Experiments and 3D analysis of ultimate bearing capacity of CFRP strengthened concrete slab

Su Yun-chao, Wang Wei & Li Shao-Fang
CCCC Road & Bridge Special Engineering Co. Ltd., China

ABSTRACT: Experiments and 3D analysis of ultimate bearing capacity on CFRP strengthening concrete slab were conducted to study the increasing of ultimate bearing capacity with CFRP strengthened and the changing of failure type. The results indicated: (1) When achieve the failure under ultimate bearing for the slab with CFRP strengthened, the utilization of CFRP is about 20% on the tensile strength.; (2) The experiment results is higher than theoretical calculation, but close to the 3D analysis, and the increasing of ultimate bearing capacity is about 75%.

1 INTRODUCTION

Concrete structure reinforced by CFRP has been a very mature application in foreign countries. Recently, some special researches had been carried out on CFRP reinforced concrete structure by domestic research institutions and academies; taking advantages of such domestic and foreign researches and studies, CFRP has been widely used in concrete structure reinforcement in China, especially bridge structure reinforcement. Specifically understanding the difference of results between contractual reinforcement and theoretical computation for CFRP reinforced concrete structure means a lot to the design and construction of CFRP reinforced concrete structure. Bangabandhu Bridge used to be the largest carriageway-railway bridge in south Asia, being subjected to long-term temperature stress and dissymmetry loadings, large quantity of cracks occurred in the main bridge and approach viaducts of the bridge. Repairing to the aforesaid cracks had been carried out twice; however, the cracks are still developing. CFRP has been bonded to both of the positive and negative moment zones on the main bridge of Bangabandhu Bridge. Due to transverse cracking were also found in the soffit of approach viaducts, targeted structural reinforcement had been performed. Bangabandhu bridge is now the bridge in the world to which most quantity of CFRP have been applied. Kinds of static tests and fatigue tests had been carried out in the positive and negative moment zones on the bridge; also, trial sections had been performed on the bridge site, in order to make sure of effect and detailed performance of the reinforcement, as well as to ensure effective bridge reinforcement. Major purpose of this article is to introduce content of the ultimate capacity test, carry out theoretical computation and finite element analysis in accordance with present specifications and design principles, compare computation results and achieved testing results for the differences among theoretical computation, finite element analysis and tests, specifically understand the loading mechanism, damage pattern of CFRP reinforced concrete structure, as well as bending capacity incensement the CFRP gave to concrete structure.

2 INTRODUCTION TO TEST

CFRP is a new material with features of light weight, high quality, durable, easy to apply, to transport and to store, therefore it has become one of the best bridge structure reinforcing materials. Bridge use CFRP is normally a kind of unidirectional fiber, to be bonded to the loaded zones by epoxy bonders, to enhance structure loading capacity by withstanding heavy loadings itself. Besides, when subjects to heavy loadings, the strain of CFRP is very low due to the high strength and high modulus of CFRP, thus, when beam deforms under loading, deformation of the beam is restrained, as well as concrete strain and cracking development, some concrete under tension also gets involved, the neutral axis rises slowly, thus concrete structure loading condition shall be improved.

There have been many static tests carried out to CFRP reinforced concrete structure both in China and in other countries, however, actual results will differ in different structures and different CFRP. Testing beam in this test is designed as per partial beams from Bangabandhu Bridge, CFRP is selected from material qualifies international standards for targeted testing study.

2.1 *Target of the Test*

Establish 3D model of CFRP reinforced concrete beam and carry out finite element analysis as well as theoretical computation before and after CFRP reinforcement, to acquire results both of the finite element analysis and the theoretical computation for ultimate beam capacity.

Prepare 2 sets (total 6pcs, 3pcs for each set) of concrete beam as per testing requirements, one set of which was not bonded of CFRP while the other set was. Perform same ultimate capacity test to both of the 2 sets for their respective ultimate capacity.

Compare all acquired results of theoretical computation, finite element analysis and ultimate capacity test before and after CFRP reinforcement: to understand difference among theoretical computation, finite element analysis and ultimate capacity test, to make sure of actual ultimate capacity incensement which CFRP reinforcement has brought to concrete beam, also to build up certain and clear study data model on ultimate capacity incensement by CFRP reinforcement, and provide guidance to constructive CFRP application in concrete structure reinforcement.

