions. Also every GFRP member, such as the upper plate, transverse and longitudinal beams, has different mechanical properties. This kind of material is so complicated to be modeled by F.E.M. A recent report on Engineering practice("Structural" 1984, chapter 3)[7)] and a state-of-art report on advanced composite materials in bridges and structures (Mufty et al. 1991)[8)] indicate that reinforced plastics generally behave linear-elastically up to failure. Therefore, a linear elastic behavior with general mechanical properties (29.43 GPa and 0.3 for the Young's modulus and the Poisson's ratio, respectively) were used in the study.

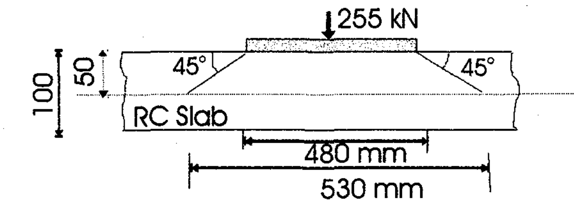

Fig. 10 Load Distribution through the Slab's Height.

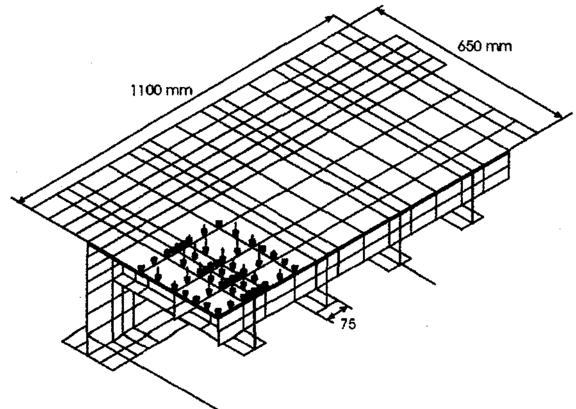

Fig 11 F.E.M Model for Specimen Reinforced by GFRP

4.2 Analytical Model for Cracked and Retrofitted Specimens

Due to double symmetry only ¼ the cracked and the retrofitted specimens were modeled by F.E.M. The cracked and retrofitted specimens were discretized into a mesh consisting of semiloof thin shell elements and three dimensional joint elements.

The semiloof shell element is a thin, eight nodded, doubly curved, isoparmentric element formed by applying Kirchhoff constraints to three dimensional degenerated thick shell element. The semiloof shell elements were used to model the RC slab , steel I-girder and the GFRP unit. The joint element, which was used to modeled the connections between RC slab ,steel I-girder and GFRP unit, is a three dimensional joint element connects two nodes by three springs. An initial gap was provided to the spring in the Z-direction, so that the partial composite action can be obtained.

In RC shell problem, the nonlinear behavior of the compressive concrete, concrete cracking and reinforcement response need a convenient representation across the structural thickness. In the present study a layered approached adopted to model the RC slab. Each layer contains stress points on its mid-surface. The stress components of the layer are computed at these stress points and are assumed to be constant over the thickness of each layer[6)].

Figure 11 shows F.E mesh for specimen reinforced by GFRP.

4.3 Analytical Results

Comparison between the analytical and the experimental load-stress relationships for specimen Types 2,3 and 4 in pre-strengthening and post-strengthening stages are shown in Figures 12,13 and 14, respectively. Also the load-deflection relationships for the same specimens are shown in Figures 15,16 and 17, respectively. The pre-strengthening results for specimen Type 4 is not presented due to a slight slip in the steel reinforcing bars of the RC slab.

The measured and the calculated results were in good agreement, any slight difference between them is due to the difficulties to provide the RC slab in the analytical models with initial cracks to be exactly like the case in the cracked and retrofitted specimens. Neglecting the initial cracking in the analytical study made the stiffness of the RC slab bigger than that in the experimental study. Attempts to reduce the stiffness of the cracked layers in the RC slab are going on for better modeling of the specimen behaviors.

