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External Reinforcement of Concrete Beams Using Fibre Reinforced Plastics

Renforcement de poutres en béton à l'aide de plaques composites

Aussenliegende Bewehrung von Betonbalken mittels faserverstärkten Kunststoffen

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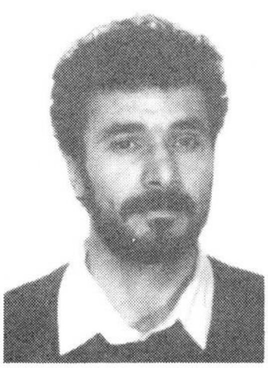

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SUMMARY

Strengthening of concrete structures in situ with externally bonded fibre-reinforced plastic (FRP) using epoxy resins appears to be a feasible way of increasing the capacity and stiffness of existing structures. A series of 32 small beams strengthened using FRP plates was tested to failure under four-point bending to measure load versus deflection and compare with predicated value in order to study the effectiveness of the different two-part epoxy and FRP types. An iterative analytical method capable of simulating material non-linearity and slip bonding based on the compatibility of deformations and equilibrium of forces was developed to predict the ultimate forces and deflections.

RÉSUMÉ

Renforcer des ouvrages en béton à l'aide de plaques composites (FRP) collées sur la face extérieure, peut augmenter leur capacité et leur rigidité. Une série de 32 poutrelles renforcées par FRP a été testée jusqu'à la rupture pour étudier l'efficacité des différentes colles et FRP. Un nouvel essai a été proposé pour déterminer les propriétés mécaniques de l'interface béton/colle/plaque et une méthode d'analyse itérative capable de simuler la non-linéarité des matériaux et le glissement des plaques a été développée pour prévoir le comportement des poutres renforcées et calculer les forces et les flèches ultimes.

ZUSAMMENFASSUNG

Für die nachträgliche Verstärkung bestehender Betontragwerke bieten sich faserverstärkte Kunststoffe mit Epoxidharzen an. Um die Wirksamkeit zweier unterschiedlicher Epoxid- und Faserkunststoffarten zu untersuchen, wurden 32 kleiner Versuchsbalken mit Klebebewehrung im 4-Punkt-Biegeversuch bis zum Bruch belastet, wobei das Last-Durchbiegeverhalten gemessen und mit vorausberechneten Werten verglichen wurde. Zur Bestimmung der Merkmale der Kontaktfläche (Beton/ Kleber/ Faserkunststoffplatte) wurden einzelne Klebestösse getestet. Mit einem iterativen Berech-nungsverfahren können die Werkstofflinearität und Verbundschlupf berücksichtigt und aus der Dehnungsverträglichkeit und dem Kraftgleichgewicht das Bruchverhalten bestimmt werden.

1. INTRODUCTION

Deterioration of older structures due to loss of material properties, inferior design, action of climate, or increases in traffic loads in the case of bridges, often requires the invention of new rehabilitation techniques. In recent years, with the development of strong structural adhesion, the use of steel plate, bonding on the tension face of beams is a relatively well known technique for strengthening. This technique is very successful by the simplicity and speed of application but it also has some disadvantages. The use of composite plate is an interesting alternative to avoid this inconvenience due to their high strength, high stiffness, resistance to corrosion and low weight. This paper briefly reports the results of tests carried out on different small beams strengthened by different FRP plates. The tests were divided into four series, in each series different adhesives were used to study the influence of a two-component epoxy on the ultimate capacity and the failure mode. To study the bond interface between plate/concrete and for the determination of an interface law (needed as input to the computational analysis), different single lap specimens on large scale were constructed and tested. An iterative analytical method capable of simulating the bond-slip and material non linearity based on the compatibility of deformations and equilibrium of forces was developed to predict load-deflection relationship, strength and failure mode.

2. EXPERIMENTAL PROGRAM AND TEST SPECIMENS

As shown in fig.1, each small beam had a cross-section of 70 mm x 70 mm and a total length of 280 mm. The experimental set-up consisted of a simple supported beam subjected to two concentrated loads, symmetrical about mid span.