2.2 *Testing Specimens*

Six reinforced concrete testing beams were prepared for this test, sized: 400cm (long) × 65cm (wide) × 28cm (thick), concrete grade C45, 2 sets of laterally zygomorphic ϕ 12HRB400 rebar meshes were provided inside the beams.

3 pieces of the above mentioned beams were directly put into static test, the other 3 pieces were firstly sandblasted on the surface, and then bonded with 3 pices of 400cm long 10cm wide and 1.4mm thick CFRP in the direction of tension loading, to which later the beam will be subjected, as per specification,

During the preparation of concrete beams, as per testing specifications, strain gauges were attached to major load-bearing rebar inside beams, beam soffit cracking area, side cracking area and CFRP surface.

2.3 *Testing Method*

Load was applied on test beams with double-point symmetrical loading method, observe the ultimate capacity incensement by CFRP reinforcement. Load application was conducted with rigid frames, tension-compression sensor and jackscrews in different levels. During the loading, beam section deflection, strain of rebar within tension zone and concrete within compression zone in the simply-bending section of beam, and strain of CFRP, were observed with static/dynamic strain testing system and portable strain gauge; observe happening, growth and development of cracking with magnifying glass; under loads of each level, observe cracking width with 20 × microscope; set deflection observing points at mid-span and supporting points, measure deflection changes of concrete beams under loads.

3 FINITE ELEMENT ANALYSES AND THEORETICAL COMPUTATION

3.1 *Establishing Testing Parameters and Models*

Concrete grade was C45, E-modulus 3.35×10^4 N/mm2, fck=29.6 N/mm^2, ftk=2.51 N/mm^2, adopted plastic damage model. CFRP E-modulus was 1.5×10^5 N/mm^2, tension strength 2300 MPa, adopted liner-elastic model. Rebar was HRB400, E-modulus was 2×10^5 N/mm^2, yielding strength was 360 N/mm^2, adopted ideal elastoplastic model. Steel cushion blocks E-modulus was taken to be 2.1×10^5 N/mm^2, strength 210 N/mm^2

Build up units for concrete beams, CFRP, transverse and longitudinal rebar, cushion blocks and rebar mesh inside beam as per testing plan. Cushion blocks and CFRP were tied to concrete beams, to build up interaction between them, while transverse and longitudinal rebar were embedded into concrete beams to build up interaction between them. Displacements of cushion blocks under beams U2,U3 and UR1 was refrained and hinge supporting were build up. Beam ends were coupled with cushion blocks placed at loading points on the beam, and apply vertical loading in grades, 10kN each grade, as shown in the following Figure 1.

C3D8R 8-node hexahedron liner reduced integration 3D solid element was adopted to cushion blocks and concrete beams; S4R 4-node quadrangle limited thin film strain liner reduced integration shell element was adopted to FRP plates; T3D2 2-node liner 3D space truss element was adopted to rebar inside beams. Mesh block took 0.05m as basic unit, and considered to divide mesh block with 0.015m as the unit, in the range of 200mm at CFRP ends, as shown in the following Figure 2.

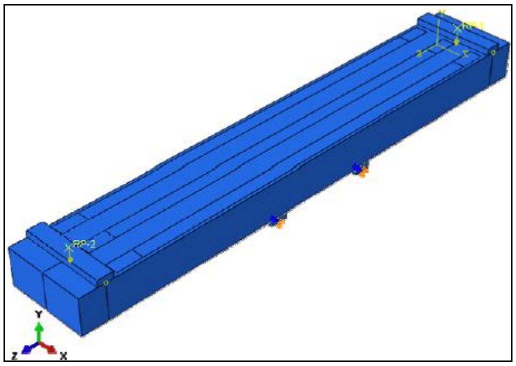


Figure 1. Loading model

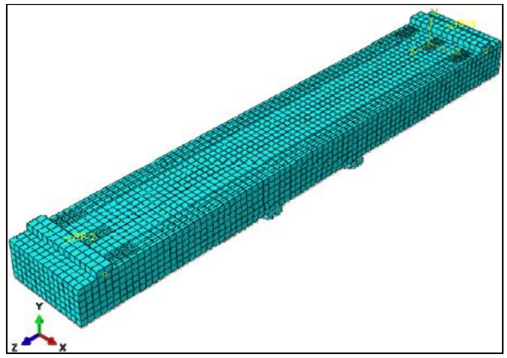


Figure 2. Block model

3.2 *Finite Element Analysis*

The following figures show stress of all the elements under ultimate loading:

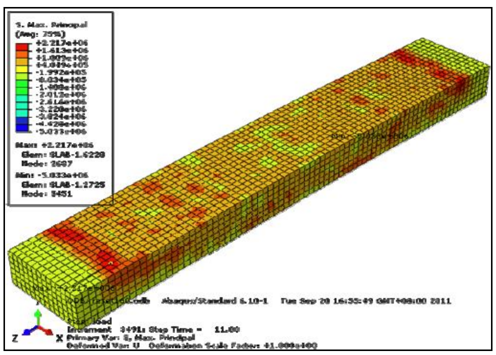


Figure 3. Cloud chart of concrete main tension stress

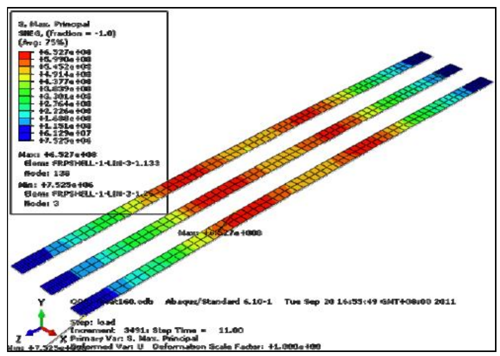


Figure 4. Cloud chart of CFRP main tension stress

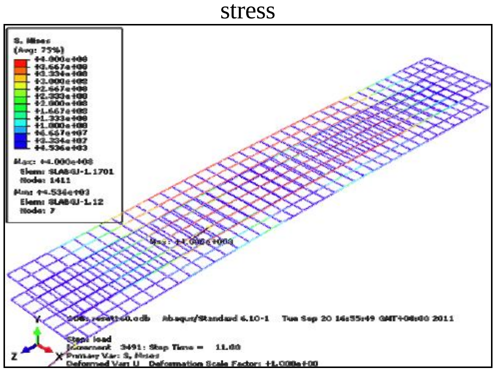


Figure 5. Cloud chart of rebar V. Mises stress

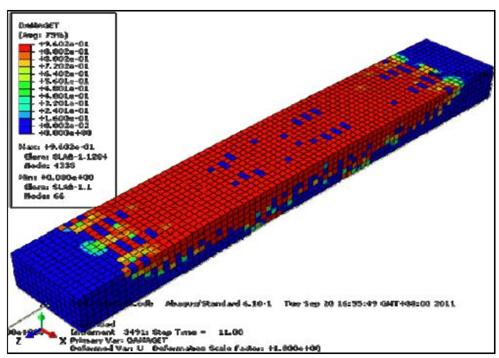


Figure 6. Cloud chart of concrete beam tension damage

Damage factor is the simulated mechanical state of concrete under tension as per energy equivalence principle, the more damage factor gets close to or equals to 1, the more concrete gets close to damage. Finite element analysis result was: before the concrete beam was reinforced with CFRP, its ultimate capacity was 86.8 kN.m; and after, its ultimate capacity was 154 kN.m.

3.3 *Theoretical Computation*

Capacity before CFRP reinforcement: as per *Design Specification for Highway Reinforced Concrete and Prestressed Concrete Bridge/Culvert* (JTG 062-2004), article 5.2.2, and related articles, rectangular section capacity should be calculated with the following formula:

$$M_u=f_{cd}bx(h_0-x/2)+f'_{sd}A'_s(h_0-a'_s)$$

After calculating, $f_{cd}=0.4\ f_{cu}=0.4\times45MPa=18$ MPa， $f_{sd}=f'_{sd}=f_y/1.15=384$ MPa， $x=(f_{sd}A_s-f'_{sd}A'_s)/f_{cd}b=53.5$ mm， $M_u=69.63$ kN.m.