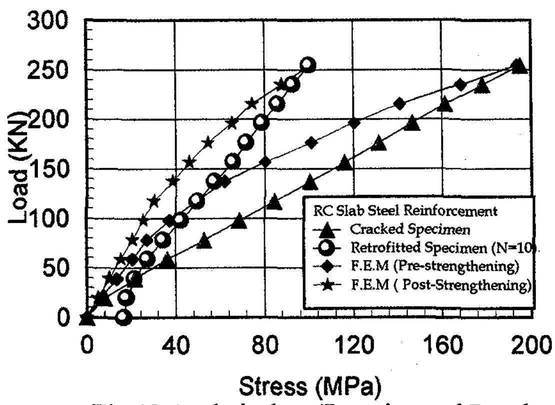

Fig.12 Analytical vs. Experimental Results
Specimen Type 2

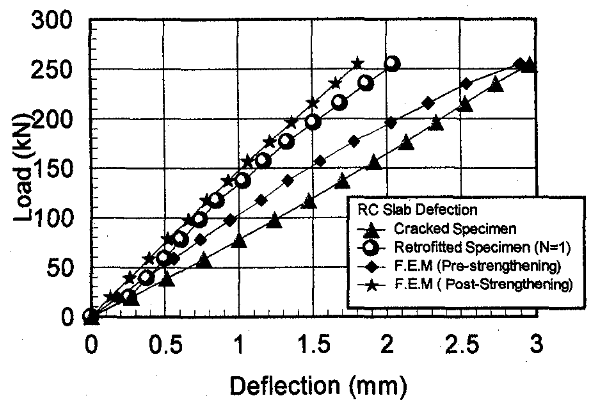

Fig.15 Analytical vs. Experimental Results
Specimen Type 2

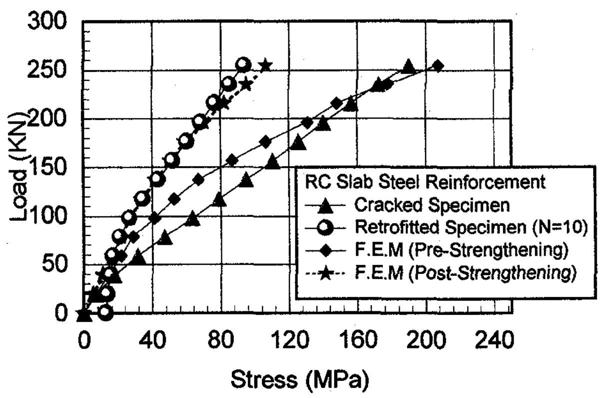

Fig.13 Analytical vs. Experimental Results
Specimen Type 3

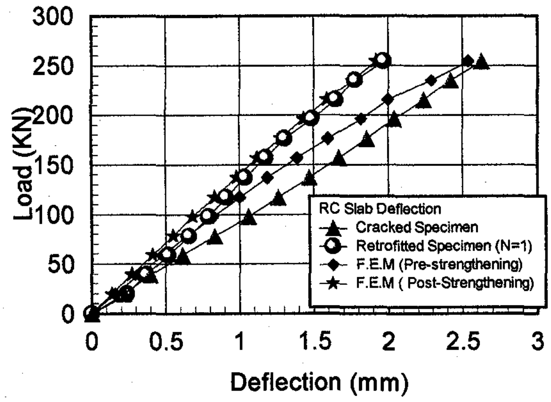

Fig.16 Analytical vs. Experimental Results
Specimen Type 3

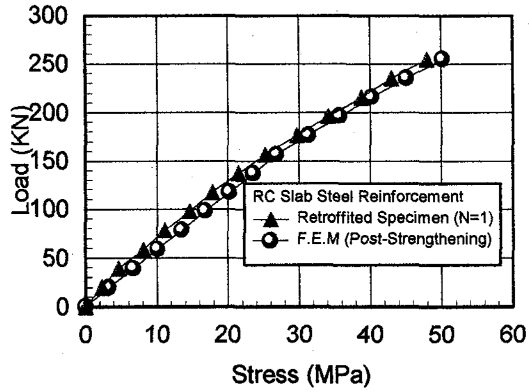

Fig.14 Analytical vs. Experimental Results
Specimen Type 4

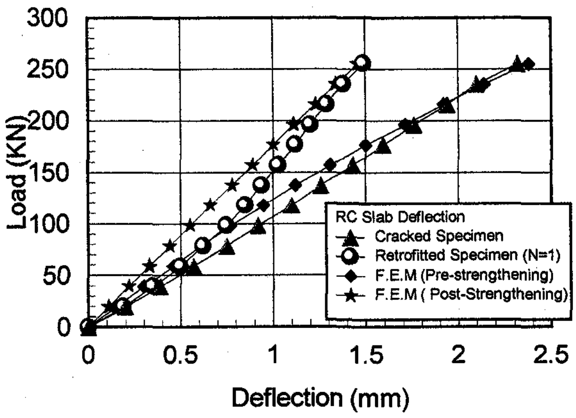

Fig.17 Analytical vs. Experimental Results
Specimen Type 4

5. Conclusions

The exploratory study has presented the feasibility of using GFRP members in combinations with RC slabs and steel I-girders for partial applications in strengthening bridges. The aim of the strengthening process is not just to present a method for enhancing the capacity of the RC slab, but it is also to improve all the functional capabilities of the steel girders.

According to the experimental and analytical studies, the following conclusions can be made;

(1) Strengthening specimen Types 2, 3 and 4 by GFRP unit had good effects not only in reducing the stresses and the deflections of the RC slab, but also on the functionality of the steel I-girders. Reducing the stresses of the main steel reinforcements of the concrete slab by 48%, 48% and 63% in model Types 2, 3 and 4 respectively were remarkable results, especially in the field of strengthening the concrete structures by GFRP.

(2) Comparing the stress and deflection reduction ratios of the specimen Types 2 and 3 show that the bonding of the cement mortar in Type 3 was a major factor in reducing the stress and the deflection of the RC slab up to the cracking of the mortar. After the bonding effects diminished, the GFRP strengthening contribution was found to be the same for Types 2 and 3. Type 4 showed the best loading capacity, as the properties of the epoxy mortar prevented the generation of cracks, allowing perfect bonding capabilities between the epoxy mortar, the GFRP plate and the RC slab.

(3) The strengthening process was not much effective in reducing the stresses and the deflections of the steel I-girders by the same ratio of the RC slab, but it generated a smooth stress distributions throughout the steel I-girder cross section. As a result, the steel I-girders were more stable and more capable of a better structural performance.

(4) The analytical results were in good agreement with the experimental results of the RC slab. Any slight divergence between the two results can be attributed to the finite elements modeling approximations that were made when constructing the numerical model.

According to this study, it has been proved that using GFRP, whose mechanical properties are in general less than that of the CFRP, for strengthening the existing steel bridges with RC slab, is sufficient and efficient to enhance the capacity of such structures. However, further investigations on the connections of GFRP-Steel and GFRP-Concrete are required. Also more optimum design for the GFRP members should be achieved.

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