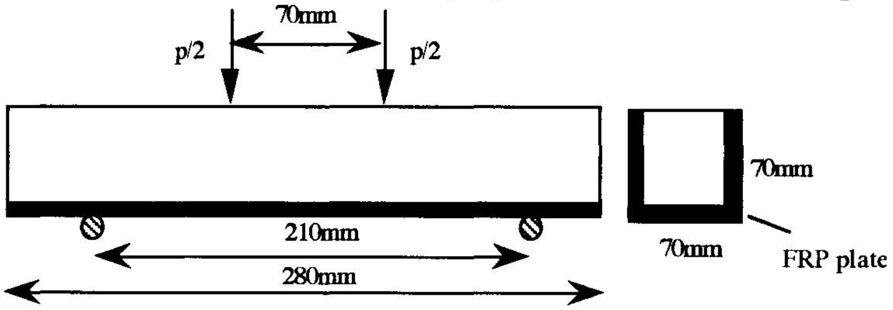

Fig.1. Beam test set-up

Similarly mixed concrete was used for all small beams The cement: sand: gravel proportions in the concrete mix were 1:2.2:3 by weight. The water/cement ratio was 0.52 and type I Portland cement (CPA55) was used. The maximum size of the aggregate was 12.5 mm. Twelve 160 mm x 320 mm concrete cylinders were cast and tested to determine the mechanical properties of the hardened concrete. The average compressive strength was 43.5 MPa and the flexural tensile strength was 6.35 MPa. The concrete had an average elastic modulus of 31 GPa for compression and 26 GPa for tension.

Plate	Code	Pattern	Weight (gr/m2)	Nominal thickness (mm)	Young's modulus (GPa)	Ultimate strength (MPa)
Glass1	1581	Satin	320	0.24	22	450
Glass2	1309	Satin	315	0.22	37.5	770
Carbon1	43377	Satin	285	0.33	57	560
Carbon2	46320	plaine weave	330	0.31	117	1350

Table 1 Physical and mechanical properties of plate

The fiber-composite material consisted of glass or carbon bonded together with an epoxy matrix. Four types of plates were utilized (70 mm x 280 mm). All the plates were subjected to longitudinal tensile tests (according to EN2561) to determine elastic modulus and ultimate strength. The FRP exhibited a linear elastic behaviour up to failure. Summary of the plate properties used in the experimental study is given in table 1. Four adhesives, including epoxies and acrylics were selected for exploration in this study after consultation with a number of manufacturers about this particular application. A summary of the properties of the adhesives is given in table 2.

Properties		Sikadur (31)	Sikadur (910)	Ciba (XB-5323)	Hexcel (HP-330)
Modulus	Mpa	8500	600	6200	-
com.Strength	Mpa	70-80	80	75	-
Ten.Strength	Mpa	20-30	20	24	21
Density	g/cm3	1.5	1.1	1.6	1.36
Viscosity	cPs	Thixotrope	2800	9000	Thixotrope

Table 2 Properties of adhesives

2.1 Preparation of test specimens and fabrication

The FRP sheets were bonded to the tension face and the lateral faces of the specimen, 28 days after casting. Before applying the epoxy the concrete surface was roughened by sand blasting and was cleaned using an airjet, to insure a good bond between the epoxy glue and the concrete surface. The surfaces of the FRP plates were sanded to remove the shine and were cleaned with propanol.

Beam	Fiber type	Plate thickness (mm)	Adhesive	Beam	Fiber type	Plate thickness (mm)	Adhesive
B111	Glass 1	0.75	Sikadur31	B113	Glass 1	0.75	Hexcel
B211	Glass 2	0.5	"	B213	Glass 2	0.5	"
B311	Carbon 1	0.65	"	B313	Carbon 1	0.65	"
B411	Carbon 2	0.7	"	B413	Carbon 2	0.7	"
B121	Glass 1	1.8	"	B123	Glass 1	1.8	"
B221	Glass 2	2.5	"	B223	Glass 2	2.5	"
B321	Carbon 1	2	"	B323	Carbon 1	2	"
B421	Carbon 2	2.6	"	B423	Carbon 2	2.6	"
B112	Glass 1	0.75	Sikadur910	B114	Glass 1	0.75	Ciba
B212	Glass 2	0.5	"	B214	Glass 2	0.5	"
B312	Carbon 1	0.65	"	B314	Carbon 1	0.65	"
B412	Carbon 2	0.7	"	B414	Carbon 2	0.7	"
B122	Glass 1	1.8	"	B124	Glass 1	1.8	"
B222	Glass 2	2.5	"	B224	Glass 2	2.5	"
B322	Carbon 1	2	"	B324	Carbon 1	2	"
B422	Carbon 2	2.6	"	B424	Carbon 2	2.6	"