Capacity before CFRP reinforcement: (to calculate capacity when $E_f=1.5\times10^6$ MPa) as per *Design Specification for Highway Bridge Reinforcement* (JTG/T J22-2008), article 7.6.2, and related articles, height x of area under compression in the rectangular section concrete when then CFRP reinforcement was bonded to the plane under tension, and tension strain of fiber polymer material at the plane under tension shall be simultaneously calculated with the following formula:

$f_{cd}bx+f'_{sd}A'_s=f_{sd}A_s+f_{pd}A_p+E_f\varepsilon_f A_f$ $(\varepsilon_{cu}+\varepsilon_f+\varepsilon_1)$ $x=0.8\varepsilon_{cu}h$ height of concrete area under compression $x<2a'_s$

$$M_u=f_{sd}A_s(h_0-a'_s)+E_f\varepsilon_f A_f(h_0-a'_s)$$

CFRP material property is: $E_f=1.6\times10^5$ MPa， $n_ft_f=1\times1.4$ mm=1.4 mm， $\varepsilon_{fu}=0.017$， $\varepsilon_{cu}=0.0033$

$$M_u=f_{sd}A_s(h_0-a'_s)+E_f\varepsilon_f A_f(h_0-a'_s)=179.88\ \text{kN.m}$$

3.4 *Measurements*

Three concrete beams without CFRP reinforcement were tested first, then the other three test pieces with CFRP reinforcement. Adopted method as: supporting at mid-span and applying load at both ends in 10 levels, until beam was damaged.

Figure 7. Loading beam without CFRP

Figure 8. Loading beam with CFRP

Figure 9. Damaged beam without CFRP

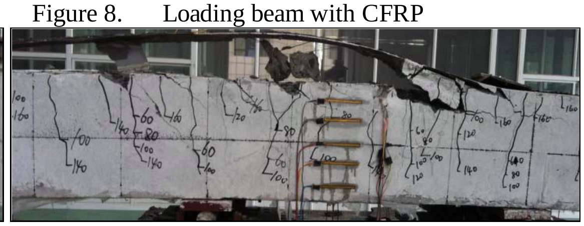


Figure 10. Damaged beam with CFRP

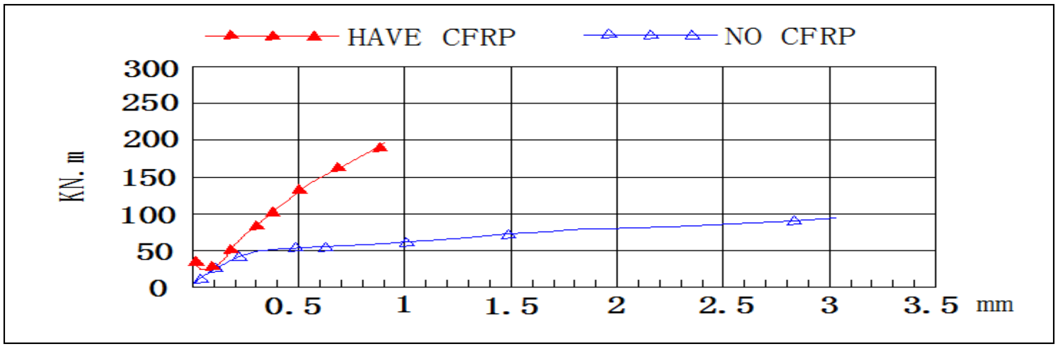
Entire loading progress of beam without CFRP was the loading progress of typical balanced-reinforced beam, which contains 3 stages as cracking, longitudinal rebar yielding, concrete damage in the compression area. In this test, rebar in tension area firstly reached its yielding strength, its stress kept unchanged while its strain increased, until the point when compression area concrete reached its ultimate compressive strain, longitudinal cracks occurred in the compression area, followed by the concrete crushing damage. Before this beams damaged, cracks in the beam developed severely, deflection was high, large plastic deformation occurred at beam section, sign of damage was apparent.