Table 3 Notation of the small beams

The epoxy was hand mixed and hand applied at an approximate thickness of 1.5 mm using a metal spatula (the adhesive was applied to both the FRP and the concrete surfaces). Bond thickness was not specifically controlled, but excess epoxy was squeezed out along the edges of the plate, assuring complete epoxy coverage. After the plate was positioned, it was held down with concrete weights during a curing period of minimum three days. The specimens were instrumented with electrical strain gauges and a LVDT, the strain gauges were positioned at the plate and on the compression zone of the concrete,a LVDT was placed in the neutral axis at mid span. The notation of the small beams are given in table 3.

3. EXPERIMENTAL PROGRAM FOR DETERMINATION OF INTERFACE MATERIAL LAW

This section describes the experimental set up of the proposed single lap specimen, used for the determination of the interface properties and the study of the interaction between the concrete/glue/plate interface. Fig. 2 shows the details of the specimen proposed, which essentially consists of two L-shaped concrete blocks which are bonded by a FRP plate 2 mm thick and 140 mm wide. The distance along the glued line was kept constant at 180 mm and glue thickness was maintained as 2 mm.

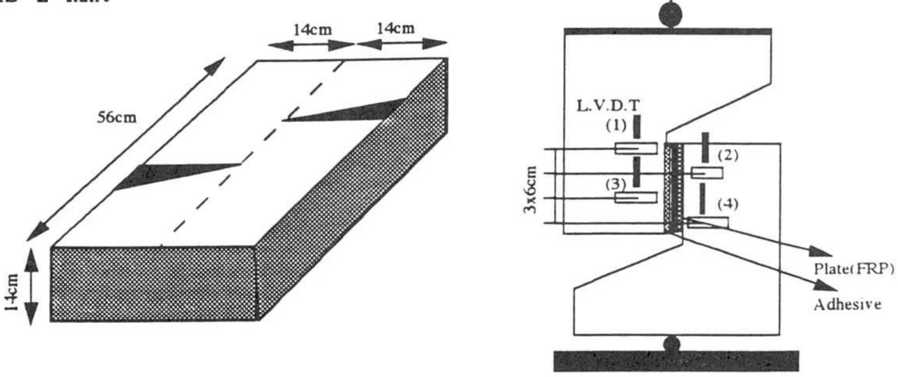

Fig. 2 Single lap specimen test details and experimental set-up

The whole assembly was subjected to a compression loading test. To determine the relative slip between the two blocks of concrete, the specimen was fitted with four LVDT's fixed at different points. The exact location of the LVDT's is shown in fig. 2. The loading was at a constant deformation rate with 0.2 mm per minute. Fig. 3 shows shear stress versus shear strain of the interface for the different interfaces types. shear stress versus the strain as determined from the LVDT reading divided by glue line thickness. The slopes of the plots indicate the shear modulus of the interface (Gint). The test results show a bi-linear behaviour between shear stress and bond slipping. The mechanical properties of the interface appears to be greatly dependent on the adhesive type. Table 4 lists the ultimate loads, shear strength and shear modulus (average result of different test), these results were used for construction of the interface model, needed as input to the computational analysis.

Adhesive	Ultimate load (KN)	Shear strength τmax(MPa)	Shear modulus Gint (MPa)
Sikadur910	77.5	4.6	50
Hexcel	141	8.5	160.5
Ciba	128	7.6	256
Sikadur31	146	8.8	240.5

Table 4 Result of shear test

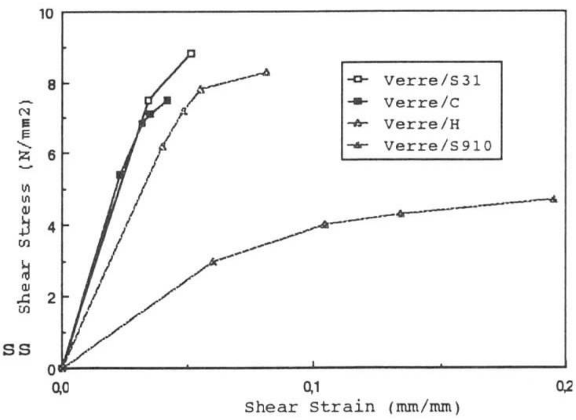

Fig. 3 Interface shear stress versus shear strain

4 THEORETICAL ANALYSIS

The method developed in this study to predict the strength and stiffness of RC beams strengthened by FRP plates is an iterative analysis technique, practicable by computer. Several assumptions commonly made in reinforced concrete theory are used, including a)plane sections remain plane, b)no slip occurs between any longitudinal reinforcement and concrete and c)stress-strain relationships of materials as determined by standard tests. This iterative analysis is capable of simulating material non-linearity including concrete cracking in tension and associated tension stiffening, plasticity of concrete in compression, plasticity of reinforcing steel and non-linearity due to bond-slip between plate and concrete (Fig. 4). This model is able to predict the ultimate strength in bending, the load-deflection characteristics and failure mode due to tensile fracture of the FRP, crushing of concrete in compression or plate separation.

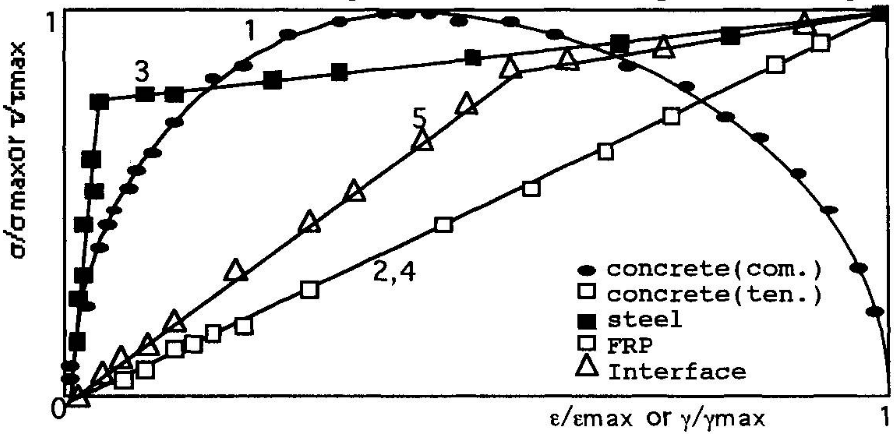

Fig. 4 Normalized stress-strain curved for idealized materials

4.1 Data required and calculating algorithm

At first, all dimensions of the beam (height, width, depth of steel, external plate dimensions) must be known. Also the span and the external load points are required to determine the load-deflection relationships. The entire stress-strain relationships of the steel, the FRP plate, the concrete (tensile, compression) and the interface material law must also be known with precision. First, a top fiber concrete strain and a neutral axis depth are assigned. The

Beam	Ultimate load(KN)			Failure mode	Beam	Ultimate load(KN)			Failure mode
	T*	T'**	E***			T	T'	E	
B111	47	46.6	41	FRP failure	B113	44	43.5	38	FRP failure
B211	50	49.5	45.5	"	B213	47	46.7	43.5	"
B311	67	66.3	65	"	B313	62	61	45	Plate separation
B411	92	89.1	63.4	plate separation	B413	85	83	44	"
B121	71	68.9	65	"	B123	65	63	62	"
B221	100	94.8	82	"	B223	92	88	63	"
B321	108	100.1	83.5	"	B323	99	90.8	64	"
B421	175	105	99	"	B423	162	92.8	63	"
B112	44	43.3	42	FRP failure	B114	47	46.7	45	FRP failure
B212	47	46.2	N.A	N.A	B214	50	49.6	41	"
B312	62	61	44	Interface	B314	67	66.4	62	Plate separation
B412	85	69	45	"	B414	92	89.3	55	"
B122	65	63.7	62	"	B124	71	70.1	72	"
B222	92	72	55	"	B224	100	93.5	75	"
B322	99	65.7	44	"	B324	108	96.5	68	"
B422	162	69.3	60	"	B424	175	98.2	84	"