As for concrete beams with CFRP, in the early loading stage when 30% ultimate capacity was reached, cracking sound made by CFRP when they came off the concrete beam became detectable, and became louder as the loading level went up. Peeling of CFRP firstly happened in mid-span, when 90% ultimate capacity was reached, CFRP was peeled off from mid-span concrete and this peeling went on to both ends of the beam as loading went up. When damaging loading was reached, slip-off happened on one beam end CFRP, which completely went off from beam end concrete and flipped up. When ultimate capacity was reached, no compression area concrete was crushed. During the peeling, in mid-span, the adhesive used to bond CFRP to concrete was peeled off at large areas due to bonding failure between adhesive and concrete, beam end CFRP slipped off adhesive, a few bonding failure between adhesive and concrete happened, cracking shape was wedge shaped, ends were narrow and middle was wide.

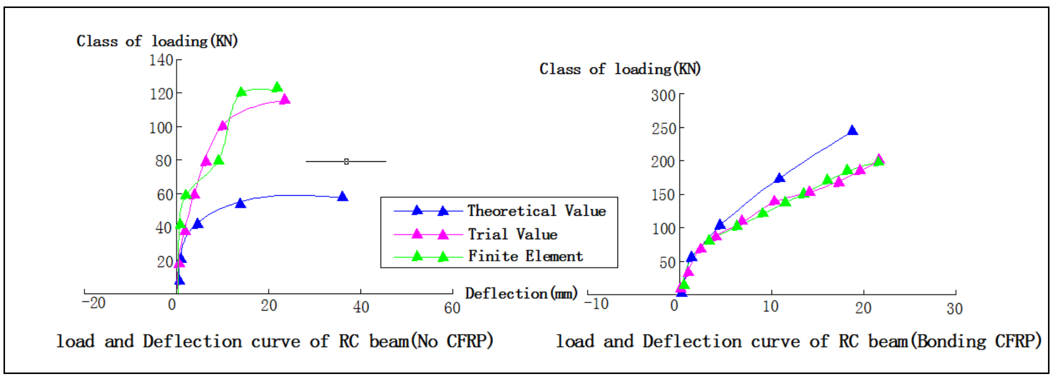
Ultimate capacity of three specimens concrete beam without CFRP was respectively 89.6kN.m, 85.4 kN.m, 97.3 kN.m; while other three specimens with CFRP was 154.7KN.m, 144.2KN.m and 179.9KN.m.

4 ANALYSIS RESULTS

4.1 *Concrete Loading Crack Width Comparison*



4.2 *Concrete Loading Deflection Comparison*



4.3 *CFRP Stress when Beam Ultimate Damage Happened*

Beam	No.	CFRP strength (MPa)	Ultimate CFRP stress when peeling damage happened (MPa)	Ratio of CFRP capacity performance (%)
Three concrete beams with CFRP	4	2300	563	24.48
	5		445	19.35
	6		589	25.61

When concrete beam ultimate damage happened, CFRP was peeled off concrete from mid-span to both ends, bonding between CFRP adhesive and concrete was damaged, at the time point of peeling off max stress of CFRP was reached, and at the very same time point, CFRP capacity performance was around 20%.

4.4 *Comparison between Theoretical Computation and Testing Results*

Beam	No.	Ultimate capacity when beam damage happened（KN.m）		
		theoretical computation	Finite element analysis	Testing
concrete beams without CFRP	1	69.63	86.8	89.6
	2			85.4
	3			97.3
concrete beams with CFRP	4	179.88	154	154.7
	5			144.2
	6			179.9

5 CONCLUSIONS

Max average cracking width when ultimate damage of concrete beam without CFRP happened was 2.75mm, while the one 0.604mm. Max average deflection of concrete beam without CFRP when 100KN loading was applied was 11.23mm, while the one with CFRP was 6.54mm. CFRP has very good restrain to concrete beam cracking, and can lower beam deflection apparently under heavy loading. CFRP capacity performance to CFRP reinforced RC (reinforced concrete) when beam ultimate damage happened is around 20%.

Acquired average concrete beam ultimate capacity from testing before and after CFRP reinforcement was respectively 90.77 KN.m、159.6 KN.m, ultimate capacity had been actually increased for around 75.8%. The average actual testing value was higher than theoretical computation and finite element analysis result, actual testing result was very close to finite element analysis result. When carrying out similar construction reinforcement simulation computation, adopting finite element analysis will acquire results closer to actual testing results, therefore it has better referencing value than theoretical computation.