* Theoretical ** Theoretical (With bond-slip effect) *** Experimantal

Table 5 Ultimate load and failure mode for each small beam

depth of the beam is divided into 200 slices, using the average strain for each slice, the compression and tensile stress can be found using the concrete stress-strain curve. Multiplying this by the area of the slice gives the compressive and tensile force. A similar method is used to determine the two tensile forces of the reinforcing steel and external plate. The tensile force of the external plate must be corrected due to the bond-slips in every iteration by determining the shear stress in the interface. The neutral axis is then adjusted until the sum of the compressive forces equals the sum of the tensile forces (equilibrium). When this is achieved, the moment and the curvature are determined. This calculation continues until the maximum strength of the beam.

5. RESULTS OF EXPERIMENT AND DISCUSSION

Experimental results for all specimens are summarized in table 5. Also the theoretical results using the iterative analysis are mentioned (with and without interface effect). The ultimate load of the control specimen (unplated small beam) is 10.5 KN. Out of the 32 small beams tested, 8 failed by FRP rupture, 6 by interface failure and the others by debonding due to plate separation. The results show that the adhesive's effect is very important in the success of this technique. Fig. 5 shows load versus deflection for two series tests using different adhesives. Notice that the epoxy properties are very important to improve cracking behaviour and stiffness.

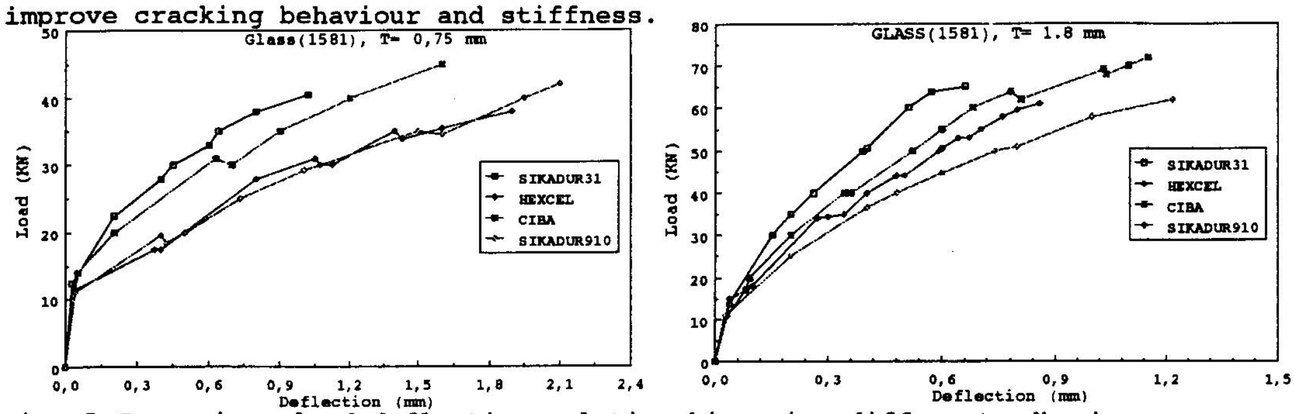

Fig. 5 Comparison load-deflection relationship using different adhesives

6 CONCLUSION

As result of the experimental and the theoretical studies, the following conclusions can be made:

1: The results of the test performed in this study indicate that significant increase in the flexural and shear strength can be achieved by bonding FRP plates to the tension face and the lateral faces of reinforced concrete beams.

2: The new single-lap test set-up introduced, proved to be a reliable specimen for measurement of the parameters necessary for the characterization of the concrete/glue/plate interface.

3: The selection of a suitable epoxy is very important in the success of this technique. The test results have shown that full FRP action can be achieved by using a rubber toughened epoxy.

4: The computer model in the form of a non-linear program developed in this study appears to be a good method for prediction of flexural strength, ultimate deflection and failure mode.

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